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STOCHASTIC LIFE CYCLE COST ANALYSIS MODEL FOR SUSTAINABLE PAVEMENT PRESERVATION TREATMENTS

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STOCHASTIC LIFE CYCLE COST ANALYSIS MODEL FOR SUSTAINABLE PAVEMENT PRESERVATION TREATMENTS

A DISSERTATION APPROVED FOR THE
DEPARTMENT OF ENGINEERING

BY

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This work is dedicated to the One who holds all understanding, knowledge and wisdom (Isaiah 40:14) and imparts it at will (Proverbs 2:6). Great is the LORD, and greatly to be praised (Psalms 48:1).

It is dedicated to those with whom I have been blessed; those He has given to be my daily SOJOURNING companions that make “hanging in there” much more enjoyable:

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ABSTRACT

Classic engineering economic theory was developed to furnish the analyst a tool to compare alternatives on a basis of life cycle cost. However, the theory is typically relevant to new construction projects with relatively long service lives. It does not accurately model the economic aspects of short-lived alternatives such as those that pavement managers must evaluate when seeking to select the most cost effective pavement preservation treatment. The field of pavement preservation seeks to "keep good roads good" and hence pavement preservation treatments are applied to extend the functional service life of the underlying pavement. As a result, no significant research has been done to quantify the actual service lives of the pavement preservation treatments themselves and furnish a model for the life cycle cost analysis of the treatments themselves. This dissertation fills those two gaps in the pavement economics body of knowledge. It proposes a new pavement preservation life cycle cost model and a methodology for using field test data to quantify the service lives of pavement preservation treatments for both asphalt and concrete pavements.

Economic and engineering technical data gathered from pavement preservation field trials can be quantified and correlated to produce meaningful, standardized economic and life cycle cost analysis information that furnishes pavement managers measurable failure criteria to estimate extended service lives of the nation's pavements. This cutting-edge research creates and validates two models, one for asphalt and the other for concrete, for developing life cycle cost analysis-based pavement preservation treatment design. The models are based on the fundamental but little used engineering economic theory of *equivalent uniform annual cost.* It is applied for the first time to pavement life cycle cost analysis and engineering technical data for highway pavement preservation projects.

Currently there is no system in place that correlates engineering technical data gathered from a wide range of competing field-tested pavement preservation options. The Oklahoma Department of Transportation pavement treatment decision-making processes are surveyed and current Federal Highway Administration life cycle cost analysis methods developed for new pavement construction projects are evaluated for applicability. The *equivalent uniform annual cost* life cycle cost analysis models eliminate some theoretical issues associated with the current Federal Highway Administration method and specifically address the short-term nature of pavement preservation treatments. Next, case studies are conducted using data from a three-year pavement treatment field trial and associated engineering technical data. *Net present value* output from those trials is used to validate the *equivalent uniform annual cost* life cycle cost analysis model results and confirm its future utility within current federal funding constraints for highway projects. Sensitivity analysis is conducted using both deterministic and probabilistic approaches, and finds that model output is sensitive to service life selection, agency costs (and associated underlying commodities) and discount rate. However, the new model furnishes a back check to permit the analyst the ability to determine whether or not these sensitivities are significant for a given project.

The models allow pavement managers to evaluate the cost effectiveness of competing pavement preservation treatment alternatives on either a deterministic or stochastic life cycle cost basis. It does so by calculating the *equivalent uniform annual cost,* which allows treatment-specific input values. The model accommodates the pavement management programming process for rehabilitation or reconstruction by furnishing a rigorous methodology to rationally truncate service lives, which is new to the FHWA life cycle cost procedure. User costs are calculated and incorporated. Additionally, the use of microtexture and macrotexture deterioration models provide local pavement condition data that correlate with service life and pavement life extension input values. This allows the extent of variability in these parameters to be exposed via sensitivity analysis and thereby enhance the credibility of results. Treatment-specific input values, such as expected service life and pavement life extension, allow the pavement manager to intuitively analyze the life cycle cost analysis results. Additionally, the research concludes that a life cycle cost analysis model based on *equivalent uniform annual cost*, rather than *net present value*, specifically addresses the relatively short term nature of pavement preservation treatments. It allows the engineer to better relate treatment life cycle cost output to annual maintenance budgets and specifically determine the most cost effective pavement preservation treatment for a given project.

1.0 INTRODUCTION

Sustainability has become an issue as state transportation agencies are increasingly challenged with "high user demand, stretched budgets, declining staff resources, increasing complexity, more stringent accountability requirements, rapid technological change and a deteriorating infrastructure" (FHWA, 2007a). A sustainable solution, *pavement preservation*, is currently being implemented. It will be instrumental in addressing pavement system needs by "keeping good roads good" instead of allowing them to deteriorate to the point of no return (Galehouse et al. 2003). According to the Federal Highway Administration, "[State transportation] agencies are focusing on maintenance and rehabilitation of existing infrastructure to a greater extent than ever before" (FHWA, 2002). It is expected that pavement preservation will become the core of all future highway programs (FHWA, 1998). Oklahoma is certainly one of those agencies for which these statements apply, as evidenced by its 2010 Asset Preservation Plan that states, "The preservation of our existing transportation system is an absolutely critical part of the Department's mission" (ODOT, 2010). Preservation is especially critical in Oklahoma due to its relatively smaller transportation budget (Gransberg et al. 2009).

1.1 BACKGROUND AND MOTIVATION

The use of economic analysis, specifically life cycle cost analysis (LCCA), to achieve the cost effectiveness by quantifying value for money in support of transportation decision making, is one way to promote sustainability in transportation (FHWA, 1999; FHWA, 2009). It also can provide economic justification for transportation decisions and pavement preservation (Bilal et al. 2009; Peshkin et al.

2004; AASHTO, 2001; FHWA, 2001). LCCA is considered a powerful project evaluation tool, yet its application is not wide-spread due to the complexity and challenges associated with engineering economic analysis theory and its application (Reigle and Zaniewski, 2002; FHWA, 1999). LCCA is rarely used at the pavement preservation level (Bilal et al. 2009; J. Hall et al. 2009; Monsere et al. 2009; Cambridge et al. 2005). State highway agencies (SHAs) have been experimenting with various LCCA tools (Hall et al. 2009), like FHWA *RealCost*, but none have been found to be consistent with project-implementation level (FHWA 2009, 2007, 2005, 2003). "Models, methods and tools to construct and analyze economic tradeoffs are still being developed" (FHWA, 2007a) as the LCCA demand grows and "will undoubtedly continue to grow as long as the public and policy makers demand better management of scarce resources in the long run" (Ozbay et al. 2004).

This research seeks to extend the previously published equivalent uniform annual cost (EUAC) LCCA deterministic model (Pittenger et al. 2011) and to identify and analyze current methods for determining stochastic life cycle costs of pavement preservation treatments. It will explore the relationship between construction cost volatility and LCCA of pavement preservation treatments (PPTs). It seeks to determine whether stochastic methods provide different results than deterministic methods at the project level that would influence pavement preservation decision making. This research seeks to provide a stochastic LCCA tool specifically for evaluating and comparing the economic impact of pavement preservation treatment alternatives for asphalt and concrete pavements. The research addresses the following question:

> *Does stochastic life-cycle cost analysis produce a different result and more meaningful than deterministic life-cycle cost analysis for pavement preservation treatment decisions?*

Answering this question requires a thorough investigation of current pavement life-cycle cost analysis methods and the applicability of probabilistic approaches to the topic.

In addition, the research seeks to demonstrate that engineering technical data gathered from a wide range of competing field-tested pavement preservation options can be correlated with an analysis of their respective short and long-term costs, benefits and value. Coupling LCCA results with field performance data is one way to gauge a pavement treatment alternative's *economic efficiency* (Bilal et al. 2009). Currently, there is no system in place that correlates engineering technical data gathered from a wide range of competing field-tested pavement preservation options with an analysis of their respective short and long-term costs, benefits and value.

1.2 RESEARCH OBJECTIVE

There are four specific research objectives and hypotheses related to answering the research question:

<u>Objective 1:</u> Create deterministic and stochastic EUAC models for evaluating asphalt and concrete pavement preservation treatment alternatives.

Hypothesis 1: Stochastic LCCA will produce a different result than deterministic LCCA for pavement preservation treatment (PPT) evaluation.

Objective 2: Understand the relationship between construction cost volatility and life cycle cost analysis of pavement preservation treatments.

Hypothesis 2: Construction cost volatility will have a material effect on PPT LCCA.

Objective 3: Understand sensitivity of deterministic and probabilistic models to input values.

Hypothesis 3: Probabilistic models will expose sensitivities to input values concealed in deterministic models.

Objective 4: Demonstrate how FHWA-recommended probabilistic methods can be adapted to PPT alternative analysis using EUAC.

Hypothesis 4: FHWA-recommended probabilistic methods can be adapted to EUAC PPT.

Tasks undertaken to meet these objectives and test the hypotheses are located in Section 1.4 - Research Methodology, along with chapter references so that the findings can easily be located throughout this writing.

1.3 LITERATURE REVIEW

1.3.1 Pavement Preservation Literature

It costs *significantly* more to fix a pavement in poor condition than it does to maintain one in fair condition (Stroup-Gardiner and Shatnawi, 2008; TRIP, 2001; AASHTO, 2001) because it “requires extensive and disruptive work” (FHWA, 1998). The result is “a gradual decline in the number of miles an agency could treat each year and a decrease in the overall condition of the pavement network” (Peshkin, et al. 2004), as well as an increase in the "potential for accidents, injuries and fatalities among the motorists and road workers" (FHWA, 1998).

The implementation of pavement preservation practices is expected to address these challenges (FHWA, 1998). Pavement preservation is a critical component of the larger concept of *Transportation Asset Management (TAM)*, which "is the key to finding the most effective and cost-efficient balance of preserving, upgrading and replacing highway assets in [today's] environment" (FHWA, 2007a). TAM is an integrated approach to asset management and is being actively promoted as a "national priority" by AASHTO and FHWA (FHWA, 2007a). TAM application is currently in the case-study phase (FHWA, 2003a; FHWA, 2005; FHWA, 2007; FHWA, 2009).

Unlike the "reactive" nature of "Worst First" pavement maintenance and repair strategies, pavement preservation is a "proactive" approach to treating pavements before they fall into disrepair (FHWA, 2005a), in other words, "keeping good roads good" (Galehouse et al. 2003). This approach is illustrated in Figure 1.1.

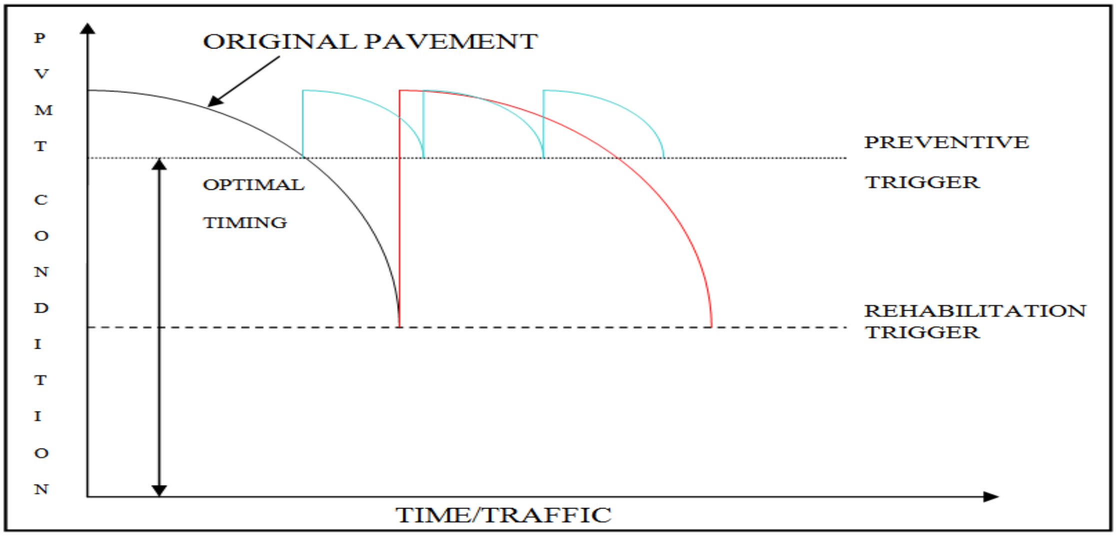


Figure 1.1 Proactive Pavement Preservation Approach versus Reactive Approach (Davies and Sorenson, 2000).

Theoretically, this proactive approach could reduce the amount of "costly, time consuming rehabilitation and reconstruction projects" and "provide the traveling public with improved safety and mobility, reduced congestion and smoother, longer lasting pavements" (FHWA, 2005a). A Pavement Preservation Program, according to the FHWA, consists primarily of three components: *preventive maintenance, minor rehabilitation* (non-structural) and some *routine maintenance.* The three components are implemented for the purposes of slowing deterioration and restoring serviceability of a pavement (FHWA, 2005a). Pavement preservation does not include *corrective (reactive)* or *catastrophic maintenance,* which only serve to restore serviceability (FHWA, 2005a). Although pavement preservation differentiates itself from corrective maintenance with its goal of extending the life of a pavement, it is not expected to increase strength or capacity like construction, reconstruction or rehabilitation (FHWA, 2005a).

The potential benefits of pavement preservation is being investigated as state transportation agencies (SHAs) search for answers, but the information that would facilitate the widespread implementation of preservation programs is lacking (FHWA et al. 2008; Gransberg et al. 2009). As with any paradigm shift, there is a learning curve. According to the *Transportation System Preservation Research, Development, and Implementation Roadmap, January 2008,* there is a "need for a comprehensive, large scale Research and Development program" in the area of preservation. The following is an excerpt:

> "Preservation practices can extend service life and can provide better, safer, and more reliable service to users at less cost. These points reflect common sense and intuitive conclusions, but many aspects of preservation actions or their effect on service have not

> been demonstrated quantitatively. The tools for pavement and bridge preservation exist, but guidelines for their application are often limited. Research, development and implementation have historically focused on construction and rehabilitation activities and not on the topics of preservation and maintenance."
> (FHWA et al. 2008)

This preservation research is well underway. The goal is to provide SHAs the information needed to apply the "*right* preservation action at the *right* time to the *right* pavement" with a focus on getting the "most benefit for the least cost" (FHWA et al. 2008).

Federal funding has also been facilitating the shift to a proactive, "Pavement Preservation" approach (FHWA, 1998).

> "With the passage of the *Intermodal Surface Transportation Efficiency Act* (ISTEA) of 1991, the National Highway System Act of 1995, and the new *Transportation Equity Act for the 21st Century* (TEA-21), pavement preservation activities are now eligible for Federal funding. ISTEA allowed Federal funds to be used for pavement preservation activities on Interstate highways. The National Highway System Act expanded that eligibility to all Federal-aid highways. TEA-21 emphasizes the need for transportation system preservation and for properly funded pavement preservation programs." (FHWA, 1998)

And the most recent modification, *The Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users* (SAFETEA-LU) in 2005 increased focus on preservation and system management (Sinha and Labi, 2007) by supporting a full suite of FHWA-designated pavement preservation treatments.

1.3.2 Pavement Texture Literature

Pavement preservation treatments restore *skid resistance* to a pavement surface. This is perhaps the most important engineering component of the road from a safety standpoint. From 1995-2001, nearly half a million injuries and over 6,000 fatalities were attributed to roadway accidents caused by slippery pavements (Noyce et al. 2005).

Slippery pavements are the result of several causes, but primarily are associated with the loss of both pavement surface *microtexture* and *macrotexture*. This makes the two parameters the most common pavement treatment performance metric (Gransberg and James, 2005; Roque et al. 1991). Essentially, microtexture is the quantitative measure of aggregate surface friction properties that contribute to skid resistance. Macrotexture is the quantitative measure of aggregate physical properties (size, shape and spacing) that contribute to drainability, thereby enhancing surface friction and skid resistance (Abdul-Malak et al. 1993). A European study found that increasing the pavement's macrotexture not only reduced total accidents under both wet and dry conditions but also reduced low speed accidents (Roe et al. 1998). Another author found the following: "The safety of a pavement surface is related to both the surface friction and the texture of the pavement. It is imperative that pavement surfaces provide adequate friction and drainage ability to minimize the number of accidents that occur as a result of frictional deficiencies" (Flintsch et al. 2003).

As a result, pavement managers must not only manage the structural condition of their roads, but also the skid resistance (NCHRP, 1989). In fact, it is possible for a structurally sound pavement to be rendered unsafe by a loss of skid resistance due to polishing of the surface aggregate or in the case of chip seals, flushing of the binder in the wheel paths (Patrick et al. 2000). This results in a safety requirement to modify the pavement surface to restore skid resistance. Many of the possible tools for restoring skid resistance, like chip seals, are also used for pavement preservation. Thus, maintaining adequate pavement skid resistance is also a pavement preservation activity (Moulthrop, 2003).

There is a wealth of information on skid resistance in the literature (Henry, 2000). However, most of the previous research has been safety related, developing the relationship between skid resistance and crashes. There is also extensive information about pavement surface treatments (NCHRP, 1989). However, the majority of the research has been in the laboratory and is focused on the material science. Very little substantive work has been done in the field regarding surface treatment performance, but the research that does exist is focused on short-term performance only (Owen, 1999). The FHWA Long Term Pavement Performance Program (LTPP) collects friction data as part of its standard protocol (Titus-Glover and Tayabji, 1999). However, the LTPP data largely relates to pavement mix design criteria. Although it does include data for chip seals, it does not collect data for any of the other potential pavement preservation treatments. Additionally, most of the extant research focuses on a single surface treatment without comparative analysis of other PPT options. Also making it more difficult for DOT pavement managers, much of the published research is commercial in nature and while completely valid, is suspected of containing a strong inherent bias toward showing the given product in its best light (ARRB, 2001; Vercoe, 2002; Bennett, 2007). Finally, with a couple of exceptions (Gransberg and Pidwerbesky, 2007; Gransberg and Zaman, 2005), virtually no research in this area has addressed the economic aspects of pavement retexturing in conjunction with the engineering aspects. Thus, the gap in the body of knowledge is the lack of engineering data correlated with a comparative economic analysis of different alternatives to restore skid resistance on a long-term basis.

1.3.3 Pavement Economics Literature

Budget shortfalls and infrastructure needs are growing and expected to reach critical levels in the next ten to twenty years (FHWA, 2008). Thus, SHAs are searching for ways to increase the cost effectiveness of the limited road maintenance funds (AASHTO, 2001). "The core of transportation decision making is the evaluation of transportation projects and programs in the context of available funding" (Sinha and Labi, 2007). Therefore, every programming framework should include an economic analysis mechanism for assessing the cost-effectiveness of alternatives considered for implementation (Sinha and Labi, 2007). Economic analysis is a vital component of Transportation Asset Management, and specifically, Pavement Preservation. It has long been promoted by the FHWA for application to "highway project planning, design, construction, preservation, and operation" (FHWA, 2003) for accountability (FHWA, 2007a). "Considering the annual magnitude of highway investments, the potential savings from following a cost-effective approach to meeting an agency's performance objectives for pavements are significant" (Peshkin, et al. 2004). This would allow agencies to stretch the budget to address sustainability needs in infrastructure and enhance stewardship.

The use of LCCA, to quantify the cost-effectiveness and identify the return, if any, on investment in transportation decision-making is one way to promote sustainability in transportation (FHWA, 2009; FHWA, 1999). It "will undoubtedly continue to grow as long as the public and policy makers demand better management of scarce resources in the long run" (Ozbay et al. 2004). The FHWA states the following purpose for LCCA use:

> "LCCA is an analysis technique that builds on the well-founded principles of economic analysis to evaluate the overall-long-term economic efficiency between [mutually exclusive] competing alternative investment options. It does not address equity issues. It incorporates initial and discounted future agency, user, and other relevant costs over the life of alternative investments. It attempts to identify the best value (the lowest long-term cost that satisfies the performance objective being sought) for investment expenditures."
> (FHWA, 1998a)

Although LCCA is considered a powerful project evaluation tool, its application is not wide-spread in transportation due to the complexity and challenges associated with engineering economic analysis theory and its application (Reigle and Zaniewski, 2002; FHWA, 1999). According to various syntheses, it is not commonly, if at all, being employed by frontline pavement managers to determine the most cost-effective pavement preservation treatment alternative for a given project (Bilal et al. 2009; J. Hall et al. 2009; Monsere et al. 2009; Cambridge et al. 2005).

Each state has three general processes that are based upon investment decision-making:

- a long-term, strategic planning process,
- a short term planning process,
- and an implementation process (FHWA, 1999).

LCCA application has generally been reserved for projects at the planning and design-level, not for the pavement-treatment-implementation level (CALTRANS, 2007; Cambridge et al. 2005; FHWA, 1999). This is evidenced by FHWA's LCCA *Interim Technical Bulletin* being addressed to assist state highway agencies in the application of

LCCA to determine the “long-term economic efficiency implications” of pavement design decisions (FHWA, 1998a). This research is interested in the implementation of pavement preservation treatment projects level of decision-making by the pavement manager. Hence, the literature review was initially focused in that subject area. Due to a limited amount of information regarding LCCA procedures employed at that level (Gransberg et al. 2009; Monsere et al. 2009; Bilal et al. 2009), however, the literature review expanded to the broader scope of LCCA application in transportation.

According to various syntheses, there is no consensus on how highway agencies determine the cost-effectiveness of pavement preservation treatment alternatives for a specific project at this time (Bilal et al. 2009; Monsere et al. 2009; Cambridge et al. 2005). “The emphasis upon economic cost analysis principles is recent, so models, methods, and tools to construct and analyze economic tradeoffs are still being developed” (FHWA, 2007a). State agency pavement treatment evaluation methods vary and can range from simple to complex. Some conduct in-house analyses (Cambridge et al. 2005), while others have outsourced the analyses at a high cost and desire in-house capability (FHWA, 2007). Some consider the initial cost of treatment and associated future maintenance, while some only consider the initial cost of construction and ignore long-term or life-cycle costs associated with those treatments (Monsere et al. 2009). Some do not consider user costs, although those costs have been shown to potentially contribute a notable difference between the life cycle costs of preservation treatment alternatives (Bilal et al. 2009).

There are a few LCCA models currently available for transportation use, such as FHWA *RealCost* that was created for design-level use (FHWA, 2004). However, according to a recent synthesis (Bilal et al. 2009), there are many project evaluation tools that could assist a pavement manager at the implementation level as the demand for pavement preservation grows, such as LCCA. But the question that state agencies must answer is how to implement LCCA, what level of complexity is desired and what type of inputs should be required (Hall et al. 2003). The FHWA states that the level of LCCA detail “should be consistent with the level of investment” (FHWA, 1998a). The level of investment of some activities at the implementation level can somewhat be inferred by the following FHWA statement: “When discounted to the present, small reactive maintenance cost differences have negligible effect on *net present value* [of pavement design alternatives] and can generally be ignored” (FHWA, 1998a).

1.3.3.1 Economic Analysis Case Studies

The FHWA has conducted a number of case studies to document LCCA use in transportation (FHWA, 2009, 2007, 2005, 2003). A Colorado DOT case study documents *RealCost* use and states that it has allowed the state to make the “best, long-range, long-term decisions” accorded to its planning and investment strategies (FHWA, 2009) but shows no evidence that it has been applied to pavement preservation/maintenance treatment decisions. The State of California Department of Transportation also uses *RealCost*, but reserves it for larger projects and exempts the smaller ones (CALTRANS, 2007).

Case studies have been conducted that involve the experimental use of LCCA at the implementation level, like in Hillsborough County, Florida (FHWA, 2005) and New York (FHWA, 2003). New York’s DOT (NYSDOT) case study conducted in 2003 reported attempts to apply LCCA to pavement treatment selection, but noted that LCCA tools for use at this level require improvement before implementation (FHWA, 2003). The NYSDOT also planned to “customize” the FHWA’s *RealCost* LCCA spreadsheet for project-level evaluation (FHWA, 2003). The *Ohio-Kentucky-Indiana Regional Council of Governments* case study also recognized an ongoing need for a project-level adaptable version of LCCA (FHWA, 2007). LCCA procedures modified specifically for implementation-level project evaluation were not found in literature.

1.3.3.2 FHWA LCCA Procedures/Methodology

LCCA can become quite complex, so an analyst should be judicious about the level of detail included (FHWA, 1998a). An analyst can simplify the analysis by including only differential costs, i.e. omitting those that cancel out, as well as disregarding those costs that contribute minimal to no impact on the final results, keeping in mind that discounting might render costs so (FHWA, 1998a). The FHWA offers “LCCA Principles of Good Practice” in its *Life Cycle Cost Analysis in Pavement Design, Interim Technical Bulletin* released in 1998, such as in selecting a discount rate. “Good Practice” is that *constant dollars* and *real discount* rate be used for the purposes of discounting future costs (i.e. omit inflation and effects). FHWA recommends a rate between 3-5% be used in analyses, which is consistent with the OMB Circular A-94. Other “LCCA Principles of Good Practice” are integrated with the LCCA procedures/methodology.

The following are LCCA procedures, as excerpted from the FHWA *Life Cycle Cost Analysis Primer* (FHWA, 2001) and the *Interim Technical Bulletin* (FHWA, 1998a):

- Step1: Establish design alternatives [and analysis period]

- Step 2: Determine [performance period and] activity timing
- Step 3: Estimate costs [agency and user]
- Step 4: Compute [net present value] life cycle costs
- Step 5: Analyze results
- Step 6: Reevaluate design strategies.

Step 1: Design Alternatives and Analysis Period

The first step in the procedure involves establishing strategies, i.e. associated rehabilitation and maintenance activities associated with each alternative expected over the analysis period (FHWA, 1998a). The analysis period can be selected by various methods when alternatives have differing performance periods for the purposes of comparing all alternatives over a “common period of time”, which is an engineering economic analysis principle (White et al. 2010). The general suggestion is that the analysis period be a standard length, such as 35-40 years (FHWA, 2004), and long enough to allow “at least one major rehabilitation activity” for each design alternative (FHWA, 2001). The *net present value* (NPV) method is the preferred analysis method, with the *equivalent periodic annual cost* (EUAC) only being used as a re-statement of the NPV (FHWA, 1998a).

Step 2: Performance Period and Activity Timing

The second step involves determining the performance period (i.e. cash flow diagram) for an alternative, which is the period that covers one life cycle of that alternative and is generally determined by the analyst’s judgment based on experience and historical data (FHWA, 1998a). Activity timing includes the determination of maintenance and other activity frequency associated with a specific alternative strategy, as established in step 1 (FHWA, 1998a). The performance period determination has a significant effect on the LCCA output, and should be considered with care (FHWA, 1998a).

Step 3: Agency and User Costs Estimation

The third step involves determining or estimating agency and user costs for each of the competing alternatives. Agency and user costs are determined for each of the competing alternatives and future costs are "discounted" to determine the NPV.

Agency costs are those costs directly incurred by the agency, such as costs for project supervision and administration, materials, labor and traffic control for the initial installation. It also includes any associated rehabilitation and maintenance costs required over the life cycle of the alternative. These costs are generally based on current and/or historical costs.

According to the FHWA, *salvage value* is the value associated with each alternative determined at the point of analysis termination and involves any *residual value* (value attributed to the reclaimed materials) or any *serviceable life* (value attributed to alternative "life" that exists after analysis termination). It should be attributed to alternatives appropriately for the purposes of analysis (FHWA, 1998a).

Sunk costs, which are costs occurring pre-analysis, should not be included in the analysis unless they specifically apply to the alternatives that are to be compared (FHWA, 1998a).

User costs relate to costs incurred by the traveling public in both *work-zone* and *non-work-zone* phases for a given extent of road for which alternatives are being compared (FHWA, 1998a). Generally, the user costs incurred during *non-work-zone* phases are disregarded in LCCA due to a lower likelihood of difference among alternatives (FHWA, 2001). Differing [work zone] user costs among alternatives are pertinent to the analyses, and generally include “[time] delay, vehicle operating, and crash costs incurred by the users of a facility” (FHWA, 1998a).

> “User costs are heavily influenced by current and future roadway operating characteristics. They are directly related to the current and future traffic demand, facility capacity, and the timing, duration, and frequency of work zone-induced capacity restrictions, as well as any circuitous mileage caused by detours. Directional hourly traffic demand forecasts for the analysis year in question are essential for determining work zone user costs.” (FHWA, 1998a)

It is suggested that “different vehicle classes have different operating characteristics and associated operating costs, and as a result, user costs should be analyzed for at least three broad vehicle classes: Passenger Vehicles, Single-Unit Trucks, and Combination Trucks” (FHWA, 1998a). User costs are generally translated into monetary terms (for the purposes of analysis) and can be ascertained from various sources, and those costs escalated with the use of the transportation component of the *Consumer Price Index (CPI)* (FHWA, 1998a). *Delay* costs are calculated by multiplying the unit of “wait” time attributed to each alternative’s work-zone timings by the monetary unit (FHWA, 1998a). *Vehicle operating costs* (VOC) are calculated by multiplying the vehicle-related cost factors attributable to each alternative’s work-zone timings by the monetary unit (FHWA, 1998a). Crash costs are calculated by multiplying the number of specific types of crashes by their respective monetary unit (FHWA, 1998a). User costs as a result of detours are typically assigned a cents-per-mile rate, such as that used by the Internal Revenue Service for mileage allowance (FHWA, 1998a).

Step 4: Compute Life-Cycle Costs (NPV)

As excerpted from FHWA’s LCCA Interim Technical Bulletin:

> “Economic analysis focuses on the relationship between costs, timings of costs, and discount rates employed. Once all costs and their timing have been developed, future costs must be discounted to the base year and added to the initial cost to determine the NPV for the LCCA alternative. The basic NPV formula for discounting discrete future amounts at various points in time back to some base year is:
>
> $$\text{NPV} = \text{Initial Cost} + \sum \text{Rehab Costs}\ [1 \div ((1 + i)^n)]$$
>
> Where: i = discount rate, n = year of expenditure and $[1 \div ((1 + i)^n)]$ = PV formula.” (FHWA, 1998a)

Step 5: Analyze Results

LCCA has two possible computational approaches: *deterministic* (for deterministic LCCA) and *probabilistic* (for stochastic LCCA) (FHWA, 1998a), which are fully discussed in the next section. To summarize, the deterministic approach involves using discrete input values and a single output value (FHWA, 2001). A *sensitivity analysis* should be conducted so that the analyst may determine the level of variability of a given input value relative to the output (FHWA, 1998a). For example, an analyst chooses a 4% discount rate to do the LCCA, which results in output (a preferred alternative). The sensitivity analysis will allow the analyst to conduct a “*What if*” scenario to determine if choosing a 5% discount rate would result in different output (different preferred alternative). This exercise must be repeated individually for other input variables to discover any effect on overall LCCA results. The sensitivity analysis is limited in application with regard to being unable to analyze simultaneous variability (FHWA, 2001).

The probabilistic approach involved with stochastic LCCA involves analyzing input value probability based on the full range of *“What if”* scenarios allowed by sensitivity analysis by providing a "distribution of PV results" (FHWA, 2001). It is generally accompanied with a *risk analysis,* which unlike sensitivity analysis, does allow the analyst to determine the level of certainty with regard to simultaneous variability in all input parameters (FHWA, 1998a).

Step 6: Reevaluate Design Strategies

LCCA results should be coupled with other decision-support factors such as "risk, available budgets, and political and environmental concerns" (FHWA, 2001). A decision-analysis framework can offer insight as to relative differences between alternatives in the areas of "uncertainty, objectives and trade-offs", but should not be expected to offer *the* answer (FHWA, 1998a; Clemen, 1996). The analyst would still need to rely on judgment in the final decision-making phase (Clemen, 1996). Considering cost-effectiveness without also considering treatment effectiveness (and vice versa), or the *economic efficiency* of a treatment, may not provide the whole picture either and may result in not selecting the "best" alternative (Bilal et al. 2009).

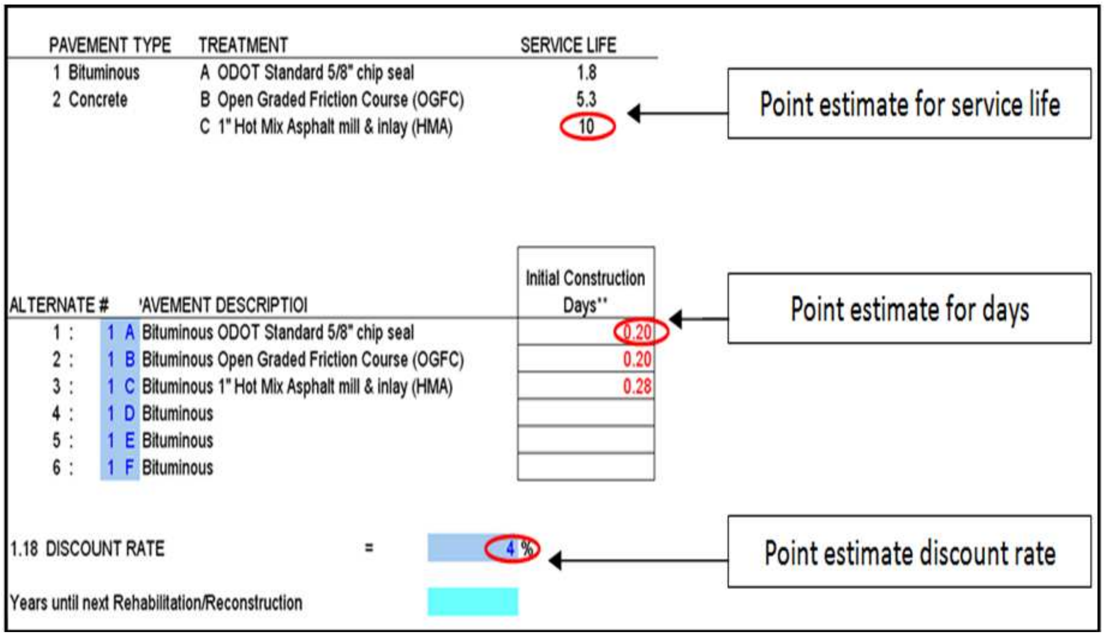
1.3.3.3 Deterministic and Probabilistic Approaches

LCCA can be conducted deterministically or probabilistically (Step 5 of the FHWA LCCA Good Practices), depending on the level of input uncertainty (FHWA, 1998a). Much debate continues about the validity of LCCA output when inherent uncertainty is not addressed, hindering the agencies' ability to justify decisions (FHWA, 2003). Transportation decision making is subject to scrutiny because of its public nature. Transportation agencies are charged with stewardship and therefore must provide justification for decision making and its inherent uncertainties. Major uncertainties in transportation projects are generally related to cost and performance (service life) and contribute to the complexity and difficulty associated with transportation decision making. Uncertainty about future events, when quantified, is known as *risk* and can be incorporated into the decision-making process. Decision analysis offers a systematic method of examining decision-related uncertainties for the purpose of making and justifying a better decision (Clemen, 1996).

A deterministic-type LCCA is less complex than a stochastic type and can be adequate, and therefore appropriate, when uncertainty is not expected to have a material effect on the outcome of the economic analysis (FHWA, 2003). However, if uncertainty could materially alter the outcome, the deterministic approach is not recommended because of its inability to effectively analyze simultaneous variability (FHWA, 2003). The probabilistic approach is used to address these issues. Stochastic LCCA specifically addresses and quantifies the *uncertainty* associated with a transportation project decision and contributes to decision validation (FHWA, 1998a).

Deterministic Approach

The deterministic approach involves using discrete input values (point estimates) that result in single output values and has been the traditional LCCA type used in transportation decision making (FHWA, 2001). Discrete input values imply certainty. However, many input values for future events, such as maintenance costs or service life length, must be estimated for the LCCA and contain inherent uncertainty. An example of discrete input values (one value per parameter) would be the expression of “service life” as ten (10) years, “discount rate” as 4% or “initial construction days” as 0.20, as shown in Figure 1.2



PAVEMENT TYPE	TREATMENT	SERVICE LIFE
1 Bituminous	A ODOT Standard 5/8" chip seal	1.8
2 Concrete	B Open Graded Friction Course (OGFC)	5.3
	C 1" Hot Mix Asphalt mill & inlay (HMA)	10

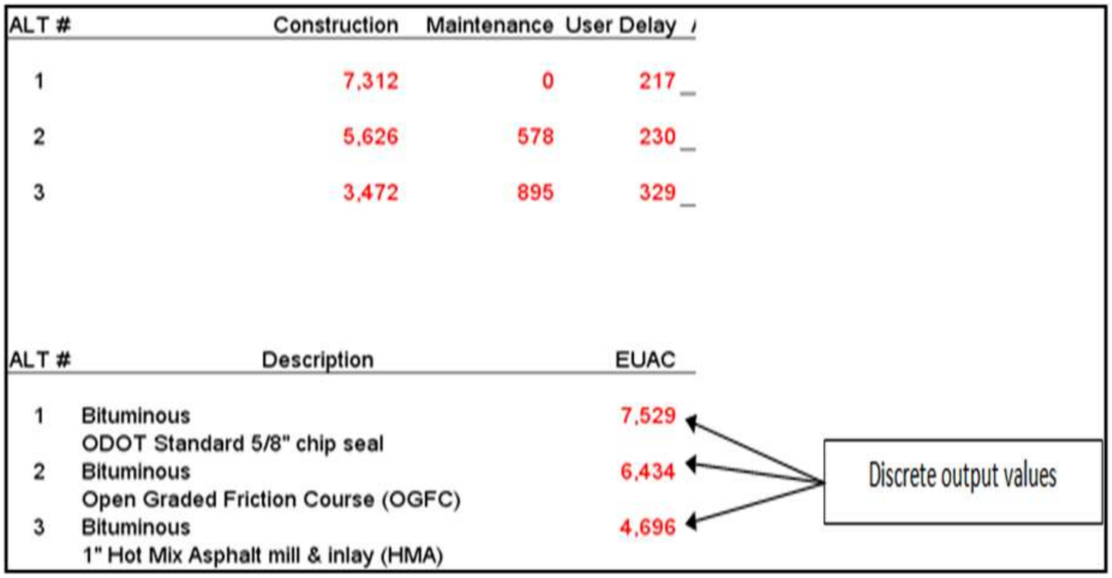
ALTERNATE #	'AVEMENT DESCRIPTIOI	Initial Construction Days**
1 :	1 A Bituminous ODOT Standard 5/8" chip seal	0.20
2 :	1 B Bituminous Open Graded Friction Course (OGFC)	0.20
3 :	1 C Bituminous 1" Hot Mix Asphalt mill & inlay (HMA)	0.28
4 :	1 D Bituminous	
5 :	1 E Bituminous	
6 :	1 F Bituminous	

1.18 DISCOUNT RATE = 4 %

Years until next Rehabilitation/Reconstruction

Figure 1.2 Deterministic LCCA with Point Estimates for Input Values.

An example of deterministic output is a single EUAC in dollars associated with the discrete input values of each of the three alternatives, as illustrated in Figure 1.3. The analyst could compare each alternative's EUAC to select a preferred alternative.



ALT #	Construction	Maintenance	User Delay
1	7,312	0	217
2	5,626	578	230
3	3,472	895	329

ALT #	Description	EUAC
1	Bituminous ODOT Standard 5/8" chip seal	7,529
2	Bituminous Open Graded Friction Course (OGFC)	6,434
3	Bituminous 1" Hot Mix Asphalt mill & inlay (HMA)	4,696

Figure 1.3 Deterministic LCCA Output.

The analyst may gain some insight about the variability (or risk) of a given input value relative to the output by including a *sensitivity analysis*, otherwise known as a

"What if?" scenario, when employing a deterministic approach (FHWA, 1998a). However, the sensitivity analysis does not quantify risk and associated likelihood of occurrence. It only shows if a discrete change in an input value would produce a different output result. If the change does result in a different outcome, then the parameter is considered sensitive.

Probabilistic Approach

In most transportation-LCCA cases, variable input values should be treated probabilistically (FHWA, 1998a). Stochastic LCCA is more robust than deterministic LCCA and involves modeling uncertainty with probabilities. It could assist SHAs in making "strategic long-term investment decisions under short-term budget constraints" on the basis of risk (FHWA, 1998a). However, this type of approach is often underutilized in transportation due to its complexity (Reigle and Zaniewski, 2002).

Unlike deterministic LCCA, stochastic LCCA cannot be easily completed by hand but can be facilitated by software (FHWA, 1998a). Deterministic LCCA only allows one input value for each parameter and provides only one outcome value for each alternative, whereas the stochastic LCCA allows all possible values for the input parameter and provides all possible outcome values, displayed as a probability distribution. Input values like costs, costs timing, discount rate and analysis period could have many possible values and result in many possible NPV, or outcomes (FHWA, 1998a). Stochastic analysis can also provide insights about correlations between input values. Input value probability, as well as simultaneous variability of all input values, is analyzed based on the full range of *"What if"* scenarios and results are displayed as an NPV probability distribution (FHWA, 1998a).

Probability Distributions

A probability distribution is a “mathematical model that relates the value of the variable with the probability of occurrence of that value in the population” and serves to quantify variation (Montgomery, 2009) or uncertainty. Therefore, it is a critical component of decision analysis (Clemen, 1996). Probability distributions can be characterized as *discrete* or *continuous*. Discrete probability distributions involve finite or count data. The random variable measured on a continuous scale, such as pavement treatment material cost and service life associated with transportation LCCA, can represent infinite possible values and is the appropriate type of distribution for this research. The total area under a continuous distribution curve represents probability and equals 1. Any random value for, say, material cost, will be located under the curve and have a certain probability range ($0 \leq \text{Cost} \leq 1$) associated with it. The probability is expressed as a percent with a range of 0 to 100, associated with each value. The probability distribution not only represents the total range of material cost, but the likelihood associated with a cost falling within a specific cost interval.

Each probability distribution has an associated mean and standard deviation. The arithmetic mean (μ) of the probability distribution provides the *central tendency* in the distribution (Montgomery, 2009). It can be estimated from the sample average ($\overline{x}$) calculation in Equation 1.1.

$$\mu_{est} = Xbar = \frac{x_1 + x_2 + \ldots x_n}{n} \qquad \text{Eq. 1.1}$$

$$\sigma_{est} = S_N = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (x_i - \overline{x})^2} \qquad \text{Eq. 1.2}$$

The variability (or range of data in relation to the mean) in a distribution is represented by the variance (σ^2) or standard deviation (σ) (Montgomery, 2009), and may be estimated by the sample deviation ($S_{N)}$ (Eq. 1.2). Figure 1.4 illustrates mean and standard deviation in a probability distribution. Both probability distributions have similar means, but the standard deviation (σ_A) for Alternative A is less than the standard deviation (σ_B) for Alternative B. In other words, one could conclude that the cost of Alternative A is less volatile, or variable, than the cost of Alternative B.

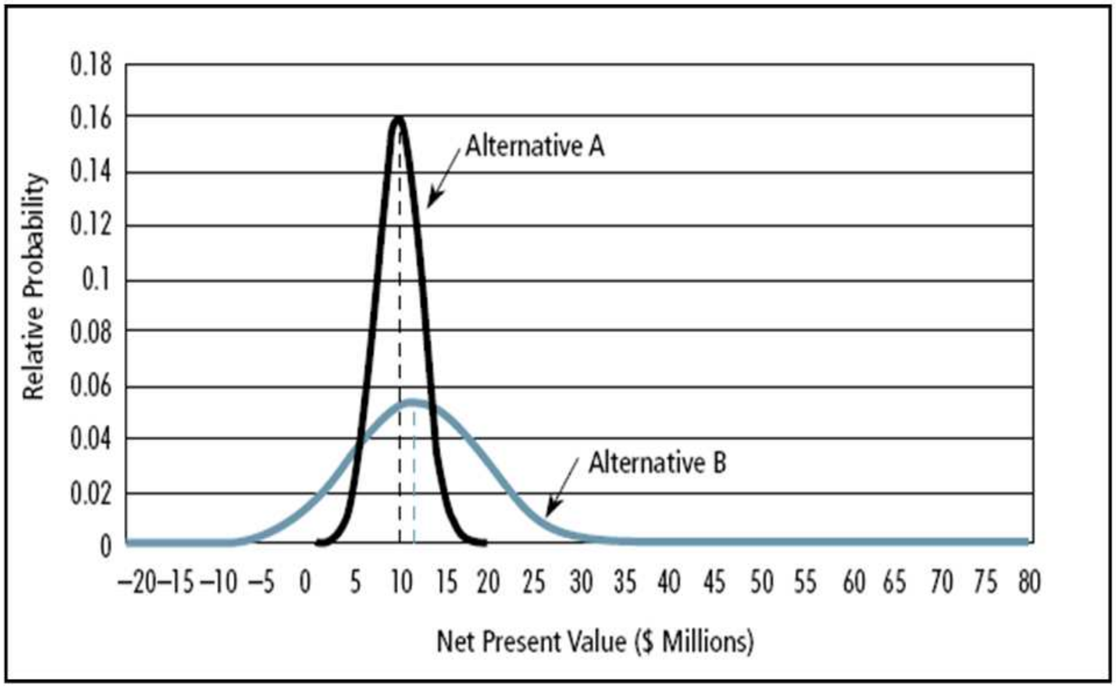


Figure 1.4 Probabilistic Outcome Distributions (FHWA, 2003).

A normal distribution or "bell curve" is a common type of continuous probability distribution that is symmetric and is defined and illustrated in Figure 1.5 for an uncertain independent input value (x).

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

The mean of the normal distribution is μ ($-\infty < \mu < \infty$) and the variance is $\sigma^2 > 0$.

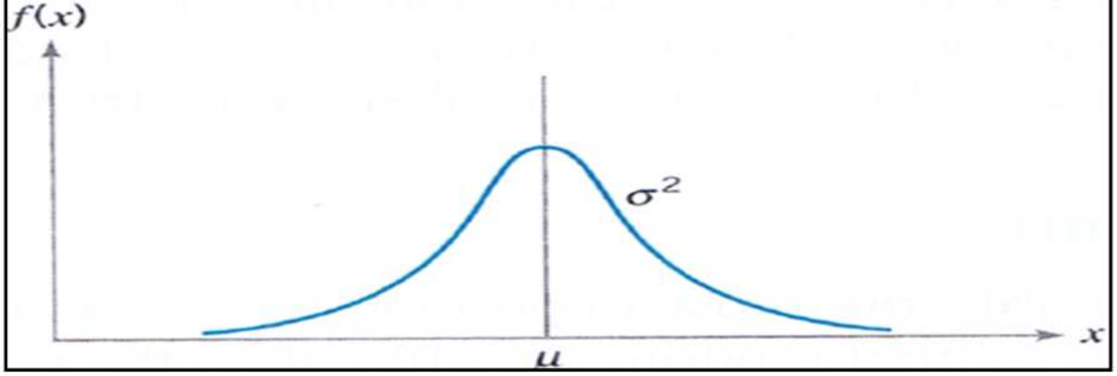


Figure 1.5 Normal Distribution Definition and Illustration (Montgomery, 2009).

For a normal distribution, it is generally expected that 68% of the population values will fall within the range of plus/minus one standard deviation away from the mean, 95% will fall in the range of plus/minus two standard deviations and 99.7% will fall within plus/minus three standard deviations, as illustrated in Figure 1.6 (Montgomery, 2009).

