DEVELOPMENT OF A LIFE-CYCLE ASSESSMENT TOOL FOR PAVEMENT PRESERVATION AND MAINTENANCE ON FLEXIBLE AND RIGID PAVEMENT

FINAL PROJECT REPORT VOLUME I

by

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16. Abstract

A complete LCA methodology was developed to quantify sustainability impacts of preservation activities for asphalt and concrete surfaced pavements. The LCA models and methodology was implemented in a software tool to support making project-level decisions in between various preservation and rehabilitation activities. The key components of the development include the inventory analysis used in the LCA calculations, treatment lifetime models and decision trees for preservation treatment selection. A nationwide survey was conducted through questionnaires. Questionnaires were designed specifically to target collecting data to build lifetime models in addition to agency experiences and practices. Decision trees were developed to guide decision makers to select from various preservation and rehabilitation options for a given existing pavement condition and traffic information. Data for the LCA also included that available in the literature or other publicly and commercially available databases to determine the LCA impacts of different preservation and maintenance schedules. The LCA scope includes materials, construction, maintenance and rehabilitation, and use stages. The inventory analysis was performed on data applicable to all regions in the United States.

A tool was developed with a user-friendly interface using pay items as the building block for the ease of future implementation. The tool was intended for the engineers in state and local agencies, practitioners in the industry, and contractors. A sustainability analysis is presented to compare individual treatments or a schedule of treatments.

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List of Abbreviations

ICT: Illinois Center for Transportation
IDOT: Illinois Department of Transportation
MSU: Michigan State University
UIUC: University of Illinois at Urbana-Champaign
WSDOT: Washington State Department of Transportation

Table of Abbreviations

AADT	Annual average daily traffic
AC	Asphalt concrete
AHP	Analytical hierarchy process
ASTM	American Society for Testing and Materials
BCOAP	Bonded concrete overlay for asphalt pavement
CIR	Cold-in-place recycling
CRCP	Continuous reinforced concrete pavement
DBR	Dowel-bar retrofitting
EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
GHGs	Greenhouse gases
GWP	Global warming potential
HIR	Hot-in-place recycling
IRI	International Roughness Index
ISO	International Organization for Standardization
JPCP	Jointed plain concrete pavement
JRCP	Jointed reinforced concrete pavement
LCA	Life-cycle assessment
LTE	Load transfer efficiency
MOVES	Motor vehicle emission simulator
NERC	North American Electricity Reliability Corporation
NIST	National Institute of Standards and Technology
PADD	Petroleum Administration for Defense Districts
PCA	Portland Cement Association
PCC	Portland cement concrete
PCI	Pavement condition index
PED	Primary energy demand
PPMS	Pavement preservation and maintenance schedules
PSAT	Preservation sustainability assessment tool
RAP	Reclaimed asphalt pavement
RCA	Recycled concrete aggregate
RSI	Roughness speed impact
SS	Single score
STAs	State Transportation Agencies
TRACI	Tool for the Reduction and Assessment of Chemical and other environmental Impacts
UTBWC	Ultra-thin bonded wearing course
UTW	Ultra-thin white topping
VBA	Visual Basic for Applications
VIT	Variable-impact transportation

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Executive Summary

Diminishing funds for transportation infrastructure projects encouraged agencies to develop and implement cost-effective preservation and rehabilitation treatments to maintain pavement serviceability while reducing the backlog in pavement network of agencies. The major philosophy of preservation suggests a long-term and cost-effective program applied at the project-level with a network wide strategic programming. Pavement preservation has recently gained wide acceptance amongst the highway agencies because of its cost effectiveness and ability to enhance pavement performance. In addition, preservation treatments can provide additional benefits in terms of reducing environmental impact of pavements. Therefore, development of a preservation program and selecting preservation treatment for a given project require consideration of the cost, performance, and environmental impact.

A LCA methodology was developed to quantify sustainability impacts of preservation activities and scheduled program of activities for asphalt and concrete surfaced pavements. The LCA models and methodology were implemented in a tool to support making project-level decisions between various preservation and rehabilitation activities and build a long-term preservation schedule. The key components of the development are the inventory analysis used in the LCA calculations, treatment lifetime models and decision trees for preservation treatment selection. A nationwide survey was conducted using questionnaires. Questionnaires were designed specifically to target collecting data to build lifetime models in addition to agency experiences and practices. Decision trees were developed to guide decision makers to select from various preservation and rehabilitation options for a given existing pavement condition and traffic information. Pay items were developed for each treatment considered and used as the building block of LCA calculations. Data collected to perform LCA from available literature and other publicly and commercially available databases to determine the LCA impacts of different preservation and maintenance schedules. The life-cycle stages considered include materials, construction, maintenance and rehabilitation, and use stages. Use-stage models were developed to calculate impact of rolling resistance and heat island.

The tool based on Microsoft Excel's Visual Basic for Applications (VBA) platform was developed with user-friendly interfaces. The tool was intended for the engineers in state and local agencies, practitioners in the industry, and contractors. A sustainability analysis is presented to compare individual treatments or a schedule of treatments for asphalt and concrete surfaced pavements.

CHAPTER 1. INTRODUCTION

There is a need for developing a generalized methodology to compare environmental impacts of various pavement preservation and maintenance schedules (PPMS), including preventive and routine maintenance as well as minor rehabilitation techniques. Many factors possibly affecting environmental impact results were taken into consideration, including treatment application timing, selection, and performance. The research approach is based on life-cycle Assessment (LCA) concept. Organizational structure of this report includes LCA methodologies, analysis tools, and case studies. This project is conducted by the Illinois Center for Transportation (ICT) of the University of Illinois at Urbana-Champaign (UIUC) and Michigan State University (MSU) research teams.

1.1 MOTIVATION

Cost-effective preservation techniques are critical to enhance pavement performance and to extend its service life amid cost increases in pavement construction and shrinking infrastructure project budgets. According to the Federal Highway Administration (FHWA) Office of Asset Management, guidance regarding pavement preservation is issued as follows (Gierger, 2005):

> Pavement preservation represents a proactive approach in maintaining our existing highways. It enables State Transportation Agencies (STAs) to reduce costly, time consuming rehabilitation and reconstruction projects and the associated traffic disruptions. With timely preservation, we can provide the traveling public with improved safety and mobility, reduced congestion, and smoother, longer lasting pavements. This is the true goal of pavement preservation, a goal in which the FHWA, through its partnership with the States, local agencies, industry organizations, and other interested stakeholders, is committed to achieve.

A successful preservation application is to apply the right treatment to the right road at the right time.

In 1997, Hicks et al. started a study which provided examples of decision tree and matrix-based methods to select appropriate preservation treatments for flexible pavement. Peshkin et al. (2004) tried to determine optimal timing of preventive treatment by considering various pavement condition indicators and associated costs. Condition indicators included the international roughness index (IRI), cracking, and rutting. At the same time, each condition indicator was also used to predict the treatment service life.

In another study by Peshkin et al. (2011), researchers specified the preservation treatment selection procedure for high-volume traffic roads. The critical factors affecting treatment selection, such as traffic level, pavement condition, environment, and cost were discussed. Pavement preservation decision-making frameworks and guidelines were developed for state and local highway agencies.

A report by Minnesota State University listed real-world application of different pavement preservation schedules as guidelines for engineers and agencies (Wilde, et, al., 2014). Data were collected information from existing pavement asset management system and developed a decision-making framework for local agencies to select maintenance and rehabilitation treatments in Iowa (Abdelaty, et al., 2015). Researchers also explored environmental benefits of pavement preservation, using single or multiple treatments, that could provide guidance to decision makers (Anastasopoulos, et al., 2013; Chan, et al., 2011; Chehovits and Galehouse, 2010; Tighe and Gransberg, 2012).

Thus, there is a need for the development of a tool to include in the decision-making framework that would consider performance and environmental benefits of asphalt and concrete surfaced pavements. Such decision-making framework and comparative analysis of commonly used treatments could be used as a guide in selecting optimum preservation treatment for any given project.

However, challenges that may arise include the evaluation of the impact of a preservation schedule as opposed to the assessment of single treatment as well as the most suitable treatment of the intended project. This could be addressed by developing a tool platform with LCA performance prediction methods. This tool would provide guidance and compare multiple options for any given project. The tool would also help to design a schedule and maximize the service life.

1.2 OBJECTIVES

The main objective of this project is to develop a framework and LCA methodology to evaluate PPMS for existing asphalt concrete (AC) and portland cement concrete (PCC) pavements. The goal is to provide guidance to local and state transportation agencies in preservation treatment selection or scheduling of treatments considering service life extension and environmental benefits. The framework and LCA methodology are included in a user-friendly tool with the following features:

- Life cycle inventories for commonly used preservation treatments for AC- and PCC-surfaced pavements
- A life-cycle estimation model to predict the service life extension
- Decision trees to select appropriate treatment
- User-friendly tool using Microsoft Excel's Visual Basic for Applications (VBA)

1.3 METHODOLOGY

Researches followed the LCA methodology in developing the tool. LCA implementation in the tool conforms to the International Organization for Standardization (ISO) 14044:2006 standards (Figure 0.1). The tool compares multiple pavement preservation treatments and schedules according the impact categories chosen in the goal and scope phase. The research team analyzed treatments using pay items as building blocks. System boundary, functional unit, data quality parameters, analysis period and other methodological choices relevant to LCA were defined in the goal and scope phase.

The inventory database covers materials, equipment, fuel and electricity used for construction of preservation and maintenance treatments. The use and end-of-life stages were included to perform complete life cycle calculations. Data for the inventory analysis were compiled from multiple sources that include commercial databases (EarthShift, 2013). In addition, questionnaires and publicly available databases were also compiled. The team developed performance models using data obtained from the questionnaires and available publications. Performance models were used to define the extent of analysis period and quantify service life extension. Last, researchers performed the impact assessment to compile the unit environmental impacts and energy consumption for each pay item.

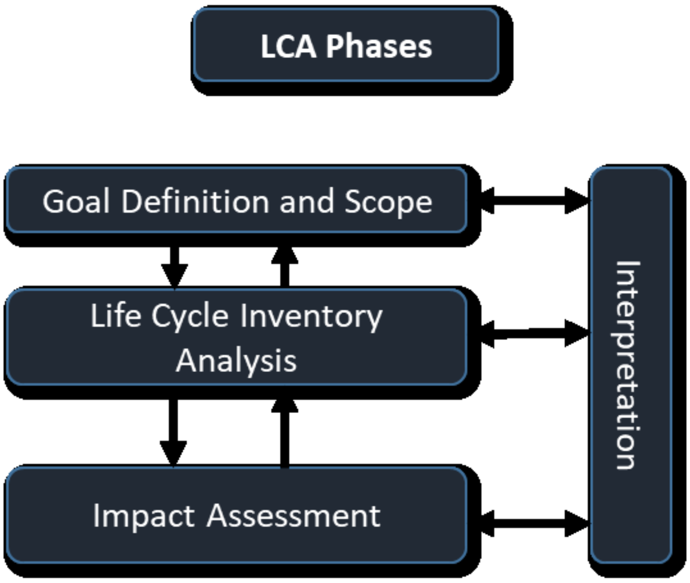


Figure 0.1. LCA phases (ISO 14044:2006)

1.4 REPORT CONTENT AND ORGANIZATION

The Illinois Center for Transportation (ICT) of the University of Illinois at Urbana-Champaign (UIUC) and Michigan State University (MSU) research teams conducted the work presented in a two-volume report. Volume I of the report presents LCA methodology, tool development and case studies. Volume II features the use-stage models. Organization of Volume I is as follows:

- Chapter 1: The motivation, main objectives, and methodology and tasks of the project are introduced.
- Chapter 2: Literature reviews about pavement preservation and maintenance techniques of flexible and rigid pavements are presented.

- Chapter 3: The goal and scope elements of the LCA performed are presented.
- Chapter 4: The life cycle inventory data collection, analysis, results and modeling procedures are presented. In addition, primary and secondary data, allocation procedures, and data quality assessment are discussed.
- Chapter 5: Decision tree to select applicable preservation treatments is presented. This chapter also provides the preservation treatment lifetime estimation models.
- Chapter 6: An overview, modules and general inputs of the tool is illustrated.
- Chapter 7: Case studies of various PPMSs have been compared as well as assessment of the effect of treatment application time.
- Chapter 8: A summary, main findings, and conclusions of the study is presented, as well as recommendations for future use of the LCA tool.