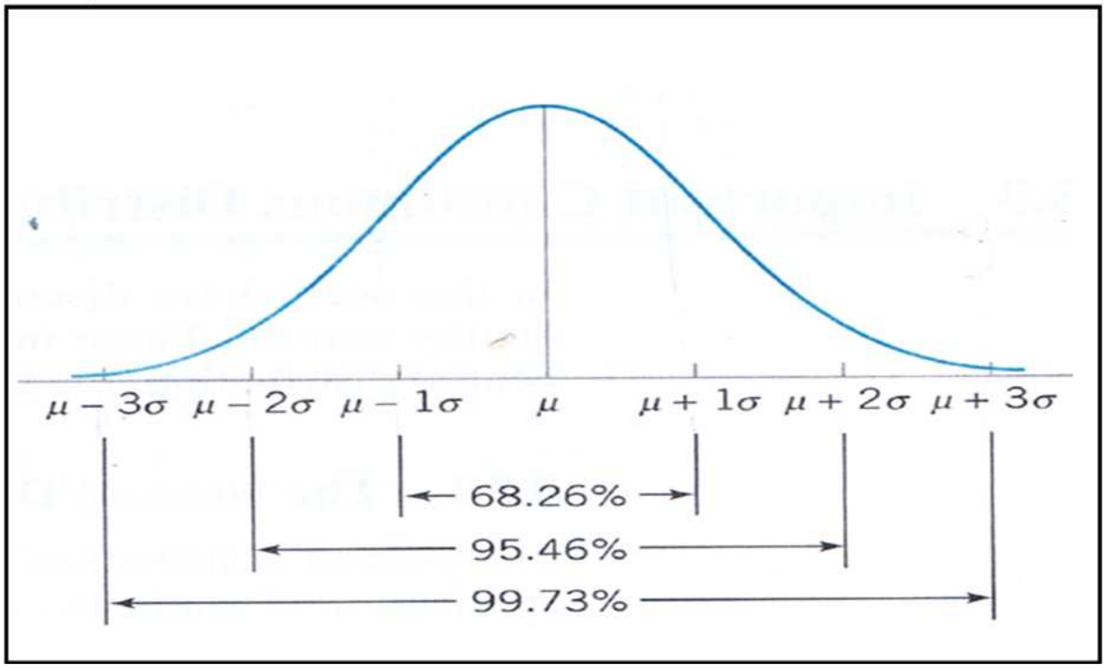
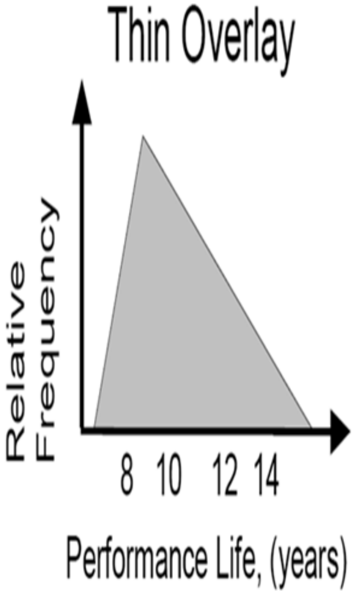


Figure 1.6 Normal Distribution Probability Intervals (Montgomery, 2009).

The normal distribution is commonly assumed to be the appropriate distribution for data and is further justified by the central limit theorem (Montgomery, 2009). The central limit theorem states that most data are "approximately normal" (or approximately symmetric in nature) and grow more normalized as sample size increases (Montgomery, 2009). It also states that it should be applicable to most cases where possible values of a given input are identically distributed and do not "depart radically from the normal" (or are not extremely skewed) (Montgomery, 2009). There is no standard rule for sample size and the central limit theorem. Some smaller samples can be approximately normal, while other cases may need larger sample sizes to fit the normal distribution.

A triangular distribution is a continuous distribution that contains user-defined values for (a) the minimum value, (b) the maximum value and (c) the most likely value for an input variable (Figure 1.7). It is commonly used for variables that have limited sample data but can be reasonably estimated. This type of distribution may be appropriate for service life input values. No significant research has been done to quantify the actual service lives of PPTs; therefore, service life data is limited. This type of distribution has also been suggested for discount rate input values of 3, 4 and 5%, the discount range suggested by the FHWA (1998a). Figure 1.7 is an example of what a triangular distribution would look like for a thin overlay pavement treatment with an expected service life of 8 to 14 years, with the most likely value being around 9 years (FHWA, 1998a).



$$f(x|a,b,c) = \begin{cases} \frac{2(x-a)}{(b-a)(c-a)} & \text{for } a \leq x \leq c \\ \frac{2(b-x)}{(b-a)(b-c)} & \text{for } c \leq x \leq b \\ 0 & \text{otherwise} \end{cases}$$

Figure 1.7 Triangular Probability Distribution Graphic and Equations (FHWA, 1998a).

1.3.3.4 FHWA Stochastic Analysis Procedure

FHWA provides guidance for conducting stochastic LCCA (FHWA, 1998a), which includes three steps. First, the analyst must decide whether to treat the input values deterministically or probabilistically. Secondly, the input data must be *fitted* to the appropriate probability distribution. Lastly, risk analysis should be conducted. The stochastic LCCA process for NPV is illustrated in Figure 1.8.

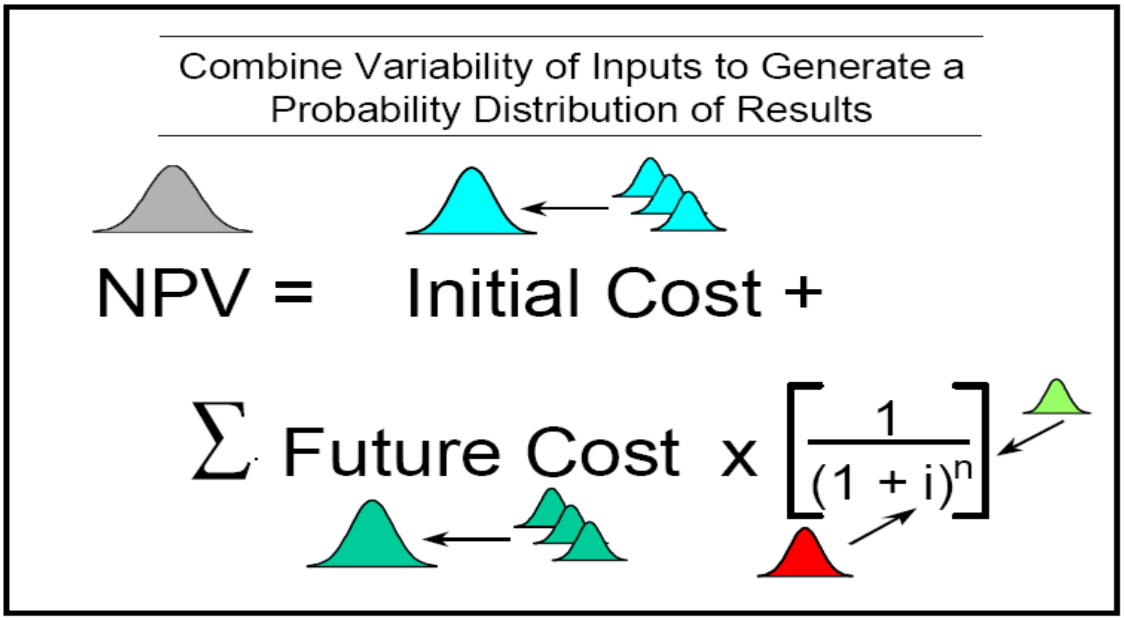


Figure 1.8 Computation of NPV using probability and simulation (FHWA, 1998a).

Step 1: Deterministic and Probabilistic Input Value Determination

Step one of stochastic LCCA requires the analyst to identify which input values have associated uncertainty and will have a material effect on the outcome (FHWA, 2004). Only those values should be treated probabilistically to simplify the analysis (FHWA, 2004). The deterministic approach does not allow probabilistic values, but the probabilistic approach allows deterministic values. If a pavement manager expected service life to contribute uncertainty that would affect outcome, then it should be incorporated into the analysis in a probabilistic manner (represented as a probability distribution). If material cost was not expected to have an impact, then it could be treated deterministically (represented as a point estimate). If the pavement treatment was expected to incur maintenance costs comparable to those of other alternatives and would not have a material effect on the output, those costs could be ignored altogether (FHWA, 1998a). Input value distributions can be subjectively defined based on the pavement manager's judgment or objectively defined based on historical or current data from sources like bid tabulations and pavement management systems. Ultimately, the analyst must use judgment to properly assess and address uncertainty in analyses.

Step 2: Selecting Appropriate Probability Distributions

The second step of a stochastic analysis is to "fit" a given data set to the "best" theoretical probability distribution. This is commonly accomplished with statistically-based *goodness-of-fit* tests, such as Anderson-Darling (A-D) and chi-squared (χ^2) tests (Lomax, 2007). Software is available that can execute the task in seconds (Pallisade, 2011). Determining the appropriate probability distribution for given data is a critical step to ensure output validity, because the LCCA is based upon the theoretical probability distribution, *not* the actual data (Lomax, 2007; Tighe, 2001). In a 2001 study conducted by Dr. Susan Tighe, it was demonstrated that the same data modeled by different theoretical distributions (normal, then lognormal) in LCCA have produced a different result. This sensitivity is based upon how well the data fits the selected distribution based on the symmetry or skewness associated with the data. Research has demonstrated that LCCA can be sensitive to distribution-type selection, especially in a low-bid environment, like transportation, where material costs do not widely vary for a given quantity and would tend to yield an asymmetric shape with a positive skew, like the lognormal distribution (Tighe, 2001).

The study also concluded that the "magnitude of the skew…is a function of quantity" (Tighe, 2001). It was noted that in transportation applications, economies of scale can create a situation where values (like material costs in dollars) would depart radically from the normal distribution based on quantity, resulting in an erroneous fit (Tighe, 2001). The term *economies of scale* simply refers to the relationship between quantity and unit price. A smaller quantity of “item x” generally has a larger unit price and a larger quantity of “item x” generally has a lower unit price. The unit prices associated with varying quantities, then, could vary greatly (representation of two populations as one) resulting in an erroneous skew and best fits to a multitude of distributions, such as Weibull, Beta, Gamma, etc. (Tighe, 2001). Therefore, data sets should contain relatively similar quantities (Tighe, 2001) so that one population is isolated from another. When data sets contain relatively similar quantities, the best-fit distributions have been shown to be normal or predominantly lognormal and have been suggested as proper to use in transportation LCCA (Tighe, 2001). It was also noted that larger quantities had lower standard deviations and vice versa (Tighe, 2001). Thus, data from smaller projects (less skew) may be better modeled by the normal distribution while the larger ones (more skew) should consider the lognormal distribution in LCCA (Tighe, 2001). Selecting a normal instead of lognormal distribution can, in some cases, introduce bias into the LCCA (Tighe, 2001).

Research has demonstrated that current market price can be fitted to distributions to track volatility in transportation-specific commodities such as aggregate, asphalt binder and diesel (Gransberg and Kelly, 2008). Volatility in material and equipment costs has been shown to be directly related to diesel fuel costs in roadway applications (Gransberg and Kelly, 2008). Underlying commodity volatility assessment can be more informative than historical pay item cost tracking so that the pavement manager can better pinpoint the source of volatility allowing for better quantification of uncertainty (Gransberg and Kelly, 2008). Current commodity data can be probabilistically interpreted (Gransberg and Kelly, 2008).

Step 3: Risk Analysis

The third step of a stochastic approach is *risk analysis,* which is based on probability theory and can be defined as a "systematic use of available information to determine how often specified events may occur and the magnitude of their consequences" (Palisade, 2011). Like sensitivity analysis, risk analysis seeks to expose uncertainty associated with input parameters. Risk analysis differentiates itself from sensitivity analysis because it combines "probabilistic descriptions of uncertain input parameters with computer simulation to characterize the risk associated with future outcomes" (FHWA, 1998a). It also allows the analyst to assess variability in all input parameters simultaneously (FHWA, 1998a). Risk analysis can be conducted on a deterministic basis or a probabilistic basis, although employing deterministic risk analysis (like triangular distribution) results in oversimplification and reduced accuracy (Palisade, 2011). Risk analysis can also be qualitative or quantitative.

A Monte Carlo simulation satisfies the conditions of a probabilistic, quantitative risk analysis. Monte Carlo simulation is a "computerized mathematical technique that allows people to account for risk in quantitative analysis and decision making" (Palisade, 2011). Palisade Corporation is the maker of ***@Risk***, a risk analysis software with Monte Carlo simulation that can be incorporated into a spreadsheet (add-in) and explains the simulation as follows:

> "During a Monte Carlo simulation, values are sampled at random from the input probability distributions. Each set of samples is

> called an *iteration*, and the resulting outcome from the sample is recorded. Monte Carlo simulation does this hundreds or thousands of times, and the result is a probability distribution of possible outcomes. In this way, Monte Carlo simulation provides a much more comprehensive view of what may happen. It tells you not only what could happen, but how likely it is to happen."
> (Palisade, 2011)

Certain issues may arise in the simulation step that could lead to error. The simulation validity is iteration dependent. A large number of iterations are desired because the approximation becomes more accurate with increasing iterations (Clemen, 1996). If fewer iterations are expected, *Latin Hypercube* sampling may be more appropriate than Monte Carlo simulation. The simulation process may eventually converge, meaning further iterations will not significantly affect the outcome results (FHWA, 1998a).

The relationships between variables should be explored. A correlation matrix can be used to define relationships so that the simulation will not sample in a manner that produces illogical results (FHWA, 1998a). For example, an inverse relationship exists between pavement treatment service life and traffic load; when a pavement segment incurs high traffic load, treatment service life is expected to be shorter due to deterioration and vice versa. It is not desirable for the simulation to sample from the high side of the two distributions representing traffic and service life in the same iteration because that scenario is illogical (FHWA, 1998a).

1.3.3.5 LCCA Issues

Although LCCA is used to compare pavement design alternatives, there are issues regarding the real value of LCCA output (Hall et al. 2003; FHWA, 2001; FHWA, 1998a). According to the FHWA, issues regarding the appropriate discount rate, user costs, traffic data, future costs, salvage/residual value and performance period, among other things, can create obstacles in conducting LCCAs (FHWA, 1999). This can create issues regarding “fairness”, resulting in “controversy” (Gransberg and Scheepbouwer, 2010) and doubt as to whether LCCA can be applied consistently and correctly to determine which alternative is truly the most cost-effective. Due to the sensitivity of LCCA output based on input values, it is possible that an analyst could “play games…that result in one’s *a priori* recommendation ‘moving to the head of the line’…and one should avoid it” (White et al. 2010). An analyst that is not thoroughly acquainted with underlying engineering economic analysis theory may inadvertently choose input values that create invalid output. This may be especially true when “asset alternatives have radically different technical aspects and dissimilar service lives” (Gransberg and Scheepbouwer, 2010).

Because of these and other relevant issues found in various steps in the LCCA process with regard to pavement design decision making, it is necessary to look at the details of the process focusing on input values and their corresponding sensitivity to ensure that assumptions do not unintentionally skew the output. Two critical input values are the analysis period and the discount rate and their selection is based on either a mandated value or the analyst’s judgment and both are often selected arbitrarily. This is because conventional microeconomic wisdom states that if one evaluates two options over the same period of time using the same discount rate that the comparison is fair (White et al. 2010; Gransberg and Scheepbouwer, 2010). While this may be true in theory, if the LCCA output effectively makes the pavement design decision (i.e. the engineer selects the one with the lowest value), then using a discount rate mandated by public entity for all analyses is tantamount to allowing an economist practice pavement engineering (Gransberg and Scheepbouwer, 2010).

Discount Rate

As previously cited, two of the most critical input values are the analysis period and the discount rate and the selection of both is based on the analyst's judgment and often selected arbitrarily (White et al. 2010). According to the FHWA,

> "Discount rates can significantly influence the analysis result. LCCA should use a reasonable discount rate that reflects historical trends over long periods of time. Data on the historical trends over very long periods indicate that the real time value of money is approximately 4 percent." (FHWA, 1998a)

The FHWA suggests 3 to 5% (FHWA, 2004), and a number of states are within that range (Hall et al. 2003). According to FHWA's Colorado case study, it requires the use of probabilistic analysis because of the sensitivity of the discount rate selection for the purposes of revealing the inherent uncertainty (FHWA, 2009). Many issues contribute to the discount rate debate (Hall et al. 2003). It has been stated that the sensitivity of this input parameter is such that, if LCCA results were strictly relied upon, fluctuations in the economy would dictate pavement design choice (Gransberg and Scheepbouwer, 2010). There is also discussion about whether the same discount rate should be used to discount both agency and user costs, or if a *social discount rate* would be more appropriate for user costs (Corotis and Gransberg, 2005).

Agency Costs

Volatility in commodity prices is cited as being an issue with regard to agency cost inputs; therefore, historical costs may be no indication of future costs (Gransberg and Scheepbouwer, 2010; Gransberg and Kelly, 2008; Wang et al. 2009).

Work Zone User Costs

User costs inclusion/exclusion can have a significant impact on LCCA output (Bilal et al. 2009; FHWA, 1998a; Hall et al. 2003). However, some of the user costs are difficult to quantify for the purposes of input values and there is debate on how to do so (Peshkin et al. 2004; Hall et al. 2003; FHWA, 1998a). Sometimes calculated user costs can be so large so as to obscure agency costs (FHWA, 2001). The concept of user costs garnering influence in LCCA output may be especially problematic for budget-constrained agencies that are more inclined to choose alternatives based on the lowest hard-dollar costs (FHWA, 2001). User costs can also impact an analysis so that it results in the alternative that has the least short-term inconvenience, when the premise of LCCA is to garner the best long-term solution (Gransberg and Scheepbouwer, 2010).

Service Life

No significant research has been done to quantify the actual service lives of PPTs; therefore, service life data is limited (Gransberg et al. 2009; Riegle and Zaniewski, 2002). However, service life determination is crucial because it is "considered the most superior performance measure because all other long-term effectiveness measures are computed on the basis of service life" (Irfan et al. 2009), like life cycle cost.

One way for pavement managers to enhance decision making and justification is to incorporate engineering-based performance data into LCCA (Bilal et al. 2009; Reigle and Zaniewski, 2002). Many agencies already collect such data, in the form of microtexture or macrotexture, to support pavement management (Gransberg and James 2006). Using this "localized" data can provide pavement treatment performance insight (Bilal et al. 2009; Reigle and Zaniewski, 2002). It can assist pavement managers in determining the *right treatment* component of the *right treatment for the right road at the right time* pavement preservation strategy (Bilal et al. 2009; Peshkin et al. 2004).

Microtexture and Macrotexture data, or "localized" performance data, is routinely collected by ODOT. A commonly used approach to determine a treatment's expected service life (effectiveness) is to extrapolate data based on surface condition (Bilal et al. 2009) such as microtexture and macrotexture data, which is the approach used in this research. Incorporating microtexture data into LCCA may reduce the level of inherent uncertainty associated with [service life] "guesses" and can yield insight to a treatment's effectiveness and cost-effectiveness (Riegle and Zaniewski, 2002). If treatment effectiveness (performance) is not considered when determining cost effectiveness, the results may be biased (Bilal et al. 2009). As pavement preservation emerges as a possible solution to the aging infrastructure problem, research has shown that coupling cost efficiency and treatment effectiveness, termed *economic efficiency* (Bilal et al. 2009) may be the key to determining the optimal preservation timing (Peshkin et al. 2004). This would assist the pavement manager in selecting the "right treatment to the right road at the right time" (Galehouse et al. 2003).

Analysis Period

Selection of an analysis period (common period of time) to accommodate alternatives with differing service lives, which is mostly the case in pavement treatment alternatives, is necessary in determining the NPV of competing alternatives. This must be done so that cost differences can be assessed and results fairly compared (FHWA,

2001) and engineering economic analysis principles upheld (White et al. 2010).

According to a recently published engineering economics text, the analysis period

> "…defines the period of time over which the comparison of investment alternatives is to occur; it is the width of the window through which you look to assess the economic performances of the alternatives. The [analysis period's] length can be less than, greater than or equal to the useful lives of the investment alternatives being considered. The ideal circumstance is for the useful lives to coincide in duration with the [analysis period]. If, on the other hand, the [analysis period] is longer than one or more lives of the alternatives, then explicit decisions must be made regarding the 'gap' that exists between the end of an alternative's useful life and the end of the [analysis period]. What about the remaining case of the [analysis period] being shorter than the longest-lived alternative? In this case, estimated values of unused lives of the alternatives are required." (White et al. 2010)

But selecting an appropriate analysis period can be problematic due to its sensitivity, meaning that with all other inputs held constant, changing the analysis period can result in different alternative rankings (White et al. 2010; Riegle et al. 2002). The use of a residual value mandated in the above quote, assumes that a facility has a quantifiable value. While this can be done easily for used cars, in order to realize the residual value of a pavement, the owner would have to tear it up and sell the salvaged materials, which is unrealistic. Additionally the nation's highway system contains many miles of road that have exceeded expected service life, are in poor condition but still provide some level of service. Thus, there is a serious question that a realistic fixed period of analysis can be found for infrastructure assets like roads (Gransberg and Scheepbouwer, 2010).

The various methods for selecting/setting an appropriate analysis period (AP) to determine the present values of competing alternatives are as follows
(White et al. 2010):

- AP Method 1: set equal to the shortest life among alternatives
- AP Method 2: set equal to the longest life among alternatives
- AP Method 3: set equal to the least common multiple of the lives of the various alternatives
- AP Method 4: use a standard AP, such as 10 years
- AP Method 5: set equal to the period the best suits the organization’s need for the investment
- AP Method 6: use an infinitely long AP

There is no consensus on which method is the “best” for selecting an analysis period, but the decision should be based on the investment scenario at hand as suggested above in (5) (White et al. 2010). This is further evidenced by the FHWA’s *Interim Technical Bulletin* referring to “LCCA Principles of Good Practice” (FHWA, 1998a). As a default, if the “best” method is not obvious, the use of a standard AP, if logical considering the investment scenario, is preferred (White et al. 2010), as illustrated in Figure 1.9.

The FHWA does suggest using a standard analysis period chosen from the range of 35 to 40 years (FHWA, 2004) that accommodates “at least one major rehabilitation activity for each alternative being considered” for pavement design decisions (FHWA, 2001).

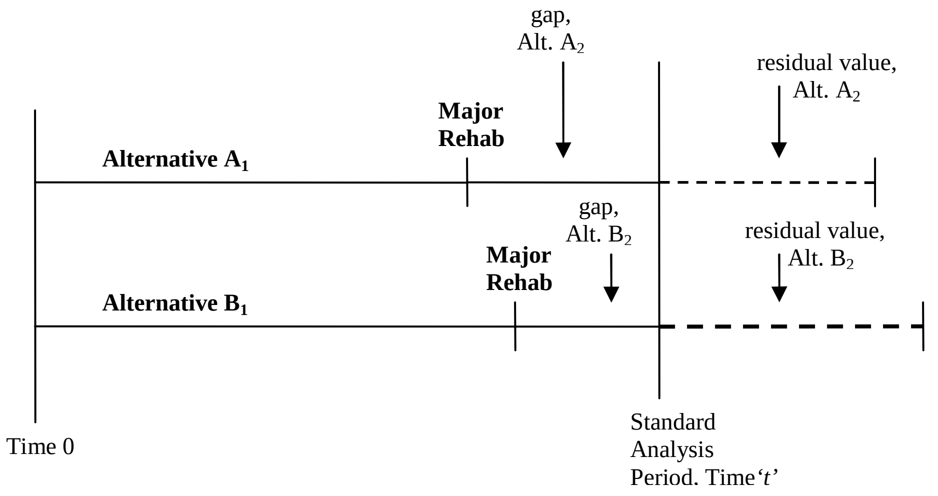


Figure 1.9 Standard Analysis Period, One Major Rehabilitation Accommodated.

It has been suggested that setting the analysis period equal to the shortest life can easily result in the shortest-life alternative being favored over the other longer-life alternatives (Hall et al. 2003), as illustrated in Figure 1.10.

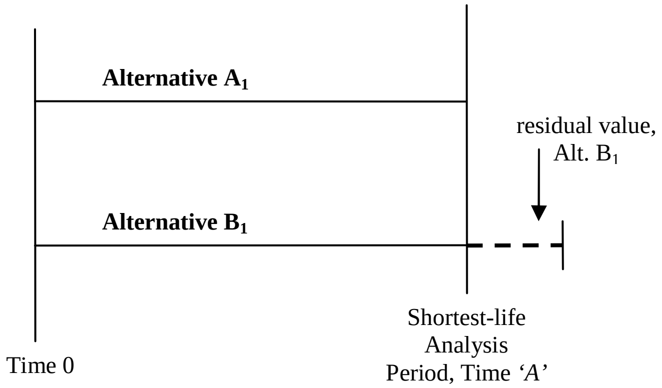


Figure 1.10 Analysis Period Set to Shortest-Life Alternative.

It has also been suggested that choosing to set the AP equal to the longest life alternative (Figure 1.11) is preferred and that an AP be "sufficiently long to reflect significant differences in performance among the different strategy alternatives" (FHWA, 1998a), but not so long that it becomes unreasonable (Hall et al. 2003).

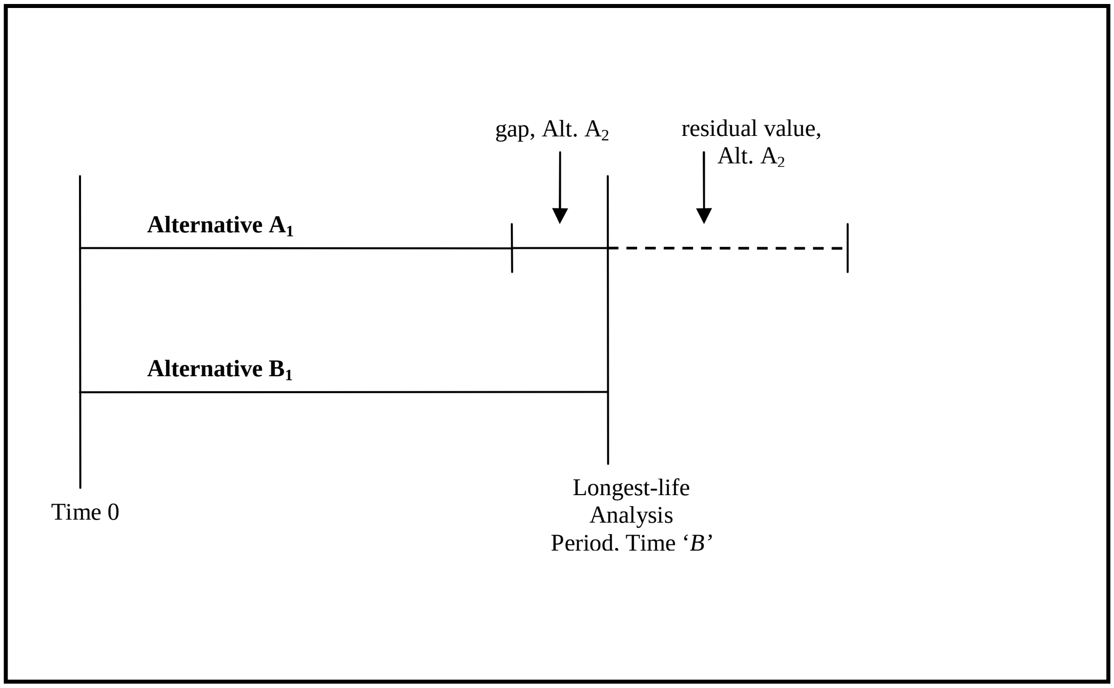


Figure 1.11 Analysis Period Set to Longest-Life Alternative.

The issues with setting the AP consistent with the methods 1, 2 and 4 are that gaps and/or residual values must be addressed for all alternatives whose service lives are shorter or longer than the AP, respectively, and are unacceptably sensitive to the input value (Gransberg and Scheepbouwer, 2010).

"Filling the gap", as illustrated in Figure 1.11, requires that a shorter life alternative (relative to the analysis period) be "adjusted" to "fit" the analysis period, and generally, repeating service lives having identical cash flow profiles are assumed to repeat until the gap is filled. This redundancy of service life length and costs issue is viewed as not realistic because it relies on an assumption that today's costs will not change for any other reason than inflation. Pavements that use large amounts of asphalt, concrete and steel are subject to commodity price volatility to a much greater degree than the average inflation rate in the US. Thus, this fundamental assumption calls into question the validity of algorithmic technique. (Gransberg and Scheepbouwer, 2010; Hall et al. 2003).

On the other hand, an alternative with a long life relative to the analysis period must be adjusted to fit the analysis period, as illustrated in Figure 1.10, with any remaining life, at the end of the analysis period, being accounted for by computing a residual of the asset at the end of the period. Residual value is based upon an alternative's *remaining service life (RSL)*. It is the portion of the alternative's lifetime that will be assumed to "continue in service" beyond the analysis period and an analyst would need to use judgment to determine that value to credit (less associated maintenance costs, etc) the alternative for analysis purposes (Lee, 2002; FHWA, 2001). The methods that can be used are a matter of debate (Gransberg and Scheepbouwer, 2010; Lee, 2002) but can be generalized as follows:

Residual Value (RV) = (RSL ÷ total service life) x initial cost (Kane, 1996),

and the treatment 'credit' = RV less associated recurring costs (Lee, 2002).

This generalization is consistent with the FHWA's method of determining residual value (FHWA, 1998a) and is similar to straight line depreciation methods (Gransberg and Scheepbouwer, 2010).

Essentially, both adjust-to-fit mechanisms based on the redundancy-of-identical-cash-flow-profile assumption to either fill the gap or determine residual value are purely mathematical means to contain a service life within a given analysis period.

Hence, setting the analysis period consistent with the shortest life, longest life or using a standard analysis period, which require adjusting alternatives to fit can yield the same ranking of alternatives as using the least common multiple of alternatives and an infinite period, which do not require the adjust-to-fit mechanisms (White et al. 2010). This renders the "arbitrarily truncated lifetime unnecessary" (Lee, 2002). If the analyst intends to assume that costs and service life lengths will remain constant over time (with only mathematical adjustments of gaps and residual values for analysis period accommodation), the method selected would be irrelevant because all should yield the same decision support (White et al. 2010).

However, it is unreasonable to assume that costs and service lives will remain constant over time (Hall et al. 2003). This is especially true when a specific pavement or treatment has its service life expressed as a range (Gransberg and Scheepbouwer, 2010). Thus, it is necessary to view the "redundant cost/service life" in a broader scope. A road segment (asset) is generally intended to remain in service indefinitely and pavement treatments are expected to be applied continuously over the life of the asset, although the service life of a treatment is finite (Lee, 2002). Because of this and the points cited above regarding the same outcomes regardless of analysis period chosen so long as gaps and residual values are proportionately spread so as to be consistent with the fully crediting the treatment, then the analysis can be considered "fair" and in accordance with engineering economic principles. This neutralizes analysis period and redundancy issues (Gransberg and Scheepbouwer, 2010).

There may be times when it is not prudent to assume that service life lengths and costs will be redundant, such as when an activity is no longer in a "continuous" state

(Figure 1.12), but rather one of “termination” (Lee, 2002), in which the analysis period defaults to be consistent with the termination (Figure 1.13). When using EUAC, the “mistake” occurs when the planning horizon is not considered or acknowledged for the investment (White et al. 2010). In the instant case, it would be a mistake to use EUAC without regard to the next rehabilitation or reconstruction.

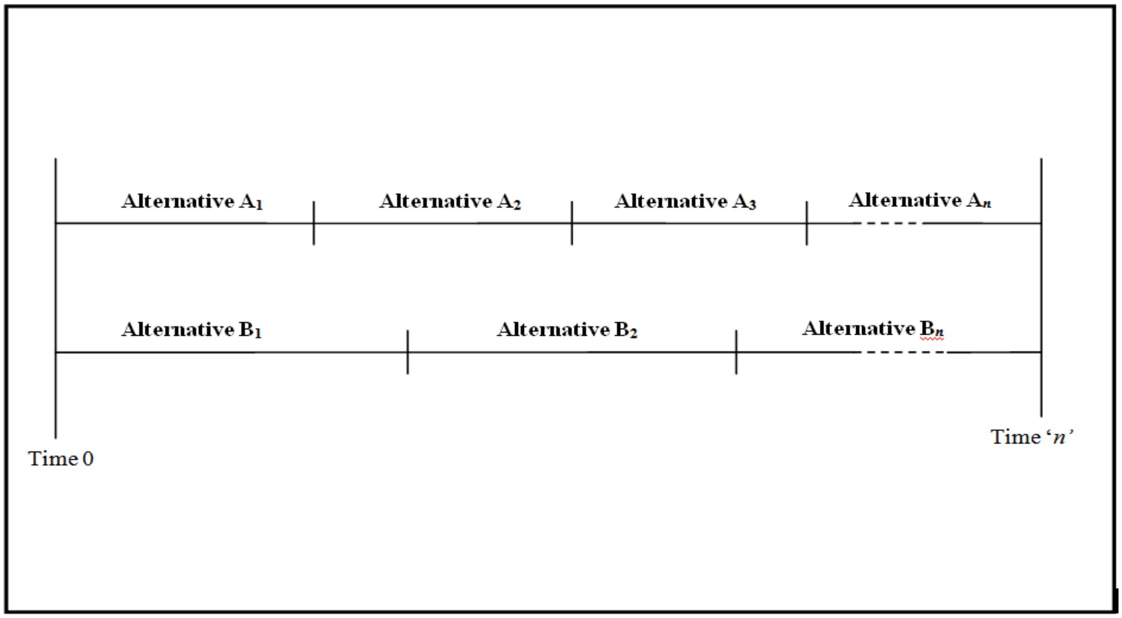


Figure 1.12 Continuous State, Next Rehabilitation/Reconstruction Unknown.

Subsequently, the “encroachment” of the analysis period on the service lives of alternatives is expected to have a material effect with regard to the treatment of residual value for one or more of the treatment alternatives. Therefore, this encroachment must be addressed in the calculations (White et al. 2010).

If the gaps or residual value are to be addressed in another manner besides those listed herein, then the analysis period should be carefully considered. The material effect is determined by the analyst’s judgment, so the sensitivity and risk become dynamic and the analysis more complex. This renders the analysis period selection relevant due to its influence on the analysis results. In other words, “slightly different assumptions regarding the [residual values] of incomplete life cycles [could] … produce different recommendations" (White et al. 2010).

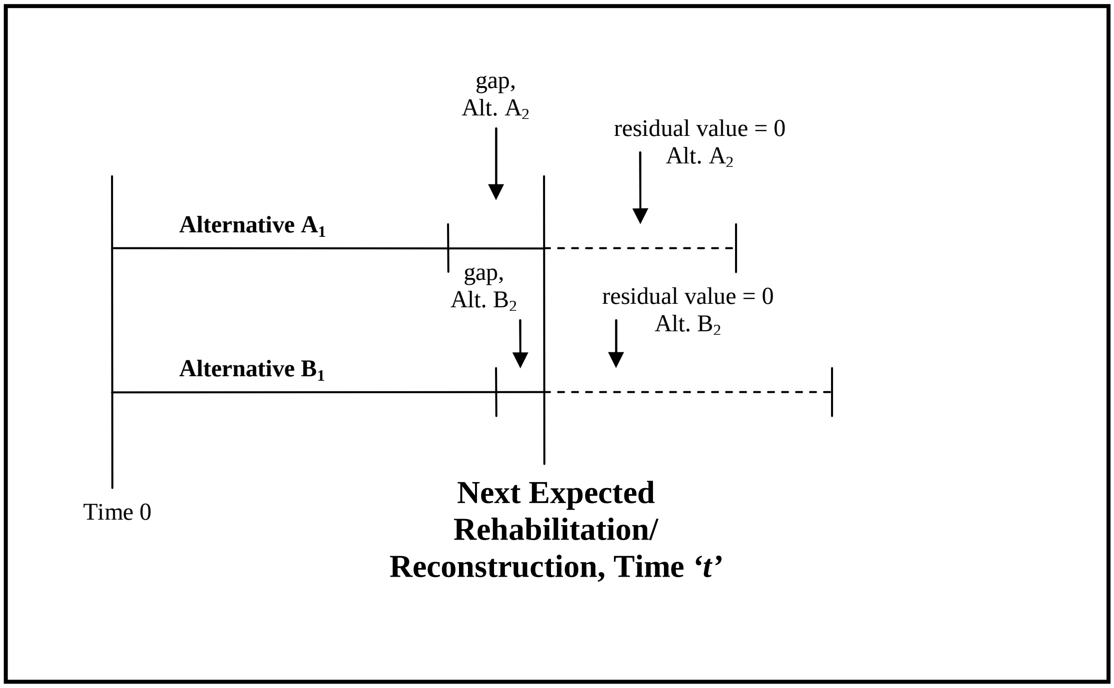


Figure 1.13 Termination State, Next Rehabilitation/Reconstruction Known.

EUAC, which is discussed throughout the remainder of this writing, is an alternative method that avoids the problems aforementioned with NPV AP (White et al. 2010). It will yield the same preferred alternative as NPV (all AP methods) if Redundant Cost/Service Life assumption is true. EUAC has been suggested as proper to use in transportation decision making when service lives differ in length for given alternatives (Thoreson et al. 2012; Gransberg and Scheepbouwer, 2010; Sinha and Labi, 2007).

1.4 RESEARCH METHODOLOGY

This section provides the general research methodology for the research effort. Because this is a paper-based dissertation, however, specific research methodology is disseminated in applicable chapters. This research is the synthesis of three independent sources of information:

- a comprehensive literature review,
- a survey of Oklahoma Department of Transportation (ODOT) pavement managers, and
- PPT field trial data.

This research employed the following research instruments:

- an analysis of current state transportation agencies decision-making processes
- a survey of ODOT pavement managers, and
- case study analyses from field trials.

Research Approach

Research objectives were met through completion of tasks described in this section. LCCA methodology was demonstrated using data from current field trial PPTs. Probabilistic results were compared to the deterministic results to determine relationships and sensitivities of input values and LCCA methods. Results are reported in subsequent chapters. The final deliverable is an EUAC-based LCCA model, with deterministic and stochastic modes, developed specifically for PPT evaluation. Figure 1.14 illustrates this approach and is followed by a detailed discussion of the associated research tasks.

Phase 1 Evaluate Current Decision-Making Processes

Task 1	Task 2	Task 3
Evaluate SHA processes	Evaluate ODOT processes	Evaluate current LCCA methods

Research Methods
- Literature review
- ODOT survey
- Document content analysis

Key Outcomes
- LCCA use determination
- LCCA method selection

Phase 2 Strategies, Methods & Tools Development

Task 4	Task 5	Task 6
Develop deterministic algorithm	Develop deterioration models	Develop stochastic algorithm

Research Methods
- LCCA step-by-step analysis
- LCCA application analysis

Key Outcomes
- Deterministic LCCA EUAC model
- Field trial deterioration models
- Stochastic LCCA EUAC model

Phase 3 Application and Validation

Task 7	Task 8	Task 9	Task 10	Tasks 11-13
Case Studies field trial data selection	Calculate EUACs	Compare EUAC Results	Explore relationships and sensitivities revealed by LCCA	Validate EUAC Models

Research Methods
- Case study output analyses

Key Outcomes
- Final Deterministic LCCA EUAC model
- Final Stochastic LCCA EUAC model
- Final Report for LCCA for Pavement Preservation Treatments

Figure 1.14 Research Approach.

Research Tasks

Task 1: Review Literature

A comprehensive literature review was conducted and relevant issues were discussed previously in this chapter. In summary, no literature was found that specifically addresses LCCA for PPT evaluation. Literature was found regarding LCCA at transportation design and network level, however, which provided sufficient guidance for this research. The review also revealed that state highway agencies are seeking and are responsible for implementation-level LCCA tools.

Task 2: Complete Oklahoma Department of Transportation (ODOT) Survey

A survey was developed in accordance with the methodology specified by Lehtonan and Pahkinen (2004). It was deployed to learn the current processes used by ODOT pavement managers when making decisions regarding pavement treatment selection. The responses indicated that initial cost plays a primary role when deciding which pavement treatment to employ and that long-term cost or cost-effectiveness of a treatment selection is not considered, i.e. LCCA is not conducted. The survey also yielded information about other decision making factors, as well as the types of preservation and maintenance treatments typically installed in Oklahoma, and each treatment's cost range, productivity range and typical service life range based on factors such as average annual daily traffic (AADT), percent truck traffic and pavement condition, as shown in Table 1.1.

Table 1.1 ODOT Survey Responses.

ODOT Survey Responses					
	Response #				
	1	2	3	4	5
LCCA used in current decisions	No				
Current decision-making methodology		Judgment	Judgment	Judgment	
Importance of decision-making factors					
(Ranking: 1-most important, 5- least or not important)					
Initial cost of pavement treatment (PT)	2	1	1	1	1
Safety	1	3	3	2	1
Traffic volume	3	3	5	2	2
Existing surface condition	1	4	1	2	2
Service life of PT	4	3	4	3	2
Availability of PT	3	2	5	5	5
Availability of trained crew to install PT	5	4	5	3	4
Weather constraints for PT	4	3	2	4	3
Past experience with PT's effectiveness	1	5	3	2	2
Most common PPTs (average service life, unit cost)	HMA (10 years, $70/ton); chip seal (5 years, $1.77/SY)				

The survey data, combined with literature review and the field trial data associated with this project, was collected for the purpose of defining the input values and other parameters with regard to costs (user, construction, etc.) and time (analysis period, service life, etc.) associated with specific field trial PPTs for use in both deterministic and stochastic EUAC models.

Task 3: Reduce and Analyze Data

Data resulting from the ODOT survey and case studies has been analyzed. Results are disseminated throughout the remainder of this writing.

Task 4: Create/Validate Deterministic EUAC LCCA Models

Chapters 3 through10 (excluding Chapter 6) describe and demonstrate the deterministic EUAC LCCA model that was created with Microsoft Excel and validated (Chapters 3,4,11) for evaluating concrete pavement treatments and asphalt pavement treatments. The model is consistent with FHWA LCCA Steps 1-6 and complies with engineering economic principles, like acknowledging the next expected rehabilitation/ reconstruction, as illustrated in Figure 1.15 and previously discussed in this chapter.

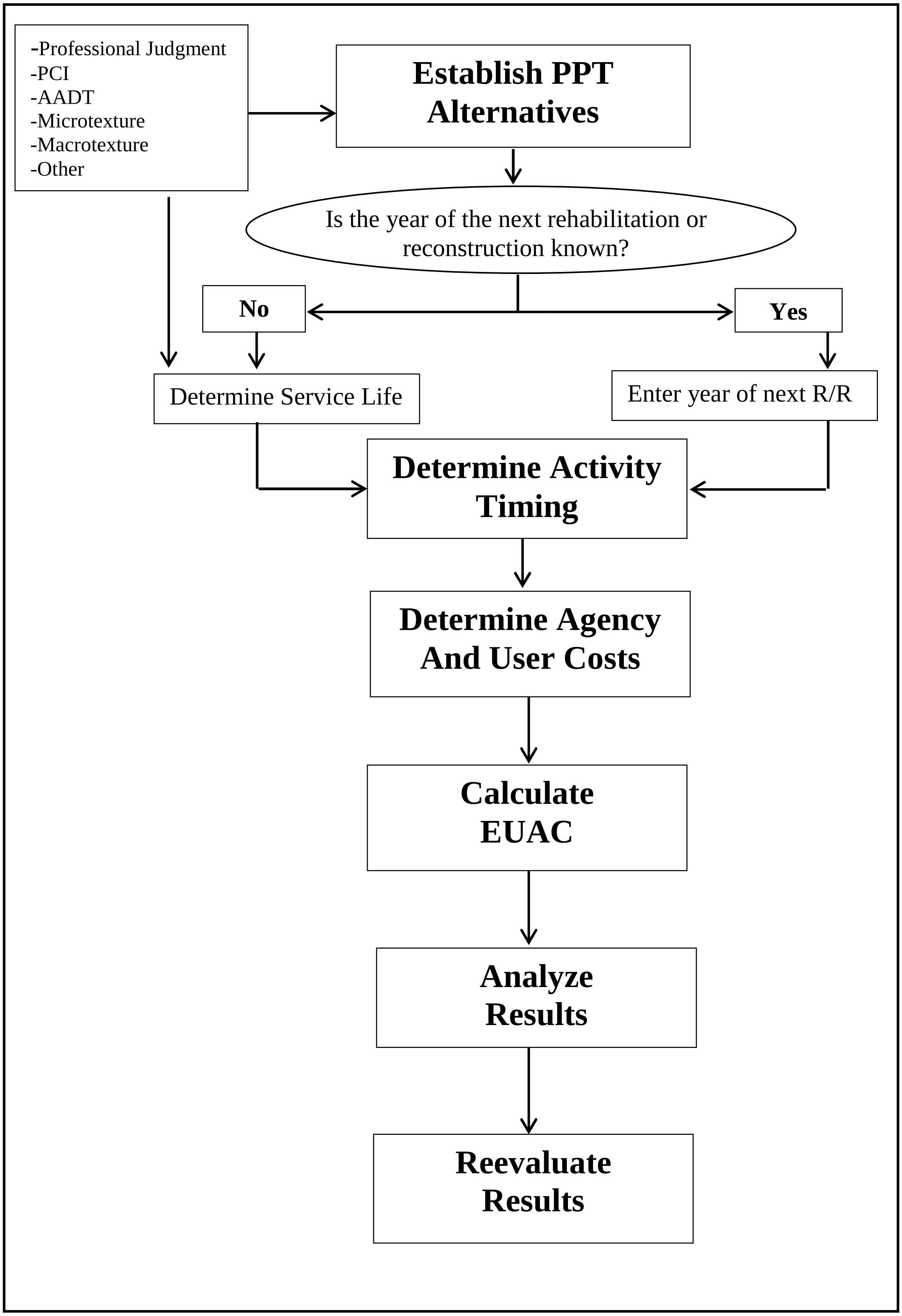


Figure 1.15 PPT EUAC LCCA Model Logic.

Task 5: Develop Deterioration Models from Field Trial Data

Chapters 4, 7 and 10 describe and demonstrate the deterioration models that have been created for the purpose of approximating LCCA service life input values for various treatments.

Tasks undertaken for stochastic LCCA model development to answer the research question: Does stochastic LCCA produce a different result than deterministic LCCA for PPT?

Task 6: Create a stochastic EUAC LCCA for PPT

Chapters 8 through 11 describe, demonstrate and validate the stochastic EUAC LCCA model that was created for this research. It incorporates @Risk Software (Palisade, 2011) into a Microsoft Excel spreadsheet that specifically allowed for probabilistic treatment of input and output values through use of Monte Carlo simulation and other tools. Model logic is the same as that for the deterministic model (Figure 1.15). However, the mechanics are inherently different and are discussed in Chapters 8 and 9 and illustrated in Figure 1.16 for the commodity-based analysis.