CHAPTER 2. PAVEMENT PRESERVATION AND MAINTENANCE REVIEWS

Pavement preservation is defined as "a planned system of treating pavements at the optimum time to maximize their useful life, thus enhancing pavement longevity at the lowest cost" (Kuennen, 2006). Preservation is a strategy to make planned, low-cost interventions to increase pavements' service life without adding considerable structural capacity. It encompasses preventive and routine maintenance as well as minor rehabilitation (Figure 0.1). In recent years, pavement preservation is widely adopted around the world including the United States (Beatty et al., 2002; Peshkin et al., 2011). The research team reviewed commonly used AC- and PCC-surfaced pavement preservation practices to capture construction practices of each treatment and its lifetime.

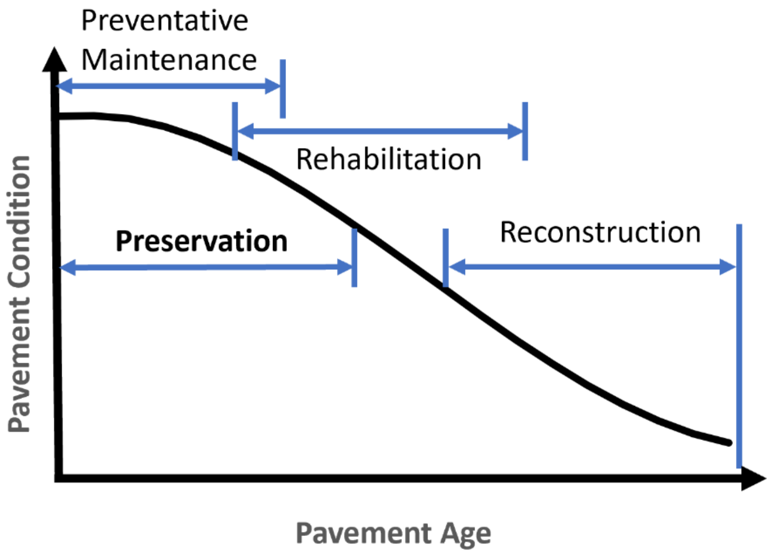


Figure 0.1. The preservation timeline (after Peshkin et al., 2007)

2.1 FLEXIBLE PAVEMENT PRESERVATION TREATMENTS

According to Peshkin (2011) and Johnson (2000), preservation treatments for AC-surfaced pavement may be listed in four categories:

- Crack treatments: crack sealing and crack filling
- Surface treatments: fog seal, chip seal, cape seal, slurry seal, microsurfacing and ultra-thin bonded wearing course (UTBWC)
- Minor rehabilitation: thin AC overlay, hot-in-place recycling (HIR) and chip seal, HIR and microsurfacing, HIR and thin AC overlay, cold-in-place recycling (CIR) and chip seal, CIR and microsurfacing, CIR and thin AC overlay, and CIR and medium AC overlay
- Treatment using PCC: ultra-thin white topping (UTW)

The range of service life extension and approximate cost for each treatment are compiled in Table 0.1.

Table 0.1 Preservation Treatment Lifetime and Cost (AC-surfaced Pavements)

Treatment	Reported Extended Service Life Ranges (Years)	Cost ($)
Crack sealing and crack filling	0-4 [3]	Crack sealing: 0.75 to 1.50 per ft [2] Crack filling: 0.10 to 1.20 per ft [2]
Fog seal	4-5 [3]	0.10 to 0.20 per square yard [2]
Chip seal	3-8 [3]	Single course: 1.50 to 3.00 per yd^2 [2]
Cape seal	6-8 [1]	2.25 to 6.00 per yd^2 (adding chip seal and slurry seal/microsurfacing) [2]
Slurry seal	4-7 [3]	0.75 to 1.00 per yd^2 [2]
Microsurfacing	3-8 [3]	Single course: 1.50 to 3.00 per yd^2 [2]
Thin AC overlay	3-23 [3]	3.00-6.00 per yd^2 [2]
Ultra-thin bonded wearing course	4-8 [2]	4.00-6.00 per yd^2 [2]
Hot-in-place recycling	3-8 [3]	2.00-7.00 per yd^2 [2]
Cold-in-place recycling	4-17 [3]	1.25 to 3.00 per yd^2 [2]
Bonded-concrete overlay	3-17 [3]	15.00-25.00 per yd^2 [2]

(1) Alan, 1999

(2) Peshkin et al., 2011

(3) Wu et al., 2010

2.1.1 Crack Treatments

Crack filling and sealing are applied using sealing materials, which help prevent moisture from infiltrating the pavement structure and, hence, control potential damage to the pavement. Crack treatments are usually applied to transverse and longitudinal cracks when the severity level is low to medium.

2.1.2 Surface Treatments

Fog seal, slurry seal, chip seal and microsurfacing are surface treatments that correct minor pavement distresses. These surface treatments also improve ride quality, service level and the safety of pavement. Each surface treatment is described as follows:

Slurry Seal

Slurry seal is a mixture of slow- or rapid-set emulsified asphalt, well-graded fine aggregate, mineral filler and water. It replaces the raveled-out surface and provides a new wearing surface for traffic. Typically, slurry seal requires longer curing time than chip seal and microsurfacing — unless using rapid-set emulsion (Hicks et al., 1997).

Slow-set emulsified slurry seal takes approximately 24 hrs to cure, which means it will have extended periods of work zone and corresponding traffic delay impacts. Unfortunately, this treatment cannot perform well if the surface layer is moderately or severely cracked or deformed. To enhance the bond between the slurry seal and the underlying surface layer, it is recommended to clean the pavement surface and apply a tack coat before the slurry seal treatment application (Brown,1988).

Microsurfacing

Microsurfacing is a cold-mix expansion of slurry seal with a high polymer and asphalt resident content and better-quality aggregates. It corrects surface deficiencies by filling and sealing the voids and cracks. Compared with the slurry seal, microsurfacing develops higher strength than slurry seal and can be applied in thicker layers, up to 2 in (Hicks et al., 1997). The cure time of microsurfacing can be as low as one hr to reduce work-zone-related impacts (Johnson, 2000). Microsurfacing also has a lower environmental footprint impact compared to AC or modified AC (Takamura et al., 2001).

Chip Seal

Chip seal, a thin-layer pavement protection, used to control moisture infiltration and also minimizes raveling. With chip seal, single-sized aggregates are mixed with emulsion (high quality asphalt content), mineral fillers and other anti-oxidation additives. Chip seal treatment has distinct texture properties as discussed in Volume II.

Fog Seal

Fog seal is an application of diluted asphalt binder without a cover of aggregate. It seals and enriches the AC pavement surface, and it is commonly for both low-volume roads and parking lots to improve pavement waterproofing and reduce its water susceptibility. The diluted emulsion application rate varies depending on surface conditions. If the surface is relatively porous and absorbent because of open voids, it requires more emulsion (0.09-0.22 gal/yd^2). Fog seal's application rate is usually 0.03-0.11 gal/yd^2 when pavement surface is relatively smooth (Hicks and Holleran, 2002).

Cape Seal

Cape seal is a chip seal covered with slurry or microsurfacing. It reduces the stone loss of chip seal since a slurry seal or microsurfacing provides a smooth surface. This treatment addresses minor cracking including low-severity alligator cracking.

Ultra-thin Bonded Wearing Course

Ultra-thin bonded wearing course (UTBWC) surface treatment is an alternative to slurry seal, chip seal and microsurfacing. It consists of a gap-graded, polymer-modified AC layer (0.4 to 0.8 in-thick) placed on a polymer-modified emulsified asphalt tack coat. Because UTBWC requires good bonding to the underlying surface, it does not require milling before paving. This treatment corrects minor surface distresses and increases surface friction (Ruranika and Geib, 2007). Unsealed moving cracks in existing underlying surface may reflect to the UTBWC layer.

2.1.3 Minor Rehabilitation Treatments

Some rehabilitation methods are usually considered as part of a preservation program. These methods are thin and ultra-thin AC overlays and HIR and CIR. Some of these methods restore the pavement functionality and structural capacity.

Thin AC Overlay

Thin AC overlays improve ride quality, correct surface distresses and enhance the life of existing AC-surfaced pavement. The effectiveness of thin AC overlays was studied in the previous works of the authors and others (Al-Qadi et al., 2015; Hernandez et al., 2018; Labi et al., 2008). Thin AC overlays can be more cost effective than microsurfacing, especially when traffic volume increases.

Hot-in-place Recycling

Hot-in-place recycling (HIR) is an on-site rehabilitation method to correct surface distresses. The procedure softens the top 2-in AC surface materials with infrared heaters, remixing them with recycling agents, and rejuvenators with/without virgin binder and virgin aggregate and repaving. This method addresses various pavement distresses, including rutting, raveling and cracking, and it eliminates costs associated with stockpiling materials (Button et al., 1994). Unfortunately, HIR performance is limited when structural problems exist. HIR can be used for low to medium traffic volume roads, but overlays or other surface treatments are recommended to support relatively high traffic loads.

Cold-in-place Recycling

Contrary to HIR, CIR cold mills and screens existing AC pavement and lower base layers and then mixes it with chemical additives to produce a restored pavement layer. The recycling depth is 4-6 in to correct distresses, including thermal cracking, raveling and rutting. CIR is a cost-effective treatment given that it recycles materials from existing deteriorated pavement rather than transporting materials from quarries.

CIR treatment is often accompanied with an overlay or surface treatment. Compared to HIR, CIR may be used at medium- to high-volume roads. Commonly used recycle agents are cement, foamed asphalt and engineered emulsions. This method reduces hauling costs and environmental impacts.

2.1.4 Concrete Type Treatments

Ultra-thin white topping (UTW) is one of the widely applied treatments as an alternative to AC overlays. It uses PCC — because of its good performance — to provide an excellent ride quality and increase surface friction (Roesler et al., 2008). Ultra-thin white topping (2-4 in) resurfaces deteriorated AC pavements using a thin 2-6 ft PCC slab. UTW performs best on roads with low-speed traffic or heavy stop-and-go traffic, such as intersections and bus stops.

This technology reduces AC pavement deformation and eliminates surface distresses. In addition, UTW increases the structural capacity of existing pavement. However, existing AC pavement and subbase should be structurally bonded to ensure surface performance.

2.2 RIGID PAVEMENT PRESERVATION TREATMENTS

Traditionally, AC pavements have been the primary treatment consideration for preservation; however, other PCC or composite pavement options are available. According to Smith et al. (2014), preservation options for PCC pavements include:

- Diamond grinding and grooving improves the smoothness and surface texture of the pavement.
- Joint resealing and crack sealing minimize ingress of water and dirt into the base layer; thus maintaining the strength of the pavement while improving surface characteristics.
- Dowel-bar retrofitting (DBR) through insert of dowel bars into existing transverse joints or cracks to prevent or mitigate further joint/crack deterioration.
- Partial-depth repair replaces limited sections and depths of the road, leaving the overall structural capacity intact.
- Full-depth repair delays or controls deterioration, and it restores the structural integrity by removing and replacing isolated areas of deterioration.
- Bonded PCC overlay eliminates surface distresses, improves friction, noise and rideability, and increases structural capacity.
- Thin AC overlay provides improved ride quality, reduces pavement distresses, maintains surface geometrics and reduces life-cycle costs.

Extended service life ranges for each concrete pavement treatment are shown in Table 2.0.

Table 2.0 Preservation Treatment Lifetime (Rigid Pavement)

Treatment	Reported Extended Service Life Ranges (Years)
Diamond grinding and grooving	8-15 [2]
Joint resealing	4-8 [2]
Crack sealing	4-8 [2]
Dowel-bar retrofitting	2-16 [3]
Partial-depth repair	5-15 [2]
Full-depth repair	10-15 [2]
Bonded-concrete overlay	15-25 [1]
Thin AC overlay	1-20 [3]

(1) Hall et al., 2001

(2) Illinois Department of Transportation, 2017

(3) Wu et al., 2010

2.2.1 Diamond Grinding and Grooving

The most fundamental aspect in maintaining the functional capacity of a pavement is to reduce the roughness of the surface and ensure a smooth ride. Over time, PCC pavements develop cracks, spalling and faulting, which increase their roughness. Diamond grinding typically involved grinding down the top pavement layer to 3/16-1/4 in, resulting in a smoother surface that provides excellent friction properties (Caltrans, 2008; Chen and Hong, 2014). Diamond grooving is similar to grinding, but differs in that the spacing between the grooves is larger, creating surface water run off channels. This treatment restores the roughness to a level that provides adequate safety through mitigating hydroplaning (Hoerner et al., 2003).