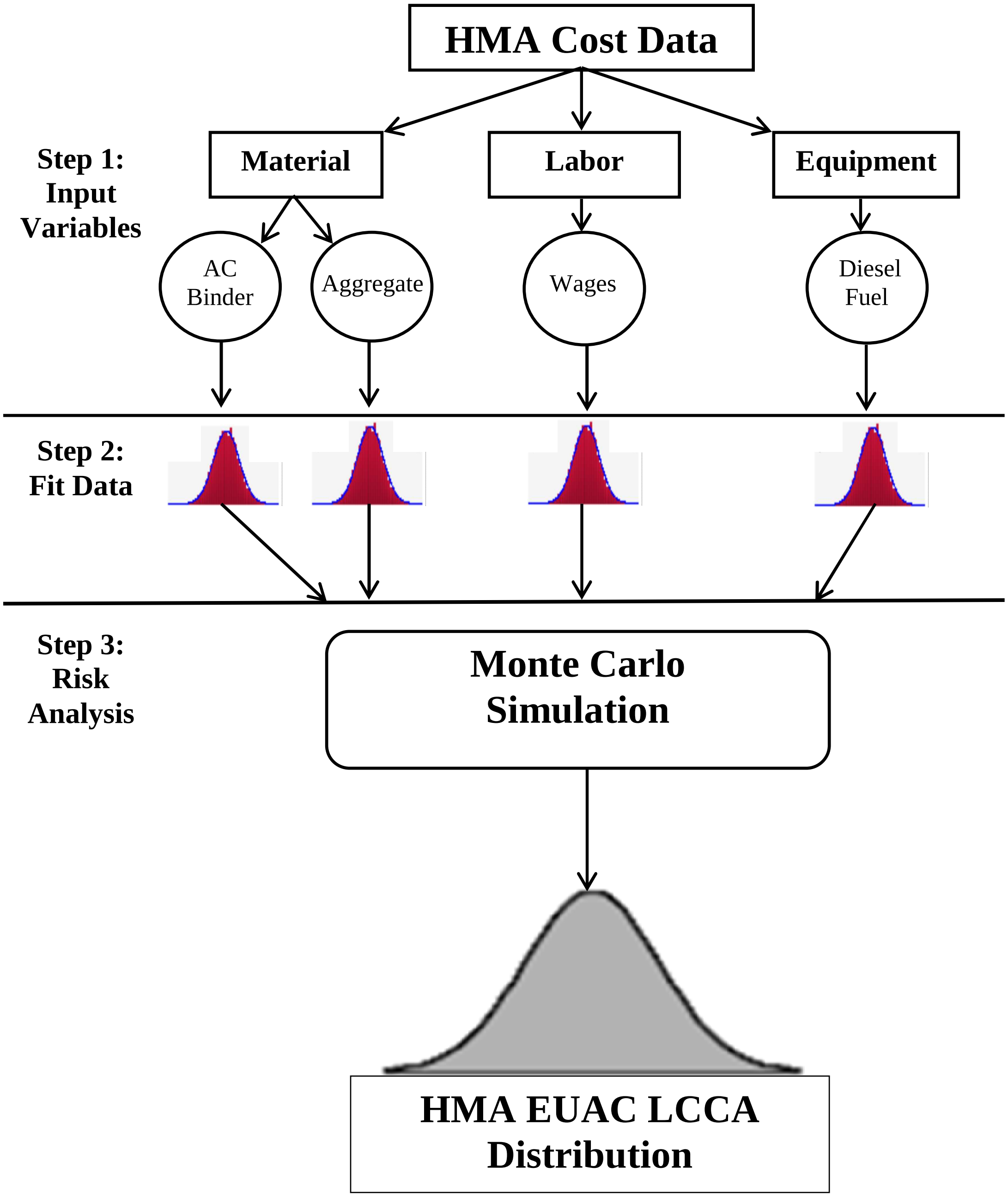


Figure 1.16 Commodity-Based Stochastic LCCA Logic.

Task 7: Select PPTs for Stochastic Analysis

Chapter 10 demonstrates stochastic LCCA using PPT data from test sections associated with this research (Chapter 2). The PPT sections correspond with those used in the deterministic LCCA case study in Chapter 4.

Task 8: Calculate LCCA for PPTs from Deterministic and Stochastic Approaches

Chapter10 discusses deterministic and stochastic LCCA calculations conducted for the various PPTs. Input values and calculations followed established protocol for deterministic or probabilistic treatment (Figure 1.15).

Task 9: Compare the Stochastic and Deterministic Results

Deterministic and stochastic LCCA results for each PPT were evaluated and reported in Chapters 8 and 10, and the research question was answered. The stochastic results did differ from the deterministic results.

Task 10: Explore the Relationships and Sensitivities of Input Values

The differences in LCCA results were explored through sensitivity analysis. The relationships and sensitivities of input values had an effect on outcomes, as noted in Chapters 8 through 10.

Task 11: Validate Stochastic EUAC LCCA PPT Model (Internal Validation)

Deterministic and stochastic modes of the EUAC model were internally validated via numerous methods, as reported in Chapter 11.

Task 12: Validate Stochastic EUAC LCCA PPT Model (External Validation)

The model created for this research was externally validated with a pilot study using macrotexture and cost data for San Antonio District chip seals, as reported in

Chapter 11.

Task 13: Validate Stochastic EUAC LCCA PPT Model (Construct Validation)

The major research assertions were reassessed in context of the literature review and it was concluded that the research exhibits construct validity, as reported in Chapter 11.

Task 14: Report Results

The case study results are reported and illustrated in subsequent chapters of this writing.

1.5 DISSERTATION ORGANIZATION

This dissertation is organized in journal-paper format with each paper presented in a logical order that promotes the flow of the reading. It presents, demonstrates and validates the deterministic/stochastic EUAC LCCA model that incorporates engineering and economic data to produce life cycle cost output that can be used by pavement managers to enhance the decision-making process and pavement preservation justification. The dissertation body has 4 logical parts, as illustrated in Figure 1.17 and further explained in the next section:

- Part 1: Introduction (Chapters 1 and 2).
- Part 2: Deterministic EUAC LCCA for PPT:

  This part contains the development and application of the deterministic model, which is appropriate when uncertainty is not expected to impact results (FHWA, 1998a) (Chapters 3-7).
- Part 3 - Stochastic EUAC for PPT:

This part contains the development and application of the stochastic model, which is appropriate when uncertainty is expected to impact results (FHWA, 1998a) (Chapters 8-11).

- Part 4 – Conclusion (Chapter 12).

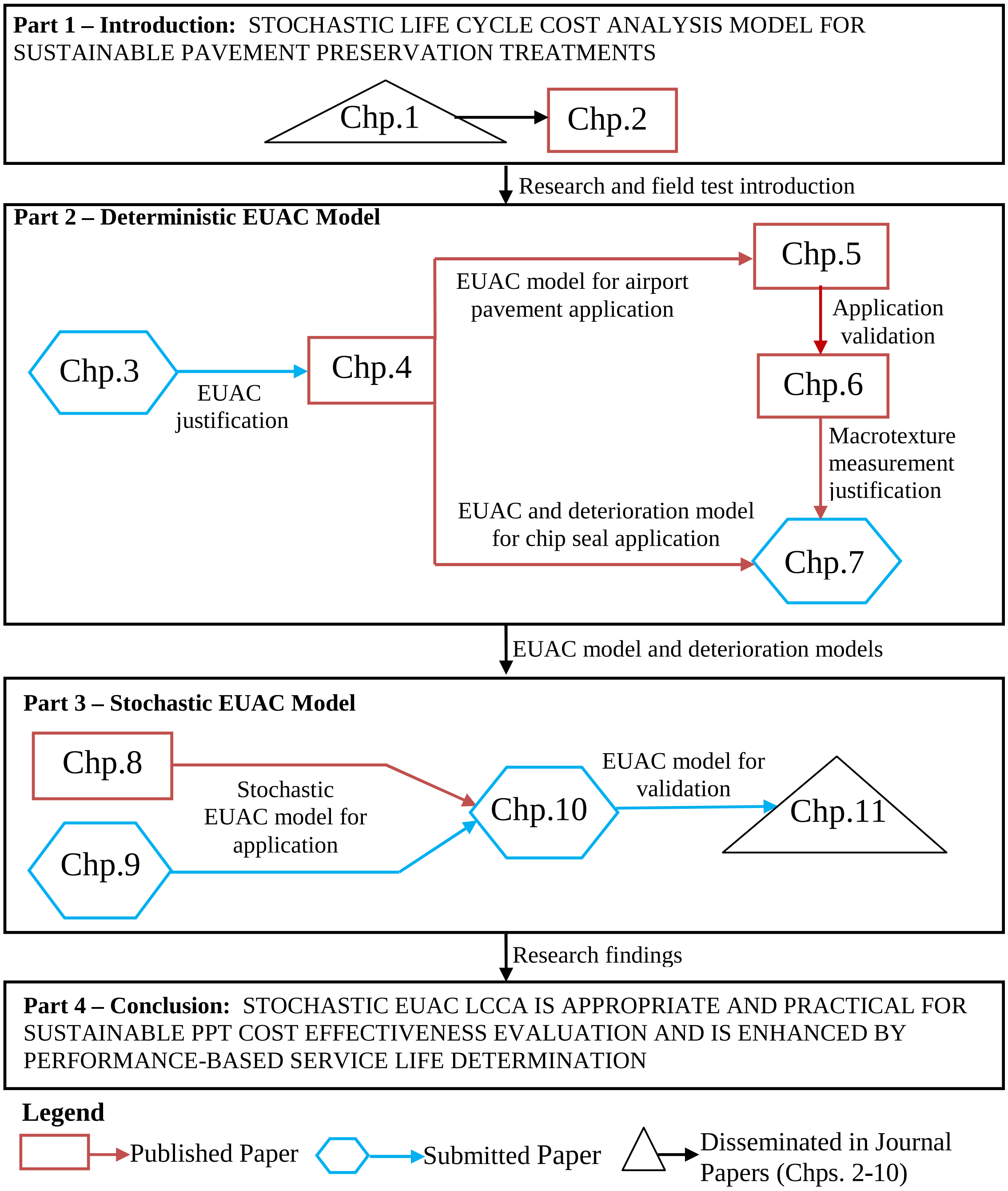


Figure 1.17 Dissertation Roadmap.

Chapter 1 provides the context for the dissertation. Chapters 2 through 10 each contain a journal paper that presents the findings of this research project: 4 published (3 peer-reviewed journal and 1 peer-reviewed full paper conference proceedings), 2 accepted for publication (1 peer-reviewed journal and 1 peer-reviewed full paper conference proceedings), and 3 that are prepared to be submitted for publication to peer-reviewed journals. Chapter 11 details research validation, and Chapter 12 consists of conclusions, contributions, and recommendations for future research.

Part 1: Introduction (includes Chapters 1 & 2)

Chapter 2 entitled "Comparative Field Testing of Asphalt and Concrete Pavement Preservation Treatments in Oklahoma" introduces the overall research project and the pavement preservation field test sections that yielded engineering data used in the LCCA and deterioration models, as discussed in subsequent chapters. Along with Chapter 1, this chapter validates the need for the research and discusses the main concept of combining engineering technical data with economic data to evaluate the cost effectiveness of PPTs, which lays the foundation for the development of this dissertation.

Part 2: Deterministic EUAC Model for PPT (Includes Chapters 3 – 7)

Chapter 3 entitled "A Comparative Analysis of Net Present Value and Equivalent Uniform Annual Cost in Chip Seal" justifies the development of a EUAC-based model for PPT evaluation. It demonstrates the complexity associated with the NPV method due to arbitrary input parameters and irrelevant output. This chapter highlights the applicability, practicality and superiority of the EUAC model and shows that it is "consistent with the level of investment" (FHWA, 2007).

Chapter 4 entitled "Life Cycle Cost-Based Pavement Preservation Treatment Design" introduces the mechanics of the new EUAC LCCA model and the deterioration models developed specifically for PPT evaluation to determine the most cost effective alternative. This chapter justifies the inclusion of the continuous and terminal modes into the EUAC model on the basis of engineering economic principles.

Chapter 5 entitled "Evaluate Airport Pavement Maintenance/Preservation Treatment Sustainability Using Life-Cycle Cost, Raw Material Consumption and *Greenroads* Standards" shows how the EUAC model discussed in the previous chapter can apply to airport pavements. It also demonstrates how LCCA results can be coupled with other sustainability metrics to assist pavement managers in pavement treatment selection.

Chapter 6 entitled "Comparative Analysis of Macrotexture Measurement Tests for Pavement Preservation Treatments" discusses appropriate methods of measuring macrotexture for specific pavement treatments. This chapter provides the justification for using TNZ T/3 sand circle measurement data to determine chip seal service life. It forms the basis for performance-based LCCA to determine chip seal cost effectiveness in Chapters 7 and 10.

Chapter 7entitled "Performance-Based Life Cycle Cost Analysis: A Chip Seal Field Test Case Study" applies the models and methodologies discussed in preceding chapters to a chip seal case study and disseminates a methodology and makes the case for including treatment performance data in LCCA.

Part 3: Stochastic EUAC LCCA Model for PPT (Chapters 8-11)

This part serves to answer the research question by demonstrating that stochastic LCCA offers a different answer than deterministic LCCA, which is demonstrated in each of the chapters.

Chapter 8 entitled “Stochastic Life Cycle Cost Analysis for Pavement Preservation Treatments” builds upon the LCCA concepts in preceding chapters and creates a stochastic EUAC model. It introduces a stochastic EUAC LCCA methodology that demonstrates the value of exposing the volatility associated with underlying construction commodities.

Chapter 9 entitled “Stochastic Pavement Preservation Treatment Life Cycle Cost Analysis Algorithm” further disseminates the development of the stochastic EUAC model by discussing the mechanics of the continuous and terminal modes. This chapter correlates with Chapter 4 that discussed continuous and terminal modes for the deterministic model. Both serve to demonstrate model adherence to engineering economic principles.

Chapter 10 entitled “Comparative Analysis of Selected Life Cycle Cost Analysis Methods: A Pavement Preservation Treatment Case Study” is the culmination of the research effort. It builds upon the methods and methodologies in the preceding chapters and conducts a comparative analysis of deterministic-based, stochastic-based and performance-based LCCA methods to show LCCA selection sensitivity.

2.0 COMPARATIVE TESTING OF ASPHALT AND CONCRETE PAVEMENT PRESERVATION TREATMENTS IN OKLAHOMA[1]

Riemer, C., D.D. Gransberg, M. Zaman, and D.M. Pittenger, "Comparative Field Testing of Asphalt and Concrete Pavement Preservation Treatments in Oklahoma," *Proceedings*, 1st International Conference on Pavement Preservation, Transportation Research Board, Newport Beach, California, April 2010, pp.447-460.

2.1 PAPER SYNOPSIS

This chapter contains the earliest publication associated with this research project and served to disseminate interim research results stemming from the PPT field tests. A PPT deterioration methodology is introduced that uses microtexture and macrotexture (performance measurements) to estimate remaining service life. The paper introduces the concept of correlating engineering technical data with economic data to determine "bank-for-buck" in support of the overall research project's primary objective.

2.2 RESEARCH METHODOLOGY

The project's major deliverable is a pavement surface texture maintenance guide that can be used by ODOT pavement managers to restore surface texture and skid resistance to various types of pavements throughout the state. This will constitute a surface retexturing "toolbox" that contains both the technical engineering information as well as the economic analysis of each treatment's efficacy. The idea is not to identify the "best" method but rather to quantify the benefits of all the treatments in a manner

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[1] The original journal paper has been reformatted to make it consistent with the other published chapters in this document.

that then allows a pavement engineer to select the right pavement preservation "tool" for the specific issue that they need to address and satisfy the fundamental definition of pavement preservation: "put the right treatment, on the right road, at the right time" (Galehouse et al. 2003).

The research project established a series of asphalt and concrete test sections on State Highway 77H (Sooner Road) between Norman and Oklahoma City, Oklahoma (Figure 2.1). Each test section is ¼ miles (400 meters) long and one lane wide. Each section has been retextured with a different type of pavement preservation process.

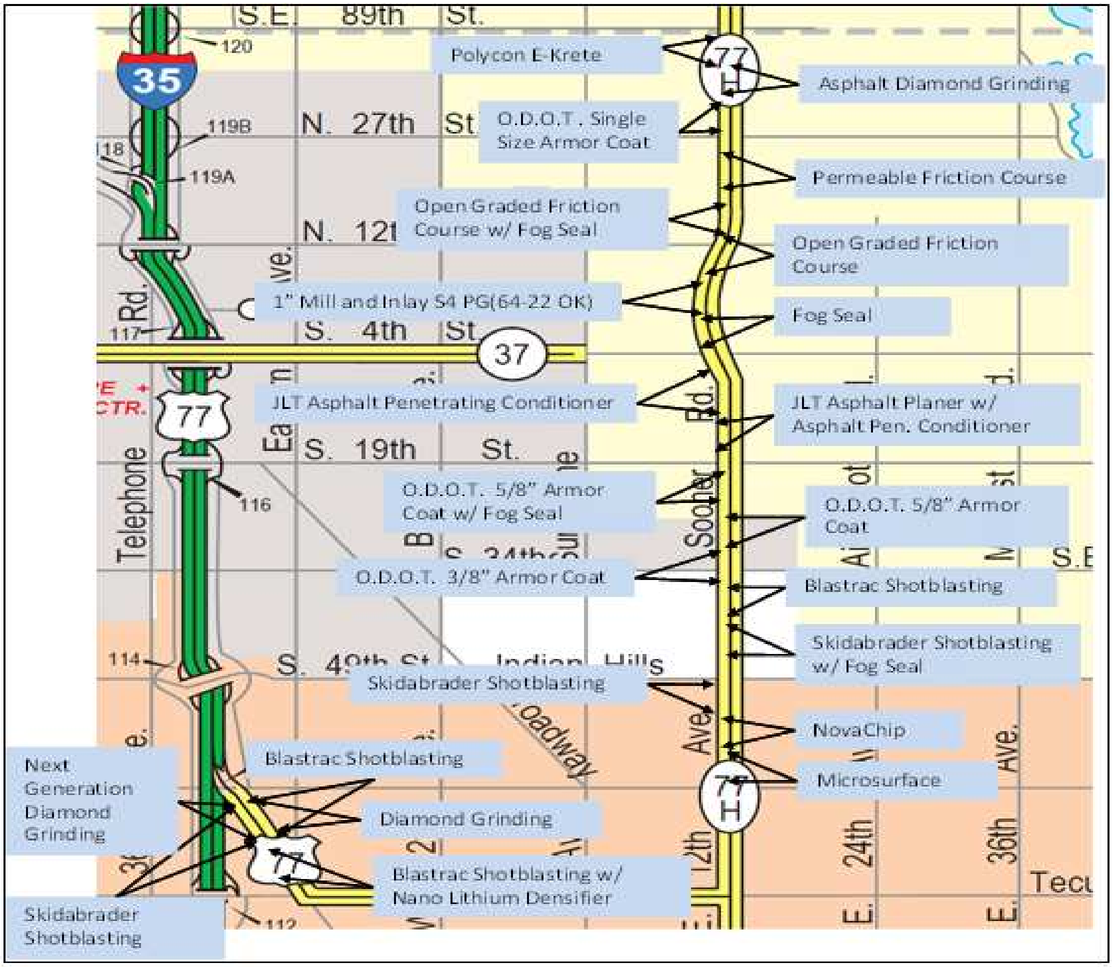

Figure 2.1 Oklahoma Pavement Preservation Test Site Map.

Table 2.1 shows the different PPTs that are included in this research. 14 of these treatments were installed during the summer of 2008 and have 12 months of data at the time of this writing. The remaining sections were installed during the summer of 2009.

Table 2.1 Oklahoma Pavement Preservation Test Sections.

Asphalt Test Sections		
Surface Treatment	**Chemical Treatment**	**Mechanical Treatment**
• Fog seal • Microsurfacing • ODOT Standard 3/8” chip seal • ODOT Standard 5/8” chip seal • ODOT Standard 5/8” chip seal with a fog seal • Single size ½” chip seal • Novachip • Open Graded Friction Course • Open Graded Friction Course with a fog seal • Permeable friction course • 1” Hot Mix Asphalt mill-inlay	• E-Krete pavement surface stabilizer • Asphalt penetrating conditioner with crack seal	• Pavement retexturing using shotblasting (48” width) • Pavement retexturing using abrading (72” width) • Pavement retexturing using abrading (72” width) with fog seal • Pavement retexturing using a flat headed planing (milling) technique with asphalt penetrating conditioner • Asphalt diamond grinding
Concrete Test Sections		
Surface Treatment	**Chemical Treatment**	**Mechanical Treatment**
	• Pavement retexturing using shotblasting treated (48” width) with Nanolithium densifier	• Pavement retexturing using shotblasting (48” width) • Pavement retexturing using abrading (72” width) • Diamond grinding • “Next Generation” diamond grinding

Surface friction and pavement macrotexture were measured on each test section before the treatments and continue to be measured on a monthly basis for three years after application. Thus, changes in both microtexture and macrotexture will be recorded over time, and each treatment’s performance can then be compared to all other treatments in the same traffic, environment, and time period.

The first step was to mark the individual test sections. Quarter mile asphalt test sections were selected along the south-bound, outside lane of SH 77H at locations where the alignment was as straight as possible. Additionally, areas at intersections and turn-outs were avoided to the greatest extent possible. Concrete test sections were located in all four lanes of SH 77 using the same standard for actual siting as the asphalt sections. A specific test location roughly in the middle of the test section was marked to ensure that measurements are taken in the same location each month. Finally, untreated control sections were established between the test sections on the existing pavement surface.

Once the test sections were properly marked and the field testing protocol was finalized, the pre-treatment condition of the existing pavement surface at each test section was characterized using the same tests used after the treatments are applied This furnishes a benchmark against which to measure the change in surface friction and macrotexture before and after the treatments for each test section before traffic and environmental conditions begin to impact the treatments.

The aggregate used in each of the treatments was restricted to the same source. Abrasion resistance and aggregate microtexture are the two characteristics that have the greatest impact on skid resistance. Therefore, prior to installation, aggregate samples were collected and characterized in the laboratory using both the Micro-Deval method to test for abrasion resistance as recommended by a FHWA report on pavement preservation (Beatty et al. 2002) and the Aggregate Imaging System (AIMS) (Bathina, 2005). The Aggregate Imaging System (AIMS) is used to provide a quantitative evaluation of the form, angularity and texture of coarse aggregates and angularity and form of fine aggregates used in surface treatment methods. All aggregates used in the research have been characterized in the same manner.

The field test section data will consist of friction measurements using the ODOT skid trailer and two types of macrotexture measurements (Outflow meter ASTM STP 583 and the Transit New Zealand TNZ T/3 Sand Circle). The TNZ T/3 testing procedure supports the TNZ P/17 performance specification which can then be used as a metric to judge the success or failure of the surface treatments in their first 12 months based on a field-proven standard (Transit 2002 and 1981). Figure 2.2 shows the skid trailer and the two field macrotexture tests being conducted in the field.

Figure 2.2 ODOT Skid Trailer, Outflow meter ASTM STP 583 and the Transit New Zealand TNZ T/3 Sand Circle Testing.

A recently completed pavement surface texture research project in Texas proved the validity of both the test procedure and the performance specification for use in the US (Gransberg, 2007). The purpose of taking two different types of measurements of pavement surface macrotexture is to allow a back-check by relative readings to be conducted and thus improve the accuracy of the discrete engineering property data collected as well as to enhance reproducibility. For more detailed information about the test methods and application guidance, see Chapter 6.

2.3 RESULTS

It would be impractical to report on the performance of all the test sections in this chapter. So, a few examples are provided that illustrate the emerging findings of the project. The fundamental objective involves measuring the change in macrotexture and skid number over time. A previous study found that “the skid number gradient with speed is inversely proportional to the pavement macrotexture” (Flintsch et al. 2003). Thus, as this study is focused on pavement preservation, it is important to observe the change over time for each measurement on each test section treatment. Figure 2.3 shows the observed change to date (11 months) for a concrete pavement retextured using the Blastrac shotblasting technology and an asphalt pavement that was covered with an open-graded friction course (OGFC).

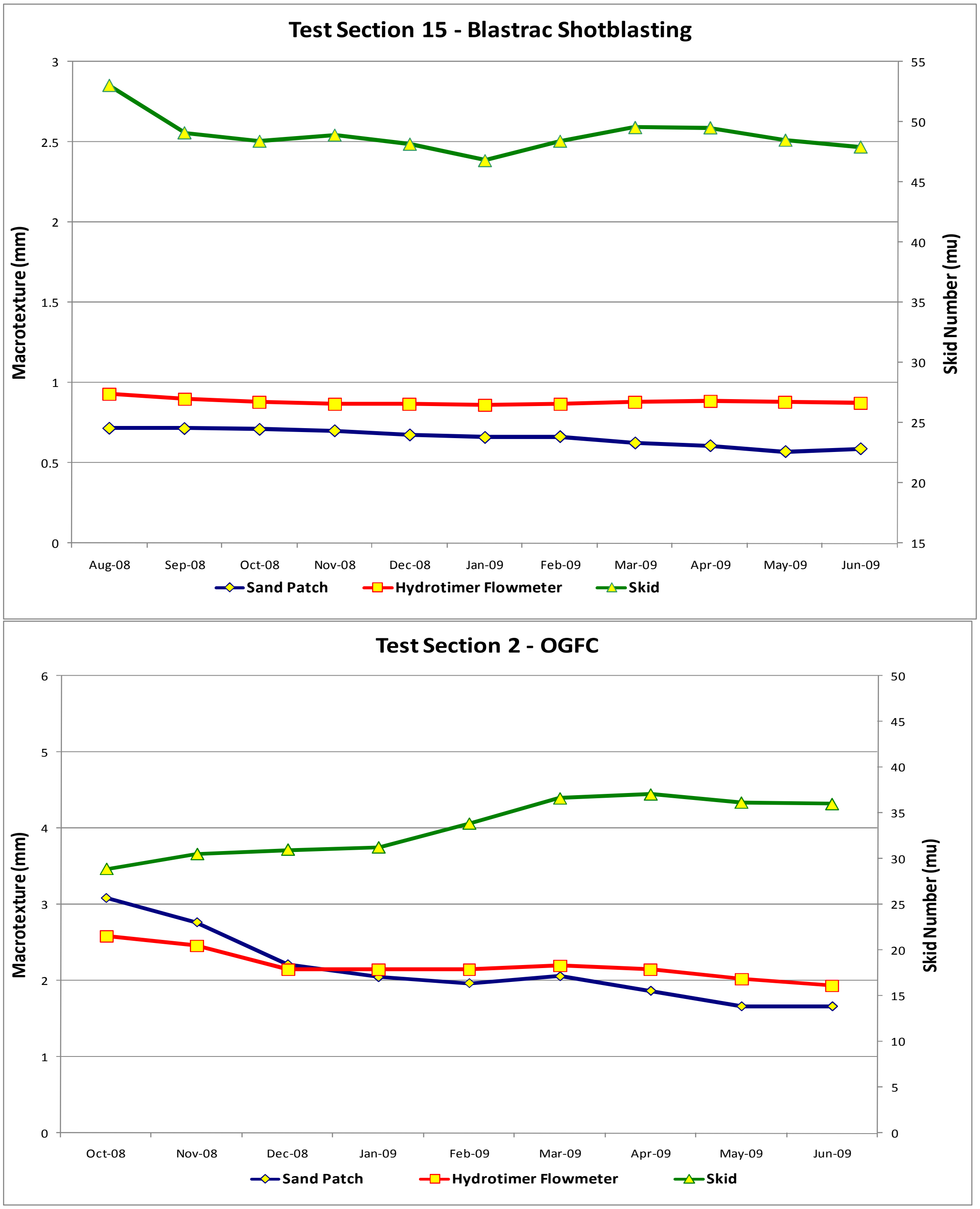

Figure 2.3 Test Sections 2 and 15, Skid Number and Macrotexture Measurements for Year 1.

Although the concrete pavement with shotblasting test section has very low macrotexture, it remained virtually constant over the year, as shown in Figure 2.3. The section exhibits high microtexture, although the skid number dropped initially. It must be noted that the test protocol was established to reduce as much variation in test locations as possible. However, all three tests are inherently variable as it is functionally impossible to take the measurements in exactly the same spot. Thus, it is the trends over time that are important rather than the individual measurements.

The next example is a test section that was treated with an asphalt penetrating pavement conditioner (i.e. one of the chemical treatments). This treatment is recommended as a PPT for structurally sound asphalt pavements whose primary distress is oxidation. This section did not receive surface retexturing, which is the cause of the two macrotexture test measurements remaining relatively constant (Figure 2.4).

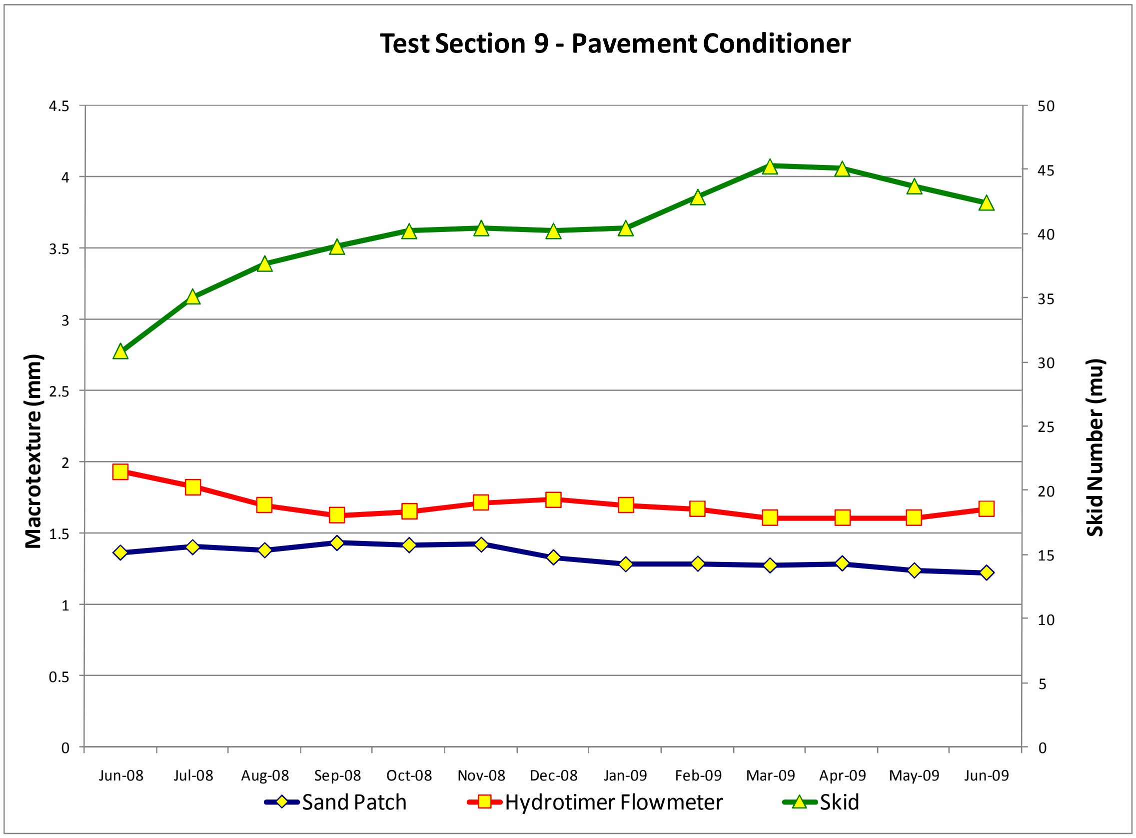

Figure 2.4 Test Section 9 Skid Number and Macrotexture Measurements for Year 1.

Although the conditioner had an initial negative impact on skid number, the loss in skid resistance dissipated as the surface film was worn away by traffic. The project has a second test section that used the same product after milling 1/8 inch off the surface. It also suffered a short-term loss of skid resistance, but exhibited increased macrotexture. This is the type of information that is currently missing in the body of knowledge. This shows that while there is a loss in skid number initially, it takes roughly 3 months to reach a level of 35 and then stays above that level for at least the remainder of the year. A maintenance engineer can now make a rational decision as to the viability of this PPT.

Figure 2.5 shows an example of the most costly of the PPTs: a thin (1 inch/2.5 cm) HMA mill and inlay that has very low macrotexture, but high skid numbers.

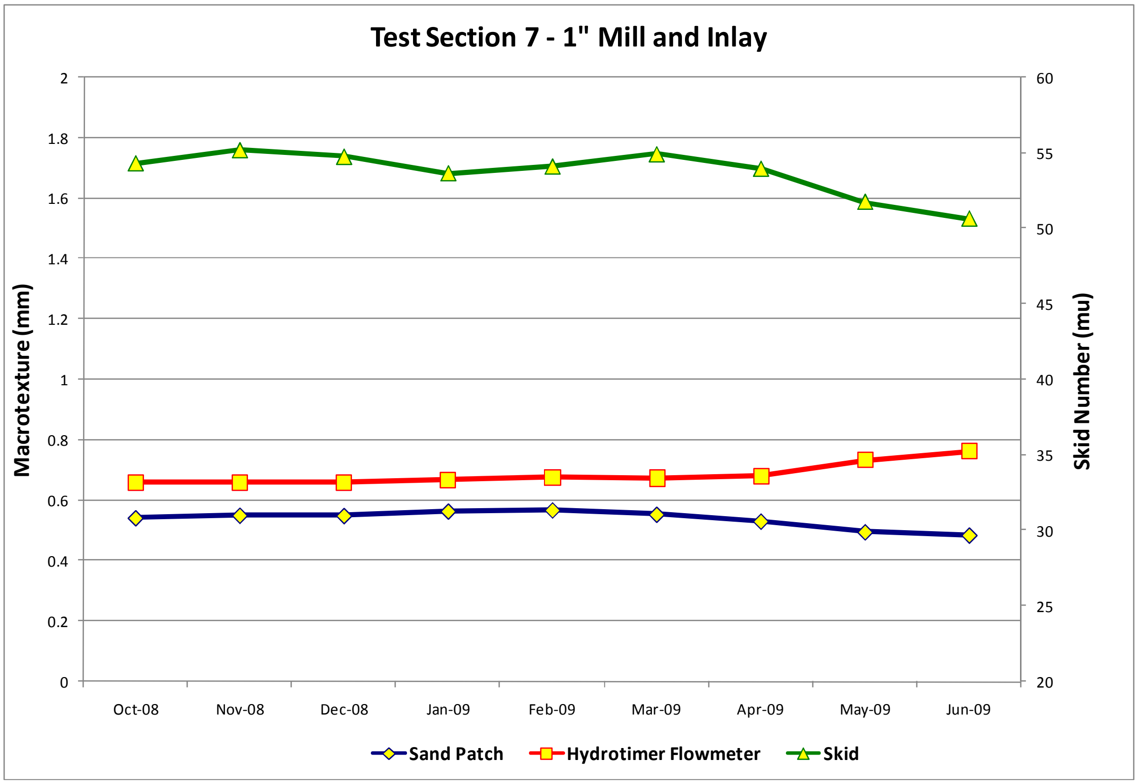

Figure 2.5 Test Section 7 Skid Number and Macrotexture Measurements for Year 1.

Given the research by Flentsch et al. (2003) that shows that macrotexture is important to pavement drainage and the reduction of hydroplaning, this treatment would be best used in areas where climatic conditions and pavement geometry do not lend themselves to periods of wet pavement. If this does not apply to the problem at hand then a treatment such as a chip seal would be a better choice.

Figure 2.6 shows the comparison with the above mill and inlay test section and a chip seal test section. First it should be noted that the inlay test section was constructed Two months after the chip seal test section, hence the different periods shown in the graph. This example graphically shows the trade-off that must be made by a maintenance engineer when deciding to which PPT is most appropriate for a given problem on the highway. A later phase of this research project will set to measuring cost effectiveness based on actual field performance. The technique that will be used will be cost index number theory (West and Riggs, 1986). This technique allows the analyst to measure the “bang for the buck.” In this case, the following equation can be used to calculate the Skid Number Cost Index for each treatment alternative (Gransberg and Zaman, 2005).

$$SNCI_i = \frac{TC_i}{\text{Ave } SN_i} \qquad \text{Eq. 2.1}$$

Where: $SNCI_i$ = Skid Number Cost Index of Treatment “i”

Ave SN_i = Average Skid Number of Treatment “i”

TC_i = Total Cost per Lane-mile of Treatment “i”

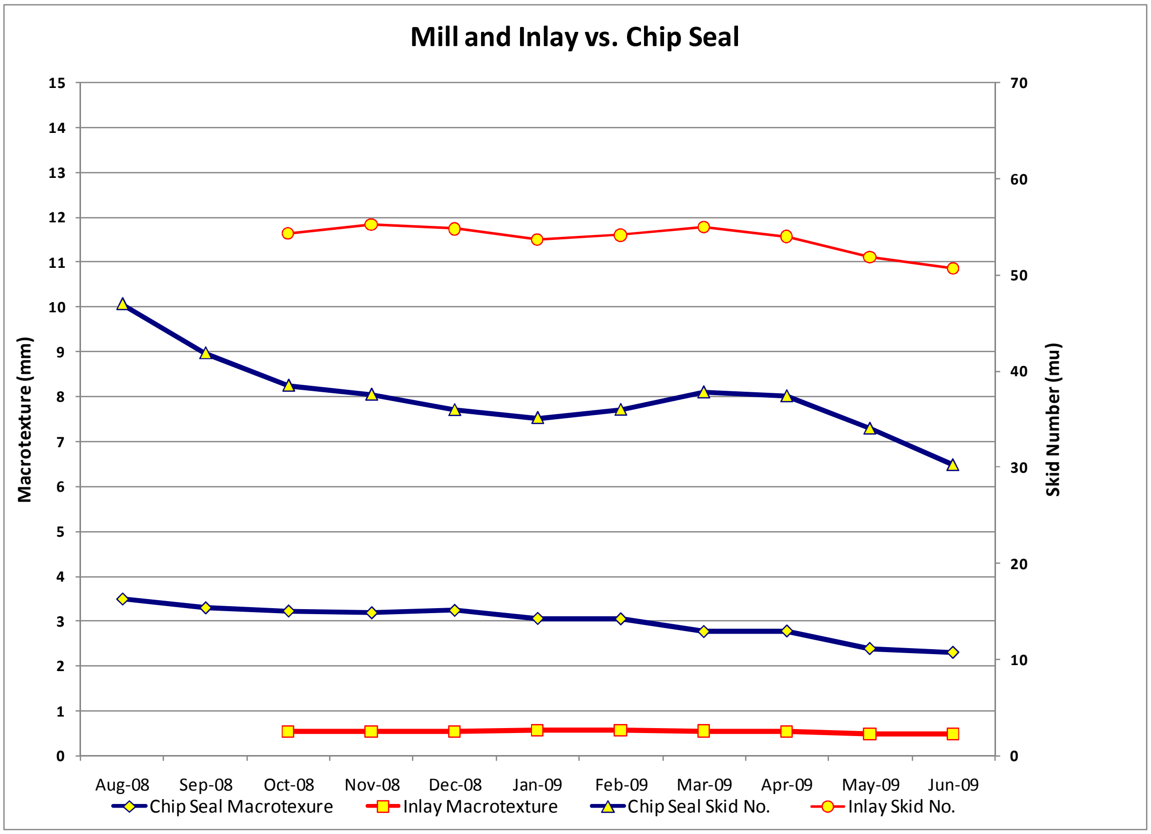

Figure 2.6 Comparison of Skid Number and Macrotexture Measurements Hot Mix Asphalt Mill and Inlay versus a Chip Seal.

Using the July 2008 prices from the Oklahoma Department of Transportation, which is the period in which these two treatments were installed, the results obtained are shown in Table 2.2. The alternative with the lower cost index number is considered the more cost effective option. Microtexture, macrotexture and cost data can provide the pavement manager with necessary decision-making information. HMA costs six-times more than the chip seal option in this case, but it increases skid number by 40%. The pavement manager would have to determine if that is sufficient to justify one alternative over another, as well as take other external factors (location, traffic level) into account. The idea is to change the decision criterion from “minimize cost” to “maximize value” by having all the necessary decision-making information in one place.

Table 2.2 Skid Number Cost Index Analysis of Treatment Alternatives.

PPT Performance-Cost Analysis				
PPT	Unit Price (July 2009)	Total Cost per Lane-Mile	Average Skid Number	Skid Number Cost Index
1” HMA Mill and Inlay	$8.52/SY	$59,981	52.6	1,141.28
Emulsion Chip Seal	$1.51/SY	$10,630	37.6	282.45
1 SY = 0.84 SM; 1 Lane-mile = 5,890 SM				

2.4 CONCLUSIONS

This study shows the value of long-term pavement preservation field research. It also shows the need to have the combination of both microtexture and macrotexture data available to the pavement manager in the PPT selection process. The combination of these two measurements, along with cost data and analysis, provides the tools necessary to support an informed engineering and management decision.

This project demonstrates a robust partnership between government, academia, and industry. The fact that over $400,000 worth of PPTs were donated as well as the in-kind donations of ODOT in providing traffic control, skid testing, and engineer’s time, shows the importance of research in pavement preservation. This project is not a competition between products. It is the start of an encyclopedia of pavement preservation comparative analysis, and projects of this nature should be instituted throughout the US to provide the unique local performance information that only long-term filed testing can generate.

3.0 A COMPARATIVE ANALYSIS OF NET PRESENT VALUE AND EQUIVALENT UNIFORM ANNUAL COST IN CHIP SEAL[2]

Pittenger, D.M. and T. McCuen, “A Comparative Analysis of Net Present Value and Equivalent Uniform Annual Cost in Chip Seal,” submitted to the *Journal of Construction Management and Economics.*

3.1 PAPER SYNOPSIS

This chapter exposes the NPV LCCA complexity issues and service life indifference that contribute to its lack of use at the pavement preservation level. The EUAC LCCA model is introduced, along with its continuous and terminal modes that allow it to adhere to engineering economic principles and be appropriate for transportation use. Chip seal LCC output from both LCCA types are compared and analyzed. The chapter concludes that EUAC is better suited to PPT evaluation because it provides a streamlined approach that accommodates its short term nature and allows the pavement manager to better relate treatment LCC output to annual maintenance budgets.

3.2 RESEARCH METHODOLOGY

The EUAC model created for this research calculates life cycle cost for each alternative based on the EUAC method. All incurred costs expected throughout the service life of an alternative are brought to a base year, summed, and then annualized according to the *treatment’s service life* as determined by field data and pavement

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[2] The original journal paper has been reformatted to make it consistent with other published chapters in this document.

manager professional judgment. In other words, the AP for each treatment alternative is equal to its own *anticipated service life*:

$[ASL_{alt} = \text{analysis period}_{alt}]$

In NPV models, the annualization is based on the common AP. This model is unique because it seemingly bypasses the common-AP selection process. It determines the EUAC based on each alternative's respective *anticipated service life* by using the following EUAC calculation:

$$EUAC\ (i\%) = [\sum P] * [i(1+i)^n \div (1+i)^n - 1)] \qquad \text{Eq. 3.1}$$

Where:

i = discount rate

P = present value

n = pavement treatment *anticipated service life*

The EUAC model is tailored to pavement-management decision-making. It considers the short-term, limited scenarios (*continuous and terminal*) that the pavement manager encounters. The pavement manager is able to intuitively analyze the LCCA results because they are displayed within the context of the pavement manager's expertise. Treatment-relevant input values, such as service life, are utilized. In contrast, other (NPV) models obscure these pavement-manager relevant values in a possibly arbitrary AP selection requiring extensive engineering economic understanding garnered from *economist* experience to extricate (FHWA, 1999). Thus, EUAC neutralizes the associated sensitivity and complexity issues. Because maintenance funding is authorized on an annual basis, comparing alternatives on a EUAC basis better fits the funding model than using NPV, which would assume availability of funds across the treatment's entire service life. Since pavement managers typically consider several alternatives with varying services lives based on available funding rather than technical superiority, the FHWA LCCA method based on NPV creates more problems than it solves. Furthermore, the EUAC method simplifies the LCCA process and results in the same ranking of alternatives as the NPV method, all else held constant (White et al. 2010), rendering the problematic AP irrelevant.

3.2.1 Continuous and Terminal Scenarios for Deterministic EUAC Model

A road segment (asset) is generally intended to remain in service indefinitely and pavement treatments are expected to be applied continuously over the life of the asset, although the service life of a treatment is finite (Lee, 2002). The pavement manager will encounter one of two scenarios in the short-term-implementation level of decision making: the year of the *next expected* rehabilitation or reconstruction will either be known (*terminal scenario*) or it will not (*continuous scenario*) (Lee, 2002). When using EUAC, the "mistake" occurs when the planning horizon, or *terminal scenario*, is not considered or acknowledged for the investment (White et al. 2010). In other words, if the *encroachment* of the next expected rehabilitation or reconstruction on the service lives of treatment alternatives is expected to have a material effect with regard to the treatment of residual value for one or more of the treatment alternatives, this encroachment must be addressed in the calculations (White et al. 2010). The intent of using EUAC as the basis of the model was to address both scenarios with its "covert" flexibility, which is recommended in economic analysis (White et al. 2010), while maintaining its efficient, "overt" inflexibility with regard to disallowing common AP selection. The continuous feature in the model disallows the "unnecessary truncating of [service] lives" (Lee, 2002) while the "automatic truncate" terminal feature is built in to ensure adherence to engineering economic principles. This *fixed flexibility* reduces the negative impact associated with standard new pavement LCCA complexities and the possibility of faulty output.

EUAC Model, Continuous Mode

EUAC accommodates the continuous, short-term nature of PPT application because the next expected rehabilitation/reconstruction of the pavement is commonly unknown, i.e. is not on the current work plan. The pavement manager must plan to continuously maintain, preserve or "do nothing" to the pavement in the undefined interim. Because encroachment is not expected in the continuous mode, material or mathematical adjustments to costs or service life lengths are not required and the pavement manager avoids the "unnecessary truncating of lives" (Lee, 2002). Therefore, each treatment's service life input value will be equivalent to its *anticipated service life* (n), which is the value used in EUAC calculations in this model to determine life cycle cost.

EUAC Model, Terminal Mode

In the terminal scenario, the pavement manager generally chooses the "do nothing" option. In other words, the pavement manager usually defers maintenance because the pavement is scheduled to be rehabilitated or reconstructed according to the work plan. Therefore, the decision essentially *is* to ignore pavement preservation on a given pavement knowing that it will be "fixed" in the near future. This permits the reprogramming of those funds to preserving other pavements in the network.

To avoid the common “mistake” associated with employing the EUAC method, the pavement manager must consider the encroachment upon (i.e. materially alter) treatment service lives to adhere to LCCA principles (White et al. 2010). For example, if the next rehabilitation is scheduled in two years and the pavement manager cannot defer maintenance due to safety concerns, any treatment service life that is expected to extend past two years must be truncated for the purpose of analysis, consistent with the “organization’s need for the investment” (White et al. 2010). If one of the alternatives is expected to have a four-year service life, it may not be able to realize the last two years of service life because its cash flow profile would have to be materially altered to accommodate the rehabilitation in two years. In other words, the residual value would equal zero at time two for the four-year alternative because it can no longer be considered continuous. It ceases having value (or remaining service life) as a pavement treatment because it will be removed when the road is rehabilitated (Lee, 2002; FHWA, 2002*)*. In a terminal scenario, it has been argued that a pavement treatment’s material salvaged from removal can have salvage value, but then the analyst must quantify the cost of removal and value what has been salvaged (Lee, 2002).

The model has been built to accommodate the terminal scenario and engineering economic principles. Each treatment’s service life input value that extends past the year of the next expected rehabilitation/reconstruction is automatically truncated to coincide with the year of the next rehabilitation/reconstruction. This truncated value becomes the treatment’s *anticipated service life* (n), which is the value used in EUAC calculations in this model to determine life cycle cost.

Pavement preservation theory asserts that proactively applying treatment extends the life of the pavement, allowing for the deferment of the expected rehabilitation/reconstruction (Peshkin et al. 2004). In this case, a sensitivity analysis is useful to determine the relative impact of the possibility of pavement life extension and encroachment of the rehabilitation activity on truncated treatment service life.

If, on the other hand, the pavement manager considers employing a one-year treatment in this example, a one-year gap would exist between the treatment's service life and the year of the expected rehabilitation/reconstruction. The EUAC model is built to ignore the gap in terminal mode and calculate EUAC for all alternatives. This situation, although rare due to the "do nothing" preference and very short-term nature of the terminal scenario, may not explicitly adhere to the specific "common period of time" engineering economic principle, but does not warrant it because the gap will most likely be filled with another "do nothing" option. All analysis-period selection methods, when applied to this scenario, have inherent issues as previously stated, so one must decide which method would yield the best information for the pavement manager. The shortest-life method would adhere to the "common period of time" engineering economic principle while EUAC would overtly not. However, if the pavement manager were to choose the shortest-life alternative to set the AP and the other longer-life alternatives were adjusted to fit in accordance with FHWA straight-line-depreciation-like method, the LCCA should still yield the same preferred alternative as the EUAC method. Because the same preferred alternative is yielded from both methods, for the purposes of a consistent model, and with all of the previously-cited issues with the AP, EUAC was selected as the appropriate terminal scenario method. Even in this rare situation, EUAC behaves essentially like a covert short-life method and can provide the pavement manager with relevant decision-making information based on cost, service life and the real possibility of “do nothing” during this state.

3.2.2 Conducting EUAC LCCA on Selected Treatments

Treatment cost-effectiveness evaluation based on engineering economic principles was conducted on PPTs. The FHWA suggests the following LCCA procedures when evaluating design alternatives
(FHWA 2002 and 1998a):

- Step 1: Establish design alternatives [and AP]
- Step 2: Determine [performance period and] activity timing
- Step 3: Estimate costs [agency and user]
- Step 4: Compute [net present value] life cycle costs
- Step 5: Analyze results
- Step 6: Reevaluate design strategies

This study has demonstrated that FHWA LCCA procedures 1, 2 and 4 in the above list do not adequately address PPT evaluation and need to be adapted so that LCCA can be used as a frontline tool by the pavement manager to determine pavement treatment cost effectiveness. To recap, EUAC LCCA procedures include:

- Step 1: Establish [treatment] alternatives, where a treatment’s *anticipated service life* equals its AP: [ASL_{alt} = analysis $period_{alt}$]
- Step 2: Determine [performance period and] activity timing, where the service life of an alternative equals the minimum value of microtexture and

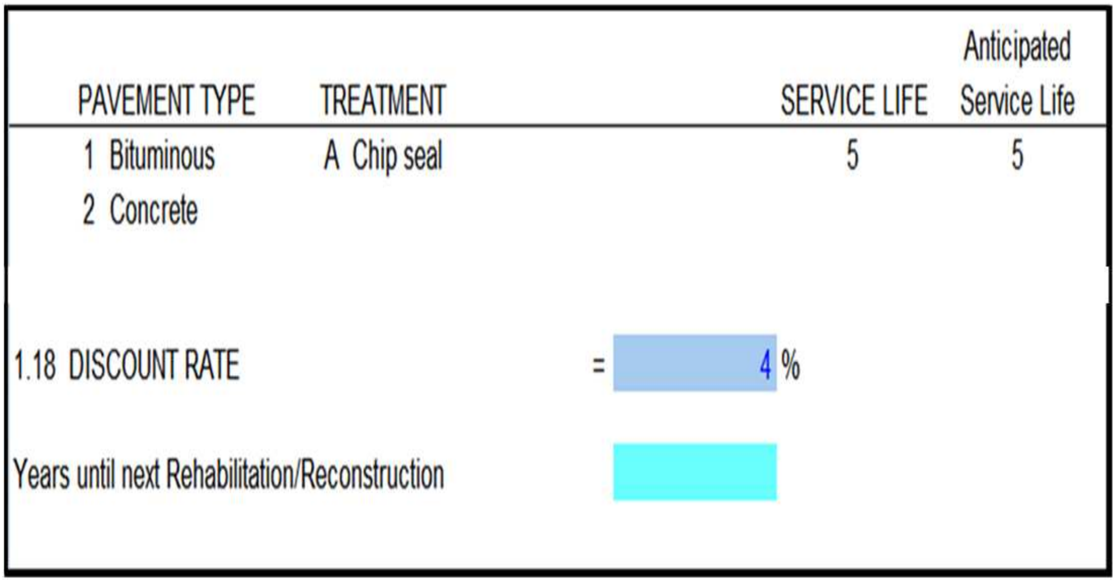
macrotexture deterioration model outputs and engineering judgment: [SLalt = MIN{Mi, Ma, Ex}]

- Step 4: Compute [EUAC] life cycle costs, where n is each treatment's *anticipated service life:*[EUAC(i%)alt = [∑P] [$i(1+i)^n \div (1+i)^n - 1$)]]

and the *anticipated service life* is further adjusted as necessary by the terminal feature of the EUAC model.

3.3 RESULTS

If chip seal service life was expected to be 5 years, then the anticipated service life will be the same value, as shown in Figure 3.1.



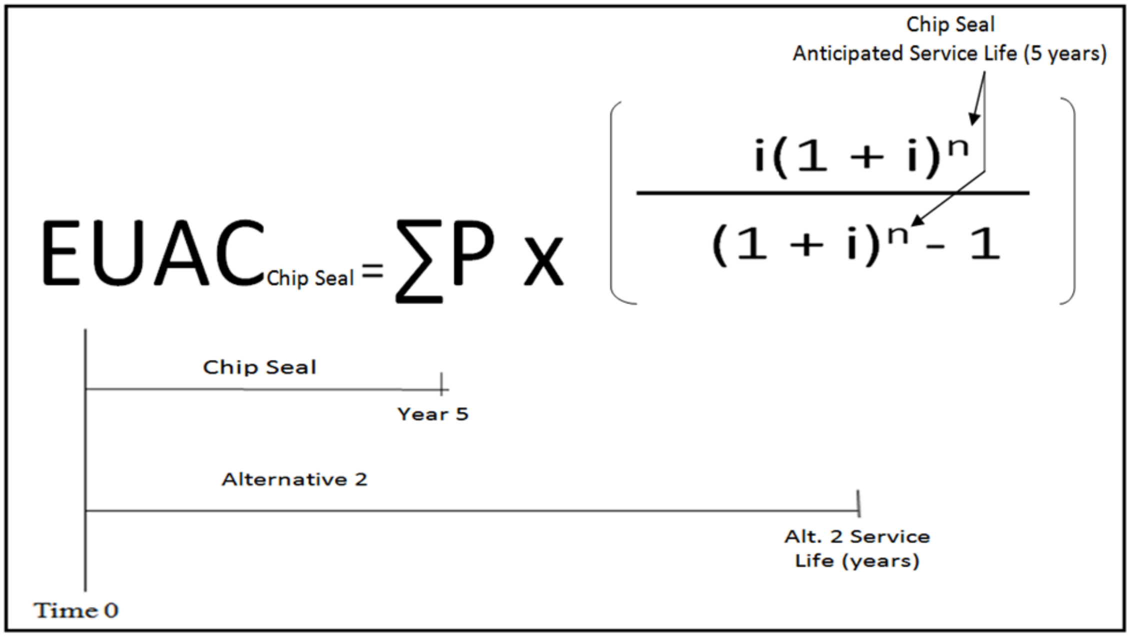
PAVEMENT TYPE	TREATMENT	SERVICE LIFE	Anticipated Service Life
1 Bituminous	A Chip seal	5	5
2 Concrete			

1.18 DISCOUNT RATE = 4 %

Years until next Rehabilitation/Reconstruction

Figure 3.1 EUAC Model Service Life/Discount Rate Input Screen, Continuous Mode.

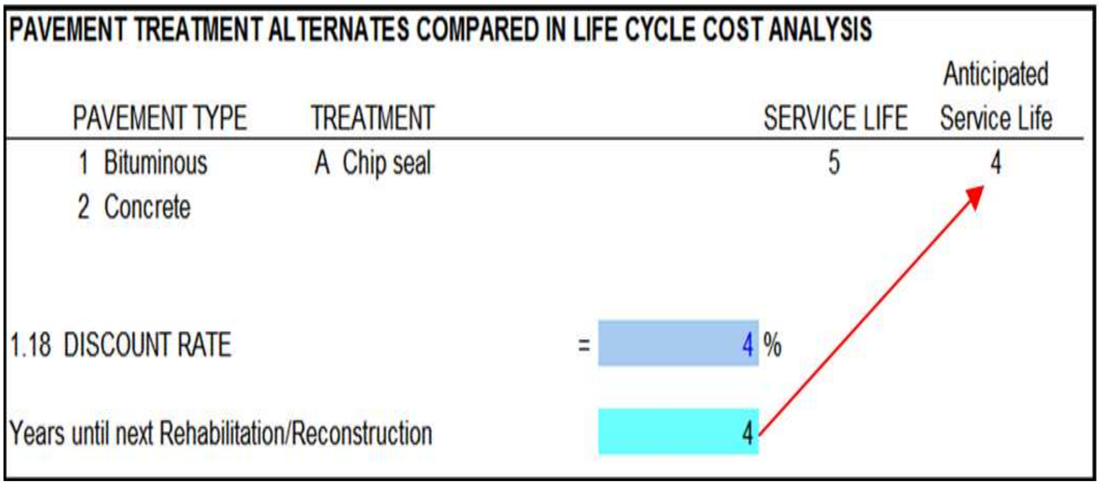
The EUAC algorithm uses the anticipated service life value to calculate the life cycle cost for chip seal, as shown in Figure 3.2, and returns an EUAC of $3,482 based on an initial cost of $12,792 and a discounted future maintenance cost of $3,049 (discount rate: 4%).



$$EUAC_{\text{Chip Seal}} = \sum P \times \left(\frac{i(1+i)^n}{(1+i)^n - 1} \right)$$

Figure 3.2 EUAC Chip Seal Calculation and Service Life Diagram in EUAC.

If the next rehabilitation or reconstruction was expected in four years, the pavement manager would insert that value into the EUAC model input screen, as shown in Figure 3.3, which automatically truncates the chip seal's anticipated service life value, since it will only realize four years of pavement preservation value. Given the initial and future costs used in the continuous mode, the terminal mode yields an EUAC value of $4,271.



PAVEMENT TREATMENT ALTERNATES COMPARED IN LIFE CYCLE COST ANALYSIS

PAVEMENT TYPE	TREATMENT	SERVICE LIFE	Anticipated Service Life
1 Bituminous	A Chip seal	5	4
2 Concrete			

1.18 DISCOUNT RATE = 4 %

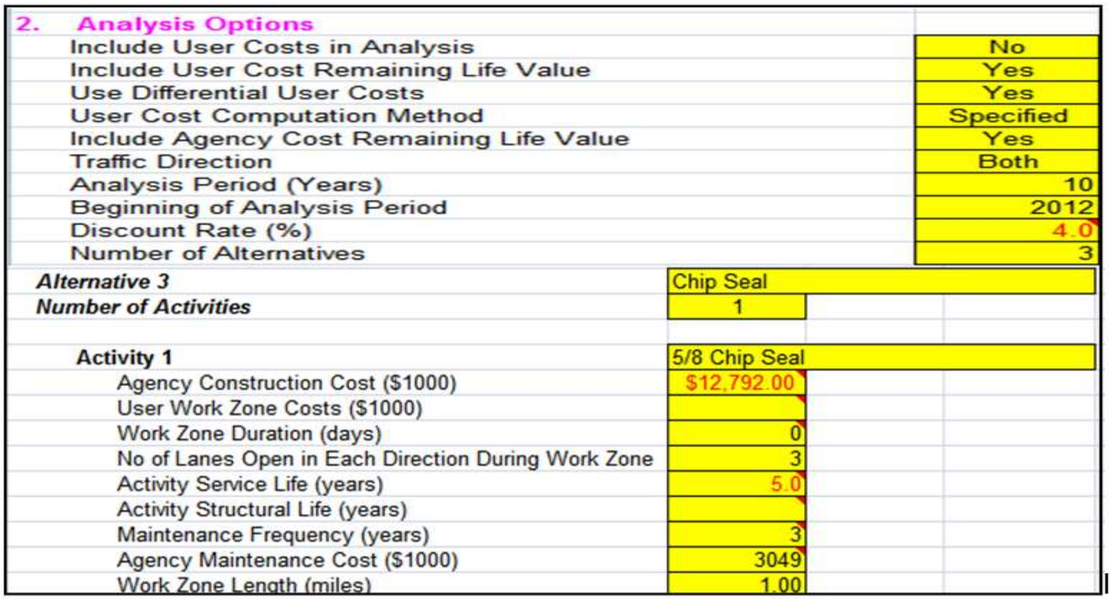
Years until next Rehabilitation/Reconstruction 4

Figure 3.3 EUAC Model Service Life/Discount Rate Input Screen, Terminal Mode.

The NPV model does not allow for direct treatment and consideration of the service life value like the EUAC model does. Economic theory asserts that alternatives with unequal service life lengths must be evaluated over a common period of time (analysis period) for the NPV evaluation to be fair (White et al. 2010). The pavement manager must use the arbitrary parameter of analysis period (AP), which is not intuitively linked with the service life parameter, significantly contributing to the complexity, training requirements and common errors associated with NPV (FHWA, 2001).

To demonstrate some of the NPV complexity issues, the following example exhibits common mistakes made when comparing alternatives. If three alternatives were being considered for a pavement preservation project and were not expected to have equal service lives, the pavement manager would have to reconcile that issue through selection of a common AP. The chip seal treatment will be examined within the following analysis scenario:

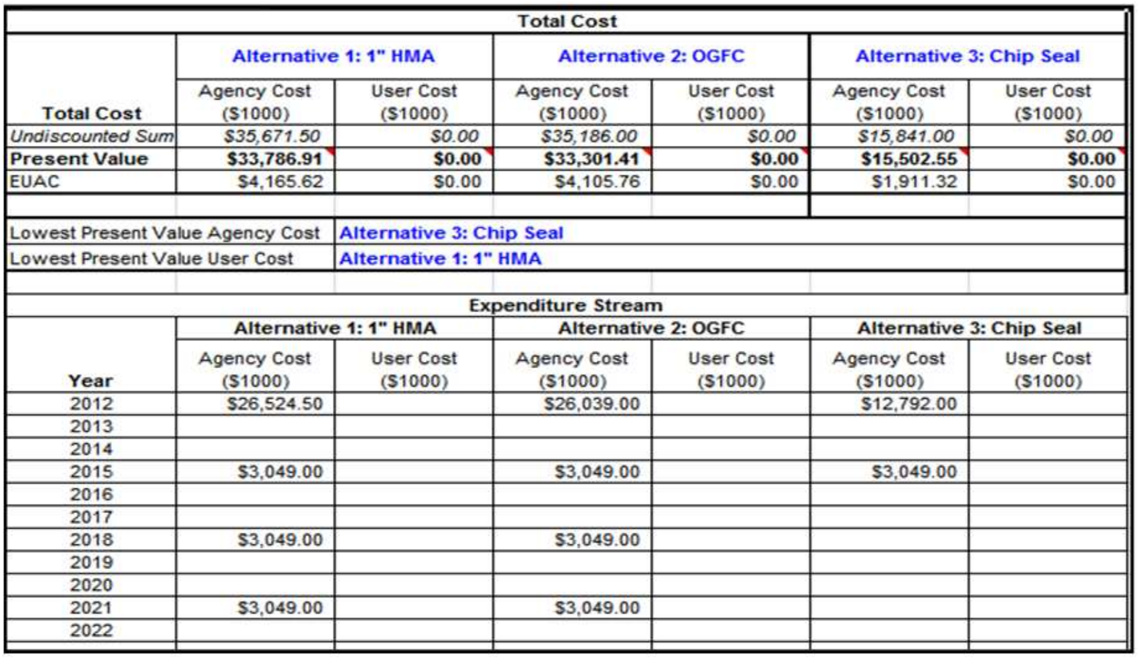
- Hot Mix Asphalt Mill & Inlay (10-year service life),
- Open Graded Friction Course (10-year service life), and
- Chip Seal (5-year service life) (Figure 3.4).



2. Analysis Options	
Include User Costs in Analysis	No
Include User Cost Remaining Life Value	Yes
Use Differential User Costs	Yes
User Cost Computation Method	Specified
Include Agency Cost Remaining Life Value	Yes
Traffic Direction	Both
Analysis Period (Years)	10
Beginning of Analysis Period	2012
Discount Rate (%)	4.0
Number of Alternatives	3
Alternative 3	Chip Seal
Number of Activities	1
Activity 1	5/8 Chip Seal
Agency Construction Cost ($1000)	$12,792.00
User Work Zone Costs ($1000)	
Work Zone Duration (days)	0
No of Lanes Open in Each Direction During Work Zone	3
Activity Service Life (years)	5.0
Activity Structural Life (years)	
Maintenance Frequency (years)	3
Agency Maintenance Cost ($1000)	3049
Work Zone Length (miles)	1.00

Figure 3.4 FHWA Real Cost LCCA Model Input Screen.

Figure 3.4 shows the same service life input values for NPV as in Figure 3.2 for EUAC. However, the pavement manager must take the additional step of determining AP when using the NPV model. The options include selecting an analysis period of 5 years, consistent with the shortest life, 10 years consistent with the longest life, 50 years as the common multiple of all lives or some other period (White et al. 2010). Based on a 10-year AP (Figure 3.4) and 5-year chip seal service life input, the NPV results for this example are found in Figure 3.5.



Total Cost	Alternative 1: 1" HMA		Alternative 2: OGFC		Alternative 3: Chip Seal	
Total Cost	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	*$35,671.50*	*$0.00*	*$35,186.00*	*$0.00*	*$15,841.00*	*$0.00*
Present Value	**$33,786.91**	**$0.00**	**$33,301.41**	**$0.00**	**$15,502.55**	**$0.00**
EUAC	$4,165.62	$0.00	$4,105.76	$0.00	$1,911.32	$0.00

Lowest Present Value Agency Cost	**Alternative 3: Chip Seal**
Lowest Present Value User Cost	**Alternative 1: 1" HMA**

Expenditure Stream

	Alternative 1: 1" HMA		Alternative 2: OGFC		Alternative 3: Chip Seal	
Year	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
2012	$26,524.50		$26,039.00		$12,792.00	
2013						
2014						
2015	$3,049.00		$3,049.00		$3,049.00	
2016						
2017						
2018	$3,049.00		$3,049.00			
2019						
2020						
2021	$3,049.00		$3,049.00			
2022						

Figure 3.5 FHWA Real Cost LCCA Output Screen.

The NPV model returns an erroneous EUAC of $1,911 for the 5-year chip seal, although the expenditure stream shown in Figure 3.5 appears correct ($12,792 for initial cost and one future maintenance cost of $3,049 at year 3). If the pavement manager changed the service life input value to 4 years consistent with the next expected rehabilitation, the EUAC remains unchanged as shown in Table 3.1. In fact, any service life input value between 3.6 years to 5.99 years would leave the EUAC value of $1,911 unchanged in the NPV model.

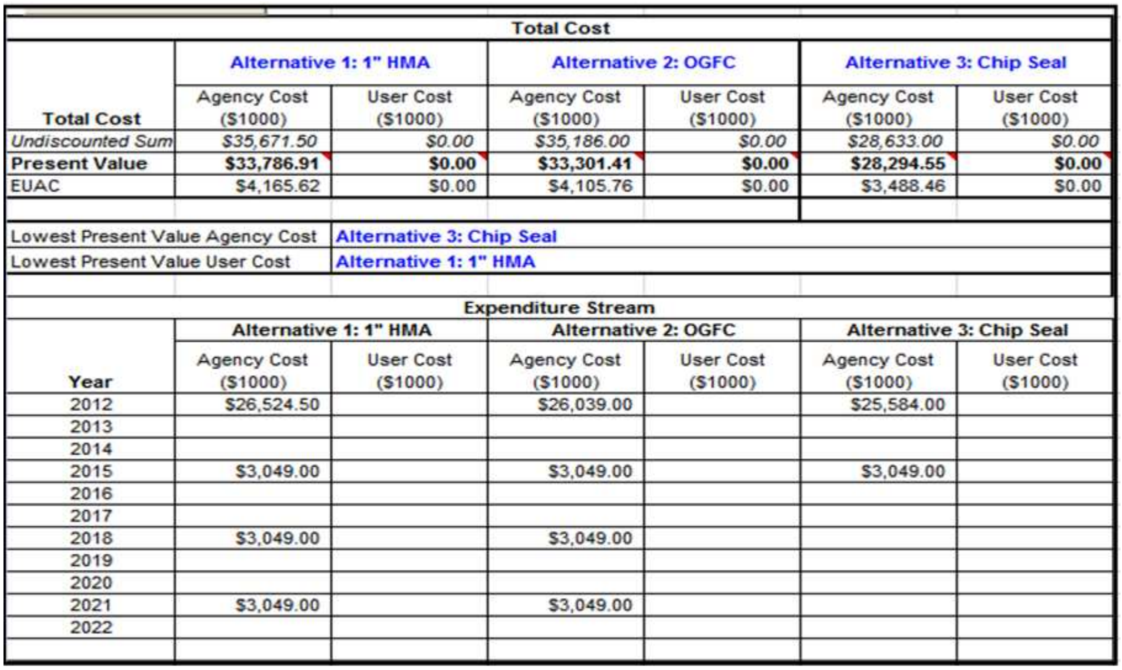
Table 3.1 FHWA Real Cost versus EUAC Model Input/Output for Chip Seal.

NPV/EUAC LCCA Values				
	Input (AP) (Real Cost only)	Input (SL)	Real Cost Output (EUAC)	EUAC Model (EUAC)
$12,792 year 1 cost	10	4	1,911	4,271
$12,792 year 1 cost	10	5	1,911	**3,482**
$25,584 year 1 cost	10	5	**3,488***	6,356
*Slight difference due to rounding				

The correct EUACs at 4 and 5 year service-life input values would be $4,271 and $3,482, respectively, which are consistent with the EUAC model output, but much greater than the erroneous NPV model output. Thus, the NPV model appears to be indifferent to service life contrary to the fact that it is a primary LCC driver (Irfan et al. 2009).

Upon investigation of the NPV model, one would find that the only purpose of the service life input parameter is to appropriate future maintenance costs. In the example, the frequency was equal to 3 years, which is why the sensitive service life parameter is not sensitive for any value within the maintenance periods in the NPV model.

Table 3.1 shows that the *RealCost* model returns the correct EUAC of $3,488 (slight difference due to rounding) only when the initial cost is doubled. However, the expenditure stream appears inaccurate because it reflects the cost of 2 chip seals at Time 1 and only 1 future maintenance cost (Figure 3.6), which would have an actual EUAC of $6,356 (Table 3.1).



Total Cost

Total Cost	Alternative 1: 1" HMA		Alternative 2: OGFC		Alternative 3: Chip Seal	
	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	*$35,671.50*	*$0.00*	*$35,186.00*	*$0.00*	*$28,633.00*	*$0.00*
Present Value	**$33,786.91**	**$0.00**	**$33,301.41**	**$0.00**	**$28,294.55**	**$0.00**
EUAC	$4,165.62	$0.00	$4,105.76	$0.00	$3,488.46	$0.00

Lowest Present Value Agency Cost	**Alternative 3: Chip Seal**
Lowest Present Value User Cost	**Alternative 1: 1" HMA**

Expenditure Stream

Year	Alternative 1: 1" HMA		Alternative 2: OGFC		Alternative 3: Chip Seal	
	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
2012	$26,524.50		$26,039.00		$25,584.00	
2013						
2014						
2015	$3,049.00		$3,049.00		$3,049.00	
2016						
2017						
2018	$3,049.00		$3,049.00			
2019						
2020						
2021	$3,049.00		$3,049.00			
2022						

Figure 3.6 FHWA Real Cost Output, Initial Cost Doubled to correct EUAC.

Thus, the NPV model returns an erroneous EUAC based on the actual chip seal scenario and returns the correct EUAC based on an erroneous scenario. Specifically, the pavement manager would have to enter the *wrong* input to get a correct EUAC output (Figure 3.6). When the NPV input/output is investigated, the erroneous EUAC is found to be the result of the problematic AP. The chip seal life cycle costs were calculated over the 10-year AP as shown in Figure 3.7. To correct this NPV issue and indirectly gain the appropriate EUAC, the pavement manager has to arbitrarily adjust the initial cost (Figure 3.6).

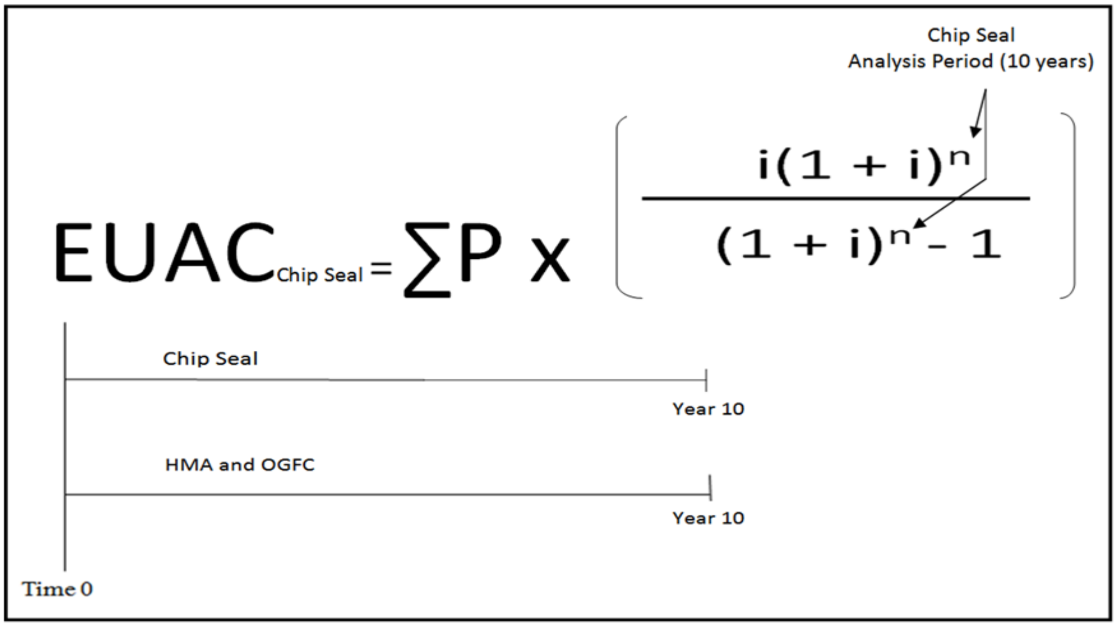
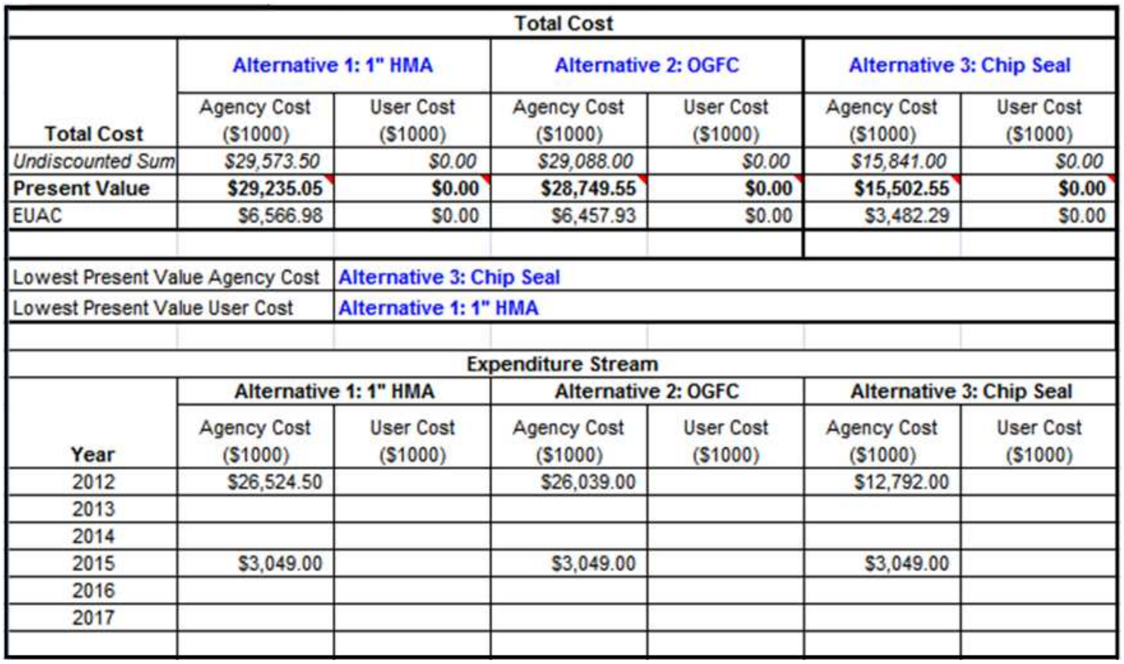


Figure 3.7 NPV Model EUAC Chip Seal Calculation and Analysis Period Diagram.

Both EUAC and NPV models should return the same preferred alternative when operated correctly (White et al. 2010). To validate the EUAC model, the NPV model AP input value was changed to 5 years, consistent with the service life value.

Figure 3.8 shows the correct cash flow and EUAC from the NPV model, consistent with the EUAC model. For more extensive discussion of the PPT EUAC model validation, see Chapters 4 and 11.



Total Cost						
	Alternative 1: 1" HMA		Alternative 2: OGFC		Alternative 3: Chip Seal	
Total Cost	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
Undiscounted Sum	*$29,573.50*	*$0.00*	*$29,088.00*	*$0.00*	*$15,841.00*	*$0.00*
Present Value	**$29,235.05**	**$0.00**	**$28,749.55**	**$0.00**	**$15,502.55**	**$0.00**
EUAC	$6,566.98	$0.00	$6,457.93	$0.00	$3,482.29	$0.00
Lowest Present Value Agency Cost	Alternative 3: Chip Seal					
Lowest Present Value User Cost	Alternative 1: 1" HMA					

Expenditure Stream						
	Alternative 1: 1" HMA		Alternative 2: OGFC		Alternative 3: Chip Seal	
Year	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)	Agency Cost ($1000)	User Cost ($1000)
2012	$26,524.50		$26,039.00		$12,792.00	
2013						
2014						
2015	$3,049.00		$3,049.00		$3,049.00	
2016						
2017						

Figure 3.8 EUAC Model Validation with NPV Output.

3.4 CONCLUSIONS

This research produced a previously unpublished EUAC-based model for LCCA that specifically addresses the nature of PPTs and develops LCCA-based PPT design. The model's *fixed flexibility* offered via continuous and terminal scenario allow it to adhere to engineering economic principles and provide the pavement manager project-level evaluation within a wider spectrum of pavement manager expertise. EUAC LCCA eliminates the problematic AP and indifferent service life issues associated with NPV. It appropriately allocates service life sensitivity to the analysis by making the service life value fundamental to the LCC algorithm, and in doing so, allows for sensitivity analysis based upon expected treatment performance, not upon an arbitrary analysis parameter. This eliminates the need for extensive economist-level training. EUAC is better suited to PPT than NPV methods because EUAC input values reflect the short term nature of the actual pavement treatment scenario, making the model more intuitive.

More importantly, the input directly correlates with output to allow the pavement manager to better relate treatment LCC to annual maintenance budgets.

4.0 LIFE CYCLE COST-BASED PAVEMENT PRESERVATION TREATMENT DESIGN[3]

Pittenger, D.M., D.D. Gransberg, M. Zaman, and C. Riemer, “Life Cycle Cost-Based Pavement Preservation Treatment Design,” *2011 Transportation Research Record*, Journal of the Transportation Research Board, National Academies, Washington, D.C. Issue 2235, 2011, pp 28-35.

4.1 PAPER SYNOPSIS

This paper served to disseminate the deterministic PPT EUAC LCCA model discussed in the previous chapter to the pavement preservation community. It addresses the gaps in the pavement economics body of knowledge by demonstrating the EUAC model and proposing a methodology for using field test data to quantify the service lives of PPTs for use in EUAC LCCA.

4.2 RESEARCH METHODOLOGY

As pavement preservation emerges as a possible solution to the aging infrastructure problem, research has shown that coupling cost efficiency and treatment effectiveness, termed *economic efficiency* (Bilal et al. 2009) may be the key to determining the optimal preservation timing (Peshkin et al. 2004). Microtexture and macrotexture data is routinely collected by the Oklahoma Department of Transportation (ODOT). Incorporating this type of *localized* performance data into LCCA may reduce the level of inherent uncertainty associated with [service life] “guesses” and can yield insight to a treatment’s effectiveness and cost-effectiveness (Reigle and Zaniewski,

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[3] The original journal paper has been reformatted to make it consistent with the other published chapters in this document.

2002). If treatment effectiveness (performance) is not considered when determining cost effectiveness, the results may be biased (Bilal et al. 2009).

4.2.1 Deterioration Models

A commonly used approach to determine a treatment's expected service life (effectiveness) is to extrapolate data based on surface condition (Bilal et al. 2009), such as microtexture and macrotexture data. This is the approach used in this research and applied to PPTs exhibited in field trials and discussed in Chapter 2. Linear regression was applied to the treatments' microtexture and macrotexture data to approximate the deterioration rate and extrapolate the remaining service life of each treatment. These were then compared to failure criteria found in the literature. Service life was determined by identifying the time it took each treatment to deteriorate to each failure criterion. The failure criterion for macrotexture was 0.9mm, which is consistent with TNZ P12 performance specification. The failure point considered for microtexture was a skid number less than 25.

Demonstrating this methodology, Figure 4.1 shows the deterioration of microtexture over time experienced in current research field trial data for chip seal. Linear regression was applied. The equation shown in the upper right-hand corner of the figure was derived and the coefficient of determination (R^2) was calculated to be 0.9191. The regression equation was then used to calculate the deterioration rate beyond the available data. These values were added to the actual data points to extrapolate the curve out to 50 months (i.e. 4+ years) as shown in Figure 4.2. Based upon this procedure and a failure criterion of 25, it appears that the chip seal will fail due to a loss of skid resistance around the 46-month (3.8-year) mark.

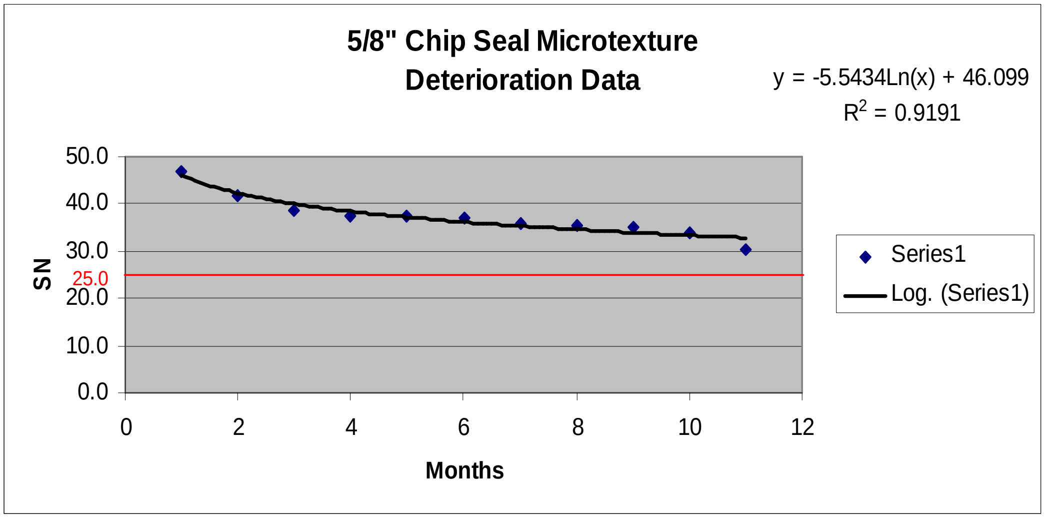

Figure 4.1 Chip Seal Microtexture Field Trial Performance Data.

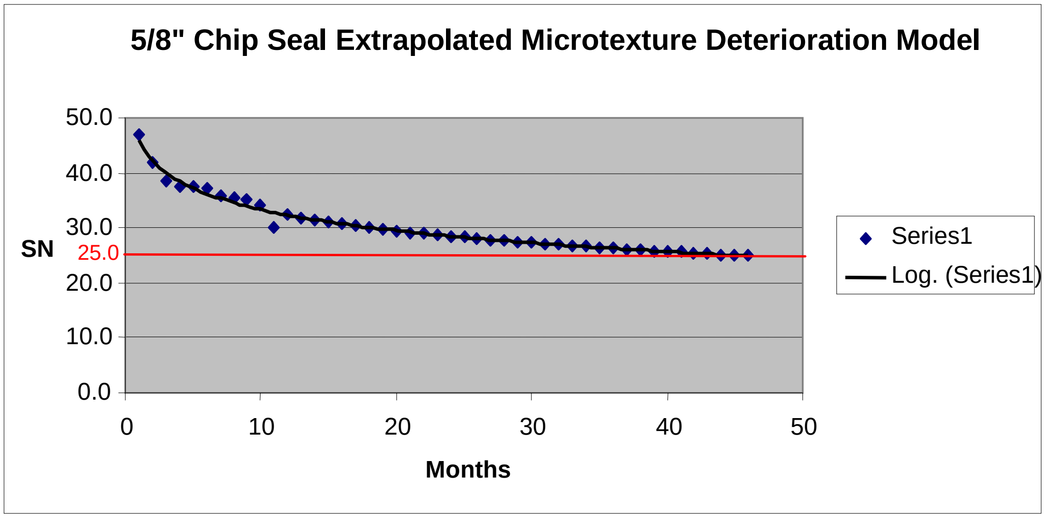

Figure 4.2 Chip Seal Microtexture Deterioration Model.

Using the same methodology outlined for microtexture data regression, chip seal macrotexture data was extrapolated (Figures 4.3 and 4.4). The chip seal is expected to fall below the failure criteria for macrotexture around 21 months (1.8 years).

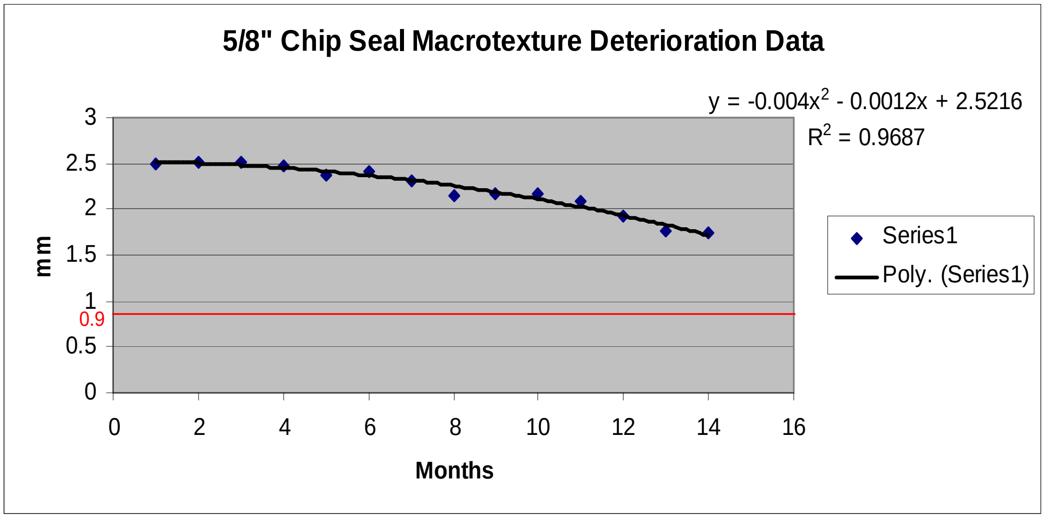

Figure 4.3 Chip Seal Macrotexture Field Trial Performance Data.

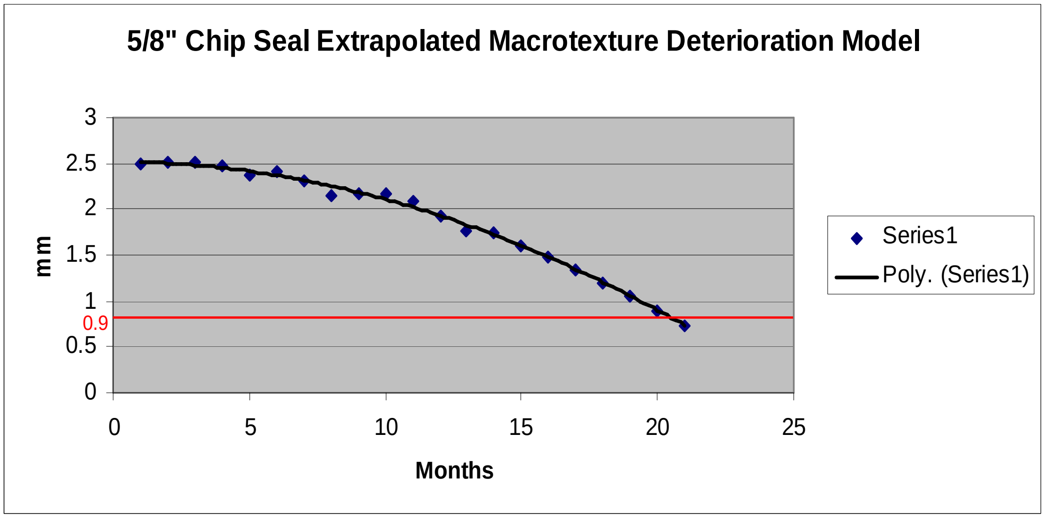

Figure 4.4 Chip Seal Macrotexture Deterioration Model.

The resulting approximate service life input values for each alternative were compared to the ODOT survey and literature review results (Stroup-Gardiner and Shatnawi, 2008; FHWA, 2005; Bausano et al. 2004). The average cost for treatments and maintenance came from the ODOT survey and was verified by field trial and vendor data, literature review results (Stroup-Gardiner and Shatnawi, 2008; FHWA, 2005; Bausano et al. 2004), and bid tabulations. These values are displayed in Table 4.1.

Table 4.1 Treatment Service Life and Average Cost.

PPT LCCA Input					
PPT on Asphalt Pavement	Service Life (years)				Average Cost
	Microtexture	Macrotexture	ODOT & Lit. Review	Min.	$/SY
5/8” Chip Seal	3.8	1.8	5	1.8	1.77
OGFC	>10	5.3	10	5.3	3.75
1” HMA Mill & Inlay	>10	N/A	10	10	4.00

The service life input value for each treatment for EUAC LCCA would be the minimum service life value represented in Table 4.1 and is expressed:

$SL_{alt} = MIN<Mi, Ma, Ex>$

Where the service life input for a treatment alternative (SL_{alt}) equals the
MIN (minimum value) of the:

Mi (microtexture deterioration model output),

Ma (macrotexture deterioration model output), and the

Ex (pavement manager’s expectation of treatment service life).

This chapter uses and references the EUAC model described in the previous chapter to conduct LCCA and should be referenced for specific model mechanics. FHWA LCCA procedures 3, 5 and 6 are incorporated into the EUAC evaluation. Initial construction costs and associated future maintenance costs were estimated for the alternatives being analyzed. Activity timing includes maintenance, which is a crack seal and 2%-of-total-area patching with a three-year frequency for all asphalt treatments. The selected alternatives and the corresponding minimum service life values from Table 4.1 were entered into the model, as well as other items required for LCCA.

User costs have been shown to potentially contribute a notable difference between the life cycle costs of preservation treatment alternatives (Bilal et al. 2009; Hall et al. 2009), so they were included in this analysis. The initial construction installation time is represented by days, to two significant digits, to capture the differences between alternatives for user cost calculations. Production rates came from the ODOT survey and vendor data. The discount rate selected for the demonstration of the model is 4%, in accordance with FHWA recommendation (FHWA, 1998a). In this calculation, the continuous state is assumed, so each treatment's service life is equal to its *anticipated service life*. Project length will be one lane-mile.

4.3 RESULTS

The pavement treatment alternative with the lowest EUAC should be considered for selection. EUAC results for the treatments were manually verified and are listed in Table 4.2.

Table 4.2 EUAC LCCA Results, Continuous Mode.

LCCA Results			
PPT on asphalt pavement	Microtexture SL	Macrotexture SL	Expected SL
	EUAC, $/lane-mile	EUAC, $/lane-mile	EUAC, $/lane-mile
5/8" Chip Seal	4,696	7,529	3,651
OGFC	4,460	6,434	4,460
1" HMA Mill & Inlay	4,696	4,696	4,696

The FHWA suggests that a sensitivity analysis be included in LCCA (Step 5) (FHWA, 1998a). The sensitivity of the service life input value for treatments is exhibited in Table 4.2. Based on this data, the service life parameter is sensitive, as one should expect, because an alternative's service life and cost are directly correlated in LCCA. By changing the service life input value of chip seal from 1.8 years (Mi) to 3.8 years (Ma) and then to 5 years (Ex), its rank changes from 3 to tied with HMA to 1, respectively.

Essentially, EUAC allows for the sensitivity to be moved from the AP parameter, which may be arbitrary and uncontrollable, to the service life parameter, which allows the pavement manager to intuitively adjust and account for service life selection and sensitivity based on professional judgment. In this case, the pavement manager can consider whether or not the chip seal is expected to remain in service for at least 3.8 years to justify the chip seal decision. Using NPV, the pavement manager would only be able to adjust an arbitrary "common period of time" to assess sensitivity, and the service life sensitivity would be obscured. Extensive economist training would be required to determine service life sensitivity and creates an LCCA-implementation obstacle.

This shows that using field data derived deterioration curves and performance-based failure criteria in an EUAC setting provides a more accurate result than the empirical values for service life in an NPV setting in use for the current FHWA-approved LCCA process. The sensitivity analysis tool, coupled with deterioration models, can yield information that would satisfy "What if" scenarios pertinent to pavement managers and gives the pavement manager the enhanced ability to truly identify, then justify, the most cost-effective pavement treatment for a given project, enhancing stewardship.

The pavement manager would need to put the LCCA results into context, then reevaluate the results in accordance with FHWA "Good Practices" (Step 6)(FHWA, 1998a). LCCA results should be coupled with other decision-support factors such as "risk, available budgets, and political and environmental concerns" (FHWA, 2002). The output from an LCCA should not be considered the *answer*, but merely an indication of the cost effectiveness of alternatives (FHWA, 1998a).

If the next expected rehabilitation/reconstruction was expected in six years and was entered into the model, the model would automatically *switch* to terminal mode. The HMA and OGFC service lives would be automatically truncated from 10 years to 6 years. Thus, the *anticipated service life* for both would be 6 years. With a 5-year service life, the chip seal EUAC would remain $3,651 as shown in Table 2. With 6-year anticipated service lives, the HMA and the OGFC would have EUAC values of $6,124 and $5,759 respectively. In this case, chip seal would be the preferred alternative. It would also be the intuitive choice because it, with a short "do nothing" period, would efficiently fill the gap. A quick sensitivity analysis, conducted in accordance with FHWA LCCA procedure 5, reveals that even if HMA or OGFC were expected to extend the life of the underlying pavement by its full, 10-year service life, chip seal would still have the lowest EUAC, as shown in Table 2. If, on the other hand, the pavement-life extension parameter was sensitive, the pavement manager may ascertain the effect by intuitively adjusting the year when the next rehabilitation is expected, which will automatically adjust a treatment's *anticipated service life* value until the preferred alternative changes, within the expected limits of service life for alternatives. As in the continuous scenario, the pavement manager is able to intuitively analyze model results in terminal mode because input and output are both in the realm of the pavement manager's expertise.