In fact, Diamond-grinding or grooving pavements achieve the same or lower IRI as AC overlays, with some pavements surviving as long as 15 years without any overlay (Rao et al., 1999). The benefits of diamond grinding and grooving also extend sustainability in the use stage, specifically by improving friction characteristics such as a reduction in tire-pavement noise and fuel consumption (Lloyd, et al., 2006; Santero, et al., 2013; Skarabis and Stockert, 2015).

2.2.2 Joint Resealing and Crack Sealing

The ingress of water and debris into the foundation layers reduces the functional capacity of a PCC pavement. Therefore, it is necessary to seal joints and cracks where water and debris can infiltrate. Joint sealing can be applied to longitudinal and transverse joints.

To evaluate the performance of sealants, researchers should consider six criteria, which include: adhesion, cohesion, compatibility, durability, elasticity and modulus (Biel and Lee, 1997). Typically, polymer-based sealants have a service life of 10 years or less, after which a new sealant needs to be applied. However, joint sealing and crack sealing were not found to be cost effective in some other studies (Hand, et al., 2000; Shober, 1997). In fact, based on Shober's (1997) experience, WSDOT has a no-seal policy for its pavements, although a few other agencies have adopted such an extreme approach.

2.2.3 Dowel-Bar Retrofitting

Slab's deterioration typically takes place at the joints and transverse cracks. This deterioration leads to additional distress development as moisture and debris enter the foundation layers. Dowel-bar retrofitting (DBR) is usually used to restore the joint efficiency. Hiller and Buch (2004) showed the benefits of DBR by improving load transfer efficiency (LTE) across joints through finite element modeling. The DBR approach has been shown to be working through a full-scale testing performed on several sections in California (Harvey et al., 2016). Similar outcome was noted based on long-term performance (Pierce et al., 2003).

2.2.4 Partial-depth Repair

One of the most common PCC pavement distresses is spalling, which entails small parts of the PCC surface, only up to a limited depth, breaking away from the rest of the slab — primarily at the joints or edges of the slab. Spalling, unless controlled, leads to even further spalling; thus, lowering the functional capacity of increasingly larger segments of the pavement (Frentress and Harrington, 2012).

Partial-depth repair removes the spalled segment of the pavement, up to a limited depth (typically, but not necessarily, 1/3 of the slab thickness), and replaces it with a shrinkage-resistant material. Partial-depth repair has shown to maintain the functional capacity of pavement for 10 to 15 years, and it is quite competitive compared to that of an AC overlay or other similar rehabilitation measures (Frentress et al., 2012). Patch types and classes are shown in Table 0.2 and Table 0.3, respectively (Illinois Department of Transportation, 2007).

2.2.5 Full-depth Repair

Instead of replacing a limited depth of PCC slab, full-depth repair (FDR) requires removing and replacing the entire deteriorated area. FDR addresses various slab distresses, including cracking, spalling and punchouts to improve pavement ride quality and structural integrity.

Unfortunately, cracks may reappear in FDR areas since the replacement or FDR of slabs cannot effectively address the underlying problems, e.g., void, poor base support, reflective cracking (Chen and Won, 2007). Thus, to enhance the performance of FDR, effective base/subgrade preparation is required.

Table 0.2 Types of Patches Used in Pavement Preservation

Type of Patch	Application Area (yd^2)
I	< 5
II	5 - 15
III	15 - 25
IV	≥ 25

Table 0.3 Classes of Patches Used in Pavement Preservation

Patch Classes	Application
A	Pavement removal and continuously reinforced portland cement concrete (PCC) replacement
B	Pavement removal and jointed PCC replacement using dowels
C	Pavement removal and PCC replacement
D	Pavement removal and hot-mix asphalt replacement

2.2.6 Bonded PCC Overlay

Bonded PCC overlay is an option for PCC resurfacing to help eliminate surface distresses when pavement is in good to fair structure condition. This treatment adds pavement structural capacity and extends the pavement life. It requires the bonding between the overlay and the existing pavement so that they can perform as one structure and continue to carry the traffic load. Thus, the coefficient of thermal expansion of overlay should be similar or less than the existing PCC pavement (Smith et al., 2014).

2.2.7 Thin AC Overlay

Thin AC overlay is a preservation treatment for both flexible and rigid pavements. It addresses surface distress, improves ride quality and reduces noise. Thin AC overlay can also keep water from penetrating into the base or subbase when a punchout is on the surface. To ensure good overlay performance, milling operation is required before applying overlays. Unfortunately, the milling operation adds to the cost of this treatment; therefore, it is a trade-off decision to balance both performance and cost.

CHAPTER 3. GOAL AND SCOPE

3.1 GOAL OF THE STUDY

The goal of the study is to develop a LCA methodology to quantify the environmental impacts and energy consumption of preservation and maintenance activities for AC- and concrete-surfaced pavements. The intended audience of the LCA study is state and local transportation agencies as well as contractors interested in making decisions for selection of a pavement preservation treatment. The intended application of the LCA study and the development of a corresponding tool are to assess the impacts of pavement projects that require preservation.

3.2 SCOPE OF THE STUDY

Scope elements of the study include the following: the product to be analyzed by the LCA, geographical region, system boundary, functional unit, analysis period, data assumptions and allocation rules. The system boundary, functional unit and analysis period are discussed separately. Listed below are definitions of the scope elements:

- Product: structural elements of the pavement system without considering road shoulder and drainage.
- Geography: U.S. region
- Data assumptions: the data used are a combination of primary and secondary data from various sources including local surveys, governmental reports and databases, industry reports, peer-reviewed sources and commercial inventory databases.
- Allocation rules: The cut-off rule was applied for materials' inputs that were considered as recycled materials, industrial by-product or waste products. Because the end-of-life stage was not taken into consideration, the end-of-life allocation rule was not applied to the preservation treatment.

3.2.1 Treatments

The following treatments are considered in the LCA and the tool development. Some of these treatments are commonly cited as rehabilitation rather than preservation; however, it was deemed important to add to the scope for completeness.

Table 0.1 Preservation Treatments Considered in LCA Scope and Tool Development

Preservation Treatment for Flexible Pavement	Preservation Treatment for Rigid Pavement
Crack sealing/crack filling	Diamond grinding/grooving
Fog seal	Joint resealing
Chip seal	Dowel-bar retrofitting
Cape seal	Partial depth repair
Slurry seal	Full-depth repair
Microsurfacing	Ultra-thin bonded wearing course

Preservation Treatment for Flexible Pavement	Preservation Treatment for Rigid Pavement
Thin AC overlay	Thin AC overlay
Ultra-thin bonded wearing course	Crack sealing/crack filling
Bonded-concrete overlay	
HIR and chip seal	
HIR and microsurfacing	
HIR and thin AC overlay	
CIR and chip seal	
CIR and microsurfacing	
CIR and thin AC overlay	
CIR and medium overlay	

3.2.2 System Boundary

This LCA focuses on preservation treatment applied to an existing pavement only. Thus, it differs from conventional LCA studies, which typically has five stages, including maintenance as a separate life cycle (Figure 3.1).

This study's LCA focus was on the maintenance stage and the interaction of the pavement with the environment after construction in the use stage. Because pavement preservation is considered part of the maintenance stage, the system boundary is focused on maintenance and use stages (Figure 0.1). Any other processes related to the production and construction of existing pavement and any other activities related to the disposal of pavement at the end of its lifetime are not included in this study.

Because the comparative analysis included multiple treatments and schedules applied to the same existing pavement, the impacts associated with the construction and material production of existing pavement can be ignored. This decision was made due to the difficulty of obtaining inventory data for the existing pavement. The condition of the existing pavement, however, was considered as it might affect the performance of subsequent treatments.

3.2.3 Functional Unit

There are two types of functional units used in this LCA study: lane miles and million vehicle-miles traveled. Lane miles compute the total impacts determined by multiplying the lane numbers and section length by unit impacts within analysis period. Million vehicle-miles traveled are a comparison among studies with different analysis periods. Since the total impacts are divided by millions of vehicles passing through one mi of analysis section, it is an efficient way to evaluate different studies regardless of analysis period.

3.2.4 Analysis Period

The analysis period is the lifetime elapsed from the application of first preservation treatment until the reconstruction of existing pavement; therefore, it may include multiple treatments. Analysis was calculated following the method presented in Chapter 5. The method allows users to design preservation and maintenance schedules for an existing distressed pavement.

Based on the pavement condition index (PCI) of existing pavement, lifetime estimation models, and annual average daily traffic (AADT) and truck percentages the life expectancy of each treatment may be predicted. PCI reflects the condition of a pavement after an evaluation of different distress types, including surface cracks, rutting and other modes of surface distresses. PCI varies between zero and 100. The analysis period is determined by summing up the life expectancies of all treatments within the designed preservation and maintenance schedule (Figure 0.2).

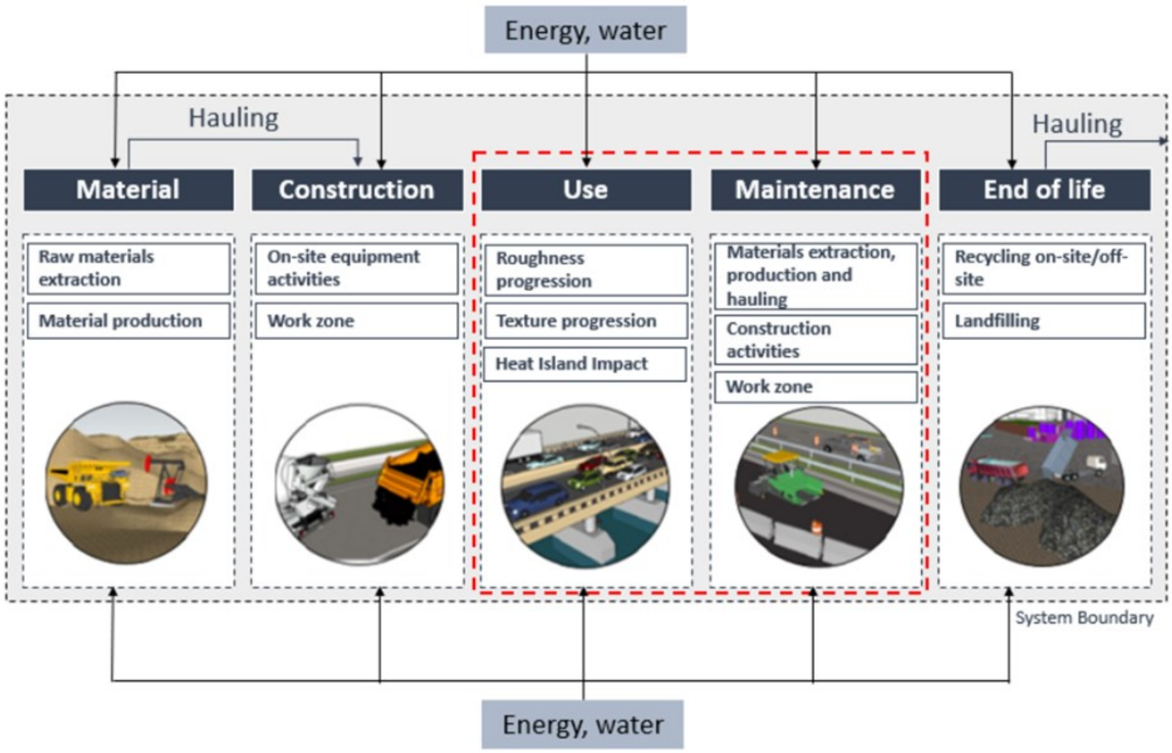


Figure 0.1. System boundary

Figure 0.1. System boundary of the pavement preservation LCA

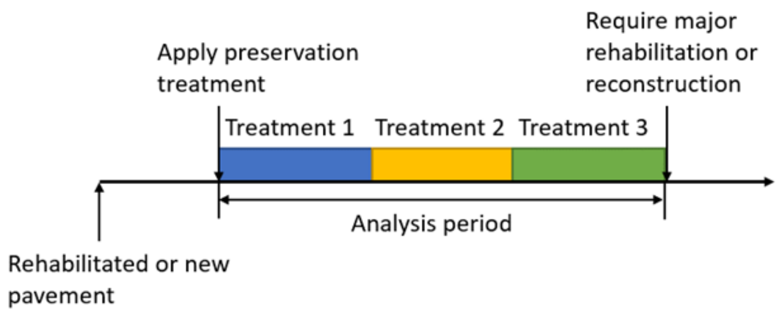


Figure 0.2. Analysis period selected to compare treatments with various lifetimes

3.3 IMPACT CATEGORIZATION

As recommended by the FHWA Pavement LCA Framework (2016), the impact characterization in this study uses the U.S Environmental Protection Agency's (EPA) Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI 2.1). As Table 0.2 shows, TRACI 2.1's impact includes 10 items along with their respective normalization and weighting factors, which produce a single score (Lautier et al., 2010; Bare et al., 2006). This report focuses on four quantitative outcomes from the LCA study, which include: global warming potential (GWP), total energy, total energy with feedstock, and single score (SS).