Comparable NPV Calculations, Continuous Mode

To verify the model, EUAC and NPV were calculated to demonstrate that all should yield the same preferred alternative when gaps and residual values are addressed as discussed and cited as appropriate in the previous sections (White et al. 2010). The standard AP was set to twenty years, consistent with an FHWA case study on project-level planning (FHWA, 2005). User costs were omitted for simplification. All methods returned the same ranking, as illustrated in Table 4.3, in support of validating the EUAC model as an appropriate pavement preservation LCCA method. This illustrates the point that using different APs corresponding with the differing service lives of alternatives in a LCCA does not remove the "fairness" nor does it result in differing benefits; it does, however, bypass the commonly problematic AP selection, associated adjust-to-fit requirements and well-cited sensitivity issues for that parameter.

Table 4.3 Comparable EUAC (Continuous Mode) and NPV Rankings.

LCCA Results				
Pavement Treatments	Service Life	Analysis Period	Agency Costs	Rank
EUAC				
5/8" Chip Seal	5	5	3,408	1
OGFC	10	10	4,150	2
1" HMA Mill & Inlay	10	10	4,367	3
NPV – Shortest Life				
5/8" Chip Seal	5	5	15,172	1
OGFC	10	5	20,463	2
1" HMA Mill & Inlay	10	5	21,343	3
NPV – Longest Life				
5/8" Chip Seal	5	10	30,344	1
OGFC	10	10	33,663	2
1" HMA Mill & Inlay	10	10	35,423	3
NPV – Standard Period				
5/8" Chip Seal	5	20	60,688	1
OGFC	10	20	67,326	2
1" HMA Mill & Inlay	10	20	70,846	3

Comparable NPV Calculations, Terminal Mode

The model should rarely be operated in terminal mode due to a pavement manager's propensity to "do nothing" when the next rehabilitation/reconstruction is known. However, if "do nothing" is not an option, the model can be used to determine the preferred alternative in this short-term period. Although it can yield the same preferred alternative as NPV regardless of AP selected as exhibited in Table 4.4, it can be sensitive to the AP selection depending on the input data. In an AP-sensitive situation, the EUAC will function like NPV when setting the AP consistent with the shortest-life alternative.

Table 4.4 EUAC (Terminal Mode-Year 6) and NPV Results.

LCCA Results				
Pavement Treatments	Service Life	Analysis Period	Agency Costs	Rank
EUAC				
5/8” Chip Seal	5	5	3,408	1
OGFC	10	6	5,553	2
1” HMA Mill & Inlay	10	6	5,889	3
NPV – Shortest Life				
5/8” Chip Seal	5	5	15,172	1
OGFC	10	5	29,111	2
1” HMA Mill & Inlay	10	5	30,871	3
NPV – Rehab year, fill gap				
5/8” Chip Seal	5	6	27,633	1
OGFC	10	6	29,111	2
1” HMA Mill & Inlay	10	6	30,871	3

4.4 CONCLUSIONS

Economic and engineering technical data gathered from pavement preservation field trials can be quantified and correlated to produce meaningful, standardized economic and LCCA information that furnishes pavement managers measurable failure criteria to estimate extended service lives of pavements. This research produced a previously unpublished EUAC-based model for LCCA that specifically addresses the nature of PPTs and develops LCCA-based PPT design. The research also developed a methodology for developing PPT-specific deterioration models and demonstrated how these provide a superior result to those based on empirical service lives. Finally, the research demonstrated how the new model could be utilized to assist a pavement manager in selecting the most economically efficient PPT for a given pavement management problem.

5.0 EVALUATE AIRPORT PAVEMENT MAINTENANCE/ PRESERVATION TREATMENT SUSTAINABILITY USING LIFE-CYCLE COST, RAW MATERIAL CONSUMPTION AND “GREENROADS” STANDARDS[4]

Pittenger, D.M., “Evaluate Airport Pavement Maintenance/Preservation Treatment Sustainability Using Life-Cycle Cost, Raw Material Consumption and *Greenroads* Standards,” *Transportation Research Record,* Journal of the Transportation Research Board, National Academies, Washington, D.C. Issue 2206, 2011, pp 61-68.

5.1 PAPER SYNOPSIS

Sustainability is increasingly becoming a priority for airport projects, as well as the foundation for future prosperity, in the global aviation community. Pavement structures are an airport’s greatest asset and greatest liability. Pavement management systems, involve an intensive, expensive enterprise and pavement maintenance projects consume massive amounts of nonrenewable resources at every airport in the nation. Little research has been conducted to assist airport pavement managers reduce the environmental, economic and social impacts of their pavement maintenance and preservation processes. The old cliché of “what is not measured is not managed” applies and so a performance metric is required to permit pavement managers to measure sustainability. There is no standard, quantitative performance metric for sustainability in use by pavement managers to assess pavement treatment alternatives. This chapter demonstrates how airport pavement managers can quantitatively analyze

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[4] The original journal paper has been reformatted to make it consistent with the other published chapters in this document.

typical pavement treatments using life-cycle cost analysis, quantification of raw material consumption and the recently developed *Greenroads* standards to measure the environmental, economic and social impact of those treatments for a given pavement treatment project to enhance the overall sustainability of their programs.

5.2 INTRODUCTION

Sustainability has been identified as being a critical issue in aviation as “stakeholders struggle to respond to uncertain fuel prices and availability, a global economic and financial crisis, and increased scrutiny of environmental impacts of aviation” (Eagan et al. 2009). Sustainability is not a new concept. Airports have been implementing a number of sustainable practices consistently over the last few decades (ACI-NA, 2010; SAGA, 2010; Eagan et al. 2009; Berry et al. 2008; ATAG, 2008). However, the sustainability movement is gaining momentum due to the current level of public scrutiny and airport policy and regulation (ACI-NA, 2010; SAGA, 2010; Eagan et al. 2009; Berry et al. 2008; ATAG, 2008). Stakeholder concerns and the global push for sustainability have added a sense of urgency to the movement (ACI-NA, 2010; SAGA, 2010; Eagan et al. 2009; Berry et al. 2008; ATAG, 2008).

Lack of funding was cited by all airports surveyed in the Airport Cooperative Research Program’s (ACRP) *Synthesis 10: Airport Sustainability Practices* (Berry et al. 2008) as the primary barrier to airport sustainability practices. The synthesis concluded that it is necessary to determine other reasons for the barrier so that the business case could be defined for sustainable practices. Many refer to the *triple bottom line* of sustainability, which consists of interrelated environmental, economic and social components. The ACRP synthesis concluded that these components require additional research to relate them to aviation. The synthesis found that sustainability is considered by airports, but that the environment and economy are in conflict with one another (Berry et al. 2008). However, there is growing proof that each can support the other (Yoshitani, 2010). The economic incentive and competitive advantage to approaching airport operations in a sustainable, triple-bottom-line manner is not lost on airport operators like Greater Toronto Airports Authority that believes “environmental initiatives should be seen as business investments” (GTAA, 2007). The Air Transport Action Group partially attributes improvements in aviation environmental performance to greater operational efficiency, an important sustainability factor (ACI-NA, 2010), that ultimately boosts profitability (ACI-NA, 2010; ATAG, 2008). Thus, lack of funding need not be a barrier to the implementation of sustainable practices, but rather, a catalyst to find more efficient solutions.

5.3 BACKGROUND AND MOTIVATION

Proactive pavement maintenance demonstrates sustainability through the interrelation of the triple bottom line components and is a solution (SAGA, 2010; Muench et al. 2010) that is being promoted by the aviation community (FAA, 2009). Pavement preservation is essentially *keeping good pavements good* by applying the *right treatment to the right pavement at the right time* (Galehouse et al. 2003). Pavement preservation is *inherently green* due to its focus on conserving energy, raw materials and reducing greenhouse gases (Galehouse and Chehovits, 2010). Getting the most benefit for the least cost is a key attribute of preserving airport pavements (FAA, 2009).

Pavement preservation and maintenance terminology is still evolving and is not consistent between highway and airport applications. However, the purpose of this chapter is to examine various pavement treatments and evaluate their sustainability, regardless of the purpose for which they are applied. The Federal Highway Administration (FHWA) provides precise definition for various pavement preservation and maintenance activities (Geiger, 2005). The Federal Aviation Administration (FAA) does not formally differentiate between pavement preservation and pavement maintenance in its Advisory Circulars (AC) (FAA, 2007 and 2006). However, it does include all of the FHWA categories under the term *pavement maintenance* to embody the proactive, preventive maintenance theory that is the primary mechanism of pavement preservation (FAA, 2007). Therefore, to avoid confusion, this chapter will adopt the FAA terminology and will term programmatic issues as *pavement maintenance*. When discussing an individual pavement treatment technology used in these programs, it will be termed as a *pavement treatment*.

Often, pavement managers select pavement treatments on a reactive basis considering only past performance and lowest cost without exploring other, more sustainable treatment options (FAA, 2006). The availability of new technology and research, however, is creating an environment where many eco-efficient pavement treatments can flourish and fill the *pavement maintenance toolbox* (FAA, 2006). The goal of a pavement maintenance program is not to identify the *best* pavement treatment. It seeks, instead, to identify the *right* treatment based on the given project’s engineering considerations, such as pavement condition, distress type, traffic and climate, as well as economic and environmental considerations, such as life-cycle cost, life-cycle emissions and energy use and resource availability. Determining the *right treatment* for the *right pavement* at the *right time* is fundamental to realizing the eco-efficiency benefits of pavement treatment (Galehouse and Chehovits, 2010).

The Economic Case for Sustainable Pavement Maintenance

"A paved runway is an airport's most valuable asset as well as its most expensive liability" (AirTap, 2005), and managing it is a critical task for the pavement manager (FAA, 2007). Pavement treatment selection is increasingly being driven by available funding (FAA, 2009). However, as demand for Airport Improvement Program (AIP) and other funds outpaces the supply pavement maintenance deferral remains a common airport practice that contributes to a growing backlog of maintenance needs, and further exacerbates the maintenance funding problem. Every $1 spent on preserving the capacity of an airport pavement today could save up to $5 in reconstruction tomorrow (FAA, 2006; AirTap, 2005). It costs *significantly* more to fix a pavement in poor condition than it does to maintain one in fair condition (FAA, 2006). Thus, failing to preserve a pavement's structural capacity results in extensive reconstruction costs (Peshkin et al. 2004), and more critically, a disruption in airport operations. Operational disruption due to construction-related pavement downtime can cost users as much as $1,000 per minute. The real value of pavement maintenance is realized through the reduction of operational disturbances and results in an increase in operational efficiency (FAA, 2007; Vreedenburgh, 1999). A pavement management program can extend the service life of an underlying pavement and potentially offset much of its cost (Peshkin et al. 2004).

The Social Case for Sustainable Pavement Maintenance

Airfield pavement deterioration and distresses caused by weathering and aircraft traffic create the potential for foreign object debris (FOD) due to delamination, which can cause aircraft damage and lead to in-flight catastrophic failure (i.e. airplane crashes) and loss of life (FAA, 2010). Climate change is expected to further exacerbate the FOD issue by creating more extreme freeze-thaw cycles (FAA, 2010). Proactive pavement treatment can maintain serviceability and improve the overall condition of an airport's inventory of pavements (Peshkin et al. 2004). This also reduces the potential for FOD and improves safety (FAA, 2010). Ensuring a FOD-free runway is an important social benefit and can be accomplished by adapting appropriate pavement treatments that address the effects of climate change (FAA, 2010).

Social benefits are also derived from the economic case for preserving airport pavements. The reduction in downtime due to less extensive maintenance can be measured in hours instead of months. This increases the availability of airport pavements to users and reduces associated user costs due to delay and disruption (Vreedenburgh, 1999). Pavement maintenance also provides enhanced fiscal stewardship through the cost-effective use of scarce public funds.

The Environmental Case for Sustainable Pavement Maintenance

Climate change is cited repeatedly as being a critical driver of airport sustainability programs (Eagan et al. 2009; Berry et al. 2008). Pavement maintenance creates a smaller environmental footprint than pavement rehabilitation and reconstruction (Galehouse and Chehovits, 2010) by reducing the impact of airport operations on climate by mitigating greenhouse gases and reducing energy consumption

(CH2M, 2009). A life cycle inventory (LCI) is a cradle-to-grave approach to quantify material flow, emissions and energy consumption of processes and systems. Recent research demonstrates the applicability of LCI to pavement maintenance (Galehouse and Chehovits, 2010). Calculators are available to assess individual pavement treatment impacts from material extrusion to installation. Using local, reusable, renewable and recyclable materials has environmental, economic and social benefits and contributes to the *green* design/construction practices that the aviation community is pursuing (Berry et al. 2008).

The Triple-Bottom Line Imperative

Selecting the most appropriate pavement treatment is a tool for pavement managers to achieve pavement sustainability (Muench et al. 2010; FAA, 2007). Sustainability does not mandate the selection of the *greenest* choice. Instead, for decision-making to be truly sustainable, the triple bottom line must be considered and yield the net benefit between those elements (Eagan et al. 2009; Berry et al. 2008, CH2M, 2009). Terms such as *eco-efficiency* are entering the vernacular and illustrate the interrelatedness of these components. The Greater Toronto Airports Authority's goal, for example, is to increase operational efficiency (profit) while maintaining safety and environmental practices (GTAA, 2007). The Air Transport Action Group's "Aviation Industry Commitment to Action on Climate Change" document calls for implementing greenhouse gas reduction measures "wherever they are cost-effective" (ATAG, 2008). Proactive pavement maintenance is a tool for pavement managers to achieve sustainability across the triple bottom line.

5.4 RESEARCH METHODOLOGY

A short questionnaire was created based on the principles laid down by Oppenheim (1992) and distributed to airports listed in the next section. Based on the literature review and the 100% questionnaire response rate, case studies were developed on nine U.S. and Canadian airports using Yin's methodology (1994). Raw data resulting from the case studies was reduced and the three sustainability measures, LCCA, raw material consumption (RMC) and *Greenroads* score (GR), were developed.

The selection of nine case-study airports was based upon geographic, climatic and size/traffic variance. Billings Logan International Airport (BIL) and Will Rogers World Airport (OKC) are small and medium airports, respectively. The large airports include Boston-Logan International Airport (BOS), Dallas-Fort Worth International Airport (DFW), Orlando International Airport (MCO), Salt Lake City International Airport (SLC), San Francisco International Airport (SFO), Seattle-Tacoma International Airport (SEA) and Toronto Lester B. Pearson International Airport (YYZ).

Based on the literature review, a list of pavement treatments was developed. The questionnaire's purpose was to validate the list of pavement treatments to be evaluated as well as to identify any common treatments that were missed. The questionnaire found that the most commonly used treatments were shotblasting, fog seal, slurry seal and microsurfacing, as well as hot mix asphalt and warm mix asphalt overlays.

The case study output was compared with the literature output to identify converging lines of data. The case study data of interest included treatments and their associated input requirements that coincide with the LCCA, raw material/recycled material consumption and *Greenroads* standards.

Information regarding the status of each airport's program to monitor pavement treatment sustainability was obtained. Table 5.1 lists airport pavement treatment practices that are collectively considered fundamental to pavement sustainability (Muench et al. 2010). Having an airport pavement management system (APMS) or program in place is considered to be one of these sustainable practices (SAGA, 2010; Muench et al. 2010; FAA, 2006) because it promotes proactive pavement maintenance. The FAA imposes the APMS program requirement as a condition of funding to foster improvement in airport safety, operational efficiency and effective use of funds (FAA, 2007). With or without the conditional funding consideration, the FAA suggests that all airports make pavement maintenance an integral part of their operations so as to preserve their large pavement investments (FAA, 2007). An APMS is a project-level tool that identifies the *right pavement, right time* based on pavement inventory and pavement condition index (PCI). The *right pavement* is defined as one that is structurally sound and the *right time* is defined as the optimum time of a pavement's life to apply treatment so that the full treatment cost-effectiveness and pavement life-extension can be realized (Peshkin et al. 2004). The APMS identifies the *right pavement* in an airport's inventory and the *right time* (PCI=70 or so for runways). It includes cost and performance data for pavement treatments that can be used to predict life-cycle cost and service life to prioritize projects and optimize the use of funds, therefore yielding better decisions and justification (FAA, 2006). Only about half of the survey respondents reported having a Pavement Management System or similar plan.

Table 5.1 Airport Survey Results.

Fundamental Pavement Treatment Sustainable Practices Airport Survey									
Sustainable Practices	BIL	OKC	BOS	DFW	MCO	SLC	SFO	SEA	YYZ
Environmental Review Process	◆	◆	◆			◆	◆		◆
LCCA								◆	
Life Cycle Inventory									
Quality Control Plan	◆	◆	◆	◆	◆	◆	◆	◆	◆
Waste Management Plan			◆			◆	◆		◆
Pollution Prevention Plan	◆	◆	◆	◆	◆	◆	◆	◆	◆
Pavement Preservation Plan	◆		◆		◆	◆			◆
Site Maintenance Plan	◆		◆	◆		◆	◆		

Although a standard tool that assists in determining the *right pavement* and *right time* exists, no standard performance metric has been developed to assist the pavement manager in determining the *right treatment* (SAGA, 2010; Eagan et al. 2009; Berry et al. 2008). Tools that support pavement treatment selection decisions are life-cycle cost analysis (LCCA) and life-cycle inventory (LCI). The value of coupling LCCA results with LCI results has been demonstrated in past research (Haas et al. 2006) and can furnish the pavement manager crucial insight about a treatment's environmental and economic impact. Yet, only one of nine airports surveyed for this study reported using LCCA for evaluating pavement treatments and none were conducting LCI.

The purpose of this research is to develop a performance metric to assist airport pavement managers determine the *right treatment*. This chapter seeks to demonstrate the framework's value by illustrating *how* a project-level, quantitative analysis of six selected airport pavement treatments could be conducted using LCCA, quantification of raw material consumption and the recently developed *Greenroads* (GR) rating system. It is intended to be scaleable and applicable to any airport and assist with treatment selection decision-making by furnishing a tool to measure relative sustainability. The framework output contained herein should not be construed to yield a preferred treatment type. It is recognized that not all possible alternatives would satisfy the technical requirements of a given pavement problem. However, all potential alternatives do have their own unique environmental footprint. The ability to compare the sustainability of alternatives allows the pavement manager a means to include relative environmental impact in the treatment selection process.

For all three metrics, output should not dictate treatment selection, but merely indicate the sustainability of alternatives and should be coupled with a pavement manager's engineering judgment (Eagan et al. 2009; Berry et al. 2008). Metric results should also be coupled with other decision-support factors such as "risk, available budgets, and political concerns" (FHWA, 1998a) to ensure sustainable decision-making. Essentially the sustainability metric will act as justification for selecting a marginally more expensive treatment over a less expensive but less sustainable treatment.

To be able to conduct a consolidated comparative analysis using three diverse measurements, each is converted to an index. The index is a number from 0 to 1, with sustainability increasing as the index gets closer to 1. To support this approach, a quantitative metric was developed for each of the three components of the analysis. The metric was created using standard utility theory (West, T.M. and J.L. Riggs, 1986) with the prime measure of utility relating directly to the specific component. The LCCA metric was assigned high utility to treatments with low life-cycle costs. In the same manner, the raw material consumption (RMC) metric assigned high utility to treatments that utilize low amounts of raw materials. Finally, the GR metric is a ratio of credits earned by a treatment divided by the total available credits. Thus, utility is measured by the number of credits earned.

LCCA Metric

"The core of transportation decision-making is the evaluation of transportation projects and programs in the context of available funding" (Sinha and Labi, 2007). Economic analysis has long been promoted by the FAA (2009) and is a vital component of effective pavement treatment (Sinha and Labi, 2007). Pavement treatment selection based solely on lowest first cost may actually result in a higher life-cycle cost relative to other treatments. Economic analysis, specifically LCCA, seeks to expose this non-sustainable approach. Because of the considerable investments airports have in their pavements, "the potential savings from following a cost-effective approach to meeting an agency's performance objectives for pavements are significant" (Peshkin et al. 2004). Implementation of economic evaluation to assess pavement treatment projects can allow airports to stretch the budget to address sustainability needs and enhance stewardship. Yet, only one of the nine airports surveyed includes LCCA in pavement treatment decision-making (Table 1).

An EUAC LCCA model was selected to conduct the calculations because pavement maintenance budgets are often constrained to a single fiscal year. Thus, comparing treatment alternatives on an annual LCC basis is logical. The FAA recommends a discount rate between 3-5% be used in analyses (FAA, 2009). This is consistent with the OMB Circular A-94, so 4% was selected for this study.

Incorporating PCI-extrapolated pavement deterioration data, or "localized" data obtained from APMS, into LCCA may reduce the level of inherent uncertainty associated with [service life] "guesses" and can yield insight to a treatment's effectiveness and cost-effectiveness (Reigle and Zaniewski, 2002). If treatment effectiveness (performance) is not considered when determining cost-effectiveness, the results may be biased (Bilal et al. 2009). In absence of local, pavement-specific deterioration and treatment cost data, the performance period and agency costs for each treatment was set equal to the average typical service life values and cost data resulting from the questionnaire, then verified by literature and FAA bid tabulations for this study and are listed in Table 5.2. A routine maintenance value to accommodate crack seal, etc. was included for every treatment based on a three-year, repetitive cycle.

Table 5.2 Airport Pavement Treatment LCCA Input/Output.

LCCA Results						
	Service Life	Initial Cost		EUAC		
Pavement Treatment	(YR)	$/SY	$/SM	$/SY	$/SM	LCCA Metric*
Microsurfacing	7	1.90	2.27	0.47	0.56	0.37
Hot Mix Asphalt (1.5")	11	3.25	3.89	0.52	0.62	0.31
Warm Mix Asphalt (1.5")	11	3.25	3.89	0.52	0.62	0.31
Slurry Seal	3	1.00	1.20	0.58	0.70	0.22
Fog Seal/Seal Coat	2	0.80	0.96	0.64	0.77	0.14
Shotblasting	2	1.25	1.50	0.75	0.90	0.00
*0 = highest LCC, 1 = lowest LCC						

User costs inclusion/exclusion can have a significant impact on pavement treatment LCCA output (Bilal et al. 2009; FHWA, 1998a). A standard LCCA model specific to airport pavements was not discovered in literature. It is likely that quantifying operational disturbance to account for user costs to be included in a LCCA is a viable option. These user costs could vary greatly depending upon factors such as airport size, time of day or pavement location. For example, pavement treatment scheduled during night hours or on a non-primary pavement may have little associated operational disturbance and may not justify any user costs being included in the LCCA. However, if the operational disturbance is significant, then user costs should be quantified and included in the analysis. A $5,000 runway pavement treatment project's liquidated damages figure was selected from literature to be included in the calculations under the assumption that these quantified the damages of a delay in runway opening to a typical airport (City of McKinney, 2007).

The EUAC was calculated for all pavement treatments being analyzed. The results are represented as an annualized, per square yard (square meter) of treatment surface, dollar amount in Table 5.2.

Performance, or analysis period, is generally a sensitive parameter (FHWA, 1998a), a fact that was confirmed by a sensitivity analysis on the performance period used in this case. The microsurfacing treatment would have the lowest annual cost based on the assumption it would last at least 7 years, if compared to the asphalt options. The 11-year asphalt options would have instead been the most cost-effective if the microsurfacing was only expected to last six years or if the asphalt options were expected to last 13 years. Restoring surface friction using microsurfacing, slurry seal or shotblasting was evaluated. In this case, shotblasting would have had the lowest life-cycle cost if it was expected to perform for at least 4 years and slurry seal would have been the preferred alternative if it was expected to have a 5-year service life when compared to microsurfacing. The results of the performance period sensitivity analysis illustrates two points: 1) that any treatment listed herein could be considered the *right treatment* based on project-specific inputs and 2) that using local performance data generated from an airport's APMS deterioration models to determine performance period would eliminate guessing and yield more insight to true life cycle cost. Standard utility theory was applied (West and Riggs, 1996) to calculate the LCCA metric as follows:

$$\text{LCCA Metric} = 1 - (\text{EUAC}_t \div \text{EUAC}_{max}) \qquad \text{Eq. 5.1}$$

where EUAC_t = annualized cost of the treatment per square yard (meters squared) of treated surface area, and

EUAC_{max} = the maximum EUAC_t value in the range of all treatments.

Treatments were then ranked, as shown in Table 5.2. A sensitivity analysis was also conducted on the user costs inclusion and yielded the same rank with and without the $5,000 value. Other sensitivity analyses should be conducted on discount rate and where applicable to ensure that all sensitivities are being exposed.

Raw Material Consumption Metric

Aviation is a key player in moving people and goods. It has been and will increasingly have to be an active participant in mitigating the environmental impact resulting from this service (ACI-NA, 2010). In the pursuit of sustainable infrastructure management, airport owners will have to accommodate new means and methods that require less input from the natural environment.

Recycling has been a long and ever-evolving process in the transportation industry. Research is currently demonstrating the sustainability value of increasing recycling quantity and using more recycled material in higher value materials, such as surface courses, and the durability of structures that contain recycled content (Söderlund et al, 2008). Currently, recycled materials are generally not allowed in surface courses per FAA specifications, and therefore are not permitted in most pavement treatments. This is demonstrated by the 100% raw material consumption of the selected treatments in this study. The exception is shotblasting, which recovers and reuses the shot (Gransberg, 2009).

Weight, in pounds (kilograms) of treatment per square yard (meters squared) of treated surface, was annualized according to expected service life. Standard utility theory was applied (West and Riggs, 1986):

$$\text{RMC Metric} = 1-(\text{RMC}_t \div \text{RMC}_{max}), \qquad \text{Eq. 5.2}$$

where: RMC_t = the pounds (kilograms) of treatment per square yard (square meter) of treated surface per year of treatment service life, and

RMC_{max} = the maximum RMC_t value in the range of all treatments.

Treatments were then ranked. If comparing microsurfacing, slurry seal and shotblasting for a particular pavement treatment solution, shotblasting would have the least raw material consumption. If comparing microsurfacing to asphalt treatments, the asphalt treatments would have the most consumption, as shown in Table 5.3.

Table 5.3 Airport Pavement Treatment Raw Material Consumption.

Raw Material Consumption							
Pavement Treatments	RMC %	Weight		Service Life	RMC Annualized		RMC Metric *
		(lb/SY)	(kg/SM)	(YR)	(lb/SY)	(kg/SM)	
Shotblasting	0	0	0	2	0.00	0.00	1.00
Fog Seal/Seal Coat	100	0.80	0.43	2	0.40	0.22	0.97
Microsurfacing	100	24	13	7	3.43	1.86	0.77
Slurry Seal	100	24	13	3	8.00	4.34	0.46
Hot Mix Asphalt (1.5”)	100	164	89	11	14.91	8.10	0.00
Warm Mix Asphalt (1.5”)	100	164	89	11	14.91	8.10	0.00
*0 = highest RMC, 1 = lowest RMC							

Greenroads Metric

Greenroads is a credit-based sustainability rating system developed by CH2M HILL and the University of Washington modeled after the Leadership in Energy and Environmental Design (LEED®) rating system (CH2M, 2009) but specifically for roadway design, construction and maintenance application (Muench et al. 2010). There are currently seven categories that contain a total of 118 *Greenroads* points: Project Requirements (PR), Environment and Water (EW), Access and Equity (AE), Construction Activities (CA), Materials and Resources (MR), Pavement Technologies (PT), and Custom Credit (CC). All categories contain Voluntary Credits with the exception of Project Requirements. The goal of Greenroads is to offer enough credits applicable to various types of projects so that all could conceivably achieve certification, if desired. Because of this, some credits will be applicable to all roadway projects that fall within the scope, but no project would be able to achieve all credits due to exclusivity. These categories assign credits to many of the processes and technologies that affect the triple bottom line. *Greenroads* assigns four levels of certification based on points earned: Certified, Silver, Gold and Evergreen.

The eleven Project Requirements (PR) category elements are collectively intended to embody the fundamental ideals of sustainability and as such must be achieved by all projects seeking certification (Muench et al. 2010). Based on the information from the surveys (Table 1), none of the airports' pavement treatment projects would meet the applicable Project Requirements (PR) credits and thus, not be considered "sustainable" by *Greenroads* standards.

Of the 118 Voluntary Credits, 60 are applicable to airfield and/or pavement treatments and, coupled with all Project Requirements, would be sufficient to achieve

Greenroads certification. The effort to pursue certification may seem disproportionate to airport pavement treatment projects, but *Greenroads* intends its framework to confer the benefit of being a sustainability benchmark whether or not certification is initiated (Muench et al. 2010). This serves the purpose of this study. Some of the Voluntary Credits apply to all airfield pavement treatment projects, such as Pavement Reuse (MR-2) since the underlying pavement, the one that is being preserved, remains in use. Others do not apply to any, such as Long-Life Pavement (PT-1). Yet others apply to some of the study treatments and not to others. For example, Paving Emission Reduction (CA-5) and (3-year) Contractor Warranty (CA-8) apply to the paving treatments that are expected to last longer than three years, but do not apply to fog seal or shotblasting. Warm Mix Asphalt gets a 3-point credit advantage because of the credit that bears its name (PT-3).

The six treatments were assigned the maximum credit attributable to it. It is noted that not all alternatives would be considered for the same design problem. Besides the exceptions previously mentioned, all shared the same number of credits, so the *Greenroads* credit variance for this study will be small. In practice, the variance could be overcome by the treatment with the least credit by achieving Custom Credit (CC-X). However, if an airport pavement manager where to use the *Greenroads* metric to assess the sustainability of competing treatment alternatives, a large variance could exist. Of the 60 airfield/pavement treatment-applicable Voluntary Credits, 36 could be project-sensitive and could clearly yield a large sustainability variance between treatments. For example, credits like Regional Materials (MR-5), Fossil Fuel Reduction (CA-4), Permeable Pavement (PT-2) and Custom Credits (CC-X) could vary greatly between alternatives, thus demonstrating that Greenroads could contribute to and justify a pavement manager's selection of the *right treatment*. The remaining credits, which detail management processes and systems, would be applicable to all treatments if applicable to one. For example, having an Environmental Management System (EW-1) or Safety Audit (AE-1) would apply to all or none of the treatments being considered for a specific project. Table 5.4 outlines credit applicability.

Table 5.4 Airport and Pavement Treatment-Applicable Greenroads Credits.

Greenroads Rating System v1.0, 2010				
Greenroads Categories	Applicable Categories	Total Credits	Non-Applicable Categories	Total Credits
Project Requirements	PR-1,2,3,4,6,7,8,9,10,11	Required	PR-5	Required
Environment & Water	EW-1,7	5	EW-2,3,4,5,6,8	16
Access & Equity	AE-1	2	AE-2,3,4,5,6,7,8,9	28
Construction Activities	CA-1,2,3,4,5,6,7,8	14		0
Materials & Resource	MR-1,2,4,5	17	MR-3,6	6
Pavement Technologies	PT-2,3,4,6	12	PT-1,5	8
Custom Credit	CC-X	10		0
	Total Applicable Credits: 60		Total N/A Credits: 58	

Standard utility theory was applied as shown in Equation 5.3 (West and Riggs, 1986):

$$\textit{Greenroads}\text{ Metric} = \textit{GR}\text{ Score}_t \div \textit{GR}\text{ Score}_{max} \qquad \text{Eq. 5.3}$$

where: *Greenroads* Score$_t$ = treatment's *Greenroads* Score

Greenroads Score$_{max}$ = the maximum *Greenroads* Score value in the range of all treatments.

Treatments were then ranked and shown in Table 5.5.

Table 5.5 Greenroads Score by Airport Pavement Treatment.

Greenroads Pavement Treatment Scoring & Metric		
Pavement Treatment	*Greenroads* Score	*Greenroads* Metric*
Warm Mix Asphalt (1.5”)	47	1.00
Microsurfacing	44	0.94
Hot Mix Asphalt (1.5”)	44	0.94
Slurry Seal	44	0.94
Shotblasting	40	0.85
Fog Seal/Seal Coat	40	0.85
*0 = lowest *GR* score, 1 = highest *GR* score		

5.5 RESULTS

The Green Airport Pavement Treatment Matrix provides a comparative analysis of both the engineering and financial information for selected airport pavement treatments for a given pavement problem. The three-part analysis will allow airport pavement engineers to make treatment decisions based on sustainability rather than merely lowest first cost.

Output from the LCCA, RMC and GR metrics were analyzed and a “Green Airport Pavement Maintenance Matrix” was prepared that rank orders the common treatments based on sustainability. A “Green Airport Pavement Index” (GAPI) calculation was exacted on each treatment based on the corresponding metric data generated. To combine the analysis, a weighted average (West and Riggs, 1986) was used to create the GAPI as shown below.

$$GAPI = X\%(LCCA) + X\%(RMC) + X\%(GR) \qquad \text{Eq. 5.4}$$

where: X% = Weight assigned to a given metric.

Three weighting methods were selected to demonstrate the framework and are shown in Table 5.6. The first weighting method sets all three metrics equal. A larger airport may primarily consider environmental factors (Berry et al. 2008), so an “Eco-driven” method was used that heavily weights the environmental components. A smaller airport may favor lower cost (Berry et al. 2008), so a “Cost-driven” weighting method was selected. In practice, the pavement manager determines the weight for each metric based on engineering and triple bottom line factors. It should also be noted that the matrix shown in Table 5.6 does not seek to compare all treatments to each other. It merely shows the GAPI for the six most common pavement treatment found in the survey.

Table 5.6 Green Airport Pavement Treatment Matrix.

Green Airport Pavement Treatment Matrix				
Pavement Treatment	Life Cycle Cost Metric	Raw Material Consumption Metric	Greenroads Credit Metric	Green Airport Pavement Index
Weight: Balanced	33.33%	33.33%	33.33%	GAPI
Microsurfacing	0.37	0.77	0.94	0.69
Fog Seal/Seal Coat	0.14	0.97	0.85	0.65
Shotblasting	0.00	1.00	0.85	0.62
Slurry Seal	0.22	0.46	0.94	0.54
Warm Mix Asphalt (1.5”)	0.31	0.00	1.00	0.44
Hot Mix Asphalt (1.5”)	0.31	0.00	0.94	0.42
Weight: Eco-driven	20.00%	40.00%	40.00%	GAPI
Microsurfacing	0.37	0.77	0.94	0.76
Fog Seal/Seal Coat	0.14	0.97	0.85	0.76
Shotblasting	0.00	1.00	0.85	0.74
Slurry Seal	0.22	0.46	0.94	0.60
Warm Mix Asphalt (1.5”)	0.31	0.00	1.00	0.46
Hot Mix Asphalt (1.5”)	0.31	0.00	0.94	0.44
Weight: Cost-driven	80.00%	10.00%	10.00%	GAPI
Microsurfacing	0.37	0.77	0.94	0.47
Warm Mix Asphalt (1.5”)	0.31	0.00	1.00	0.35
Hot Mix Asphalt (1.5”)	0.31	0.00	0.94	0.34
Slurry Seal	0.22	0.46	0.94	0.32
Fog Seal/Seal Coat	0.14	0.97	0.85	0.29
Shotblasting	0.00	1.00	0.85	0.19

Once the matrix is developed, the pavement manager can then use this output to compare the sustainability of alternatives being considered for a given pavement maintenance project. For example, if the airport had scheduled an overlay for a given pavement, the GAPI for hot mix can be compared to the GAPI for warm mix to give the pavement manager a means to incorporate the relative sustainability of the two treatments in the final treatment selection decision. If a pavement manager was comparing microsurfacing to slurry seal and shotblasting as possible alternatives to restore surface friction on a given pavement, Table 6 shows that microsurfacing would have the highest GAPI, i.e. be the most sustainable option, in the balanced, “Cost-driven” and “Eco-driven” weighting methods. If microsurfacing was dropped for some external reason, then shotblasting would be preferred to the slurry seal in all but the “Cost-driven” method. A sensitivity analysis was conducted on each component to determine the impact of variations in parameter weighting values. If the LCCA component is weighted 16% or less, the shotblasting option would be considered the most sustainable of the options, depending upon the weighting for the RMC and GR metric and consistent with Tables 5.3 and 5.5 results.

The intent of this chapter is to demonstrate a sustainability evaluation framework for pavement treatments. It is not a representation of specific sustainability attributes of the listed treatments. Many project-specific factors contribute to the three metrics that comprise the GAPI and are subject to project-sensitive parameters, supporting the fundamental premise that choosing the *right treatment* for a specific project is not attempting to determine the best overall treatment for all projects. Any of the pavement treatments, such as the hot mix asphalt or slurry seal, could garner the highest GAPI, regardless of weighting methodology, and when coupled with engineering factors, be the *right treatment* for the pavement treatment project at hand.

5.6 CONCLUSIONS

Proactive pavement maintenance is fundamental to airport sustainability. It is a solution that a pavement manager can implement to preserve the airport's biggest investment. This can yield significant cost savings, increased operational efficiency and safety and reduced environmental impact. Airports that do have a pavement management program can identify the *right pavement* and *right time,* but lack a tool to evaluate the sustainability of the *right treatment*. This may be attributable to the lack of a standard, scaleable airport pavement treatment performance metric that could provide necessary information to the pavement manager regarding the economic, social and environmental impacts of competing treatments. The "Green Airport Pavement Index" (GAPI) could be used by a pavement manager to provide a performance benchmark for the *right treatment* and enhance the overall sustainability of the pavement maintenance program.

Future applications could include the development of tools, such as LCCA, LCI and a sustainability rating system, that are specific and proportionate to airport pavement treatment, which would simplify the GAPI process. It could also include application to a specific airport pavement problem and consideration of technical issues.

6.0 COMPARATIVE ANALYSIS OF MACROTEXTURE MEASUREMENT TESTS FOR PAVEMENT PRESERVATION TREATMENTS[5]

Aktas, B., D.D. Gransberg, C. Riemer, and D.M. Pittenger, "Comparative Analysis of Macrotexture Measurement Tests For Pavement Preservation Treatments," *2011 Transportation Research Record,* Journal of the Transportation Research Board, National Academies, Washington, D.C. Issue 2209, 2011, pp 34-40.

6.1 PAPER SYNOPSIS

This chapter reports the results of field pavement preservation research discussed in Chapter 2 with regard to macrotexture. At the time of publication, the project had provided two and a half years of texture data from two accepted methods for measuring pavement macrotexture: the outflow meter ASTM STP 583 and the Transit New Zealand TNZ T/3 sand circle. As a result of the protocol which calls for monthly macrotexture measurements in the field, functional limitations regarding the accuracy of macrotexture measurements were observed on both standard tests. The chapter furnishes guidance to researchers and practitioners in selecting a pavement macrotexture test method. It was also the basis of macrotexture measurement methodology in Chapter 7.

6.2 BACKGROUND AND MOTIVATION

In 2001, the Virginia Department of Transportation (VDOT) started experimenting with applications for using macrotexture measurement in pavement management programs (Flintsch, 2003). The Texas Department of Transportation

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[5] The original journal paper has been reformatted to make it consistent with the other published chapters in this document.

(TxDOT) sponsored a 3-year project to test the Transit New Zealand (TNZ) P/17 performance specification and found that TNZ deterioration models were directly applicable to the US environment (Gransberg, 2007). This led to a TxDOT program that is experimenting with using macrotexture measurements to set binder application rates on distributors with variable spray bars (Yildirim, 2009). Additionally, de León et al. (2009) proposed a technique based on stereoscopic imaging, which was not unlike a 2D imaging method based on information reported by Pidwerbesky et al. (2006). As this approach gains acceptance, the need to fully understand the capabilities and limitations of the available suite of macrotexture measuring and testing procedures will be important to the development of PPT trigger points that will assist pavement engineers in selecting not only the right treatment but also the proper time to apply that treatment.

There have been a number of research studies published on various methods to take these measurements. In 2003, Flintsch et al. (2003), compared the ASTM E965 sand patch method with the Mean Profile Depth determined by a laser profiler and the ASTM E2157 Circular Track Meter (CTM) and achieved “excellent correlation” on HMA pavements at the Virginia Test Road. The objective of that study was to use measured macrotexture as a metric to detect segregation in the mix. Weissman and Martino (2009) studied the correlation between the CTM and the ASTM E2380 outflow meter with the objective of developing macrotexture failure criteria for chip seals in Texas. Their development of a failure criterion came from crash data from roads in the French Alps found in the literature (Gothie, 1993). They then converted the French texture data to mean texture depth (MTD) using the ASTM equation and found the failure criterion to be 0.46mm (0.02 in.). Transit New Zealand also has a macrotexture failure criterion (TNZ, 2002) that was developed from rigorous field testing. The field data analysis resulted in a deterioration model which is used extensively in their performance-based maintenance contracts for chip seals (Manion and Tighe, 2007). The failure criterion used in New Zealand is 0.9mm (0.035 in.), double that proposed by the French study. The TNZ criterion was proved to be applicable to the US environment in a 3-year field test of chips seals in south Texas (Gransberg, 2007). However, the purpose of this chapter is not to recommend chip seal failure criteria but rather to add another brick in the body of knowledge related to measuring the macrotexture of PPTs like chip seals. Additionally, the TNZ T/3 sand circle provides an alternative to the ASTM sand patch, which comes from New Zealand where it is the primary field test performance measurement (Pidwerbesky et al. 2006) that provides input to the TNZ performance-based pavement preservation and maintenance program. Finally, to avoid possible confusion, it must be noted that the chapter is *not about measuring skid resistance* or *pavement surface friction* (microtexture). Research has shown that the locked-wheel skid numbers commonly used by transportation agencies reflect the surface microtexture *not* macrotexture *(*Gransberg and James, 2005; TNZ, 2005; Flintsch et al. 2003). While macrotexture does contribute to skid resistance, the purpose for measuring it is to monitor the pavement’s drainage characteristics (i.e. reduced probability of hydroplaning) not its surface frictional characteristics (Erwin and Tighe, 2008).

6.3 RESEARCH METHODOLOGY

The research reported in this chapter is based upon the research project introduced in Chapter 2, which currently has three years of texture data for the field test sections of 23 different PPTs on both asphalt and concrete pavements located on State Highway 77 between Oklahoma City and Norman, Oklahoma. The remainder of this chapter will focus on the differences between the ASTM STP 583 outflow meter measurements and the TNZ T/3 sand circle test for measuring mean texture depth (MTD) on a variety of surfaces with a broad range of textures, as shown in Figure 2.2 in Chapter 2. The 23 - 0.25 mile (0.4 km) test sections represent the full range of FHWA approved PPTs for both asphalt and concrete pavements (Geiger, 2005) and include a range of treatments from fog sealing on asphalt and shotblasting on concrete to a thin hot-mix overlay and “next generation” diamond grinding. Because of this project’s broad scope, it furnishes a perspective on macrotexture measurement that is not found in previous research which is typically concentrated on a single pavement surface type. Thus, the results reported in this chapter can be taken as representative to a single highway agency’s *program* rather than just for a single type of *project*.

Pavement macrotexture was measured using the sand circle and that outflow meter on each test section before the treatments were applied and on a monthly basis for three years after application. The TNZ/3 protocol requires a series of three sand circles spaced one meter apart be taken and the results averaged (TNZ, 1981) and ASTM protocol (ASTM, 2009) is similar but calls for the average four outflow measurements at roughly the same spacing. Thus, this project developed a test pattern that started with the outflow meter tests alternated with the sand circles between the outflow meter tests. Tests were taken in the right wheel path and between the wheel paths for each section, yielding a total of eight outflow meter and six sand circles tests each month on each section. This permits changes in pavement macrotexture are recorded over time, and each treatment's performance can then be compared to all other treatments under the same traffic, environment, and period. Regressing the final data in the same manner as that used by Austroads and TNZ ultimately results in a simple deterioration model for each treatment applicable to central Oklahoma and the traffic conditions observed on State Highway 77, as demonstrated in Chapters 4 and 7. An unintended output from this project is the ability to check correlations between the two macrotexture measurement methods on a variety of surfaces and perhaps make recommendations as to which testing methods are most appropriate for each treatment.

TNZ/3 Sand Circle Test

The sand circle test is used to measure the texture of the chip seal road surface. Surface texture refers to the macrotexture of the pavement surface (Austroads, 2004). Surface texture is a measurement which influences the nominal size of aggregate used for the chip seal and thus, ultimately determines material application rates, skid resistance, and road noise. Characterization of the pavement's surface texture is a critical step in the design process because non-uniform surface textures in both the transverse and longitudinal directions make it difficult to design a binder application rate.

Historically, macrotexture has been measured using volumetric techniques, and the most common US test procedure is the ASTM E-965 (2006) Sand Patch Method. Austroads (2004) is a proponent of the Sand Circle Method which has been adapted by Transit New Zealand under TNZ T/3 test method specification (TNZ, 1981). This method involves spreading 45 ml (15.22 oz) of sand (particle size of 300 μm to 600 μm) by revolving a straight-edge until the sand is level with the tops of the cover aggregate

(TNZ, 1981). The volume of material that fills the surface voids determines the surface texture. The greater the average texture depth, the greater the quantity of material lost in the surface voids and the smaller the diameter of the sand circle. The average texture depth is calculated by dividing the volume of sand by the area of the sand circle (TNZ, 1981). The sand should be dry and fine grained or and the testing surface should also be dry and swept free from detritus. The ASTM test differs from the TNZ test in that the sand is finer (pass the #60, retained on the #80 versus TNZ gradation of pass the #40, retained on the #80) and it requires about half the TNZ volume of sand for the test. The mean texture depth for the 45 ml (15.22 oz) of sand specified in NZ T/3 is determined by:

$$MTD=57300/D^2 \qquad \text{Eq. 6.1}$$

where *MTD* is mean texture depth (mm) and *D* is diameter of the sand patch (mm). The technique, although simple, is vulnerable to operator inconsistencies and can be distorted by individual aggregate particles forming atypically high peaks. Therefore, repeat measurements at regular intervals are required to characterize a particular section of road. The results obtained vary from wheel path to wheel path, and also in the areas of roadway outside the normal wheel paths. The method is slow to execute and traffic management is required to protect the operator. Therefore, the technique is ill-suited for routine monitoring of road surface texture over a large road network (Austroads, 2005).

Outflow Meter Tests

The test method for the outflow meter is specified by ASTM E2380/E2380M (2009). This method does not measure the texture depth directly. It measures the ability of the depth and interconnected nature of the voids in the surface to let water pass through the road’s surface. It is based upon a known volume of water, under a standard head of pressure, which is then allowed to disperse through the gaps (macrotexture) between a circular rubber ring and the road surface. The time it takes to pass the known volume of water (the outflow time) is measured. As the water can disperse very quickly in a coarse-textured surfacing, this method is only appropriate for surfaces with low texture depth. A European standard for this method is currently under development (Austroads, 2005). The method is especially useful with certain surfacing types, e.g. Open Graded Friction Course (OGFC), that are designed to allow water to pass into and through the body of the material. In such cases, this is a measure of the drainage characteristic (permeability) as well as the effect of the texture depth.

The outflow meter test quantifies the connectivity of the texture as it relates to the drainage capability of the pavement through its surface and subsurface voids. The technique is intended to measure the ability of the pavement surface to relieve pressure from the face of vehicular tires and thus is an indication of hydroplaning potential under wet conditions. A faster escape time indicates a thinner film of water may exist between the tire and the pavement, thus more macrotexture is exposed to indent the face of the tire and more surface friction is available to the tire. The lower the number of seconds it takes to evacuate the water, the lower the water pressure under the tire. The engineer must then compare the results of this test to other pertinent factors such as expected rainfall intensity and frequency, aggregate type, consistency of texture, grade, slope, expected vehicular speed, and accident history, to determine the relationship between the outflow meter reading and the likelihood of hydroplaning on a given surface. Comparing the outflow meter reading of a pavement known to have a history of hydroplaning, against one with little hydroplaning history provides the engineer an indication of the outflow meter number that will be necessary to promote wet weather safety. To calculate mean texture depth the following equation is used (ASTM, 2006).

$$MTD = 3.114/OFT + 0.636 \qquad \text{Eq. 6.2}$$

where MTD is mean texture depth (mm) and OFT is outflow time (sec).

Reproducibility

The New Zealand seal design algorithm requires texture depth of the existing surface as a key input. This texture has been measured using the sand circle test. Even with experienced, skilled operators, the test takes some time to perform, and is normally done in live traffic conditions with varying levels of traffic control. Even though the reproducibility (40%) of the sand circle test is poor, it is the most common means to measure texture in Australia and New Zealand (Patrick et al. 2000). A field study in Texas found that when a large number of macrotexture tests must be conducted in the field that the TNZ T/3 protocol was more reproducible than the ASTM sand patch (Gransberg, 2007). This was due to the sand circle test using about twice the volume of a coarser gradation of sand than the sand patch test. That study found that it was nearly impossible to get consistent sand patch tests in the field when conditions were windy, regardless of the precautions taken to break the wind from blowing away a significant portion of the sampling sand. This finding is confirmed by a 1974 California Department of Transportation study that found that the sand patch test had 24% reproducibility (Doty, 1974). Another study found that the outflow meter's reproducibility was "poor" (Henry and Hegmon, 1975).

6.4 RESULTS

In this study, macrotexture data was analyzed in 23 Test Sections (TS). Sand circle and outflow meter tests were completed on each test section once a month, and macrotexture depths on the road surfaces were calculated. Macrotexture depths and relative differences between both methods taken in November 2009 are shown in Figure 6.1.

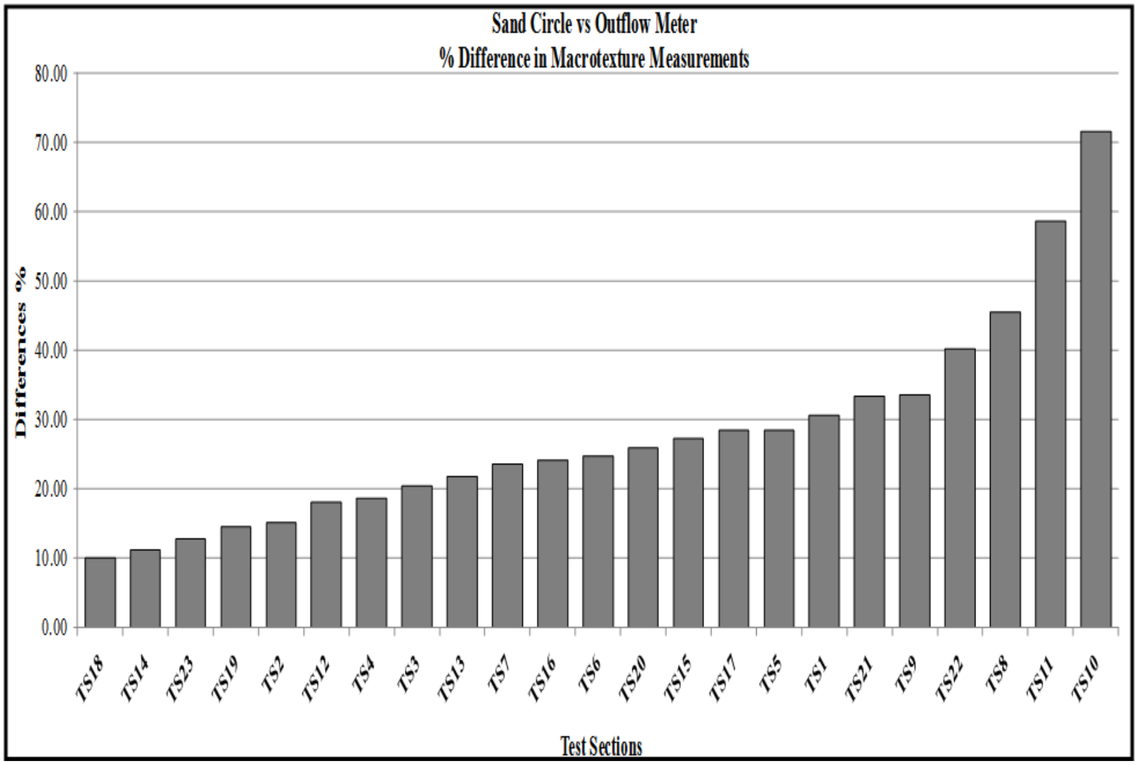

Figure 6.1 Test Sections Macrotexture Results and Differences of Two Test Methods as of 2009.

The difference in macrotexture measured by each method is expressed as a percentage of average test result deviation and thus, furnishes a relative difference from test section to test section. This permits comparison of the two test methods on surfaces of varying materials as well as material-specific macrotexture. Figure 6.1 shows that the largest relative difference between the test methods are on TS21, TS9, TS22, TS8, TS11, and TS10 (from left to right in Figure 6.1 starting at TS21). Those test sections showed a difference between the two test methods that is greater than 30%. These test sections are all chip sealed surfaces, which have greater macrotexture depths than the other surface treatments. Thus, the outflow meter test outflow times are very low, which yields calculated macrotexture depths that are excessive. Chip seal surface smoothness that is not regular due to different aggregate dimensions, creates a situation where the bottom surface of the outflow meter test device cannot completely cover the road surface causing the water to flow out very quickly. In many cases the outflow time was one second or less. This creates a limitation within the equipment since the smallest measurable unit of time is one second. For these reasons, the calculated macrotexture depth differences are great when compared to the sand circle. TS11 consists of shotblasting on HMA. This section has structural and capillary cracks on the road's surface, which affect the outflow time by providing a channel for the water to pass that is not related to macrotexture. This explains the high relative difference between the two methods on this test section

In other test sections, the relative macrotexture value differences between the two test methods were less than 30%. The lowest differences occurred in test sections 2, 3, 6, 7, 12, 13, 14, 16, 18, and 23. These test sections had macrotexture depths between 1.00 – 2.00 mm (0.04 – 0.08 in.) and the difference in the two test methods is less than 25%. In test sections 1, 5, 15, 17 and 20, macrotexture depths are less than 1.00 mm (0.04 in.) and the difference between the two methods is between 25% and 30%. In TS4 the macrotexture depth is less than 1.00 mm (0.04 in.) and the difference is 18.6%.

Figure 6.2 illustrates the average macrotexture results and differences between the two test methods in the test sections over a total of 24 months.

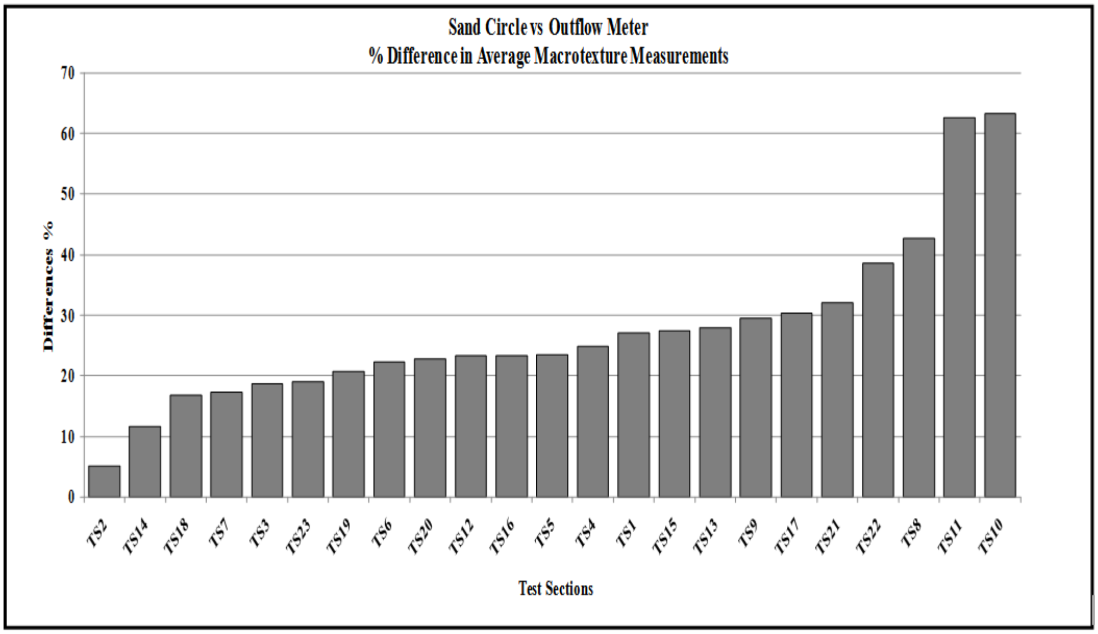

Figure 6.2 Average Macrotexture Results and Differences between Two Test Methods Over 24 Months.

This graph's results are similar to the results shown in Figure 6.1, the results for a single month. Therefore, Figure 6.2 validates the Figure 6.1 trend showing differences between the two methods are high on surfaces where macrotexture depth is high (roughly greater than 1.5 mm (0.06 in.)) and low (roughly less than 1.00 mm (0.04 in.)).

This leads to the conclusion that each method has its own inherent functional limitations. The outflow meter is not ideal for high macrotexture surfaces because it cannot measure outflow times less than one second. The sand circle's limitation is for low macrotexture surfaces. The limitation here is the ability of the engineer to be able to reliably observe when all the voids have been filled and stop expanding the sand circle. On a totally smooth surface such as glass, the circle would be one grain of sand deep and could be theoretically expanded to infinity since there are no voids to fill. In fact, TNZ (2005) specifies the functional limit of sand circles to be 300 mm (11.8 in.) in diameter or less. Any larger measurements are deemed to be unreliable. The results of these analyses indicate that neither test method is appropriate for all surfaces.

Figure 6.3 shows the percentage difference in calculated macrotexture values versus outflow time. It shows that the relative change in macrotexture is very high in the initial seconds of the outflow meter test.

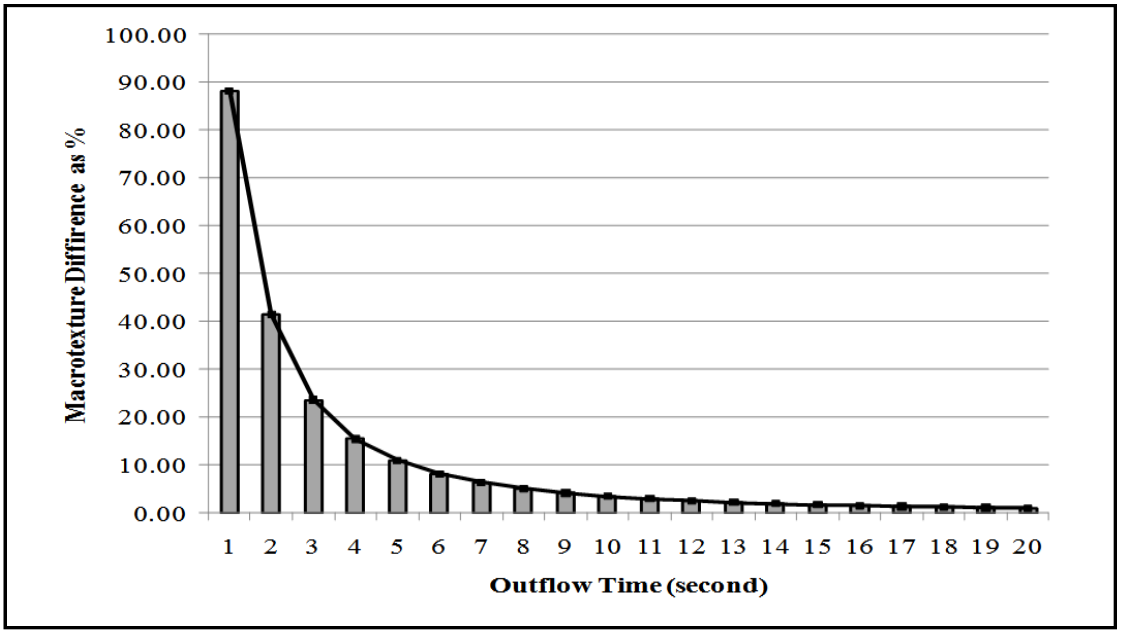

Figure 6.3 Macrotexture Percentage Differences between Seconds in Outflow Meter Test.

For example, if the outflow time were to be 0.1 second, which cannot be measured by the current device, then the calculated macrotexture is 31.7 mm (1.25 in.), and if outflow time is 1.0 second then macrotexture is calculated 3.75 mm (0.15 in.). Difference between those values is 88.20%. Since the device cannot measure outflow times of less than 1.0 seconds, the engineer will get the same outflow time value across the range from 3.7mm to 31.7 mm (0.15 in. to 1.25 in.). Since macrotexture values decrease as the outflow time increases, this trend continues until the curve flattens out.

If the calculated macrotexture value changes 41.52 % between 1-2 seconds, 23.67% between 2-3 seconds, 15.50% between 3-4 seconds, and 11.01% between 4-5 seconds. If outflow time is more than 5 seconds, macrotexture changes per second of outflow time are less than 10%. This leads to the conclusion that the 5th second of outflow time portrays a functional limiting point past which the calculated macrotexture values become more reliable. Taking this information, one can infer that the outflow meter method should not be used on surfaces that result in outflow times less than 5 seconds. This translates to a macrotexture value of 1.26 mm (0.05 in.) or more.

Macrotexture curves that are derived from outflow meter and sand circle methods are shown as a theoretical curve in Figure 6.4. It shows that across the initial 5 seconds in the outflow meter test the macrotexture curve is steep which means measurements will be unreliable.

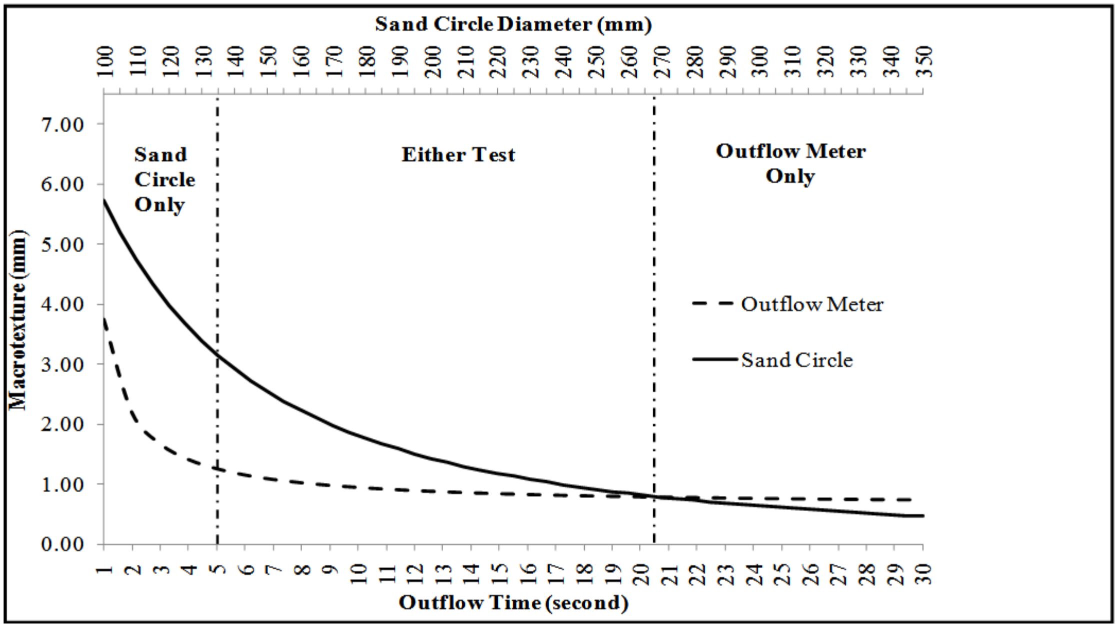

Figure 6.4 Theoretical Curves of Outflow meter and Sand Circle Tests.

Hence, if outflow time is less than 5 seconds then the sand circle method should be used for macrotexture measurements. The outflow meter and sand circle curves cross at 0.79 mm (0.03 in.) macrotexture value. This value is equal at the 20th second in outflow meter method and a sand circle with a diameter of 265 mm (10.4 in.). The sand circle diameter is large because the surface's macrotexture values are low. This value is close the TNZ specified maximum diameter of 300mm (11.8 in.). The difficulty of creating a large circle during the testing, results in a testing error and poor reproducibility. The outflow meter method is faster and easier than the sand circle test and should be used on surfaces where the macrotexture value is less than 0.79 mm (0.03 in.).

6.5 CONCLUSIONS

Determining macrotexture on pavement correctly and quickly is important for safety and economy in pavement preservation testing. This study investigated and compared two methods commonly used to determine macrotexture on pavement surfaces: the outflow meter and the sand circle test. The research and analysis results show that there are functional limitations in each method's ability to accurately measure pavement macrotexture. The outflow meter provides users with results measured in seconds. It is portable, practical on wet surfaces, inexpensive, and fast, but the measured outflow time can be inaccurate for PPTs with high macrotextures. The opposite is true for the sand circle method which should be avoided on surfaces with low macrotexture. This results in the following recommendations for appropriate use of each test method:

- If macrotexture < 0.79mm (0.03 in.), use the outflow meter only.
- If macrotexture > 0.79mm (0.03 in.) and < 1.26mm (0.05 in.), either test is appropriate
- If macrotexture > 1.26mm (0.05 in.), use the sand circle test only.

Previous studies have been conducted to establish relationships of various test methods to measure macrotexture. However, those typically looked at a single surface treatment and as a result did not create an opportunity to observe the relative differences between two or more macrotexture measurement methodologies. The results discussed above are the first to give quantitative guidance to researchers and practitioners regarding trigger points where the two test methods become most appropriate for differing pavement surfaces. It is recommended that the macrotexture limitations for each test method should be contained in specifications for each test to ensure that those agencies that use these tests are made aware of each test’s functional limitations.

7.0 PERFORMANCE-BASED LIFE CYCLE COST ANALYSIS: A CHIP SEAL FIELD TEST CASE STUDY[6]

Pittenger, D.M. and D.D. Gransberg, "Performance-Based Life Cycle Cost Analysis: A Chip Seal Field Test Case Study," submitted for 2012 International MAIREPAV (Maintenance and Rehabilitation of Pavements and Technological Control) 7 Conference in The University of Auckland.

7.1 PAPER SYNOPSIS

This chapter demonstrates application of the methodology for quantifying service lives for use in LCCA discussed in previous chapters. Performance data based on microtexture and macrotexture from three US chip seal field test sections tracked over a three-year period is used to demonstrate the methodology. The chapter concludes that using performance-based service life values based on deterioration model data in LCCA provides a superior result to those based on assumed/empirical service lives and can be utilized to assist a pavement manager in selecting the most cost effective PPT for a given pavement management problem.

7.2 BACKGROUND AND MOTIVATION

Chip seal is a PPT option (FHWA 2011) that is essentially "a single layer of asphalt binder that is covered by embedded aggregate (one stone thick), with its primary purpose being to seal the fine cracks in the underlying pavement's surface and prevent water intrusion into the base and subgrade" (Gransberg and James 2005). It is also used to restore skid resistance to a pavement surface for traffic safety (Gransberg and James 2005, Roque et al. 1991). Two common measurements used to assess chip

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[6] The original journal paper has been reformatted to make it consistent with the other published chapters in this document.

seal performance are *microtexture* and *macrotexture* (Gransberg and James, 2005; Roque et al. 1991). For more information regarding these measurement methods, refer to Chapters 1, 2 and 6.

Fog seal is a PPT option (FHWA, 2011; AEMA, 2011; Outcalt, 2001) that is essentially “a light spray application of dilute asphalt emulsion” (AEMA, 2011). Aggregate loss is a failure criterion associated with chip seal (McLeod, 1969) that can be mitigated by applying fog seal to the chip seal surface, whereby maintaining macrotexture (Roque et al. 1991). Although performance information is limited, fog seals have been found to enhance short-term pavement performance (Outcalt, 2001), but have not been shown to enhance skid resistance or slow surface deterioration over the long term and more research is needed (Lu and Steven 2006; Prapaitrakul et al. 2005; Outcalt, 2001; Estakhri and Agarwal, 1991).

One way for pavement managers to enhance decision making and justification is to incorporate engineering-based performance data into LCCA (Bilal et al. 2009; Reigle and Zaniewski, 2002). Many agencies already collect such data, in the form of microtexture or macrotexture, to support pavement management (Gransberg and James, 2006). Using this “localized” data can provide chip seal performance insight (Bilal et al. 2009; Reigle and Zaniewski, 2002) and assist pavement managers in determining the *right treatment* component of the *right treatment for the right road at the right time* pavement preservation strategy (Bilal et al. 2009; Peshkin et al. 2004). The objective of this research is to propose a methodology for extending the use of microtexture and macrotexture data to produce meaningful input values to LCCA and furnish pavement managers measurable failure criteria to estimate service lives of

PPTs. The methodology is demonstrated by using data from three US chip seal field test sections tracked over a three-year period.

7.3 RESEARCH METHODOLOGY

The methodology used in this chapter is the same as in Chapters 2 and 6 and should be referenced for detail. The underlying asphalt pavement was in good structural condition at the time of test section construction, consistent with pavement preservation guidelines (Galehouse et al. 2003). The three chip seal test sections have been exposed to the same environmental conditions and traffic volume (approximately 12,000 vehicles per day) over the three-year period. The test sections were constructed in smooth traffic-flow sections of Highway 77H and away from areas where vehicle stopping or slowing was expected. Each test section is 1,320 feet (402 meters) long and one lane wide. The chip seal materials in all sections were obtained from same sources and installed in accordance with ODOT specifications. Cationic High Float Rapid Set – 2P was used for the asphalt emulsion binder. One chip seal test section is classified as an ODOT 3/8” chip seal which has a nominal maximum aggregate size (NMAS) of 3/8 inch (9.5 mm). The other two sections are classified as ODOT 5/8” chip seals, which have NMAS of 5/8 inch (16mm). Immediately after construction, one of the 5/8” sections was fog sealed with an SS-1 oil diluted to a ratio of 5:1 water to oil and applied to the surface at a rate of 0.1 gallons per SY (0.32 liters per SM) across the entire lane of the test section.

The testing protocol included gathering micro and macrotexture measurements for the three test sections (Chapters 2 and 6). The initial measurements were taken immediately after construction for the establishment of baseline measure, then monthly thereafter for three years.

The New Zealand Transport Agency (NZTA) TNZ T/3 - *Standard Test Procedure for Measurement of Texture by the Sand Circle Methods* (TNZ 1981), which is commonly used in Australia and New Zealand to gauge macrotexture, has been found to be an appropriate chip seal performance measurement in the US (Gransberg, 2007) (Chapter 6). The macrotexture measurements used for this study were taken with this equipment, which is pictured in Figure 2.2.

The monthly microtexture and macrotexture performance data was gathered from the three chip seal field trials and used to create deterioration curves that show the rate at which the skid number (microtexture) and MTD (macrotexture) decreased over the three-year evaluation period, then extrapolated to provide localized service life insight. Three service life values based on microtexture, macrotexture and assumption were used in the LCCA calculations to produce an EUAC for each chip seal type. The chip seal EUAC values were then evaluated to demonstrate the methodology for comparing PPTs with performance-based LCCA.

7.3.1 Deterioration Models

Linear regression was applied to each chip seal's microtexture and macrotexture data, as described in Chapter 4. Figure 7.1 shows the deterioration of macrotexture over time exhibited by the 5/8" (16mm) chip seal (without fog seal) test section. The equation derived for the linear regression is shown in the upper right-hand corner of the figure. The coefficient of determination (R^2) was 0.9105. The regression equation was then used to calculate the deterioration rate beyond the available 33-month data.

These values were added to the actual data points to extrapolate the curve out to 36 months (i.e. 3-year service life expected), where it falls below the failure criterion of 0.9mm as shown in Figure 7.2.

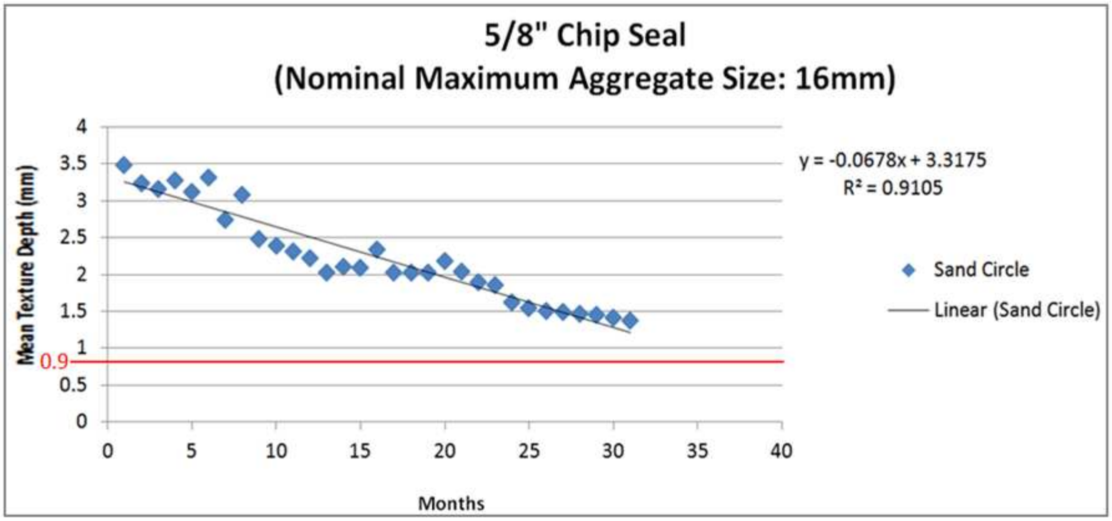

Figure 7.1 Untreated 5/8” Chip Seal Macrotexture Deterioration.

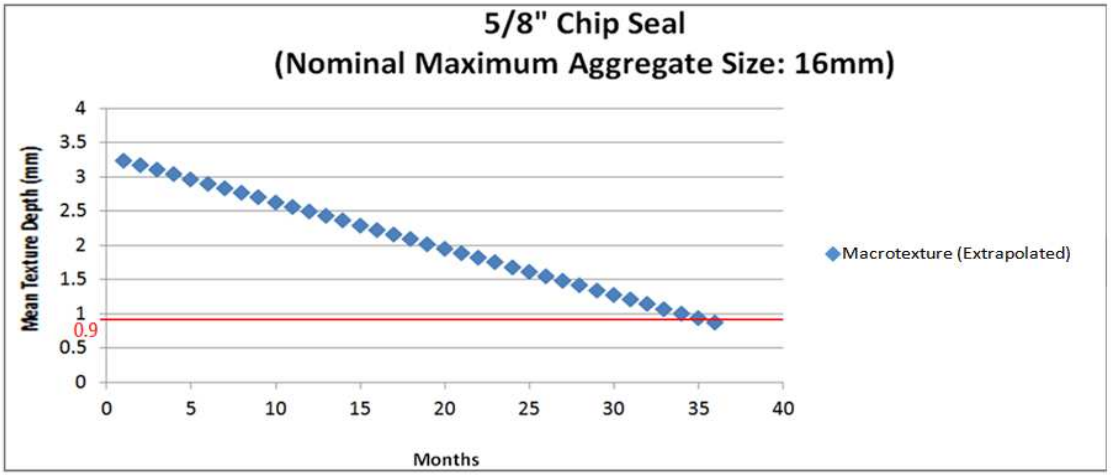

Figure 7.2 Untreated 5/8” Chip Seal Macrotexture Deterioration, Extrapolated.

When considering the same test section on the basis of microtexture, the extrapolated curve (R^2 = 0.8583) extends out to 110 months (i.e. 9-year service life expected), where it falls below the failure criterion of 25, as shown in Figure 7.3.

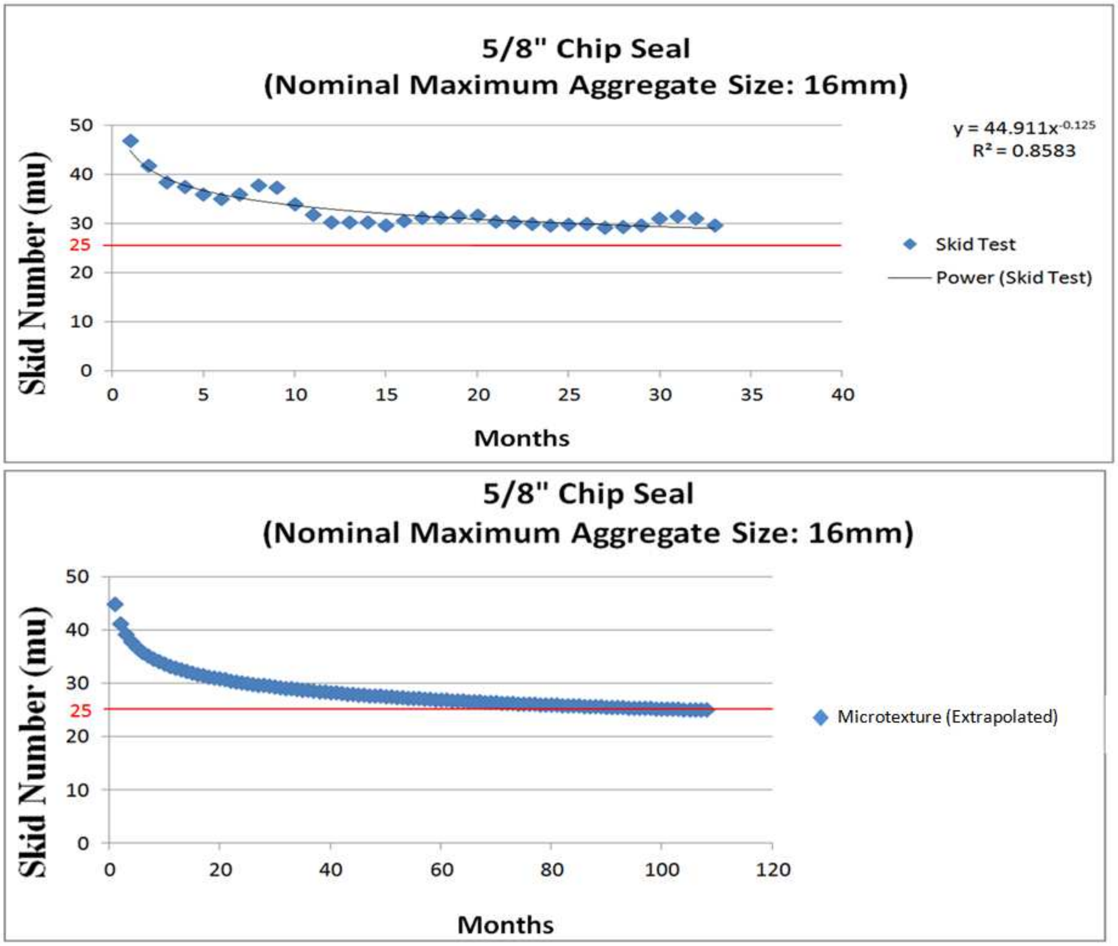

Figure 7.3 Untreated 5/8" Chip Seal Microtexture Deterioration and Extrapolation.

7.3.2 Deterministic EUAC Life Cycle Cost Analysis

EUAC LCCA was conducted in accordance with the methodology described in Chapters 3 and 4. Chip seal service life was either the assumed value or estimated from the deterioration models. The discount rate (*i*) was 4%, in accordance with FHWA recommendation (FHWA 1998). Present value of chip seal costs (*P*) contained initial costs for the chip seals (materials and construction) obtained from ODOT (Table 7.1) and discounted future maintenance cost estimations. Activity timing for future maintenance included a three-year frequency for crack seal and 2%-of-total-area patching.

Table 7.1 Initial Field Test Chip Seal Costs.

Chip Seal Cost (in US Dollars)		
PPT	Per Square Yard	Per Square Meter
3/8” Chip Seal (NMAS 9.5mm)	1.62	1.92
5/8” Chip Seal (NMAS 16mm)	1.66	1.98
5/8” Chip Seal with Fog Seal (NMAS 16mm)	1.87	2.22

7.4 RESULTS

Performance-Based Service Life Estimation for LCCA

The estimated service life values for the three chip seal field test sections based on their actual performance are shown in Table 7.2. These values differ significantly from each other, as well as from the 5-year-average assumed value determined through ODOT and literature.

Table 7.2 Performance-Based Service Life Values For Chip Seal.

Performance-Based Service Life Estimation for LCCA (in years)			
PPT	Macrotexture	Microtexture	Lit. Review & ODOT Survey
3/8” Chip Seal (NMAS 9.5mm)	1.2	3.33	5
5/8” Chip Seal (NMAS 16mm)	3.0	9.1	5
5/8” Chip Seal with Fog Seal (NMAS 16mm)	3.4	8.3	5

The 3/8” (9.5mm) chip seal has already failed on macrotexture and is nearing microtexture failure. The fog-seal treated 5/8” (16mm) chip seal is expected to have a longer service life (3.4 years) than the untreated 5/8” section (3 years) on the basis of macrotexture (aggregtate retention), consistent with literature. However, the treated section is not expected to have a longer service life based on microtexture (skid resistance), also consistent with literature.

Performance-Based LCCA

LCCA sensitivity to the service life parameter is exposed by the different EUAC results shown in Table 7.3. The chip seal with the lowest EUAC (rank) would be considered the most cost-effective option. If the pavement manager conducted the LCCA with an empirical service life estimate of five years, then the 3/8” (9.5mm) chip seal, which had the marginally-lower initial cost, would be selected. However, the field trial showed that it resulted in the highest life-cycle cost and was the least cost-effective option *for this specific project* based on its actual performance.

The premise of pavement preservation is that no one treatment is best, but that each case should be evaluated to determine the *right treatment for the right road at the right time* (Peshkin et al. 2004). Therefore, it should not be construed that a 3/8” (9.5mm) chip seal is never a cost-effective option and it should be expected to be the preferred treatment for some projects based on conditions.

Table 7.3 LCCA Values For Chip Seal Field Test Sections.

Equivalent Uniform Annual Cost (in US Dollars per Lane-mile*)			
PPT	Macrotexture EUAC (Rank)	Microtexture EUAC (Rank)	Lit. Review and ODOT Survey EUAC (Rank)
3/8” Chip Seal (NMAS 9.5mm)	9,923 (3)	3,726 (3)	3,123 (1)
5/8” Chip Seal (NMAS 16mm)	4,211 (1)	2,186 (1)	3,186 (2)
5/8” Chip Seal with Fog Seal (NMAS 16mm)	4,218 (2)	2,574 (2)	3,518 (3)
*1 Lane-mile = 5,890 SM			

If the pavement manager considered only macrotexture data, then it would appear that both the treated and untreated 5/8”(16mm) sections would provide similar returns on investment. The treated section had a higher initial cost due to fog seal application, but the cost was offset by the longer service life estimation. If the pavement manager only considered microtexture, then the untreated 5/8” section clearly appears to have the lower life-cycle cost.

Although the micro and macrotexture service life values (and EUACs) significantly differed, the chip seal rankings are the same for both categories. The performance-based LCCA showed that the untreated 5/8” (16mm) chip seal is the most cost-effective option, returning a different preferred alternative than the LCCA based on the empirical service life value. This shows that using localized performance-derived deterioration curves and failure criteria for LCCA provides a more accurate result than the empirical values for service life.

7.5 CONCLUSIONS

This chapter demonstrated a performance-based evaluation methodology to determine the cost effectiveness of PPT alternatives using treatment deterioration and life cycle-cost modeling. Commonly collected engineering technical data, like microtexture and macrotexture, can reflect localized conditions and give realistic insight to treatment performance. If this is not considered in LCCA service-life determination, output may be skewed and the most cost effective option may be obscured. When the performance data is quantified and used in LCCA, however, it can furnish pavement managers LCCA results that are superior to those based on empirical input values and can provide the enhanced ability to truly identify, and then justify the most cost effective pavement treatment for a given project.

8.0 STOCHASTIC LIFE CYCLE COST ANALYSIS FOR PAVEMENT PRESERVATION TREATMENTS[7]

Pittenger, D.M., D.D. Gransberg, M. Zaman and C. Riemer, "Stochastic Life Cycle Cost Analysis for Pavement Preservation Treatments," *Transportation Research Record*, Journal of the Transportation Research Board, National Academies, Washington, D.C. (Accepted for publication 2012).

8.1 PAPER SYNOPSIS

This paper served to disseminate the stochastic EUAC LCCA model to the pavement preservation community. The use of LCCA as a decision-making tool in pavement design and the analysis of competing alternatives is recommended by the FHWA. However, dependence on deterministic LCCA produces validity issues regarding the accuracy of input information because of the degree of construction price volatility found in the underlying commodities used in pavements. Stochastic LCCA has been shown to provide superior results when used at the new pavement design or network level and is suggested for transportation use by the FHWA. However, no project-level tools exist to facilitate use of a stochastic approach to PPT evaluation. This chapter proposes a practical stochastic LCCA model based on EUAC specifically for comparing PPT alternatives. The chapter explores statistical LCCA techniques that expose inherent uncertainties to identify and quantify the risk of commodity price volatility. The proposed methodology enhances a pavement manager's ability to address budget issues and mitigate risk while justifying PPT decisions. It is concluded that underlying commodity price volatility in pavement treatment costs can be

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[7] The original journal paper has been reformatted to make it consistent with the other published chapters in this document.

effectively modeled using stochastic LCCA. It also answers the research question: stochastic LCCA does provide a different answer than deterministic LCCA.

8.2 RESEARCH METHODOLOGY

Deterministic sensitivity analysis cannot address simultaneous input variability, quantify risk, nor provide associated likelihood of occurrence like a probabilistic approach can (FHWA, 1998a). It only shows if a discrete change in an input value would produce a different output value, as demonstrated in Table 8.1. If the change results in a different outcome, then the parameter is considered sensitive. Table 8.1 shows the EUAC and service life/discount rate sensitivities of a one lane-mile one-inch Hot Mix Asphalt (HMA) overlay treatment that includes user costs and future maintenance costs. The FHWA suggests a discount rate in the range of 3% - 5% (FHWA, 1998a) be used in analyses. An 8-12 year HMA service life for LCCA calculations was supported by the literature (Bilal et al. 2009; Stroup-Gardiner and Shatnawi , 2008; Bausano et al. 2004). Table 8.1 shows sensitivity in the deterministic method that provides an estimated EUAC range of $3,759 and $5,259, based on the input assumptions.

Table 8.1 EUAC LCCA Results, Deterministic Method with Sensitivity Analysis.

HMA EUAC ($/lane-mile), Deterministic Method			
	Discount Rate		
Service Life (YR)	3%	4%	5%
8	4,917	5,086	5,259
10	4,387	4,551	4,719
12	3,759	3,933	4,111

The primary objective of this study is to examine the stochastic LCCA approach specifically for a PPT application. Figure 8.1 adapts the FHWA stochastic LCCA methodology (FHWA, 1998a) by calculating EUAC instead of NPV.

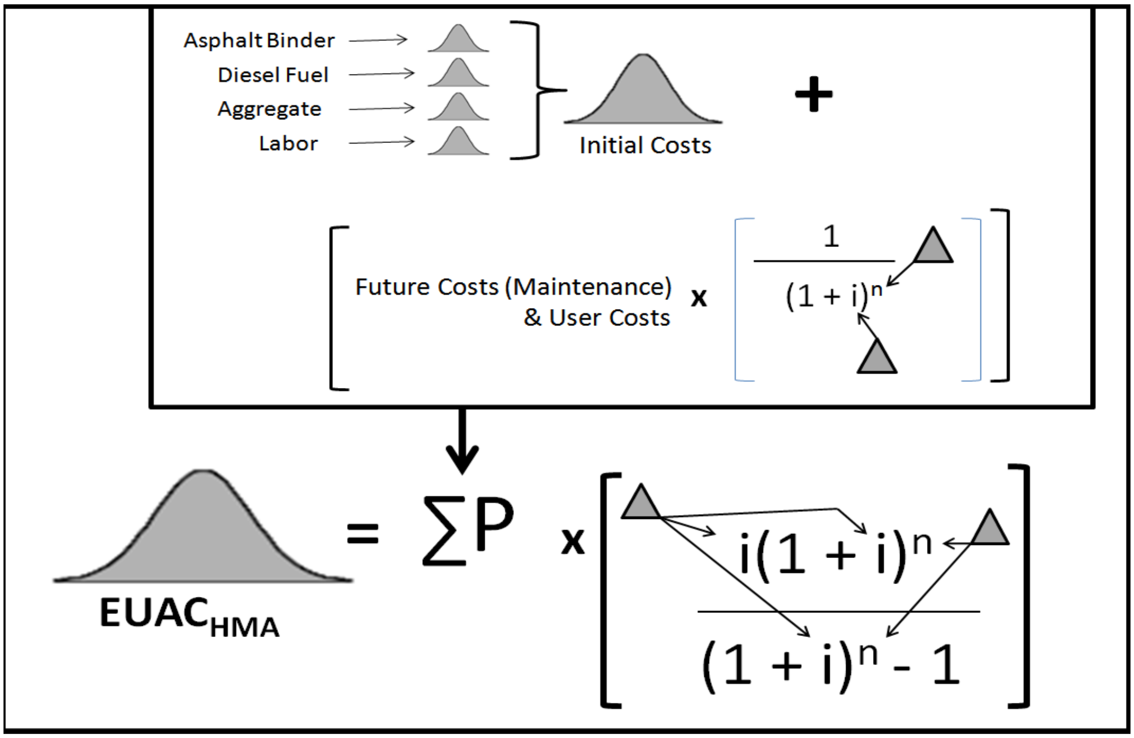

Figure 8.1 Stochastic EUAC Approach for Commodity-Based LCCA. (Adapted from FHWA (FHWA, 1998a))

This study followed FHWA guidance for conducting stochastic LCCA (FHWA, 1998a) and is outlined in Chapter 1. Several steps were considered for model construction, including whether to treat the input values deterministically or probabilistically, fitting the commodity sample data with the appropriate distribution and developing the algorithm for risk analysis.

Step 1: Deterministic and Stochastic Input Value Determination

Step one of a stochastic approach requires the analyst to identify which input values have associated uncertainty *and* will have a material effect on the outcome (Gransberg and Kelly, 2008; Reigle and Zaniewski, 2002; Tighe, 2001; FHWA, 1998a).

Those values should be treated probabilistically, while all others are treated deterministically to simplify the analysis. (Figure 8.1 denotes those to be treated probabilistically with a probability distribution.)

Service life uncertainty is what creates sensitivity in LCCA results (White et al. 2010; Hall et al. 2003; Reigle and Zaniewski, 2002) and make it a good candidate for stochastic treatment (Bilal et al. 2009; Reigle and Zaniewski, 2002). The triangular probability distribution has a minimum value, maximum value and most likely value, and is commonly used for variables that have limited sample data but can be reasonably estimated, like service life (FHWA, 1998a). Therefore, this study uses the triangular distribution to describe the one-inch HMA pavement treatment's service life, with a minimum value of 8 years, maximum value of 12 years, and most likely value of 10 years, consistent with literature (Bilal et al. 2009; Stroup-Gardiner, M. and S. Shatnawi, 2008; Bausano et al. 2004). This study uses the previous 30 years of discount rate data from the Federal Reserve (2011), fitted to the appropriate probability distribution.

Agency costs of a pavement treatment, such as initial and future costs, are considered in LCCA. If a pavement treatment is expected to incur future costs, like maintenance, comparable to those of other alternatives and would not have a material effect on the output, those costs could be treated deterministically or ignored altogether (FHWA, 1998a). Because of this reason, this study treats the future costs deterministically. The discounting of those costs, however, will be treated probabilistically, as discussed in the previous section.

Initial pavement treatment material and installation costs constitute a major part of the pavement treatment expenditure and should be treated probabilistically due to uncertainty. Research has shown that the impact of underlying construction material price volatility should be quantified and is vital to analyses (Wang et al, 2009; Gransberg and Kelly, 2008). Relying on historical costs alone, while ignoring the impact of escalating construction costs can introduce substantial risk and bias into analyses (Wang et al, 2009; Gransberg and Kelly, 2008). Current market price can be used to track volatility in transportation-specific commodities such as aggregate, asphalt binder and diesel (Gransberg and Kelly, 2008). The asphalt binder, diesel fuel, aggregate and labor components of the one-inch HMA treatment initial cost are treated probabilistically for this study (Figure 8.1). The cost of these commodities was determined from US Bureau of Labor Statistics (USBLS) data (2011) and Engineering News Record magazine's *Quarterly Cost Reports* (2011), which derives its cost data from the US Bureau of Labor Statistics. Historical and current cost data comprise the data sets. Three sample data sets were obtained for each commodity on the basis of volatility to check for LCCA sensitivity: data from the previous 1-year period (July 2010 – June 2011), 2-year period (July 2009 – June 2011) and five-year period (July 2006 – June 2011). Figure 8.2 also includes a 25-year sample data period (July 1986 – June 2011) to further illustrate the quantified volatility and cost pattern in the asphalt binder portion of the agency costs.

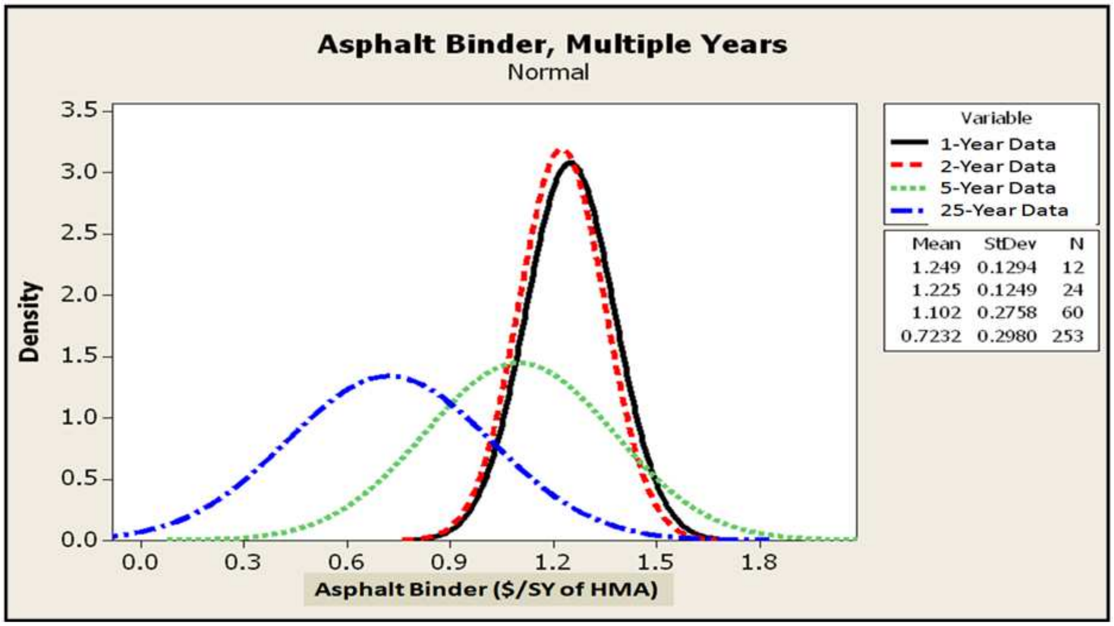

Figure 8.2 Asphalt Binder Probability Distributions for Various Sample Data Sets.