Table 0.2 TRACI Impacts with Normalization and Weighting Factors

Impact Category	Unit	Normalization	Weighting
Global warming	kg CO_2 eq	0.0000413	0.349
Ozone depletion	kg CFC-11 eq	6.20	0.024
Smog	kg O_3 eq	0.00718	0.048
Acidification	kg SO_2 eq	0.0110	0.036
Fossil fuel depletion	kg MJ surplus	0.0000579	0.121
Eutrophication	kg N eq	0.0463	0.072
Respiratory effects	kg PM2.5 eq	0.0412	0.108
Non-carcinogenics	CTUh	952	0.060
Carcinogenics	CTUh	19,706	0.096
Ecotoxicity	CTUe	0.0000905	0.084

3.3.1 Global Warming Potential

Greenhouse gases (GHGs) warm the earth by absorbing energy and slowing the rate of energy escape to space. Various GHGs can have different effects on the earth's warming. Global Warming Potential (GWP) compares global warming impacts of different gases.

According to the EPA (2017,) "GWP is a measure of how much the emissions of 1 ton of a gas will absorb over a given period of time, relative to the emissions of 1 ton of carbon dioxide (CO_2)." The larger the GWP, the more that a given gas warms the earth compared to CO_2 over that time period. The time period usually used for GWPs is 100 years." This impact is given in a kilogram unit of carbon dioxide equivalence (CO_2 eq). The GWP of each comparative case of preservation projects was calculated from materials inputs, construction- and use-stage inventory items using the EPA's TRACI 2.0.

3.3.2 Energy Indicators

Two energy consumption indicators were included in the impact assessment: energy and total energy with feedstock. Energy refers to combusted or expended energy as fuel, while total energy with feedstock includes energy that embodies fuel, e.g. diesel or natural gas, and energy that embodies material, e.g. plastic or asphalt binder (Overgaard, S. 2018). The energy embodying material is also called feedstock energy, which is the "fuel" used as a material retains its potential energy rather than combusting or expending to release its energy. These types of energy are reported separately to provide a complete view of energy consumption over the life cycle.

3.3.3 Single Score

The single score is subjectively representing a simplified compilation of 10 environmental impact categories in a condensed format. This study presents the environmental impacts of the 10 normalized factors through calculation of the unit-less parameter, single score (Lautier, et al., 2010; Bare, et al., 2006), as shown in Table 0.2. The weighting factor determined by the National Institute of Standards and Technology (NIST) is specific to the U.S region;

3.4 USE-STAGE MODELS

Heat island and rolling-resistance-related impacts are part of the use stage. The development for heat island and rolling resistance models is presented in Volume II.

CHAPTER 4. LIFE-CYCLE INVENTORY DESIGN

Life-cycle inventory analysis is the second phase of an LCA study. This phase aims to qualify and quantify collected and processed data as defined in the study's goal and scope. This chapter summarizes data collection and provides an overview of unit processes and pay items as well as data quality assessments.

4.1 DATA COLLECTION

This study collected primary and secondary data from various sources. Primary data refers to data specific to the unit processes or pay items often collected from first-hand sources, such as questionnaires, surveys, observations, experiments, interviews, etc. Secondary data is generic and represents average characteristics of a unit process.

4.1.1 Primary Data

Researchers collected primary data early in the project to gather information about the pavement preservation practices in different states. The team distributed questionnaires to DOTs throughout the nation in 2017-18.

One of the goals with the questionnaire was to analyze the service life of different treatments to determine the project analysis period. Researchers prepared questions with a specific format and intent to collect information that can be used as direct input for lifetime modeling development. Relevant factors that can impact the treatment performance were also evaluated. This information was also used to support the development of the decision matrix for applicable treatment selection for existing pavement. In addition, researchers collected examples of treatment schedules in the questionnaires, Contractors and agencies were asked about the following information:

- Annual average daily traffic (AADT) and truck percentage where pavement preservation treatments commonly used.
- Treatment application frequency.
- Lifetime estimation of treatments when applied to pavements in poor and good condition.
- Patching activities prior to overlay and their typical percentage range.
- The important weights of the existing pavement's Pavement Condition Index (PCI), AADT, and truck percentages that affect the life of each treatment.
- Application time of preservation treatments for flexible and rigid pavements.
- Typical treatment schedules for each pavement type.

Figure 0.1 represents the DOTs that responded to the questionnaires and shared their field project experiences.

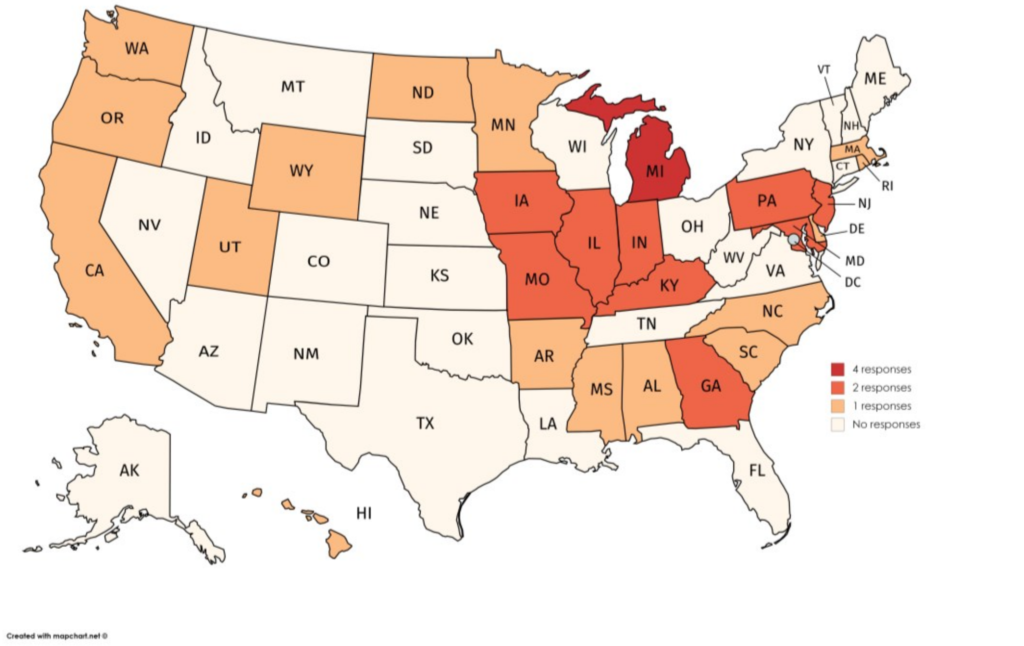
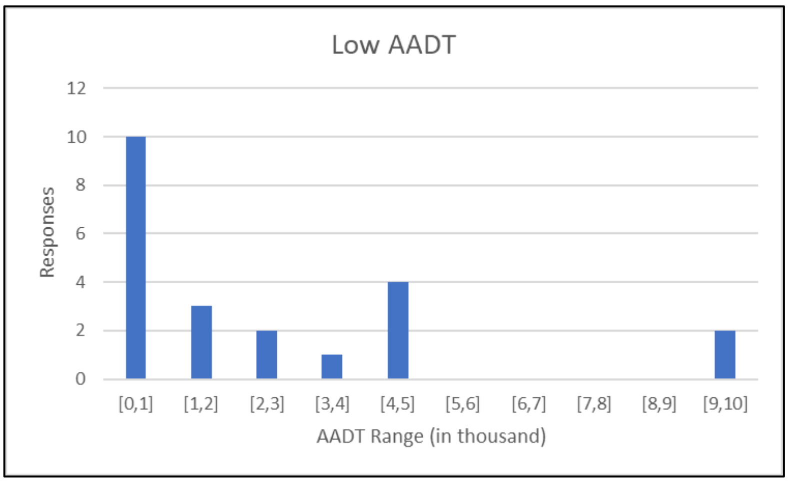


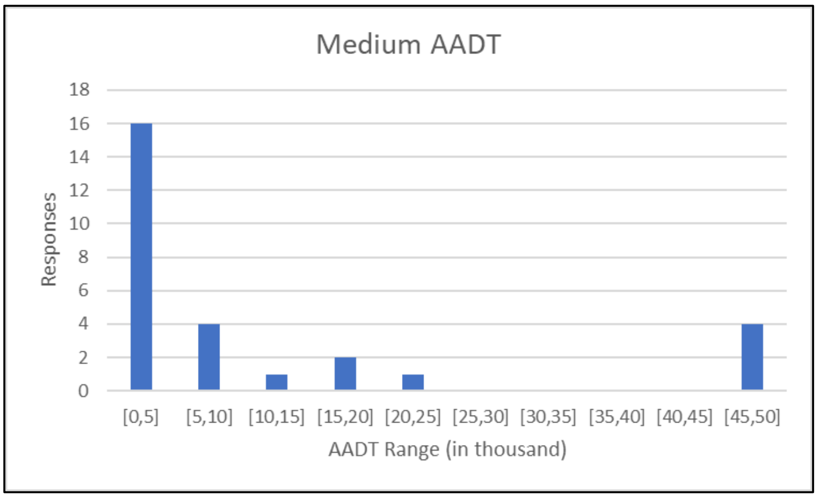
Figure 0.1 Representative map of responses from DOTs

Questions type Nos.1, 3 and 5 helped develop AC pavement preservation treatment lifetime estimation models, which is discussed in Chapter 5. In question type No.1, researchers collected information about the AADT and truck percentage, which helped the team learn the range of commonly applied traffic volume where preservation activities are used. Results are shown in Figure 0.2 and Figure 0.3.

Researchers determined the AADT and truck percentage values for each level by average weighting survey results (Table 0.1). Similarly, the team asked the condition of the pavement, represented by PCI, where preservation was applied. Responses from question type Nos. 1, 3 and 5 were used to categorize three conditions where pavement preservation can be applied (Table 0.1).



(a)



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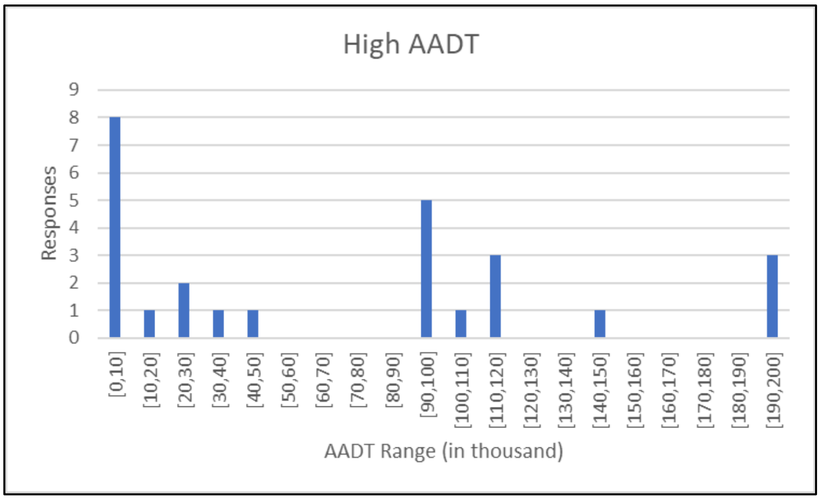
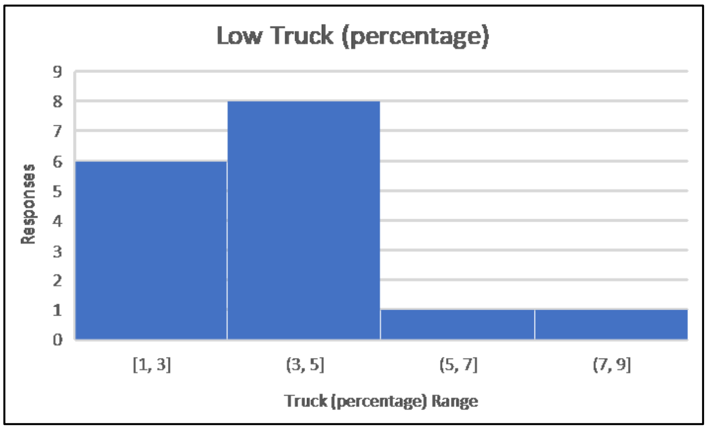
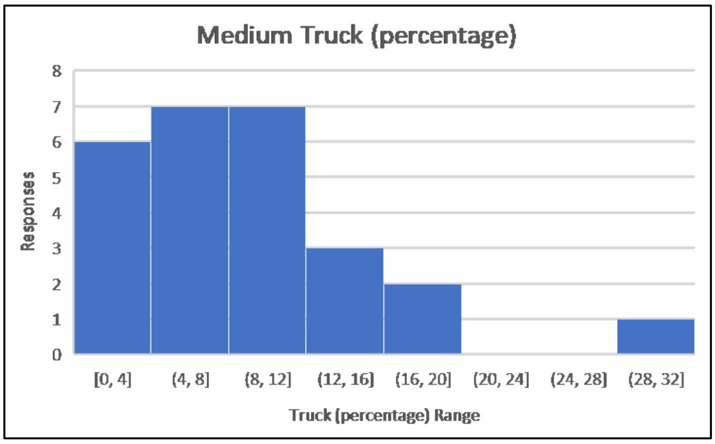


(c)

Figure 0.2. Survey responses regarding the range of various AADT levels, including low (a), medium (b) and high (c) AADT ranges.



(a)



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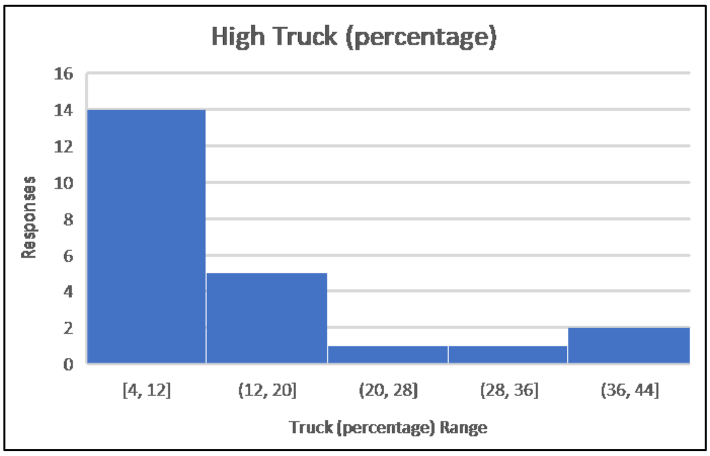


(c)

Figure 0.3 Survey responses concerning the range of different truck percentage, including low (a), medium (b) and high (c) truck percentages.

Table 0.1 AADT and Truck Percentages for Various Levels

Level	AADT	Truck (%)	PCI (%)
Low	1,000	4	65 (Fair)
Medium	5,000	10	75 (Good)
High	95,000	16	85 (Very good)

In question type No. 2, the application frequencies of various preservation treatment types for flexible pavements were collected. Results are shown in Figure 0.4. Frequently used techniques included microsurfacing, thin AC overlay, chip seal and UTBWC.

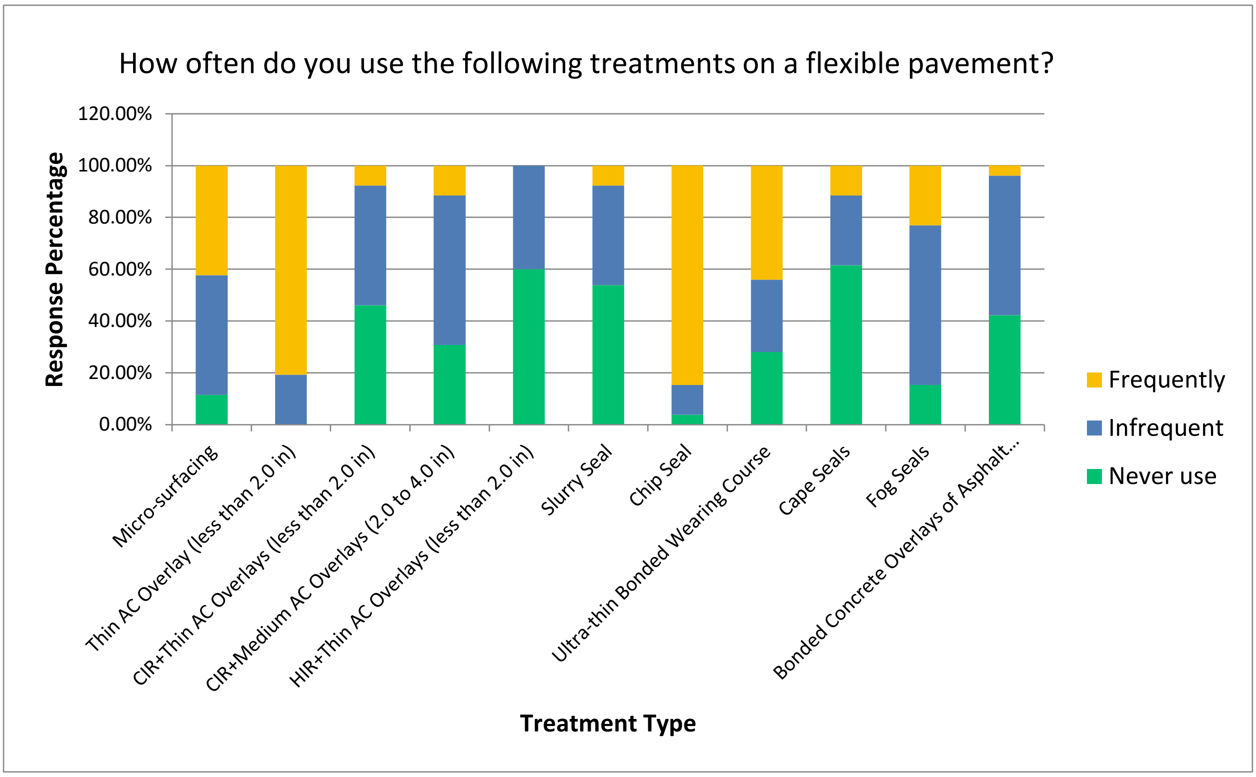


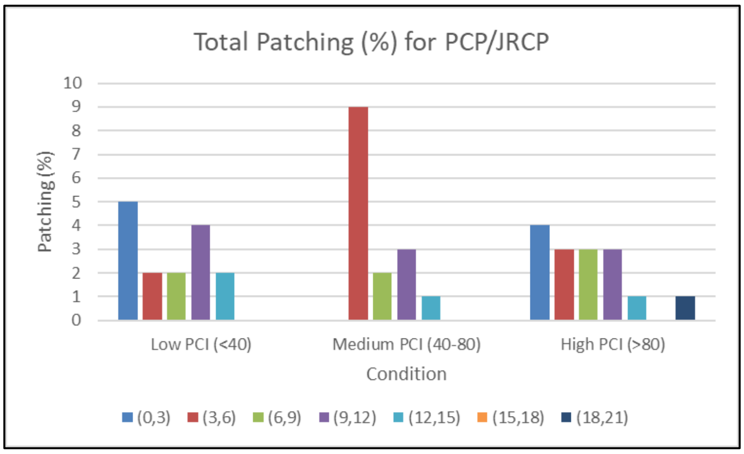
Figure 0.4 Treatment application frequency information

Question type No.4 relates to patching practices for PCC pavement. The questions collect feedback for jointed plain concrete pavement (JPCP) and jointed reinforced concrete pavement (JRCP) and continuously reinforced concrete pavement (CRCP). The goal was to learn a reasonable percentage of full- or partial-depth patching for PCC pavement under different condition levels. Results are shown in Figure 0.5. This information is used as the recommended patching percentage for a given project.

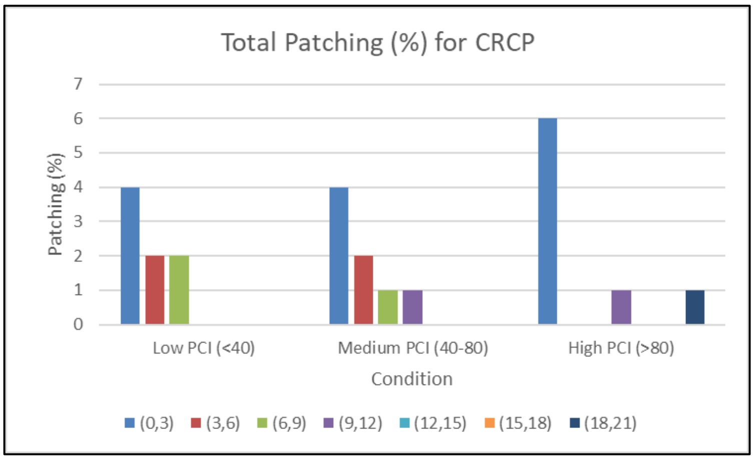
In question types Nos.6 and 7, the goal was to learn about agency's practices for scheduling preservation activities, which produced maximum benefits. Table 0.2 presents the list of treatment schedules provided in the responses. In the questionnaires, researches collected more than 10 schedules for each structure, which are used in the tool as default preservation schedules.

Table 0.2 Pavement Preservation Schedule Example

AC over-jointed concrete pavements		AC over CRCP		Conventional AC	
Year	Treatment	Year	Treatment	Year	Treatment
8	UTWC	10	Thin AC overlay	4	Chip seal
14	Cape seal	20	UTWC	10	Cape seal
20	Chip seal	26	Cape seal	20	BCOAP
28	Thin AC overlay	30	Chip seal	28	UTWC



(a)



(b)

Figure 0.5 Patching percentages for various PCP/JRCP types (a) and CRCP (b) pavements

4.1.2 Secondary Data

To complement the aforementioned collected primary data, the research team used various sources to compile the inventory data. Examples of these secondary data sources include the following:

- Commercial LCI databases (e.g. Ecoinvent 2.2 [Frischknecht et al., 2005] and 3.0 [Wernet et al., 2016] and U.S.-Ecoinvent 2.2 [EarthShift, 2013]).
- Software (e.g. EPA MOVES2014 [EPA, 2014b] and eGRID2010 [EPA,2016]).
- Governmental databases and reports.
- Peer-reviewed literature.
- Industry reports.

Secondary data also included activity-level information, such as raw material usage, general production activity characteristics, average energy consumption of construction equipment and pavement performance evaluation. Other information collected includes the following:

- Asphalt binder production.
- Aggregate (natural and crushed) production.
- Asphalt concrete plant production.
- Cement production.
- Ready-mix concrete plant.
- Recycled materials production.
- Supplementary cementitious materials.
- Construction procedures and equipment lists.
- Equipment conductivity and fuel consumption ratios.
- Pavement deterioration rates.

4.2 MODELING PROCEDURES

4.2.1 Major unit processes modeled and included in the database

Since the goal of the study is to develop a tool for all regions in the U.S, the inventory database should be customized for various states. To simplify the environmental impacts computation, major unit processes were introduced to represent "the smallest element considered in the life-cycle inventory analysis for which input and output data are quantified." A unit process compiles material, construction, fuel and/or hauling process from its upstream data so that final results can be computed by counting the number of units of each process. SimaPro is a commercial software used to generate models for each unit process in the LCA study (Figure 0.6).