Figure 8.2 shows the probability distributions for the asphalt binder input variable based on the different sample data sets. There is negligible difference between the “current” data sets (1-YR and 2-YR). However, both of the “historical” data sets (25-YR and 5-YR) have greater variability (volatility). When one considers the data closely, the 25-YR data set contains values close to $142 per ton of asphalt binder on the low end, which has not been experienced since the 1980’s. Both the 25-YR and 5-YR data sets contain a value of $720/ton when binder price hit an unprecedented high in 2008. These extreme values are the cause of the high variability (standard deviation values) of their probability distributions and represent scenarios that are unlikely to occur again in the future. The implication of relying on the “historical” data, in this case, is that the resulting EUACs will be lower and biased due to the extreme values. The “current” data sets will yield higher EUAC values, but may be more reliable. These results are exhibited in Figure 8.2 in the Results section of this chapter.

Historical data may be too conservative and minimize current volatility in EUAC output, or it may be the converse, which means that historical data actually contributes to the variability of the EUAC output. Sample data sets should be carefully considered so as not to inadvertently introduce bias into the analysis (Wang et al, 2009; Gransberg and Kelly, 2008). Input value distributions can be subjectively defined based on the pavement engineer's judgment or objectively defined based on sample data gathered from historical or current data from sources like bid tabulations and pavement management systems (Wang et al, 2009). Ultimately, the analyst must use judgment to properly assess and address uncertainty in analyses (FHWA, 1998a).

User costs can affect pavement treatment LCCA outcome (Bilal et al. 2009; Hall et al. 2003), and can be treated deterministically or probabilistically (Reigle and Zaniewski, 2002; FHWA, 1998a). The FHWA suggests that the level of LCCA effort "should be consistent with the level of investment" (FHWA, 1998a). For this reason, the future costs and user costs associated with the HMA will be treated deterministically, but the discounting of these costs will be determined using a stochastic approach due to the probabilistic treatment of the service life (analysis period) and the discount rate (Figure 8.1).

Step 2: Selecting Appropriate Probability Distributions

The second step of a stochastic analysis is to "fit" a given data set to the "best" theoretical probability distribution. Research has demonstrated that LCCA can be sensitive to distribution-type selection, especially in a low-bid environment, like transportation, where material costs do not widely vary for a given quantity and would tend to yield an asymmetric shape with a positive skew, like the lognormal distribution

(Tighe, 2001). For these reasons, normality is not assumed and the initial construction commodity costs (binder, diesel, aggregate and labor) are "fitted" to the best theoretical distribution.

Step 3: Risk Analysis

The third step of a stochastic approach is risk analysis, which is based on probability theory and can be defined as a "systematic use of available information to determine how often specified events may occur and the magnitude of their consequences" (Pallisade, 2011). A Monte Carlo simulation is a probabilistic, quantitative risk analysis method.

The Monte Carlo simulation is used in the model and based on the following output algorithm:

$$EUAC_{PPT} = [\sum P] * [\ i\ (1+i)^{n} \div (1+i)^{n} -1)\ ] \qquad \text{Eq. 8.1}$$

where:

$EUAC_{PPT}$ = EUAC probability distribution for PPT

$\sum P$ = the sum of present values of agency costs and user costs

i = discount rate, represented as a probability distribution

n = pavement treatment service life, represented as a triangular distribution

and the sum of present values of agency costs and user costs is:

$$\sum P = AB_{P} + DF_{P} + AG_{P} + L_{P} + D_{V} + FC_{D\text{-}P} + UC_{D\text{-}P} \qquad \text{Eq. 8.2}$$

where:

AB_{P} = Expected value of asphalt binder (probabilistic)

DF_{P} = Expected value of diesel fuel (probabilistic)

AG_P = Expected value of aggregate (probabilistic)

L_P = Expected value of labor component (probabilistic)

D_V = Deterministic value of other initial agency costs (such as equipment, traffic control, striping)

FC_{D-P} = Expected value of future (maintenance) costs (probabilistic discount rate and service life components, deterministic cost)

UC_{D-P} = Expected value of user costs (probabilistic discount rate and service life components, deterministic cost)

8.3 RESULTS

The simulation output should not be blindly accepted. The pavement manager should verify the reasonableness of output considering the problem at hand. The results provide much statistical information about competing alternatives and should be thoroughly analyzed (FHWA, 1998a). Sensitivities are exposed through use of the stochastic approach. First, deterministic results (Table 8.1) are compared to stochastic results (Table 8.2). Secondly, the normality assumption is examined to see if it would create sensitivity in the model. Third, the EUAC variability is explored based on selection of current data versus historical data. Lastly, risk drivers of the EUAC are considered. The simulations each lasted from 4 to 45 seconds for this study. The results of the simulations are displayed in Table 8.2.

Table 8.2 EUAC LCCA Results, Commodity-Based Stochastic Method.

HMA EUAC ($/lane-mile)				
	Variable-Year Commodity Data Sets			
		1-Year	2-Year	5-Year
Best Fit Commodity Distributions	Mean	4,743	4,712	4,563
	St. Deviation	550	551	575
	5th Percentile	3,876	3,850	3,682
	95th Percentile	5,681	5,679	5,560
	Max. Value	7,215	6,872	7,683
Normal Commodity Distributions	Mean	4,742	4,712	4,565
	St. Deviation	557	552	580
	5th Percentile	3,844	3,823	3,632
	95th Percentile	5,669	5,630	5,542
	Max. Value	7,191	7,129	7,382

Deterministic EUAC versus Stochastic EUAC and Distribution-Type Sensitivities

Both the deterministic and stochastic approaches appear to yield similar results, as does the best fit and normal distributions. However, the stochastic approach yields more information than the deterministic approach that is crucial to the decision-making process. Consider the following:

- The deterministic EUAC is $4,551 at the 4% and 10-YR input values (Table 8.1). The limitation of the deterministic method is that the analyst is unsure of how probable this EUAC value is. However, when considering the same evaluation scenario stochastically (Table 8.2), it becomes clear that the $4,551 value falls below the 50th percentile (mean). It falls around the 37th percentile, which means that there is a 63% probability that the actual EUAC will exceed $4,551.

- Table 8.1 also shows the deterministic sensitivity analysis which yields a range of $3,759 to $5,259, based on discount rate-service life input assumptions of 3%-12yr and 5%-8yr, respectively. The lowest-EUAC scenario ($3,759) appears to correlate with the 5th percentile values listed in Table 8.2, meaning the analyst should only expect that value around 5% of the time and should not set the budget by that EUAC.
- On the other hand, the highest-EUAC scenario ($5,259) is lower than the 95th percentile values in Table 8.2. That value would fall around the 82nd percentile for the 1 and 2-year results. This means that the analyst could expect the actual value to exceed $5,259 in one of five projects. The compounding effect of this type of underestimation, especially when the maximum expected value is two-thousand dollars greater, would have a substantial impact on the budget.

Current Data versus Historical Data and Volatility Sensitivities

Figure 8.3 shows that the 1 and 2-year commodity data sets produce similar EUAC results. In contrast, the EUAC results based on 5-year commodity sample data sets had a lower mean (EUAC) and greater standard deviation, meaning that it contains more variation (volatility) and may be a less reliable indicator of cost effectiveness. It follows the same pattern as the asphalt binder in Figure 8.2.

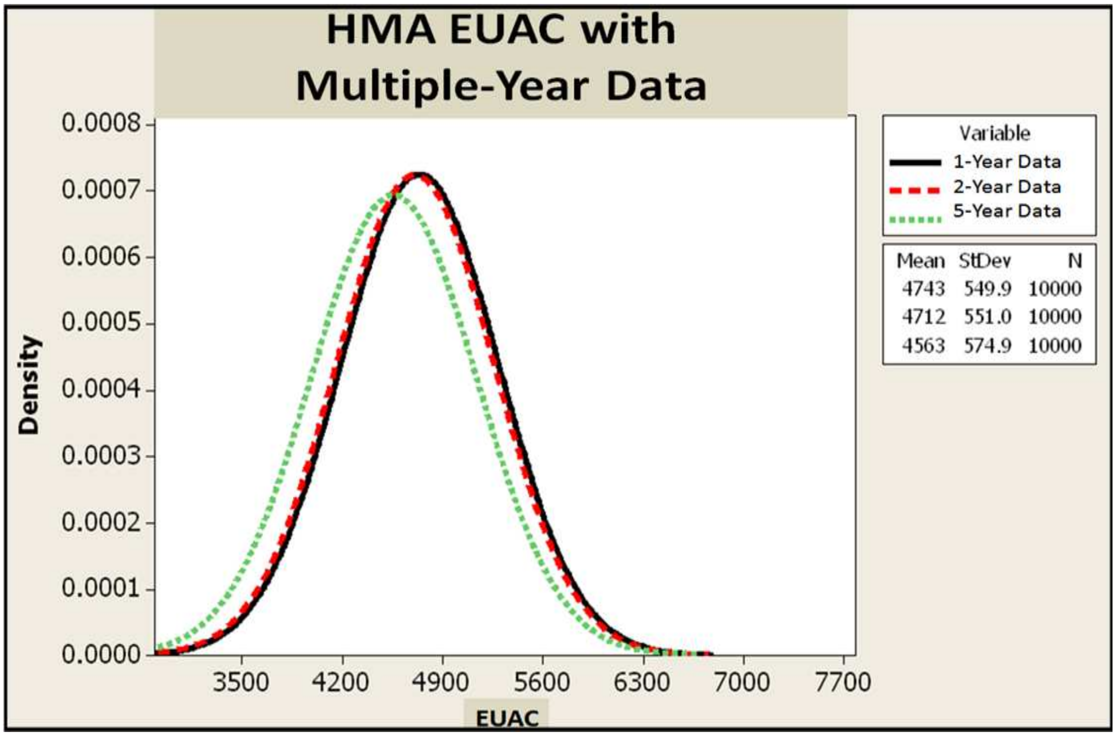

Figure 8.3 HMA EUAC Stochastic Results with Varying-Timeframe Data Sets.

Risk Driver Sensitivities

The stochastic approach also provides risk quantification based on input value variability and its effect on the EUAC (FHWA, 1998a). It does so by regression analysis, which tracks the change in EUAC for a given change in an input variable, as noted by the regression coefficient. Table 8.3 displays the sensitivity analysis results. The "Net Change EUAC" column is simply the regression coefficient converted to $ of EUAC change. It can be read "for every one standard deviation increase in the input variable results in the net change EUAC value", allowing the analyst to quantify the effect of variability on the final results. For example, for every 1.2 year increase in service life length, the EUAC decreases by around $230. One can also ascertain from Table 8.3 that discount rate is the parameter that primarily drives risk (causes the most change in EUAC) in this scenario. Not surprisingly, the discount rate, binder cost and service life input variables constitute the highest risks in this study.

Table 8.3 Commodity-Based LCCA Sensitivity Analysis: Regression.

Regression Analysis			
Input Variable	St.Deviation	Regression Coefficient	Net Change in EUAC
Discount Rate	2.76%	0.869	478.09
Service Life	1.2 yr	-0.419	-230.63
Asphalt Binder	$0.13	0.203	111.74
Diesel	$0.008	0.015	8.38
Labor	$0.006	0.011	5.84
Aggregate	$0.006	0.009	5.07

Stochastic LCCA Application

A stochastic approach exposes uncertainty that may be concealed when employing the deterministic approach and therefore assists SHAs in making “strategic long-term investment decisions under short-term budget constraints” on the basis of risk (FHWA, 1998a). A pavement engineer can specifically address and quantify the uncertainty associated with the PPT selection decision and this will contribute to decision validation.

To illustrate, when comparing a 1-inch HMA overlay and a 5/8-inch chip seal (Table 8.4), the deterministic EUAC values provide the “best” and “worst” case scenarios. However, those values do not reveal the probabilities of those values actually occurring.

Table 8.4 Commodity-Based Stochastic LCCA for PPT Evaluation.

LCCA Results				
	1" HMA		5/8" Chip Seal	
Deterministic	Service Life, Discount rate	EUAC ($/lane-mile)	Service Life, Discount rate	EUAC ($/lane-mile)
Low	12-YR, 3%	3,759	6-YR, 3%	3,019
Average	10-YR, 4%	4,551	4-YR, 4%	4,478
High	8-YR, 5%	5,259	2-YR, 5%	6,900
Probabilistic				
Mean		4,742		4,574
St. Deviation		557		983
5th Percentile		3,844		3,288
95th Percentile		5,669		6,505
Max. Value		7,191		8,633
		Net Change in EUAC		Net Change in EUAC
Regression Analysis (Service Life)		-230.63		-911.66

The probabilistic approach provides more decision-making information, as listed in Table 8.4 and explained below.

- As noted previously, the actual HMA EUAC should be expected to exceed the high value of $5,259 in one of five projects (82nd percentile). In contrast, the actual EUAC for chip seal should be expected to exceed the high value of $6,900 in less than 1 project in 100 (P<99th percentile).

- The chip seal average EUAC is more probable (53rd percentile) than the HMA average EUAC (37th percentile).
- The low EUAC chip seal value has less than 1% probability of occurrence, and reliance on this or the HMA low value may substantially increase budget risk.
- The regression analysis reveals that the chip seal is more sensitive to the service life assumption than the HMA option. A given change in service life will have 4-times the impact on the chip seal EUAC versus the HMA EUAC.

This information enhances a pavement manager's ability to make and justify decisions. Lastly, LCCA results should be coupled with other decision-support factors such as "risk, available budgets, and political and environmental concerns" (FHWA, 2002). The output from an LCCA should not be considered the answer, but merely an indication of the cost effectiveness of alternatives (FHWA, 1998a).

8.4 CONCLUSIONS

This chapter proposed a stochastic EUAC-based, LCCA model whose level of effort is consistent with the level of investment at the PPT level. The research demonstrated how deterministic EUAC (with sensitivity analysis) can provide a range of EUAC output values comparable to those calculated in the stochastic approach and is the appropriate approach when uncertainty is not expected to alter the outcome. However, since the inherent uncertainty in construction material commodities, such as asphalt, are known to be high, the stochastic approach is the better method because it exposes LCCA sensitivities that are obscured in the deterministic approach. The research also demonstrated that considering commodity volatility enhances LCCA by accounting for material price volatility as well as sensitivities due to discount rate and analysis period selection. Lastly, the availability of commercial software accommodates the implementation of stochastic LCCA for frontline PPT selection decisions. It can also enhance a pavement engineer's ability to address budget issues while mitigating risk and furnishing a rational justification for PPT selection decisions.

9.0 STOCHASTIC PAVEMENT PRESERVATION TREATMENT LIFE CYCLE COST ANALYSIS ALGORITHM[8]

Pittenger, D.M. and C. Ramseyer, “Stochastic Pavement Preservation Treatment Life Cycle Cost Analysis Algorithm,” submitted to the *International Journal of Pavement Engineering*.

9.1 PAPER SYNOPSIS

Stochastic LCCA has been shown to provide superior results (and decision justification) when used at the design or network level and is suggested for transportation use by the Federal Highway Administration when uncertainty is expected to impact LCCA outcome. However, no project-level tools exist to facilitate SHA employment of the probabilistic approach. This chapter explores probability theory concepts in the context of probabilistic LCCA and develops a stochastic algorithm for use in PPT evaluation. It adapts the continuous and terminal modes (Chapter 3) that keep the EUAC LCCA in compliance with engineering economic principles to the stochastic model. The model is then demonstrated using data from PPT field trials to show that stochastic and deterministic LCCA can offer different results.

9.2 RESEARCH METHODOLOGY

If uncertainty is expected to impact LCCA results, stochastic analysis is the appropriate approach (FHWA, 1998a), as discussed in Chapter 1. This study followed FHWA guidance for conducting stochastic LCCA (FHWA, 1998a). Several steps were considered for model construction, including whether to treat the input values

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[8] The original journal paper has been reformatted to make it consistent with other published chapters in this document.

deterministically or probabilistically, fitting the initial costs and discount rate with the appropriate distribution and developing the algorithm for risk analysis.

Step 1: Input Value Consideration

The first step in probabilistic analysis is to determine which input values to treat deterministically and which to treat probabilistically based on the uncertainty expected of each parameter (Tighe, 2001; FHWA, 1998a). For this study, the initial costs, service life and discount rate will be treated probabilistically and the rest will be treated deterministically. The following will constitute the sum of present values:

$$\sum P = PPT_P + D_V + FC_{D\text{-}P} + UC_{D\text{-}P} \qquad \text{Eq. 9.2}$$

where:

PPT_P = Expected initial cost of PPT (probabilistic)

D_V = Deterministic value of other agency costs (such as equipment, traffic control, striping)

$FC_{D\text{-}P}$ = Expected value of future (maintenance) costs (probabilistic discount rate and service life components, deterministic cost)

$UC_{D\text{-}P}$ = Expected value of user costs (probabilistic discount rate and service life components, deterministic cost).

The expected initial costs of treatments (PPT_p) were probabilistically determined from ODOT and Oklahoma Department of Central Services (DCS) bid tabulations for the calendar years 2010-2011 and are consistent with ODOT survey and literature and are listed in Table 9.1. Prices from projects with similar quantities and in similar geographic locations were used so as to not inadvertently skew output (Tighe, 2001).

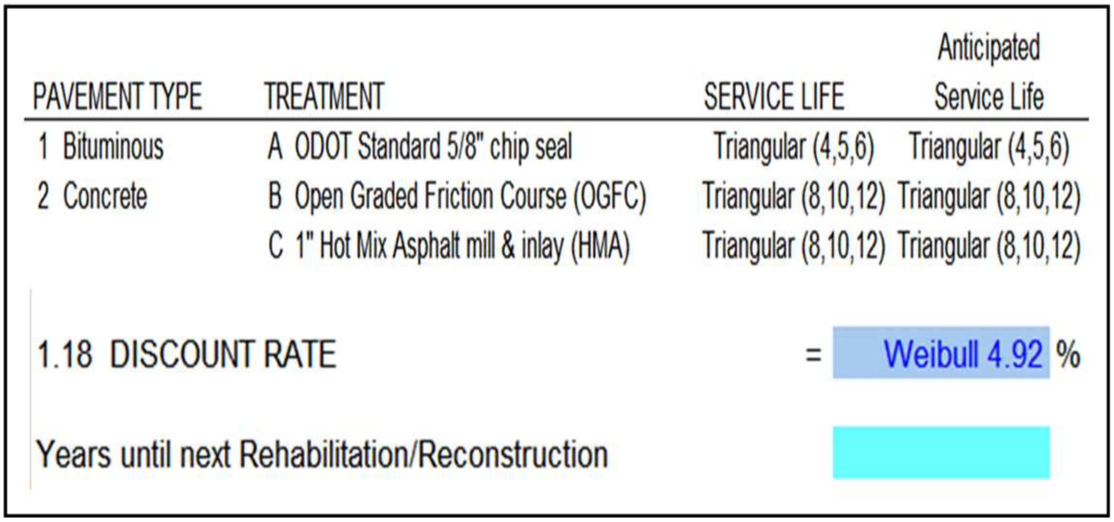
Table 9.1 Treatment Agency Costs Used in EUAC LCCA.

Agency Costs ($ per Square Yard)		
PPT	Deterministic Value	Probabilistic Value Mean (Standard Dev.)
Chip Seal	1.77	1.82 (0.07)
OGFC	3.75	3.88 (0.39)
1” HMA Mill & Inlay	4.00	3.78 (0.49)

Treatment agency costs for deterministic LCCA were found in literature (Stroup-Gardiner and Shatnawi, 2008; FHWA, 2005; Bausano et al. 2004) and ODOT survey (Table 9.1). Activity timing for future maintenance included a three-year frequency for crack seal and 2%-of-total-area patching.

Step 2: Goodness-of-Fit Tests

The second step in the stochastic process is to conduct goodness-of-fit tests for the stochastic parameters determined in the first step. A triangular distribution is a continuous distribution that contains user-defined values for the minimum value, the maximum value and the most likely value for an input variable. It is commonly used for variables that have limited sample data but can be reasonably estimated (FHWA, 1998a), which is the case for service life. In the continuous mode, 4-5-6 years were used for the chip seal service life distribution parameters. 8-10-12 years were used in the OGFC and HMA distributions, consistent with literature and ODOT survey. This common pavement management scenario is illustrated in Figure 9.1.



PAVEMENT TYPE	TREATMENT	SERVICE LIFE	Anticipated Service Life
1 Bituminous	A ODOT Standard 5/8" chip seal	Triangular (4,5,6)	Triangular (4,5,6)
2 Concrete	B Open Graded Friction Course (OGFC)	Triangular (8,10,12)	Triangular (8,10,12)
	C 1" Hot Mix Asphalt mill & inlay (HMA)	Triangular (8,10,12)	Triangular (8,10,12)

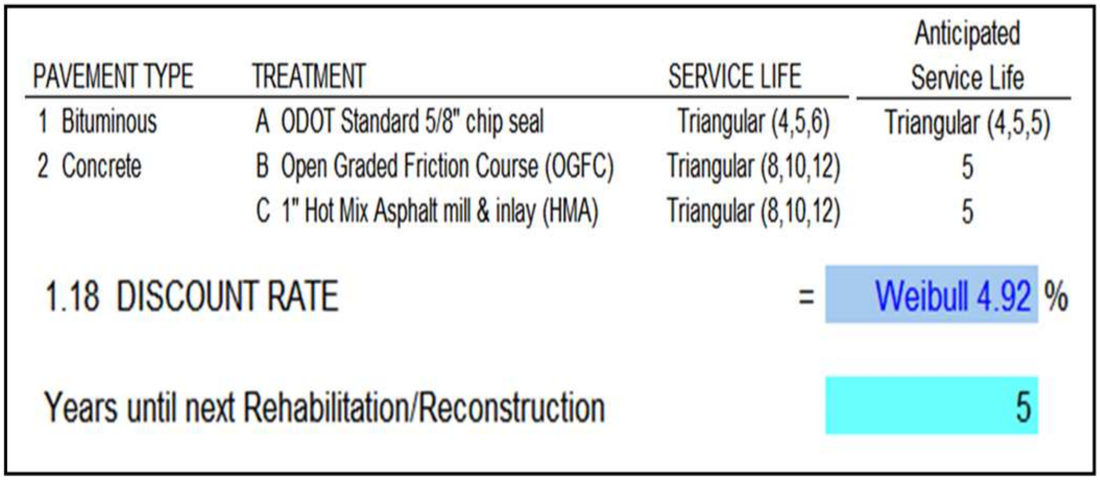
1.18 DISCOUNT RATE = Weibull 4.92 %

Years until next Rehabilitation/Reconstruction

Figure 9.1 Stochastic EUAC Input Screen, Continuous Mode.

In the continuous mode, the "Years until next Rehabilitation/Reconstruction" is unknown, so that field is left blank. Therefore, the service life value is equal to the anticipated service life value. The service life distribution is also noted in the entry screen as a triangular distribution and the low, most likely and high values are noted in parentheses. For more discussion on the mechanics of continuous and terminal modes in the EUAC model, see Chapter 3.

The terminal mode is used when the next rehabilitation or reconstruction year is known. If the next rehabilitation is expected in 5 years, then that value is entered into the "Years until next Rehabilitation/Reconstruction" field, as shown in Figure 9.2.



PAVEMENT TYPE	TREATMENT	SERVICE LIFE	Anticipated Service Life
1 Bituminous	A ODOT Standard 5/8" chip seal	Triangular (4,5,6)	Triangular (4,5,5)
2 Concrete	B Open Graded Friction Course (OGFC)	Triangular (8,10,12)	5
	C 1" Hot Mix Asphalt mill & inlay (HMA)	Triangular (8,10,12)	5

1.18 DISCOUNT RATE = Weibull 4.92 %

Years until next Rehabilitation/Reconstruction 5

Figure 9.2 Stochastic EUAC Input Screen, Terminal Mode.

Based upon the rehabilitation year (RY), the terminal mode automatically truncates the service life values of the alternatives to provide the anticipated service life (ASL). Both the HMA and OGFC service lives are truncated because the low value of their triangular distributions is 8, which is greater than RY, so their EUACs will be figured deterministically with an ASL of 5 years. The chip seal service life will also be truncated at 5 years; however, the 5-year value falls within its distribution, so it will be treated probabilistically. For the triangular distributions, if:

RY $\leq$ SL$_{low}$, then ASL = RY (deterministic);

RY > SL$_{low}$ and RY $\leq$ SL$_{high}$, then ASL = RY as triangular max value (probabilistic);

RY $\geq$ SL$_{high}$, then ASL = SL (probabilistic).

The chip seal's terminal service life distribution will have parameters of 4-5-5, instead of its continuous distribution of 4-5-6, as shown in Figure 9.3.

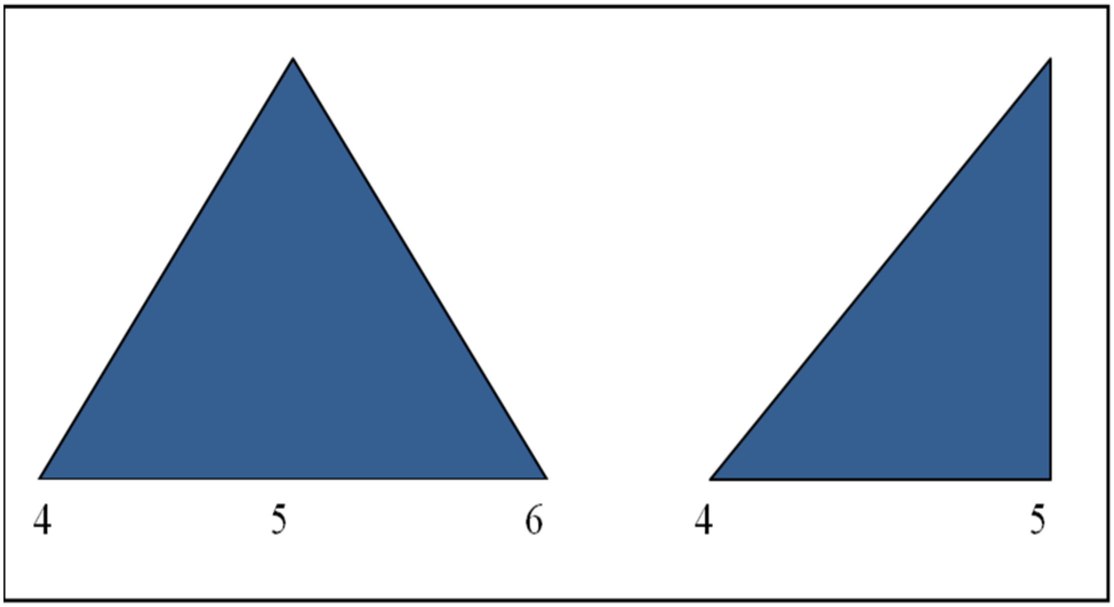


Figure 9.3 Chip Seal Service Life Probability Distributions, Continuous (left) and Terminal (right) Modes.

The future maintenance costs and user costs are deterministic values in the analyses, but are discounted probabilistically so that the discounting period and discount rate are consistent within each iteration. This study used the previous 30 years of discount rate data from the Federal Reserve (2011), best fitted to the Weibull distribution (μ: 4.92, sd: 2.76). Next, initial PPT costs were considered. The best fit for the OGFC bid tabulation data is the normal theoretical distribution, which has a chi-squared (χ^2) value of 5.94, followed by the extreme value distribution ($\chi^2 = 11.71$) (Table 9.2).

Table 9.2 Goodness-of-Fit for PPTs.

Bid Tabulation Data Fit ($/Square Yard)					
PPT	# of Data Points	Distribution Type	Chi-Square Value	Mean	Standard Deviation
Chip Seal	25	Normal	7.60	1.817	0.0704
		Extreme Value	5.20	1.812	0.0799
OGFC	36	Normal	5.94	3.88	0.391
		Extreme Value	11.71	3.88	0.391
1” HMA Mill & Inlay	222	Normal	9.51	3.78	0.49
		Gamma	15.7	3.78	0.49

The extreme value distribution was also the best fit for chip seal, while the gamma distribution best described the HMA data. In all cases, the χ^2 values are minimal, meaning the theoretical distributions closely approximate the data. In addition, the best fit distributions returned the same (similar) means and standard deviations as the normal distributions, consistent with the central limit theorem that states data *normalizes* with increasing number of data points (Montgomery, 2009). Therefore, the EUACs yielded from the normal distribution of bid tabulations is sufficient and will be used in this chapter.

Step 3: Risk Analysis

The third step of stochastic analysis involves risk analysis. The algorithm developed for Monte Carlo simulation is based upon the EUAC equation and is illustrated in Figure 9.4. It incorporates the costs, service life and discounting methods discussed in the previous two steps to produce the sampling distribution that provides the expected EUAC for each alternative being considered.

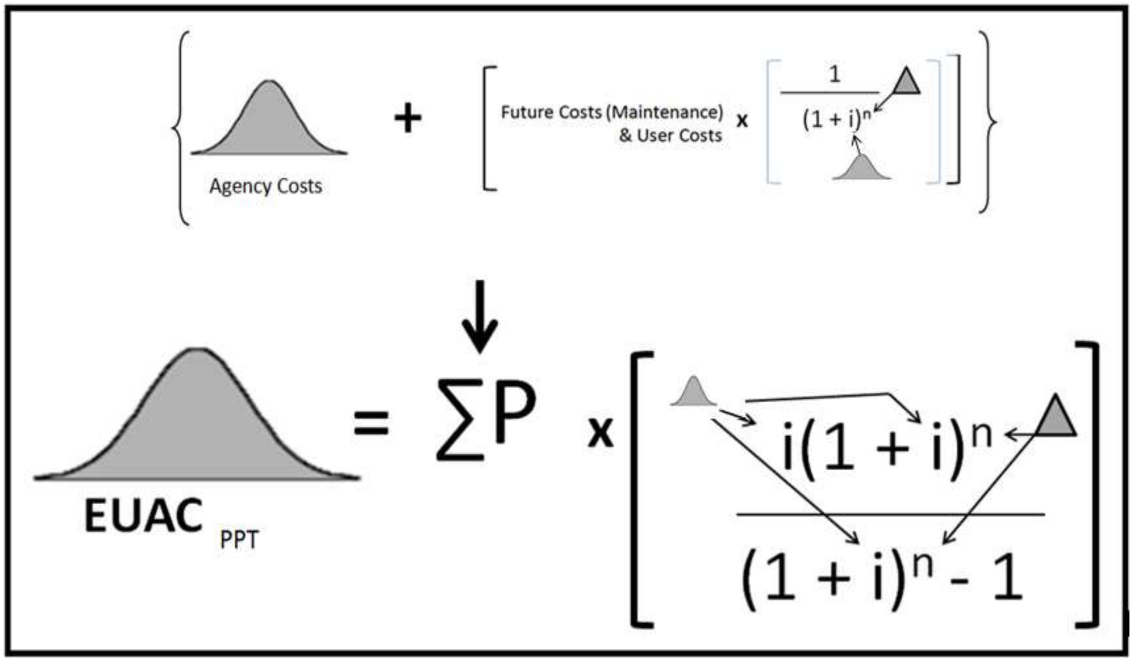


Figure 9.4 Stochastic EUAC LCCA Approach. (Adapted from FHWA, 1998a)

9.3 RESULTS

The model in continuous mode returns EUAC distributions for the three alternatives, as shown in Figure 9.5. The curves show that the chip seal and OGFC have similar variability, which is less than the HMA. Additionally, the chip seal has a lower life cycle cost, as demonstrated by its curve being to the left of the other two alternatives.

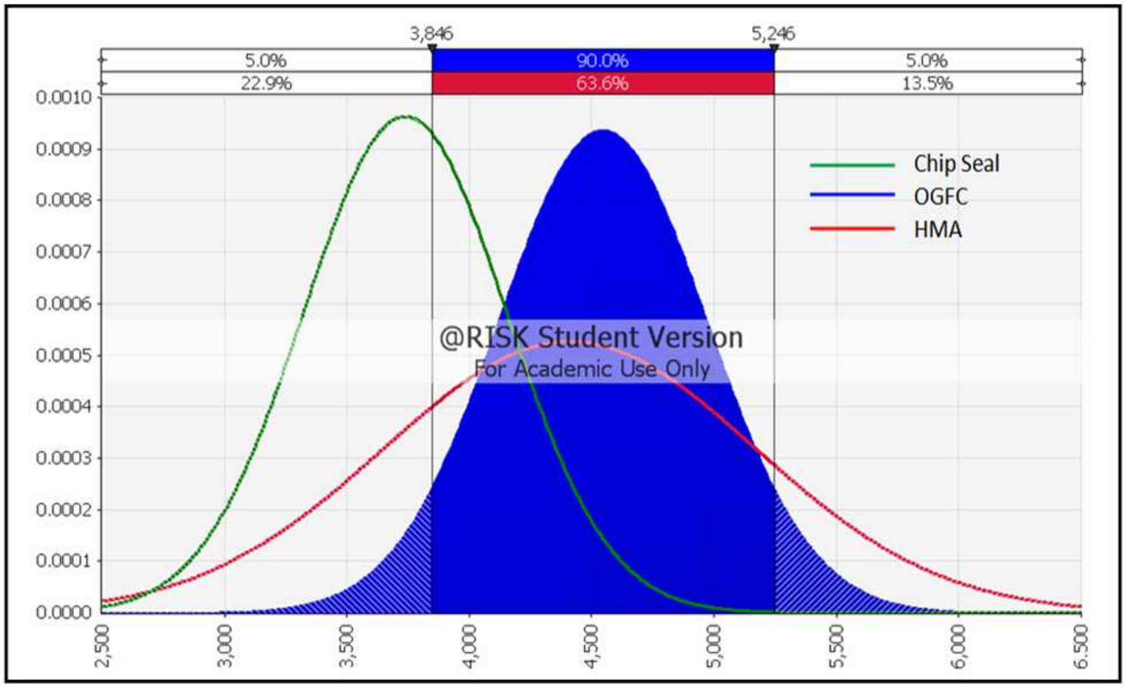


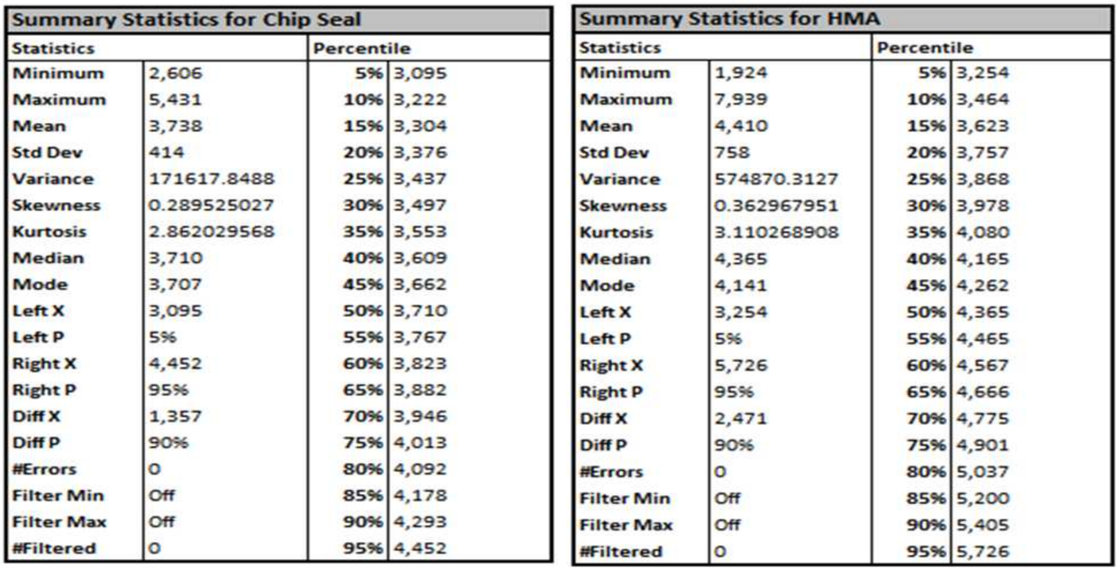
Figure 9.5 PPTs Stochastic EUAC Probability Distributions.

Numeric values associated with these distributions are shown in Table 9.3 and Figure 9.6. Based on these values, it would appear that chip seal would be the most cost effective option in this specific case.

Table 9.3 Stochastic EUAC Results, Continuous Mode.

EUAC ($/lane-mile), Stochastic Method (Continuous Mode)			
	Chip Seal	OGFC	HMA
Mean	3,738	4,546	4,410
Standard Deviation	414	426	758
5th Percentile	3,095	3,856	3,254
95th Percentile	4,452	5,275	5,726

Stochastic analysis offers a wealth of decision-assisting information, such as percentile statistics. Percentiles can provide the pavement manager relative probabilities associated with each pavement treatment alternative being considered. For example, the mean EUAC of HMA ($4,410) falls around the 95th percentile of the chip seal EUAC range, as shown in Figure 9.6. This means that the central tendency, or bulk, of possible HMA EUACs would be higher than the expected chip seal EUAC 95% of the time.



Summary Statistics for Chip Seal			
Statistics		**Percentile**	
Minimum	2,606	5%	3,095
Maximum	5,431	10%	3,222
Mean	3,738	15%	3,304
Std Dev	414	20%	3,376
Variance	171617.8488	25%	3,437
Skewness	0.289525027	30%	3,497
Kurtosis	2.862029568	35%	3,553
Median	3,710	40%	3,609
Mode	3,707	45%	3,662
Left X	3,095	50%	3,710
Left P	5%	55%	3,767
Right X	4,452	60%	3,823
Right P	95%	65%	3,882
Diff X	1,357	70%	3,946
Diff P	90%	75%	4,013
#Errors	0	80%	4,092
Filter Min	Off	85%	4,178
Filter Max	Off	90%	4,293
#Filtered	0	95%	4,452

Summary Statistics for HMA			
Statistics		**Percentile**	
Minimum	1,924	5%	3,254
Maximum	7,939	10%	3,464
Mean	4,410	15%	3,623
Std Dev	758	20%	3,757
Variance	574870.3127	25%	3,868
Skewness	0.362967951	30%	3,978
Kurtosis	3.110268908	35%	4,080
Median	4,365	40%	4,165
Mode	4,141	45%	4,262
Left X	3,254	50%	4,365
Left P	5%	55%	4,465
Right X	5,726	60%	4,567
Right P	95%	65%	4,666
Diff X	2,471	70%	4,775
Diff P	90%	75%	4,901
#Errors	0	80%	5,037
Filter Min	Off	85%	5,200
Filter Max	Off	90%	5,405
#Filtered	0	95%	5,726

Figure 9.6 Summary Statistics for Hot Mix Asphalt EUAC Distribution.

However, the HMA EUAC range does reach the lower end of the chip seal range. The summary statistics reveal that the chip seal mean of $3,738 lies around the 20th percentile of the HMA range, so HMA should be expected to be less than the mean value of chip seal 20% of the time.

For detail about deterministic calculations, see Chapter 4 Methodology and Results sections. The deterministic EUAC values and subsequent rank for HMA, OGFC and chip seal were $4,696 (3), $4,460 (2) and $3,651 (1), respectively. If the pavement manager was only considering the HMA and OGFC options, then the stochastic and deterministic outcomes would be different because the stochastic results show HMA having the lower LCC, based on actual bid tabulations. When considering the deterministic and stochastic HMA values, the stochastic analysis reveals that the

EUAC should not be expected to exceed $4,696 70% of the time, while the chip seal is at 45% probability.

The stochastic approach also offers a comprehensive sensitivity analysis based on regression. The sensitivity analysis reveals that the chip seal is most sensitive to the service life parameter, the OGFC is most sensitive to discount rate and the HMA is most sensitive to the agency cost parameter, as shown in Table 9.4. The pavement manager may take the following into consideration: if chip seal was not expected to realize its' full service life due to traffic conditions, the pavement manager may select the HMA treatment, which is not as sensitive to the parameter. However, if commodity volatility (agency costs) were expected to increase, the chip seal may be the better option because it is less sensitive to the cost parameter than HMA. Although both treatments contain the same volatile commodity (asphalt binder), the sensitivities reflect the different methods of procurement. The HMA agency costs are based upon monthly ODOT bid prices, whereas the chip seal is based upon DCS bid prices that are “locked-in” for some time period. The stochastic analysis offers this type of critical information that the deterministic analysis cannot.

Table 9.4 Stochastic EUAC Sensitivity Analysis.

Sensitivity Analysis									
	Discount Rate			Service Life			Cost		
PPT	Standard Deviation (%)	Regression Coefficient	Net Change in EUAC ($)	Standard Deviation (Years)	Regression Coefficient	Net Change in EUAC ($)	Standard Deviation ($)	Regression Coefficient	Net Change in EUAC ($)
Chip Seal	2.76	0.688	285.21	0.410	-0.657	-272.06	0.07/SY	0.277	114.61
OGFC	2.76	0.808	601.11	0.816	-0.313	-233.14	9.30/ton	0.484	360.30
1” HMA Mill & Inlay	2.76	0.771	584.55	0.816	-0.302	-228.77	8.37/ton	0.558	422.98

The model in terminal mode returns the EUAC distributions as shown in Table 9.5. The OGFC and HMA values are substantially higher than the values returned in the continuous mode (Table 9.3), and the chip seal and HMA EUAC distribution curves do not overlap, except for the extreme (tail) values that have little associated probability.

Table 9.5 Stochastic EUAC Results, Terminal Mode.

EUAC ($/lane-mile), Stochastic Method (Terminal Mode)			
	Chip Seal	OGFC	HMA
Mean	3,962	7,191	7,015
Standard Deviation	362	827	942
5th Percentile	3,399	5,898	5,540
95th Percentile	4,580	8,622	8,627

In the continuous mode example, the decision would require pavement manager judgment, facilitated by percentiles and sensitivity analysis, to justify a decision due to the overlapping EUAC distributions. In the terminal case, the chip seal appears to be the best option.

The stochastic results reveal that the impact of terminal mode on the chip seal probability associated with the $3,651 (deterministic EUAC) dropped from 45% to 20%, meaning the chip seal is 25% more likely to exceed that value. There is a greater than 95% chance that HMA will exceed its deterministic value. This demonstrates the impact of the rehabilitation year on service life and justifies the inclusion of the terminal mode in the EUAC model for upholding engineering economic principles (White et al. 2010). For validation of the stochastic EUAC model, see Chapter 11.

9.4 CONCLUSIONS

Stochastic EUAC for PPTs adheres to engineering economic principles with the inclusion of the continuous and terminal modes. Software can facilitate the risk analysis, making it a practical tool at the implementation level. The stochastic approach can reveal sensitivities that the deterministic model conceals, and is therefore recommended when uncertainty is expected to impact LCCA results to allow pavement managers to understand and mitigate budget risk.

10.0 A COMPARATIVE ANALYSIS OF EUAC LCCA METHODS: A PAVEMENT PRESERVATION TREATMENT CASE STUDY[9]

Pittenger, D.M. and D.D. Gransberg, "A Comparative Analysis of EUAC LCCA Methods: A Pavement Preservation Treatment Case Study," submitted to the *Journal of Construction Management and Economics.*

10.1 PAPER SYNOPSIS

This chapter is the culmination of the main concepts presented in the dissertation. All of the EUAC LCCA methods are compared and demonstrated using pavement preservation field tests. This chapter shows that LCCA results are sensitive to LCCA method selection on all levels as demonstrated through the use of deterministic-based, stochastic-based and performance-based methods. It also demonstrates the value of including performance-based service life input values. It concludes that the pavement manager should consider the LCCA method selection process when evaluating PPTs.

10.2 BACKGROUND AND MOTIVATION

It costs *significantly* more to fix a pavement in poor condition than it does to maintain one in fair condition (Stroup-Gardiner and Shatnawi, 2008; TRIP, 2001; AASHTO, 2001) because it "requires extensive and disruptive work" (FHWA, 1998). The result is "a gradual decline in the number of miles an agency could treat each year and a decrease in the overall condition of the pavement network" (Peshkin, et al. 2004), as well as an increase in the "potential for accidents, injuries and fatalities among the motorists and road workers" (FHWA, 1998).

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[9] The original journal paper has been reformatted to make it consistent with other published chapters in this document.

The implementation of pavement preservation practices is expected to address these challenges (FHWA, 1998). Pavement preservation "is the key to finding the most effective and cost-efficient balance of preserving…highway assets in [today's] environment" (FHWA, 2007a). It aims to "keep good roads good" (Galehouse et al. 2003) specifically to get the "most benefit for the least cost" (FHWA et al. 2008) "as the public and policy makers demand better management of scarce resources in the long run" (Ozbay et al. 2004). The value of pavement preservation lies in its cost effectiveness. "Considering the annual magnitude of highway investments, the potential savings from following a cost-effective approach to meeting an agency's performance objectives for pavements are significant" (Peshkin, et al. 2004), thus, allowing agencies to stretch the budget to address sustainability needs in infrastructure and enhance stewardship.

LCCA is a powerful tool that can be used to demonstrate cost-effectiveness and identify return on investment (FHWA, 2009; FHWA, 1999) to justify pavement preservation. According to various syntheses, there is no consensus on how highway agencies determine the cost-effectiveness of pavement preservation treatment alternatives for a specific project at this time (Bilal et al. 2009; Monsere et al. 2009; Cambridge et al. 2005). "The emphasis upon economic cost analysis principles is recent, so models, methods, and tools to construct and analyze economic tradeoffs are still being developed" (FHWA, 2007a).

Three methods that could be used to assess PPT cost effectiveness include deterministic-based, stochastic-based and performance-based LCCA. Traditionally, deterministic and stochastic methods have been recommended for use at the network-level of transportation and they rely on assumptions for service life input (FHWA, 1998a; FHWA, 2004).

A deterministic-based LCCA is less complex than the stochastic-based LCCA and can be adequate, and therefore appropriate, when uncertainty is not expected to have a material effect on the outcome of the economic analysis (FHWA, 2003). The deterministic-based LCCA accepts only one value (a point estimate) for PPT service life (FHWA, 1998a).

If uncertainty could materially alter the outcome, the stochastic approach is recommended because the deterministic approach cannot effectively analyze simultaneous variability (FHWA, 2003). The stochastic approach can handle all possible service life values; however, service life data is limited (Gransberg et al. 2009; Riegle and Zaniewski, 2002; FHWA, 1998a). A triangular distribution, characterized by its three values of “minimum value”, “most likely value” and “maximum value”, is suggested proper for use when limited data exists but can be reasonably assumed, and is used for service life input (FHWA, 1998a).