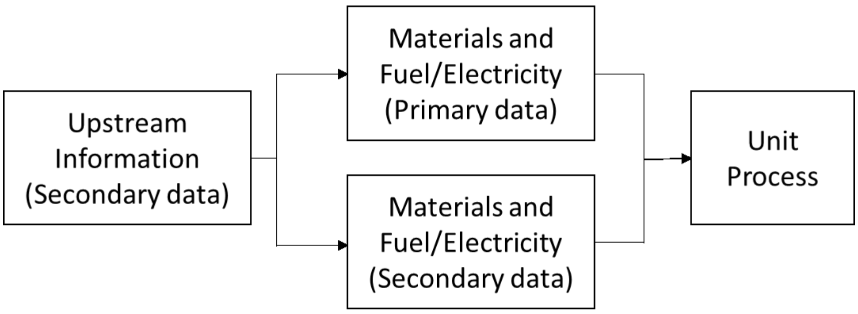


Figure 0.6 General unit processes modeling approach

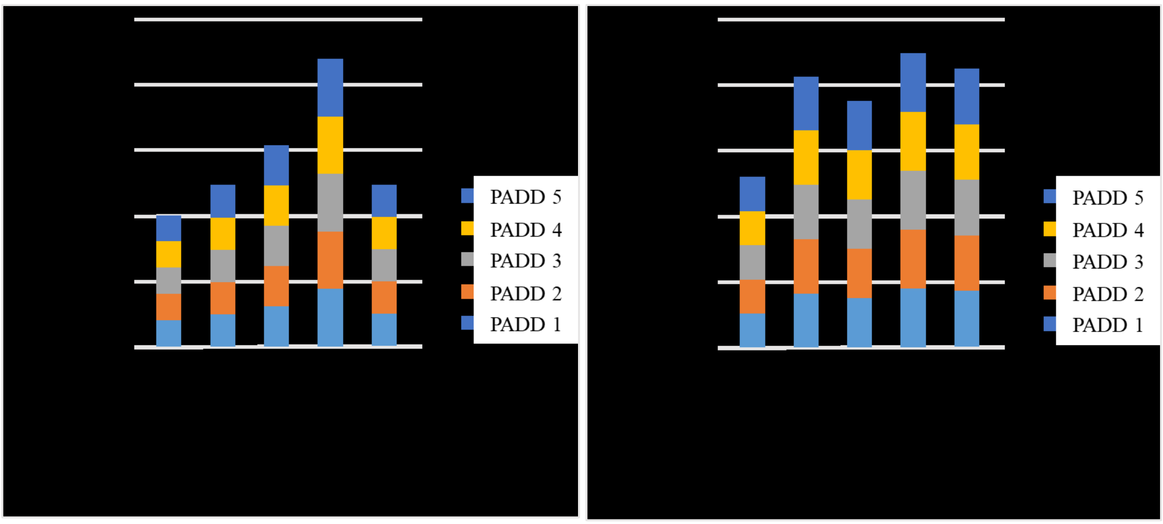
ICT's previously developed databases in the various LCA-focused projects were adopted (Yang et al., 2014; Al-Qadi et al., 2015; Senhaji et al., 2017). Listed below are the commonly used unit processes:

Fuel and Electricity

The energy inputs to the upstream processes were developed on a national scale to cover all U.S. states. The Petroleum Administration for Defense Districts (PADD) map is shown in

Figure 0.7. The same database was also used to develop an asphalt binder model. Figure 0.8 shows the energy demand of various asphalt products produced in all PADDs.

Figure 0.7. PADD map (U.S. EPA, 2013)



(a) (b)

Figure 0.8. Energy of different asphaltic materials' production in the five PADD regions without (a) and with (b) feedstock (Yang et al., 2016).

As for electricity, the U.S. has 10 North American Electricity Reliability Corporation (NERC) regions, as illustrated in Figure 0.9 (U.S. EPA, 2015). The available U.S. EPA resources were used to model the electricity production unit processes for each state using the commercial LCI databases available in SimaPro. For an example, Figure 0.10 illustrates the GWP and primary energy demand (PED) needed for producing 1 kilowatt of electricity for each state.

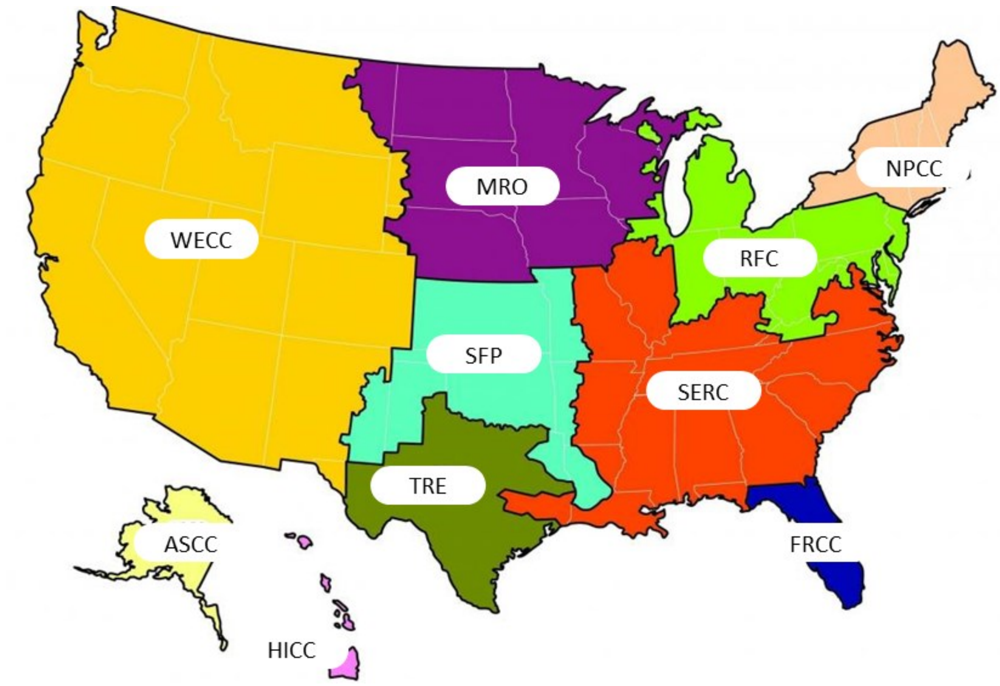
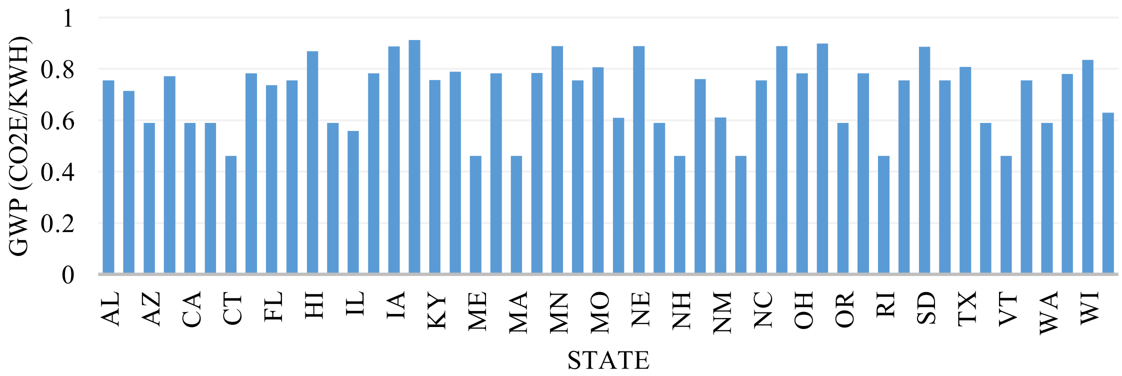
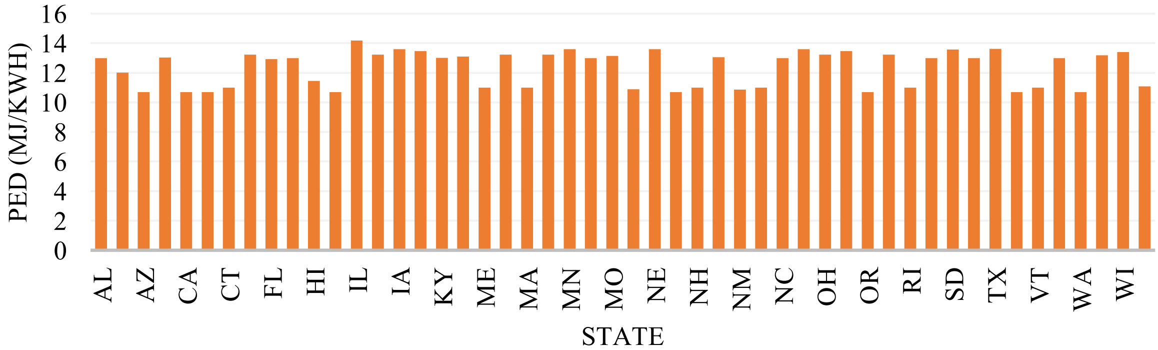


Figure 0.9. U.S. NERC regions (U.S. EPA, 2015)



(a)



(b)

Figure 0.10. GWP (a) and PED (b) for electricity generation of 1 kilowatt (a) (Senhaji et al, 2017).

Pavement Materials

Asphalt and concrete pavements' preservation treatments require raw materials including aggregate, asphalt, cementitious, recycled and other materials (i.e., rejuvenating agents, stabilizers, reinforcement, etc.). Impacts associated with producing these materials were calculated using relevant unit processes in the U.S. Ecoinvent (US-EI) 2.2 database (Earthshift, 2013).

Aggregate acts as the skeleton for AC, and it is about 70 to 80 percent of PCC by volume. Aggregate is also an important component in preservation treatments, such as chip seal, microsurfacing, slurry seal, etc. Quarried crushed and natural aggregates were included in the inventory database. Aggregate production was regionalized using the upstream unit processes to consider the regional electricity and fuel impacts (Yang et al., 2016).

The regionalized asphalt binder model was adopted in this study (Al-Qadi et al., 2015). Using the same framework as the asphalt binder model, other asphaltic products were developed to include emulsion, ground-tire-rubber modified binder, polymer-modified binder and foam asphalt.

Portland cement is one of the essential ingredients of concrete mixtures. The procedure to manufacture Portland cement include quarrying raw materials (i.e. limestone, clay), which entails crushing the rock, blending it with additives, processing and then finishing its grinding. The data from Portland Cement Association (PCA) were used to model its unit process for cement production (Marceau et al., 2006). Similarly, other cementitious materials, such as fly ash, are a by-production from coal combustion, and they can be modeled based on data collected from the coal plant (Chen et al., 2010).

Recycled materials, such as reclaimed asphalt pavement (RAP), recycled asphalt shingles (RAS) and recycled concrete aggregate (RCA), were also included in the database. Since the cut-off allocation approach was assumed, the processes to prepare recycled materials for the next pavement project were only considered. Operations like milling, removal and hauling to the yard were not included in the system boundary for recycled materials. Plant operations were modeled using fuel upstream data collected by Yang et al. (2016) and activity level data by Al-Qadi et al. (2015).

Plant operations include asphalt-mix plant and ready-mix concrete plant. Fuel and electricity are required in different plant operation processes, such as mixing and drying the drums, heating units, front wheel loaders, trucks, etc. Plant models were developed using the regionalized electricity and fuel models as well as the activity level information developed in earlier works (Al-Qadi et al., 2015).

Hauling

Within the life cycle of each preservation treatment, materials and equipment are required to be transported from plant/quarry to the site or from the quarry to the plant. Fuel consumption and associated impacts because of hauling processes may not be negligible due to the heavy loads and long transportation distances. The variable-impact transportation (VIT) model was established based on simulations using the U.S. EPA's MOVES to evaluate the fuel economy and emission of heavy-duty trucks (Kang et al., 2018). In this model, all the impact categories in the EPA's TRACI 2.0 and energy consumption of transportation can be computed.

At the same time, fuel consumption from hauling varies by region because the local temperature, humidity and road grade are performing important roles in the hauling impacts. Types and values of variables considered in the VIT model are summarized in Table 0.3. This VIT model can also be used to identify the extra fuel consumption of vehicles due to work zone traffic delays.