The performance-based LCCA is a relatively new concept that can be used to assess PPTs’ *economic efficiency* that derives cost as a function of service life (Pittenger et al. 2011; Bilal et al. 2009; Reigle and Zaniewski, 2002) where the service life value is based upon *actual* performance data rather than assumption. Incorporating performance data into analyses may contribute to determining the optimal preservation timing (Peshkin et al. 2004) so that a pavement manager can install the “right treatment to the right road at the right time” (Galehouse et al. 2003). Data in the form of microtexture and macrotexture is extrapolated to estimate service life duration on the basis of *localized* performance (Pittenger et al. 2011). (For more discussion on performance-based service life input, see Chapters 4 and 7.) The model accepts the performance-based service life value in deterministic form (point estimate) or stochastic form (triangular distribution).

This study presents a comparative analysis of the three types of LCCA methods based upon service life input treatment to determine if LCCA is sensitive to method selection.

10.3 RESEARCH METHODOLOGY

Various LCCA methods were conducted on three PPT field tests for comparison. The field test sections are listed in Chapter 2 and include the 1" inch HMA mill and inlay, the open graded friction course (OGFC) and the 5/8" chip seal. The HMA section was constructed by contract forces using an Oklahoma DOT mix design classification of S4 PG (64-22 OK) which is a standard hot mix asphalt normally used in maintenance applications. The existing surface was milled to a depth of 1 inch and the HMA was then laid in the void. The OGFC was installed by a contractor following the ODOT standard specifications. The ODOT 5/8" chip seal has NMAS of 5/8 inch (16mm) and uses Cationic High Float Rapid Set – 2P for the asphalt emulsion binder.

10.4 RESULTS

Deterministic LCCA vs. Stochastic LCCA

Deterministic and stochastic LCCA results were generated based upon the methodology described in Chapters 4 and 9. The stochastic EUAC LCCA Results are in Chapter 9, Table 9.3. The deterministic LCCA was conducted for three scenarios that a pavement manager might consider: the worst case scenario, the most likely scenario and best case scenario. These scenarios are based on the two most sensitive LCCA parameters: service life and discount rate. The EUAC for each treatment is in Table 10.1.

Table 10.1 Deterministic LCCA Results.

EUAC ($/lane-mile), Deterministic Method with Sensitivity Analysis			
PPT	3% EUAC (Service Life)	4% EUAC (Service Life)	5% EUAC (Service Life)
Chip Seal	$3,019 (6 YR)	$3,651 (5 YR)	$4,557 (4 YR)
OGFC	$3,771 (12 YR)	$4,460 (10 YR)	$5,117 (8 YR)
1” HMA Mill & Inlay	$3,963 (12 YR)	$4,696 (10 YR)	$5,413 (8 YR)

The deterministic and stochastic methods provide different results. The most likely scenario value for chip seal has only 43% probability, whereas the HMA has a 70% probability, as shown in Table 10.2.

Table 10.2 Deterministic and Stochastic EUAC Comparison.

EUAC ($/lane-mile), Deterministic EUAC with Corresponding Probability			
PPT	Deterministic Best Case EUAC (Probability)	Deterministic Most Likely Case EUAC (Probability)	Deterministic Worst Case EUAC (Probability)
Chip Seal	$3,019 (<5%)	$3,651 (43%)	$4,557 (95%)
OGFC	$3,771 (21%)	$4,460 (56%)	$5,117 (82%)
1” HMA Mill & Inlay	$3,963 (28%)	$4,696 (70%)	$5,413 (91%)

The best case scenario EUAC is not a likely case for chip seal and is only expected to occur less than 5% of the time, but the low HMA value should be expected to occur in 1 of 4 projects. However, the worst case chip seal EUAC is still less than the most likely case for HMA, which would provide a pavement manager justification for choosing chip seal on the basis of LCC in this example.

Stochastic LCCA: Deterministic v. Probabilistic Treatment of Service Life

Expected service life values for each of the treatments was determined from extrapolated macrotexture and microtexture data from field trials through linear regression using the same methodology described in Chapter 4 and are shown in Table 10.3.

Table 10.3 Performance-Based Service Life Values for PPT Field Tests.

Performance-Based Service Life Values (in Years)			
PPT	Macrotexture	Microtexture	Triangular
Chip Seal	3 YR	9.1	3-5-9.1
OGFC	>12	>12 YR	10-12-12
1” HMA Mill & Inlay	>12 YR	N/A	10-12-12

The service life parameter was treated deterministically and probabilistically for each of the performance measures for comparative analysis, as noted in Figure 10.1. Probabilistic modeling of service life based upon microtexture and macrotexture measurements was accomplished with the triangular distribution. The third value (5 for chip seal, 10 for OGFC/HMA) is consistent with ODOT expected values.

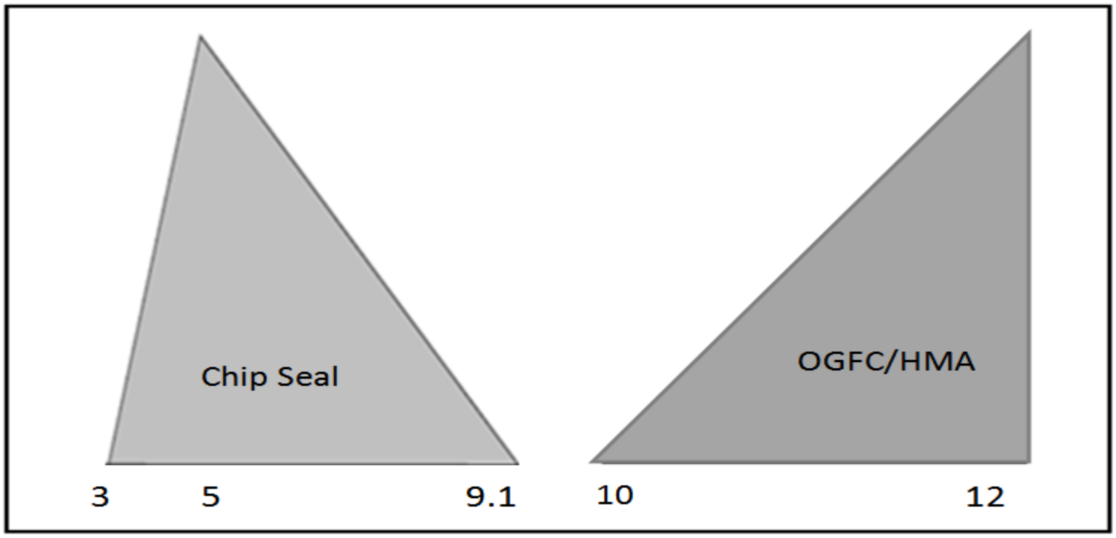


Figure 10.1 Performance-Based Triangular Service Life Distributions.

The Monte Carlo simulation was set to “fixed” mode so that it would run the same iterations run for the stochastic EUAC values in Table 9.3, so that differences can only be attributed to the change in service life treatment.

Table 10.4 Performance-Based Stochastic EUAC Results.

EUAC ($/lane-mile), Stochastic-Method, Performance Based			
	Deterministic		Probabilistic
	µ (SD) (Macrotexture)	µ (SD) (Microtexture)	µ (SD) (Triangular)
Chip Seal	$5,340 (282)	$2,712 (245)	$3,466 (774)
OGFC	$3,904 (688)	$3,904 (688)	$4,105 (710)
1” HMA Mill & Inlay	N/A	$3,839 (706)	$4,009 (727)

Performance-based service life values are listed in Table 10.4, along with corresponding EUACs. The different EUACs demonstrate LCCA sensitivity to deterministic and probabilistic treatment of service life input.

Stochastic LCCA: Empirical vs. Performance-Based Treatment of Probabilistic Service Life

The chip seal stochastic EUAC value based upon the empirical 4-5-6 service life distribution was $3,738 (std. dev: $414), as noted in Table 9.3 in Chapter 9. When compared to the EUAC using the performance-based 3-5-9.1 service life distribution ($3,466, sd: $774; Table 10.4), it is apparent that the LCCA is sensitive to the service life parameter, as noted by the different EUAC values. The performance-based EUAC exhibits greater variability due to the wider range in possible service life values.

Service Life Treatment Method Impact on LCCA

Figure 10.2 shows distributions based upon the four service life assumptions for stochastic analyses listed in Tables 9.3 and 10. 4: (1) 4-5-6 empirical service life, shown by the blue distribution, (2) 3-5-9 performance-based service life, shown by the green distribution, (3) 3-year performance-based (macrotexture) deterministic service life, shown by the purple distribution and (4) 9.1-year per performance-based (microtexture) deterministic service life, shown by the red distribution.

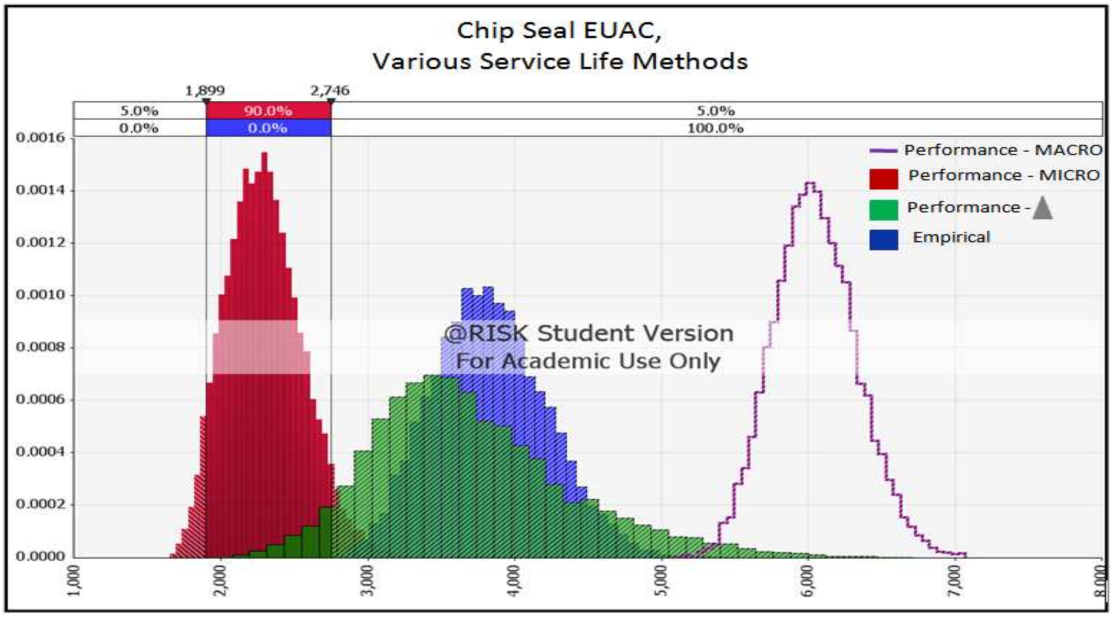


Figure 10.2 Impact of Service Life Method on Chip Seal EUAC.

The deterministic performance methods put the distributions on far ends of the chip seal EUAC spectrum, while the triangular (stochastic) distributions cover the middle portion. Also, the stochastic treatments (green and blue) differ from each other. This illustrates the deterministic-treatment effect, the stochastic-treatment effect and the performance-based treatment effect on the service life input parameter, and subsequently the LCCA output.

LCCA Sensitivity to LCCA Selection Method

Chip seal deterministic EUACs (Table 10.1) and performance-based EUACs (deterministic treatment, Table 10.4) are charted on the empirically-based stochastic EUACs (Table 9.3) cumulative curve for chip seal in Figure 10.3.

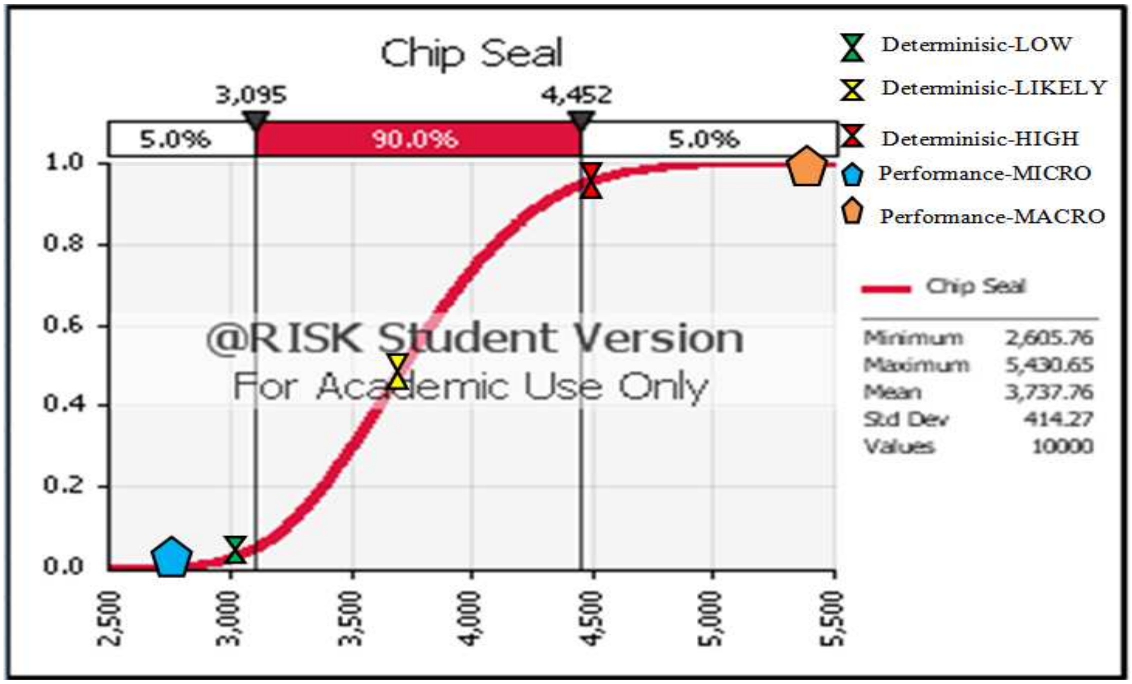


Figure 10.3 Deterministic and Performance-Based Chip Seal EUACs on Stochastic Empirical-Service-Life Cumulative Curve.

Although empirical and performance-based stochastic LCCA both result in chip seal being the preferred alternative (Table 10.5), the performance-based mean EUAC values do not fall within the 90% probability range of the empirical LCCA. This shows that although the ranking is the same and it may be the most cost effective choice, the output is different and empirical LCCA may miss the budgetary mark (Bilal et al. 2010, Reigle and Zaniewski, 2002).

LCCA results in rankings that order alternatives on the basis of cost effectiveness. This study has shown that LCCA results are sensitive to LCCA method, as shown in Table 10.5 by the different rankings based only on LCCA method selection.

Table 10.5 LCCA Sensitivity to LCCA Selection.

<table>
<tr><th colspan="6">EUAC Rankings, Various LCCA Methods</th></tr>
<tr><th rowspan="3"></th><th rowspan="3">Deterministic (TABLE 10.1)</th><th rowspan="3">Stochastic, Empirical (TABLE 9.2)</th><th colspan="3">Performance Based (TABLE 10.4)</th></tr>
<tr><th colspan="2">Deterministic</th><th rowspan="2">Stochastic</th></tr>
<tr><th>MACRO</th><th>MICRO</th></tr>
<tr><td>Chip Seal</td><td>1</td><td>1</td><td>2</td><td>1</td><td>1</td></tr>
<tr><td>OGFC</td><td>2</td><td>3</td><td>1</td><td>3</td><td>3</td></tr>
<tr><td>1” HMA Mill & Inlay</td><td>3</td><td>2</td><td>N/A</td><td>2</td><td>2</td></tr>
<tr><td colspan="6">(1 – Lowest EUAC; 3 – Highest EUAC)</td></tr>
</table>

The analysis reveals that chip seal would be the preferred alternative in all of the LCCA methods except for the deterministic performance-based (macrotexture) LCCA. If only the OGFC and HMA were being considered, it appears that the HMA would be the preferred alternative in all but the deterministic LCCA case. The assumed cost for OGFC is less than HMA, shown by its better deterministic analysis ranking. However, in the rest of the analyses which use actual bid tabulations, the HMA is better positioned, showing the superiority of using stochastic methods. The different rankings for alternatives based upon deterministic-based, stochastic-based and performance-based methods reveal the sensitivity of LCCA to LCCA method selection and demonstrate the need for consideration.

Lastly, the simulation output should not be blindly accepted. The pavement manager should check the output to see if it is reasonable considering the problem at hand. The results provide much statistical information about competing alternatives and should be thoroughly analyzed (FHWA, 1998a).

10.4 CONCLUSIONS

This study showed that LCCA results are sensitive to LCCA methods on all levels, as demonstrated through the use of deterministic-based, stochastic-based and performance-based methods. On the global level, it showed that the deterministic and stochastic LCCA produce different results. On the next level, it showed that even within the stochastic LCCA analysis, deterministic and stochastic treatment of service life produces different results. On the local level, it showed that stochastic treatment of service life based upon empirical and performance-based treatment produced different results. Therefore, the pavement manager should consider the LCCA method selection process when evaluating PPTs so as not to inadvertently skew output results. Stochastic EUAC provides another brick in the justification for pavement preservation.

11.0 RESEARCH VALIDATION

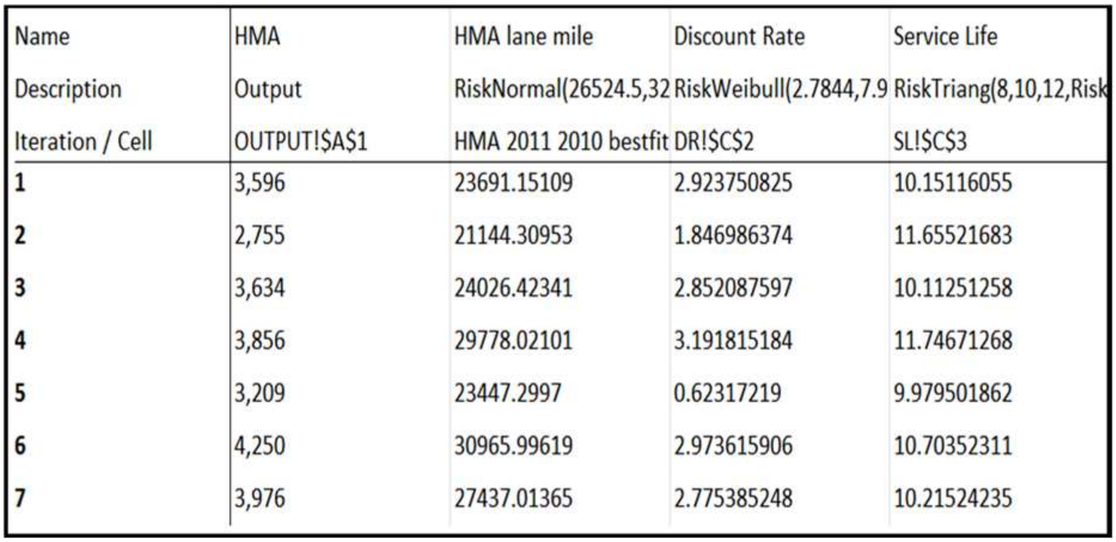
This research was validated internally, externally and through construct. The validation methods are discussed in each of the following sections.

11.1 INTERNAL VALIDITY

The deterministic and probabilistic EUAC models proposed in this research were internally validated in a number of ways (Pallisade, 2011; FHWA, 2001). First, model calculations were manually verified by calculator (Pallisade, 2011; FHWA, 2001). Secondly, the same input values were entered into the FHWA *RealCost* Model and the EUAC models to verify that both yielded the same preferred alternatives. Lastly, the stochastic EUAC model was checked for errors (Pallisade, 2011).

Manual Verification of EUAC Models

For the deterministic EUAC model, output of $4,696 was verified by calculator for the 1” HMA treatment in Chapter 4 using the EUAC equation when the agency and user costs total is $38,092, service life is 10 years and discount rate is 4%. The stochastic EUAC model can be validated using the same method and equation used for the deterministic model validation by selecting iterations of the simulation (Pallisade, 2011; FHWA, 2001), like 1-7 of 10,000 iterations shown in Figure 11.1.

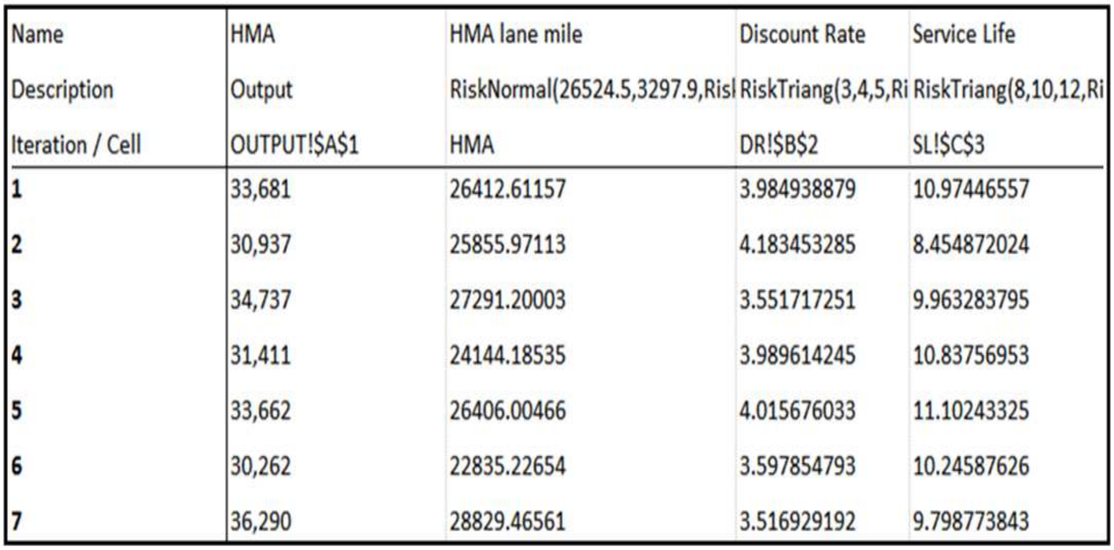


Name	HMA	HMA lane mile	Discount Rate	Service Life
Description	Output	RiskNormal(26524.5,32	RiskWeibull(2.7844,7.9	RiskTriang(8,10,12,Risk
Iteration / Cell	OUTPUT!$A$1	HMA 2011 2010 bestfit	DR!$C$2	SL!$C$3
1	3,596	23691.15109	2.923750825	10.15116055
2	2,755	21144.30953	1.846986374	11.65521683
3	3,634	24026.42341	2.852087597	10.11251258
4	3,856	29778.02101	3.191815184	11.74671268
5	3,209	23447.2997	0.62317219	9.979501862
6	4,250	30965.99619	2.973615906	10.70352311
7	3,976	27437.01365	2.775385248	10.21524235

Figure 11.1 EUAC Simulation Output.

For example, iteration 1 was calculated based upon a 10.15 year service life using a 2.92 value for discount rate and $23,691.15 for agency costs. Future maintenance costs of $3,049 are expected to occur at years 3, 6 and 9, with the discounted values being $2,797, $2,566 and $2,353 respectively. Manually calculating the EUAC based on these values returns the output value listed in iteration 1 (less rounding error), thus, manually validating the stochastic EUAC model.

As stated in Chapter 1, there are no models available for comparing alternatives on the basis of probabilistic EUAC. The only readily-available model is the FHWA *RealCost* Model, so that was used to validate the proposed models output. However, *RealCost* does not provide a probabilistic EUAC for comparison, so the output from the stochastic EUAC model was converted to NPV-form (Figure 11.2) to serve as a basis for the next phase of internal validation found in the next paragraph that compares overall probabilistic results. After the conversion, a few iterations were selected to manually verify the model, as shown in Figure 11.2.



Name	HMA	HMA lane mile	Discount Rate	Service Life
Description	Output	RiskNormal(26524.5,3297.9,Risl	RiskTriang(3,4,5,Ri	RiskTriang(8,10,12,Ri
Iteration / Cell	OUTPUT!$A$1	HMA	DR!$B$2	SL!$C$3
1	33,681	26412.61157	3.984938879	10.97446557
2	30,937	25855.97113	4.183453285	8.454872024
3	34,737	27291.20003	3.551717251	9.963283795
4	31,411	24144.18535	3.989614245	10.83756953
5	33,662	26406.00466	4.015676033	11.10243325
6	30,262	22835.22654	3.597854793	10.24587626
7	36,290	28829.46561	3.516929192	9.798773843

Figure 11.2 EUAC Model Output Converted to NPV-Form.

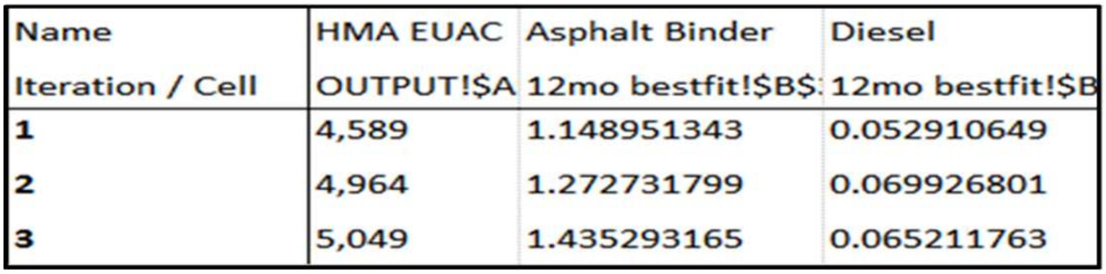
Iteration 1 was calculated with a service life value of 10.97 years. Future maintenance costs are calculated to occur every 3 years, so 3 costs should be calculated given the service life. Using the PV equation to discount future costs (PV = FV * (1/(1+i)^n)), the $3,049 expected to occur at year 3 is $2,711.73 based on the 3.98 discount rate in iteration 1. PV of $3,049 expected at year 6 is $2,411.76, and year 9 is $2,144.98. These future costs are added to the present cost of $26,412.61 to get a NPV of $33,681, verified by the HMA output column. For iteration 2, only include the $3,049 maintenance cost for year 3 ($2,696.26) and year 6 (2,384.32) for the less-than-nine-year service life at a discount rate of 4.18 to get an NPV of 30,937. Convergence occurred at 650 iterations with final error of 1.55%.

EUAC Models Provide Same Rankings

NPV and EUAC (continuous mode) models should return the same ranking (White et al. 2010), which is demonstrated in Chapters 3 and 4 (Figure 3.8, Tables 4.3 and 4.4).

Stochastic EUAC Model Error Check

Lastly, the stochastic EUAC model was checked for errors (Pallisade, 2011). First, the correlation feature was checked for error by verifying that the random values were consistent for the correlated items of asphalt binder (μ=1.25, sd= 0.13; in $/SY) and diesel fuel (μ=0.063, sd=0.008; in $/SY), since both are refinery products and their prices rise and fall together. In Figure 11.3, iteration 1 contains a $1.14 value for asphalt binder pulled on the lower end of its distribution and a $0.05 value for diesel fuel pulled from the low end of its distribution, and so on.



Name	HMA EUAC	Asphalt Binder	Diesel
Iteration / Cell	OUTPUT!$A	12mo bestfit!B	12mo bestfit!$B
1	4,589	1.148951343	0.052910649
2	4,964	1.272731799	0.069926801
3	5,049	1.435293165	0.065211763

Figure 11.3 Correlation Error Check in Stochastic Model.

Next, the simulation setting for initial seed setting was changed from “choose randomly” to “fixed” so that the simulation would run the same iterations and produce the exact same output (Pallisade, 2011). If the model in the “fixed” setting returns different output with each new simulation, this is an indication of model error. The stochastic EUAC model returned same results for two different simulations and it was concluded that the model was free from simulation error.

11.2 EXTERNAL VALIDITY

The following study was used to externally validate the EUAC PPT LCCA deterministic and stochastic models: “Evaluate TxDOT Chip Seal Binder Performance Using Pavement Management Information System and Field Measurement Data San

Antonio District," (Gransberg, 2008; Gransberg, 2007). Twelve Farm-to-Market roads in the TxDOT San Antonio district served as test sections and were comprised of six hot applied and six emulsion chip seals sections. Macrotexture measurements using the Transit New Zealand (TNZ) T/3 Sand Circle test described in Chapters 2 and 6 were gathered over a three-year period commencing in 2005. Treatment costs were also gathered for comparing the two chip seal types: \$0.92/SY (average) for the hot applied and \$0.82/SY for the emulsion. The study found that the emulsion chip seal was more cost effective than the hot applied chip seals for the test section roads on a cost-index basis.

To validate the EUAC PPT models proposed in this research, the macrotexture and cost data resulting from the test sections were processed using the same methodology described in Chapter 4. LCCA calculations were made via EUAC models to determine if the research models yielded the same preferred alternative reported in the study.

The methodology for developing deterioration models to approximate service life based upon MTD values is described in Chapter 4. MTD values were interpolated between the months in which measurements were taken (Table 11.1), then extrapolated beyond December 2007 to estimate service life. The hot applied chip seals (R^2= 0.8936) were only expected to have 75% of the service life expected of the emulsion chip seal (R^2=0.8521), which were 3 and 4 years, respectively. Because the emulsion chip seal has the longer service life and lower initial cost, the models should result in the emulsion having the lower LCC, consistent with the study.

Table 11.1 Average MTD values for test sections.

Average MTD for Chip Seal Sections (mm)		
Testing Date	Emulsion	Hot Applied
June 2005	3.35	3.36
August 2005	3.12	2.91
December 2005	3.46	2.97
March 2006	3.14	2.84
May 2006	2.79	2.16
July 2006	2.41	1.69
November 2006	2.27	1.61
February 2007	2.26	1.55
May 2007	2.17	1.49
September 2007	1.98	1.45
December 2007	1.90	1.36

The service life value for each alternative was entered into the probabilistic model as a deterministic value to produce consistent results for the purpose of validating the model. The San Antonio cost data was entered, keeping the means consistent with the average values provided by the study. Table 11.2 shows that the output from both deterministic and stochastic EUAC models was similar, and both show the same preferred alternative of emulsion chip seal on the basis of LCC, externally validating both models.

Table 11.2 External Validation Model Results.

Model EUAC ($/lane-mile)		
PPT	Deterministic	Probabilistic μ, (SD)
Emulsion Chip Seal	1,590	1,589 (39)
Hot Applied Chip Seal	2,334	2,337 (42)

11.3 CONSTRUCT VALIDITY

Assertions made by this research are supported by literature, as listed. Main assertions are listed with corresponding citations in Table 11.3.

Table 11.3 Construct Validity.

Research Assertion #	Assertion	Literature Citation
1	Stochastic LCCA does produce a different result than deterministic LCCA	(Pallisade,2011) (Gransberg and Kelly,2008) (Tighe, 2001) (FHWA, 1998a)
2	Pavement preservation requires economic analysis for demonstration of return on investment due to its' proactive nature	(Peshkin et al. 2004) (Galehouse et al. 2003)
3	NPV LCCA methods are not consistent with the level of PPT investment due to associated complexity and training requirements and therefore, they are not commonly used	(FHWA 2009, 2007, 2005, 2003, 1999) (Bilal et al. 2009) (Hall et al. 2009) (Monsere et al. 2009) (Reigle and Zaniewski, 2002)
4	LCCA demand is growing and SHAs are currently looking for LCCA tools to assess cost effectiveness of implementation-level projects and currently, no common tools exist	(Bilal et al. 2009) (Hall et al. 2009) (Monsere et al. 2009) (FHWA, 2007) Ozbay et al. 2004)
5	LCCA based upon EUAC is appropriate for PPT evaluation because of the short, unequal service lives	(Gransberg and Scheepbouwer, 2010) (Bilal et al. 2009) (Sinha and Labi, 2007)
6	Deterministic and stochastic LCCA can be appropriately and practically applied to PPT evaluations, based upon level of uncertainty and easily facilitated by software	(FHWA 2004, 1998a)
7	EUAC algorithms are based upon engineering economic equations	(White et al. 2010) (Lomax, 2007)
8	EUAC methodology is based upon standard transportation LCCA "Good Practices"	(FHWA 2001, 1998a)
9	EUAC does not arbitrarily truncate service life	(Lee, 2002)
10	The continuous and terminal modes in the EUAC model are required to uphold engineering economic principles	(White et al. 2010) (Lee, 2002)
11	EUAC continuous mode is required to reflect the continuous nature of a pavement segment, although the pavement treatment is finite	(Lee, 2002)
12	EUAC LCCA can produce the same rankings (preferred alternative) as NPV LCCA	(White et al. 2010) (FHWA, 1998a)
13	Residual value/salvage value is not appropriate (unless reasonably quantified) in LCCA and user cost inclusion is appropriate	(Gransberg and Scheepbouwer, 2010) (Bilal et al. 2009) (Lee, 2002)
14	Stochastic EUAC LCCA should use *goodness-of-fit* tests, check the normality assumption (central limit theorem) and can use	(Tighe, 2001) (FHWA, 1998a)

	the triangular distribution for service life and discount rate	
15	LCCA does not provide *the answer*	(FHWA, 1998a) (Clemen, 1996)
16	Underlying commodity volatility can be modeled and incorporated in stochastic EUAC LCCA	(Wang et al. 2009) (Gransberg and Kelly, 2008)
17	Pavement treatment performance can be modeled and serve as service life input in economic analysis	(Bilal et al. 2009) (Reigle and Zaniewski, 2002)
18	Pavement preservation and conducting LCCA are activities that promote sustainability	(Muench et al. 2010) (Galehouse et al. 2003) (FHWA, 1998a)
19	LCCA methods must be determined by each state based on complexity, local data availability and needs	(Hall et al. 2003) (Peshkin et al. 2004)
20	LCCA results should be coupled with treatment effectiveness to assess *economic efficiency*	(Bilal et al, 2009) (Reigle and Zaniewski, 2002)
21	LCCA should be adapted to the specific investment scenario at hand instead of employing a rule-of-thumb analysis period selection method, such as the FHWA's suggested standard 35-40 year period	(White et al. 2010) (FHWA, 1998a)
22	LCCA should be used for decision support and enhanced stewardship	(FHWA, 2001)

12.0 CONCLUSIONS AND RECOMMENDATIONS

12.1 GENERAL

LCCA can be correlated with engineering field data to assist Oklahoma Department of Transportation (ODOT) pavement managers in determining the “right treatment” component of the “right treatment for the right road at the right time” pavement preservation strategy and increase the effectiveness of budget expenditure resulting in decision making validation and justification and enhanced stewardship.

However, there is no standard process for state transportation agencies to determine the cost effectiveness of PPT alternatives, although it is widely accepted that incorporating the process into agency decision-making processes can enhance sustainability in infrastructure management. LCCA application to implementation-level pavement treatment projects was rarely found and not demonstrated in the literature and is still being developed to address inherent complexity issues (Gransberg and Scheepbouwer, 2010; FHWA 2009, 2007, 2005, 2003, 1999). This research addressed this issue.

Based on the research assertions listed in Chapter 11, the EUAC method was found to be the most efficient method to determine the cost effectiveness of treatment alternatives. Specific pavement-preservation LCCA adaptability issues were addressed, and subsequently the research contribution made, by building LCCA asphalt and concrete models based on stochastic and deterministic methods. EUAC makes the process less complex, more consistent with investment level, more efficient and provides relevant decision-making information for the pavement manager applicable to the short term window of pavement treatment operations based on treatment-relevant input.

The EUAC models address the limited scenarios the pavement manager faces at the pavement-treatment-implementation level: the year of the next rehabilitation or reconstruction is either expected or it is not. The models are “fixed” with corresponding continuous and termination features, reducing the negative impact associated with standard new pavement LCCA complexities and possibility of faulty output associated with analysis period selection application error while still ensuring compliance with engineering economic principles verified by rankings equivalent to those produced by the present value method. The continuous feature disallows the unnecessary truncating of service lives while the “automatic truncate” termination feature is built in to ensure adherence to engineering economic principles when the next expected rehabilitation/reconstruction is expected to encroach one or more service lives of evaluated alternatives. The intent of using EUAC as the basis of the model was to address the various scenarios a pavement manager faces with its “covert” flexibility, while maintaining its efficient, “overt” inflexibility with regard to disallowing the adjust-to-fit mechanisms, whereby reducing the well-cited complexities and sensitivity factors associated with analysis period selection on a non-treatment-relevant basis. This is believed to be appropriate due to the short-term nature of the implementation level decision-making, as well as the likelihood of “do nothing” occurrences.

Sensitivity in treatment-relevant parameter values, such as service life and pavement extension, is exposed and presented. These treatment-relevant input values allow the pavement manager to intuitively analyze the LCCA results because they are factors within the realm of the pavement manager’s expertise, rather than suppressed in a possibly arbitrary analysis period selection requiring engineering economic understanding to extricate. Additionally, the use of microtexture and macrotexture deterioration models provide local pavement condition data that correlate with service life and pavement extension input values and allow the extent of variability in these parameters to be exposed, contributing to the credibility and justification of results. Using field data derived deterioration curves and performance-based failure criteria provides a more accurate result than the empirical values for service life in use for the current FHWA-approved LCCA process.

The deterministic sensitivity analysis tool, coupled with deterioration models, can yield information that would satisfy “What if” scenarios pertinent to pavement managers. However, a deterministic approach may obscure risk associated with pavement treatment selection and inhibit a state highway agency’s (SHA) ability to mitigate budget risk and is only appropriate when uncertainty is not expected to materially affect the outcome of the economic analysis. When uncertainty is expected, stochastic LCCA is recommended. This gives the pavement manager the enhanced ability to truly identify, then justify, the most cost-effective pavement treatment for a given project.

Maintenance funding is authorized on an annual basis making comparing alternatives on an annual cost basis more closely fit the funding model than using NPV which would assume availability of funds across the treatment’s entire service life. Since pavement managers typically consider several alternatives with varying services lives based on available funding rather than technical superiority, the FHWA LCCA method based on NPV creates more problems than it solves.

Because EUAC is an acceptable and suggested economic analysis method, as long as its applicability and appropriateness is thoroughly investigated (White et al, 2010), and because of its efficiency in the pavement-treatment decision-making case at this level of investment, it was selected as the appropriate method. EUAC LCCA results combined with professional judgment and other factors, the pavement manager can make sound economic and justifiable decisions regarding pavement treatment selection.

12.2 CONCLUSIONS

Transportation agencies are charged with stewardship and therefore must provide justification for decision-making and its inherent uncertainties. Stochastic LCCA enhances a pavement manager’s ability to justify decisions. Although the stochastic approach is more computationally complex than the deterministic approach, software is currently available that makes its application practical. Input value probability, as well as simultaneous variability of all input values, is analyzed based on the full range of “what if” scenarios, via Monte Carlo simulation. Software can conduct these simulations that provide a plethora of decision-making statistical information within seconds, making stochastic EUAC practical at the PPT level. Other findings include:

<u>Conclusion 1:</u> *Hypothesis 1* supported: Probabilistic LCCA did produce a different result than deterministic LCCA for PPT evaluation.

Conclusion 2: *Hypothesis 2* supported: Construction cost volatility did have a material effect on PPT LCCA.

Conclusion 3: *Hypothesis 3* supported: Probabilistic models did expose sensitivities to input values concealed in deterministic models.

Conclusion 4: *Hypothesis 4* supported: FHWA-recommended probabilistic methods could be adapted to EUAC PPT.

Conclusion 5: EUAC LCCA can evaluate PPTs on the basis of cost effectiveness.

Conclusion 6: EUAC LCCA is better for use at implementation-level than NPV because it accommodates the short and differing service lives of pavement treatment alternatives.

Conclusion 7: EUAC LCCA eliminates the problematic AP and indifferent service life issues associated with NPV and therefore eliminates the need for extensive economist-level training or expensive LCCA outsourcing.

Conclusion 8: Continuous and terminal features can be added to a EUAC model for engineering economic principle adherence.

Conclusion 9: Underlying commodity volatility can be modeled and incorporated in stochastic EUAC LCCA for PPT.

Conclusion 10: Pavement treatment performance can be modeled and serve as LCCA service life input for performance-based analyses, which provides superior results over empirical methods.

Conclusion 11: LCCA can be coupled with other sustainability metrics to assess the sustainability of PPTs.

Conclusion 12: Economic and engineering technical data gathered from pavement preservation field trials can be quantified and correlated to produce meaningful, standardized economic and LCCA information that furnishes pavement managers measurable failure criteria to estimate extended service lives of Oklahoma pavements.

Conclusion 13: PPT EUAC LCCA is intuitive because it uses pavement-manager relevant input values, such as service life for the analysis period.

Conclusion 14: PPT EUAC LCCA provides output in EUAC form, consistent with annual budgets.

Conclusion 15: Sensitivity analysis, coupled with deterioration model information, can enhance the PPT decision-making process by providing insight to the most cost effective alternative.

Conclusion 16: PPT EUAC LCCA can enhance stewardship and support pavement preservation through cost effectiveness assessments.

Conclusion 17: Deterministic EUAC can provide comparable results to stochastic EUAC when volatility does not have a material impact on outcome and is appropriate for use.

Conclusion 18: Stochastic EUAC is appropriate when uncertainty/volatility impacts results.

Conclusion 19: EUAC LCCA is consistent with PPT level of investment.

Conclusion 20: FHWA LCCA “Good Practices” can be used as the basis for the EUAC LCCA methodology.

Conclusion 21: LCCA is sensitive to LCCA methods on all levels as demonstrated with the deterministic-based, stochastic-based and performance-based methods.

Conclusion 22: LCCA is sensitive to deterministic and stochastic treatment of service life.

Conclusion 23: Stochastic LCCA is sensitive to empirical and performance-based treatment of service life in stochastic LCCA.

Conclusion 24: The pavement manager should consider LCCA method selection process when evaluating PPTs so as not to inadvertently skew output results.

Conclusion 25: Stochastic EUAC provides another brick for the justification of pavement preservation.

12.3 LIMITATIONS

The objective of the research was to develop LCC and deterioration models and methodologies. The findings were derived from specific PPT field test sections located on Highway 77 in Norman, Oklahoma that were subject to the same market, traffic and environmental conditions. Therefore, a major limitation of this research is that the findings cannot be generalized because they apply only to the traffic, environment, and climatic conditions found in the Oklahoma City region. Researchers and pavement managers can replicate this project's methodology but must collect their own data for cost and performance-measurement models that reflect local conditions.

The second major limitation can be best expressed as: LCCA output is very sensitive to LCCA input. This research focused primarily on the analysis period/service life LCCA input parameters. Hence, a major limitation of this research involves the other LCCA input parameters that contribute sensitivity to the analysis, such as discount rate, user costs and salvage/residual values. Discount rate treatment is a contentious LCCA issue (Gransberg and Scheepbouwer, 2010; Hall et al. 2009) and research has shown that discount rate selection can dictate project selection (Corotis and Gransberg, 2005). The FHWA suggests a deterministic treatment of the discount rate, while research has shown that probabilistic treatment may be more appropriate (FHWA, 2009). There is also debate about whether or not a social discount rate should be included in analyses (Corotis and Gransberg, 2005). Both user costs and salvage/residual values are difficult to quantify for the purposes of input value determination and there is debate on how to do so (Hall et al. 2009; Lee, 2002). This research made no attempt to reconcile these issues.

Another limitation is that LCCA does not calculate a single best solution for a given project; it merely *provides an indication of cost effectiveness*. LCCA output is only one component of the larger PPT decision framework that includes other decision-support factors, such as “risk, available budgets, and political and environmental concerns” (FHWA, 2001).

12.4 RECOMMENDATIONS

The recommendations for future research are based on the findings of this research project and include the following:

- There are limited performance measures that are globally applied to all PPTs (Chapters 2 and 6). PPT-specific performance measures with associated failure criteria need to be developed to furnish metrics that describe treatment performance. Doing so would provide better data for deterioration models/LCCA service life input. Deterioration models could then be developed that are applicable to specific AASHTO climatic regions as well as for urban versus rural traffic.

- The issue of determining an appropriate discount rate for pavement LCCA critically needs to be addressed. Various LCCA discount rate methodologies have been researched (Gransberg and Scheepbouwer, 2010; Corotis and Gransberg, 2005) but no definitive guidance is currently available. Commodity specific discount rates seem a logical candidate for pavement alternative analysis and deserve to be thoroughly investigated for inclusion in LCCA.
- Methodologies for quantifying [PPT] environmental impact are being disseminated, commonly referred to as life cycle inventory (LCI), and are based upon measurements of emissions, raw material usage, etc. (Galehouse and Chehovits, 2010; Muench et al. 2010; CH2M HILL and Good Company, 2009). An LCCA model that incorporates LCI could provide more insight about PPT sustainability.

12.5 CONTRIBUTIONS

This research made two significant contributions to the body of knowledge in pavement economics. No significant research has previously been done to quantify the actual service lives of PPTs and furnish a model for the LCCA of those treatments, which would contribute to the justification of pavement preservation. This research fills those two gaps. First, a methodology for estimating LCCA service life based upon PPT performance, instead of the current use of service-life assumptions, was developed and demonstrated with superior results. Second, an LCCA model with deterministic and stochastic capability was created for PPTs and demonstrated that EUAC is more appropriate for PPT evaluation than NPV because of the short and differing service lives.

Other contributions include a PPT LCCA model that is applicable to both concrete and asphalt pavements in highway and airport applications. Specific EUAC algorithms were developed for deterministic LCCA, stochastic LCCA, commodity-based LCCA and performance-based LCCA. Continuous and terminal LCCA modes were developed. A performance-based sensitivity analysis methodology for deterministic LCCA was developed. A methodology was created for assessing PPT sustainability.

The EUAC LCCA model eliminates some of the theoretical issues associated with the current FHWA method and specifically addresses the short-term nature of pavement preservation treatments. This finding was validated by Tashia Clemons, the FHWA Planning Program Manager, who expressed the value of including the methodology into the current FHWA LCCA methodology after attending a presentation by the author on the EUAC methodology completed in this research. The model accommodates the pavement management programming process for rehabilitation or reconstruction by furnishing a rigorous methodology to rationally truncate service lives, a concept not covered by the current FHWA LCCA procedure. Representatives of the asphalt and concrete industry (National Asphalt Pavement Association and American Concrete Pavement Association), an industry where LCCA has always been a contentious issue, have also been in direct contact with the author about the EUAC model proposed in this research.

Additionally, SHA representatives have expressed interest in the research because it fills a gap in the body of knowledge that provides PPT justification on the basis of cost, as a function of performance. The use of microtexture and macrotexture deterioration models provide local pavement condition data that correlate with service life and pavement life extension input values for LCCA and allow the extent of variability in these parameters to be exposed via sensitivity analysis and thereby enhances the credibility of results. These pavement-manager relevant input values allow for intuitive analysis of the LCCA results. Additionally, the EUAC model specifically addresses the relatively short term nature of pavement preservation treatments, allowing the manager to better relate treatment LCCA output to annual maintenance budgets and determine the most cost effective PPT for a given project. Thus, the work contained herein can be used to justify installing a PPT that is marginally more expensive on a basis of either increased service life or lower LCC.

Lastly, the performance-based elements of the research have generated interest and future research funding from the PPT industry, specifically from suppliers and manufacturers, who are interested in how their products “stack up” to the competitors’ products on a performance-cost basis. This research has shown that PPT performance can be quantified and correlated with cost data to provide a “bang for the buck” analysis.

Economic and engineering technical data gathered from pavement preservation field trials can be quantified and correlated to produce meaningful, standardized economic and life cycle cost analysis information that furnishes pavement managers measurable failure criteria to estimate extended service lives of the nation’s pavements. This research contributes a performance-cost tool/methodology that can assist the pavement manager in effectively allocating limited resources and provides the vital return on investment information needed to justify the pavement preservation philosophy and enhance the safety and accessibility of the nation’s road network.

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