Table 0.3. Range of Variable Considered for the MOVES Simulation (Kang et al., 2018)

Parameters	**Quantity**	**Unit**
Vehicle speed	Idling, 1,2.5,5,10,20,30,40,50,55,60 and 70	mph
Vehicle weight	9.1, 15.3, 24.6, 30.1, 33.4 and 36.3	tn.sh
Road grade	0, ±1, ±2, ±3, ±4, ±5, ±6 and ±8	%
Temperature	0-110 (increment of 10)	ºF
Relative humidity (RH)	30-100 (increment of 10)	%
Year	2015, 2050 (increment of 5)	N/A

Construction Equipment

The impacts corresponding to the construction stage are associated with the on-site equipment's fuel and electricity consumption. The construction equipment data was collected from contractors and agencies in earlier works at ICT (Yang et al., 2016; Senhaji, et al., 2017). These data have already been compiled in the construction LCI database, which allows users to customize the equipment considered in the preservation activities. The equipment is characterized using the parameters described in Table 4.2.

4.2.2 Pay Items

A pay item is a unit of work for which a price is provided and a contractor is paid for any construction work. This is the common language used in the construction industry. Therefore, pay items were considered in the development of the preservation LCA tool for ease of future implementation.

A list of pay items were developed for each preservation treatment (Figure 4.11). Pay items combine materials, mixtures and equipment by adding corresponding unit processes.

Preservation activities were decomposed into tasks, and tasks were compiled under pay items specific to each treatment.

Table 0.4. Equipment Unit Process Parameters

Parameter	Description
Fuel type	Diesel, two- and four-stroke gasoline, electricity and labor
Description	Type of equipment (e.g. wheel loader, pneumatic roller, etc.).
Horsepower	Varying from three to 3,000 depending on the description
Technology	Currently, the simulated year uses the average NONROAD2008 technology, but future updates to the database can include various engine tiers.
Year	This parameter is automatically determined based on the in-use equipment's initial construction or maintenance year. Note: Years before 1999 refer to the 1999 database while years after 2015 refer to the 2015 database.
Number of equipment	Amount of equipment used for construction
Time not in use (%)	Estimated time that the equipment is not in use during construction hours
Fuel usage (gal/hr)	Amount of fuel consumed per hour of work with the construction equipment
Mobilization distance (miles)	Transportation distance of construction equipment from storage center to work site

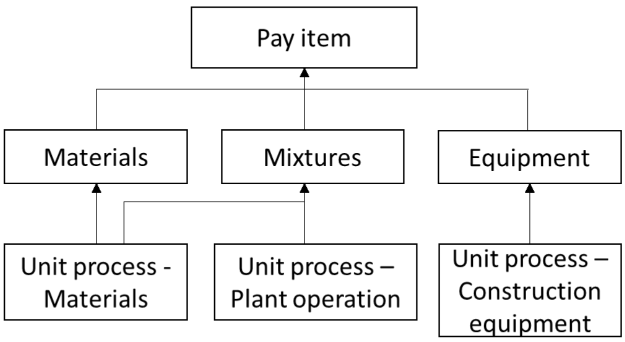


Figure 0.11 Pay item framework

4.3 DATA QUALITY ASSESSMENT

As it was recommended in the ISO 14044: 2006 and FHWA pavement LCA framework (Harvey et al., 2016), data quality assessments and requirements are necessary (Table 0.5). The data quality assessment was evaluated based on the Greenhouse Gas Protocol developed by Weidema and Wesneas (1996), which scores data quality from one to five using six indicators shown in Table 0.5. In this project, the data quality assessments refer to previously conducted

LCA studies (Yang et al., 2016; Senhaji et al., 2017). The results are shown in Table 0.66.

Table 0.5 Data Quality Requirements

Data quality indicator	Description
Time-related coverage	Age of the data, and the timeframe in which data should be collected
Geographical coverage	An area of land from which data or a unit process should be collected to satisfy the goal of study
Technology coverage	Specific technology or technology mix
Data precision	Measure of variability for the data values in each expressed data
Completeness	Percentage of flow that is measured or estimated
Consistency	Qualitative assessment of whether the study methodology is applied uniformly to the various components of the analysis

Table 0.6. Data Quality Assessment of Major Modeled Unit Processes (Yang et al., 2016)

Process type	Unit process	Data source	Score
Fuel and Electricity	Coal	Public and government databases	Fair
	Natural gas	Public and government databases	Fair
	Electricity	Government and commercial database (Earthshift, 2013; EPA, 2016)	Good
Construction	Equipment operation	MOVES 2014 simulation	Good
Transportation	Hauling trucks	EPA MOVES simulations and commercial database	Good
	Single-unit truck	EPA MOVES simulations and commercial database	Good
	Passenger car	EPA MOVES simulations and commercial database	Good

CHAPTER 5. PAVEMENT PRESERVATION SCHEDULE DESIGN

5.1 OVERVIEW OF METHODS

The design and schedule of a preservation activities can play a critical role in evaluating life-cycle benefits of a preservation program. A pavement-preservation schedule design consists of treatment selections and lifetime estimations of corresponding treatments. Scheduling of preservation treatments was done using two methods. First, a schedule of activities was recommended automatically through the decision tree models integrated in the software tool. A user, however, could manually input the activities. Once the treatment was selected, the second method involved estimating the lifetime based on lifetime estimation models developed by an analytical hierarchy process (AHP). Lifetime can also be manually adjusted by the users based on their experiences with the practices in the region. The preservation schedule design is shown with the schematic in Figure 0.1.

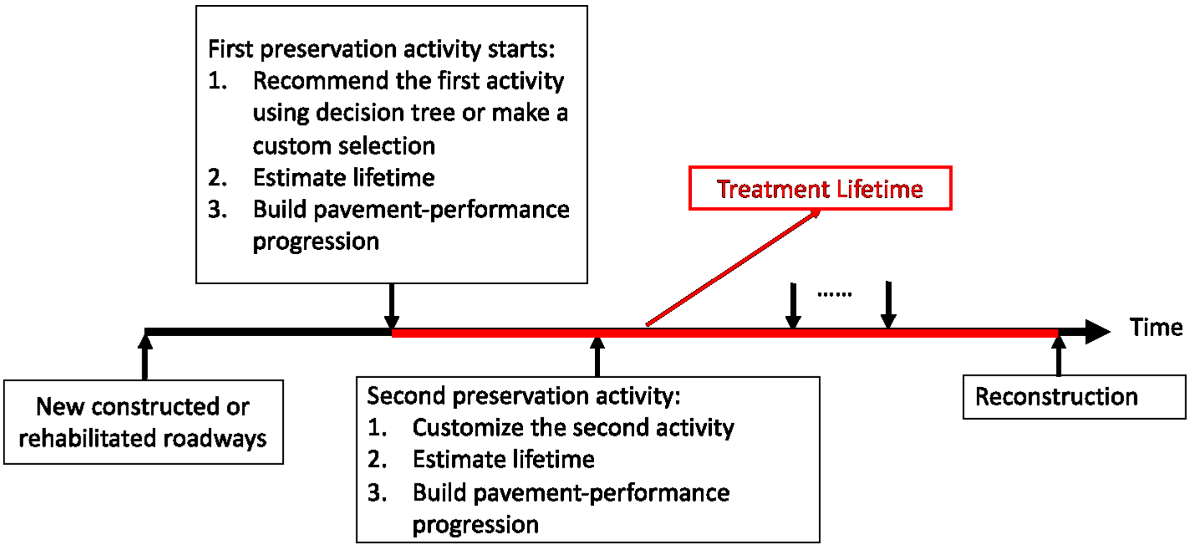


Figure 0.1 Pavement preservation schedule design schematic

The analysis period is determined as soon as the user finalizes the schedule of activities. One of the most critical steps in the analysis is to select the first activity. The information to estimate lifetime of the selected treatment includes existing pavement condition, traffic volume and composition. Subsequent treatments can be scheduled based on the user's experience or default scenarios to maximize the life-cycle benefits.

Lifetime prediction is the next step for each treatment selection. Treatment lifetime is the time elapsed until the pavement surface condition deteriorates to the level where major rehabilitation or new construction is needed. The AHP method was applied to develop lifetime prediction models using questionnaire responses as input (Ozer et al., 2018). The AHP was found to be applicable in this project in the absence of historical pavement condition. Therefore, the models were built based on expert opinion solicited through questionnaires. The lifetime prediction models will be represented as linear deterioration of pavement condition under critical factors which are also determined by the questionnaire responses.

The input obtained from the questionnaires were used to develop coefficients of the model. Three parameters were included to develop a linear-life estimation model as follows: the existing pavement condition, traffic volume and truck percentage. The models were only developed for asphalt-pavement preservation treatments. The lifetime range was selected from the literature review. Questionnaires responses are shown in Table 2.0 and were recommended to the user as default. The user is recommended to input a reasonable value to build the preservation schedule for concrete pavement preservation and maintenance.

5.2 TREATMENT SELECTION DECISION TREE

Rehabilitation and preservation decision trees are tree-like models commonly used as a decision support tool to educate and guide decision makers in selecting the optimum rehabilitation or preservation treatment for a given project. In this study, the decisions trees were developed to determine the schedule of activities. The decision trees were adopted from the methods recently developed for IDOT's Bureau of Design and Environment manuals Chapters 52 and 53. The decision tree approach allows for an easy and efficient treatment selection process incorporated in the software tool.

5.2.1 AC-surfaced Pavements

Primary decision-making variables for this study are traffic volume and existing pavement conditions with select critical distresses. The decision trees start with the AADT to differentiate the different levels of preservation techniques, as shown in Figure 0.2. The idea is to categorize major and minor treatments and use traffic volume as the initial decision-making variable to select one of those categories.

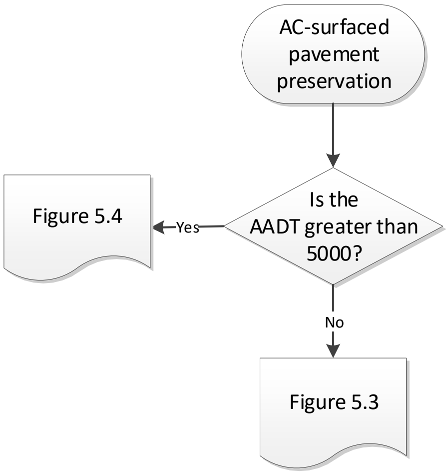


Figure 0.2 Decision tree for AC-surfaced pavement preservation

The second level of decision making depends on the distress severity and extent (Table 5.1). Severity indicates the degree of distress while the extent describes the range of distress. These criteria can comprehensively evaluate the pavement condition and are helpful in determining the right treatments given the condition of the pavement.

Table 0.1 AC Distress Severity and Extent (IDOT, 2010; Abdelaty et al., 2015)

Distress	Severity*		Extent*	
Alligator cracking	Low	Few connected cracks	Low	1-9% of wheel path affected
	Moderate	Interconnected cracks forming patterns	Moderate	10-24% of wheel path affected
	High	Severely interconnected cracks	High	More than 25% of wheel path affected
Rutting	Low	Mean depth < 7 mm	Low	1-9% of wheel path affected
	Moderate	Mean depth 7-12 mm	Moderate	10-24% of wheel path affected
	High	Mean depth > 12 mm	High	More than 25% of wheel path affected
Longitudinal cracking	Low	Mean width < 6 mm	Low	< 500 m/km
	Moderate	Mean width 6-19 mm	Moderate	500-1,000 m/km
	High	Mean width > 19 mm	High	≥ 1,000 m/km
Transverse cracking	Low	Mean width < 6 mm	Low	< 150 m/km
	Moderate	Mean width (6-19) mm	Moderate	150-300 m/km
	High	Mean width > 19 mm	High	≥ 300 m/km

*1 in = 25.4 mm

When the traffic volume is low (AADT less than or equal to 5,000), the first step is to check if existing pavement has any structural problems. If the pavement has severe structural problems (i.e. alligator cracking, rutting), the rehabilitation option should be applied. If the AADT is less than 1,000, CIR+chip seal or CIR+microsurfacing options are available instead of more costly rehabilitation options involving overlays, such as CIR+thin AC overlay and CIR+medium AC overlay.

If there are no severe structural problems, the second step is to check the PCI value of the existing pavement. If the PCI value is less than 60, rehabilitation options, such as HIR+thin AC Overlay, HIR+chip seal and HIR+microsurfacing, are recommended. If the PCI value is greater than 75, crack treatments, such as crack sealing/filling and fog seal, can be applied if longitudinal or transverse cracking is minor to moderate. Otherwise, surface treatments, such as AC overlays, cape seal, microsurfacing, slurry seal and chip seal, should be applied if longitudinal or transverse cracking is moderate to severe.

If PCI value is between 60 and 75, structural problems may not be present or can be minor or moderate. If the structural problems are moderate, major treatments, such as HIR+chip seal or HIR+microsurfacing, should be used when the AADT is greater than 1,000. Thin AC overlay or UTBWC are recommended when the AADT is less than 1,000. If the structural problems are minor or do not exist, crack treatments are recommended when longitudinal or transverse cracking are minor to moderate. Surface treatment options are recommended when longitudinal or transverse cracking are moderate to severe.

The branch of the decision tree for high traffic volume (AADT less than 5,000) follows the similar steps as shown in Figure 0.4. First, check the severity and extent of alligator cracking and rutting. When moderate to severe structural problems occur, rehabilitation techniques are recommended, such as CIR+thin AC overlay or CIR+medium AC overlay. If there are no severe structure problems, the second step is to check the overall condition of the pavement using PCI.

If the PCI value is less than 60, HIR+thin AC overlay is recommended. If PCI is between 60 and 75, use HIR+thin AC overlay if only moderate structural problems exist. If problems are minor, evaluate the longitudinal and transverse cracking distresses. Crack-filling and sealing treatments are recommended for minor to moderate non-structural distresses, and thin AC overlay and UTBWC are recommended for moderate to high cracking problems. If PCI is greater than 75, the pavement section is in good condition. Crack treatments are applied only if longitudinal and transverse cracking are minor. For moderate to server longitudinal and traverse cracking, apply a thin AC overlay and UTBWC.

5.2.2 Concrete Surfaced Pavements

The decision tree for concrete-surfaced pavements are developed based on the distress types and severity levels. Distress severity and extent level threshold values were obtained from the work of Abdelaty et al. (2015), as shown in Table 0.2. The primary decision parameter is the presence or absence of durability cracking. When there is durability cracking, such as D-cracking or ASR, the available treatment options are full-depth and partial-depth repairs.

If no durability problems exist, the next step is to differentiate between jointed plain or reinforced concrete pavements (JPCP or JRCP) and continuously reinforced concrete pavement (CRCP). For CRCP, crack treatments are recommended for pavements with a PCI greater than 80. Thin AC overlay and partial-depth repairs are applicable when the PCI is between 65 and 80. Full-depth repair, however, is required when the PCI is less than 65.

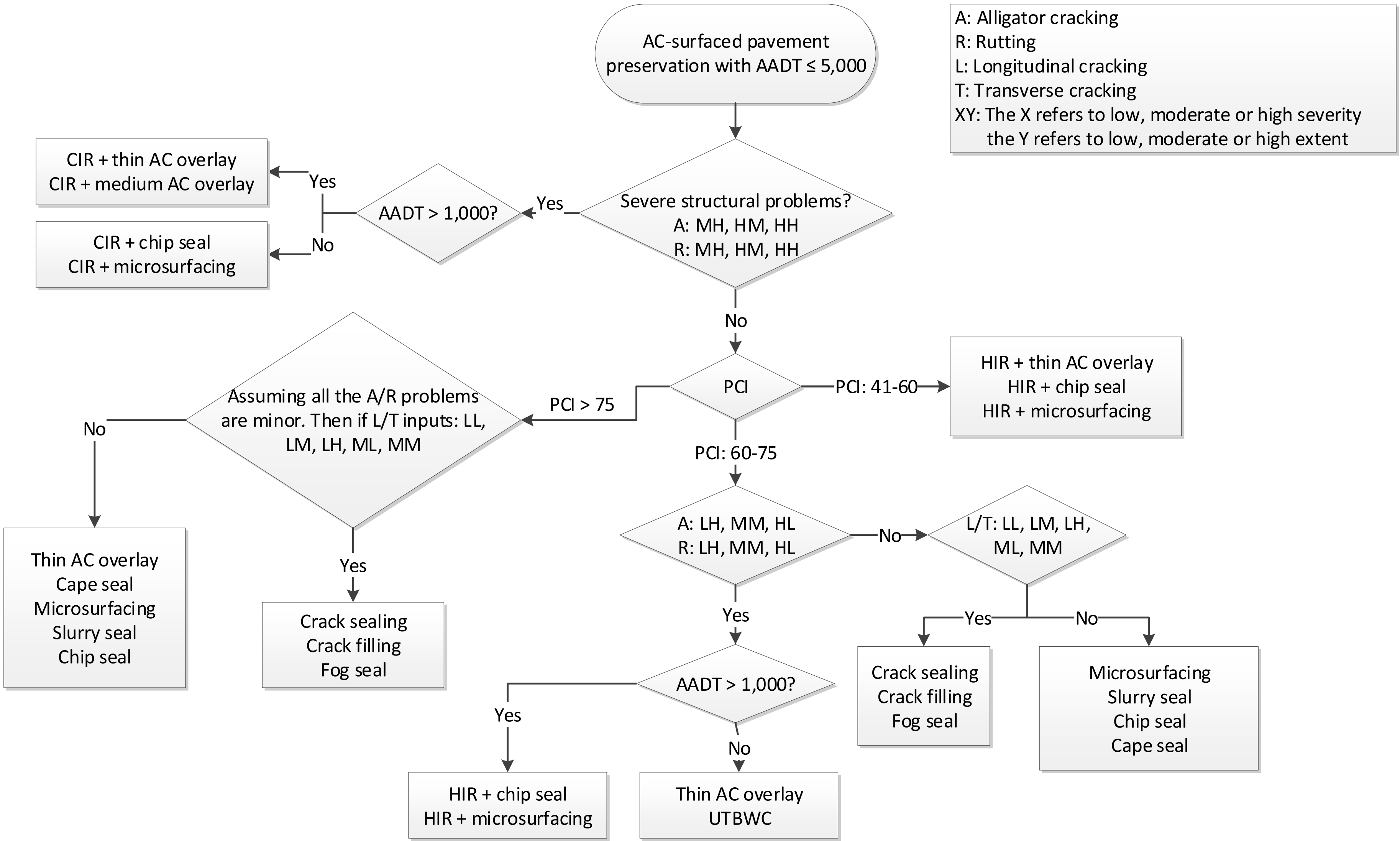


Figure 0.3 Pavement preservation treatment decision tree branch for AC-surfaced pavement under low traffic volumes

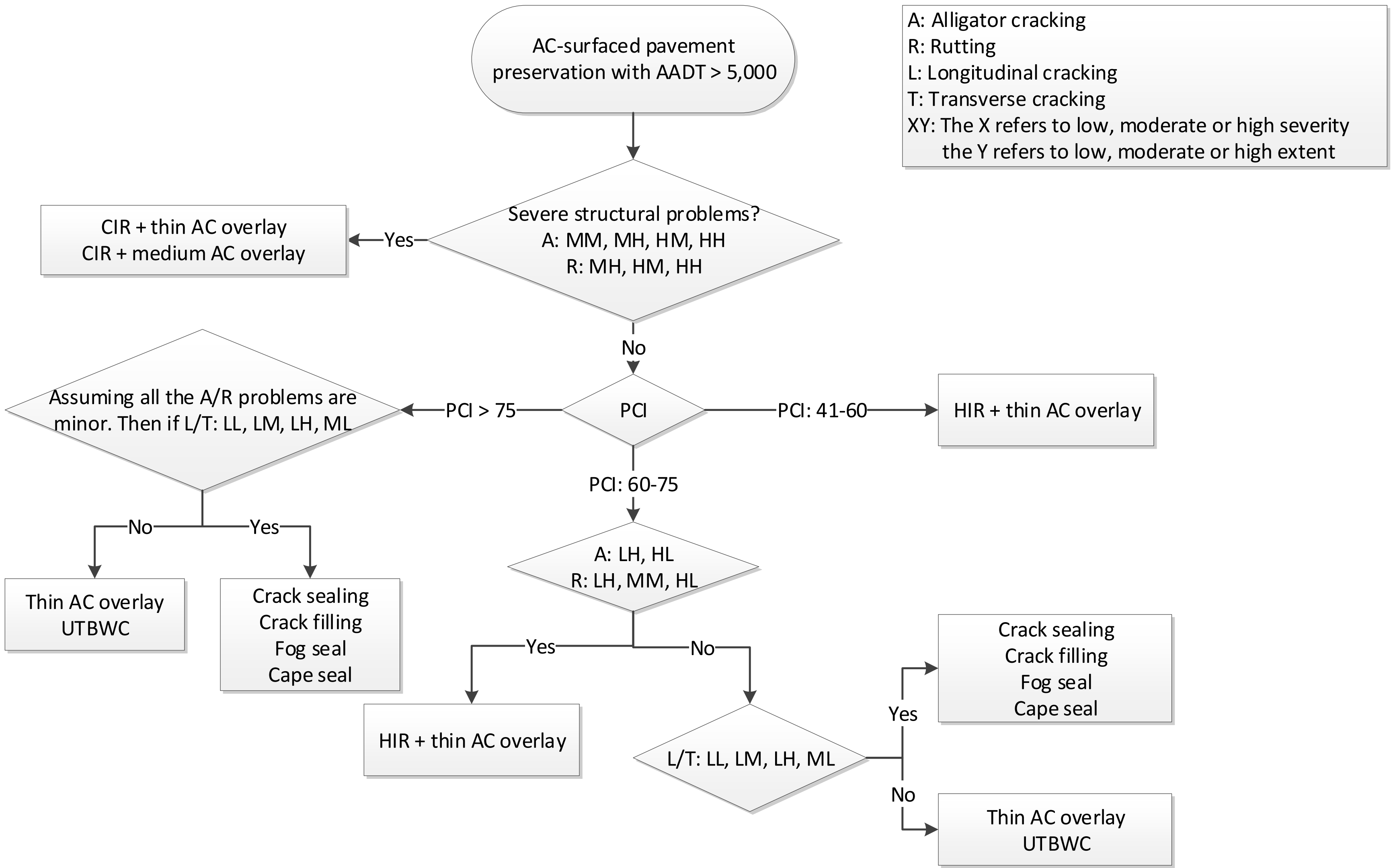


Figure 0.4 Pavement preservation treatment decision tree branch for AC-surfaced pavement under high traffic volumes

Table 0.2 PCC Distresses Severity and Extent Level

Distress	Severity		Extent	
Transverse cracking	Low	Mean width < 3 mm	Low	< 75 m/km
	Moderate	Mean width 3-6 mm	Moderate	75-149 m/km
	High	Mean width ≥ 6 mm	High	≥ 150 m/km
Longitudinal cracking	Low	Mean width < 3 mm	Low	< 125 m/km
	Moderate	Mean width 3-13 mm	Moderate	125-249 m/km
	High	Mean width ≥ 13 mm	High	≥ 250 m/km
D-cracking	Low	Tight with no loose pieces	Low	1-9% of slab affected
	Moderate	Well-defined cracks	Moderate	10-24% of slab affected
	High	Well-developed pattern	High	More than 25% slab affected
Faulting	Low	Fault < 5 mm	Low	1-9% of slab affected
	Moderate	Fault 5 to 7.5 mm	Moderate	10-24% of slab affected
	High	Fault > 7.5 mm	High	More than 25% slab affected
Joint spalling	Low	Joint width <12.7 mm and/or spalling <75 mm	Low	1-9% of slab affected
	Moderate	Joint width 12.7 to 25.4 mm and/or spalling 75-150 mm	Moderate	10-24% of slab affected
	High	Joint width > 25.4 mm and/or spalling > 150 mm	High	More than 25% slab affected

*1 in = 25.4 mm

For jointed pavements, dowel-bar retrofitting and diamond grinding is necessary when the faulting problem is moderate to severe. If there is severe spalling problem, full-depth repair is required. Partial-depth repair is efficient for moderate spalling problems. If there is only minor faulting and spalling problems, treatments are selected based on the cracking conditions. Crack sealing/filling and UTBWC can be used when longitudinal and transverse cracking are minor. Thin AC overlay and partial-depth repair will be recommended when longitudinal and transverse cracking are moderate, and full-depth repair is used only in severe cracking conditions.

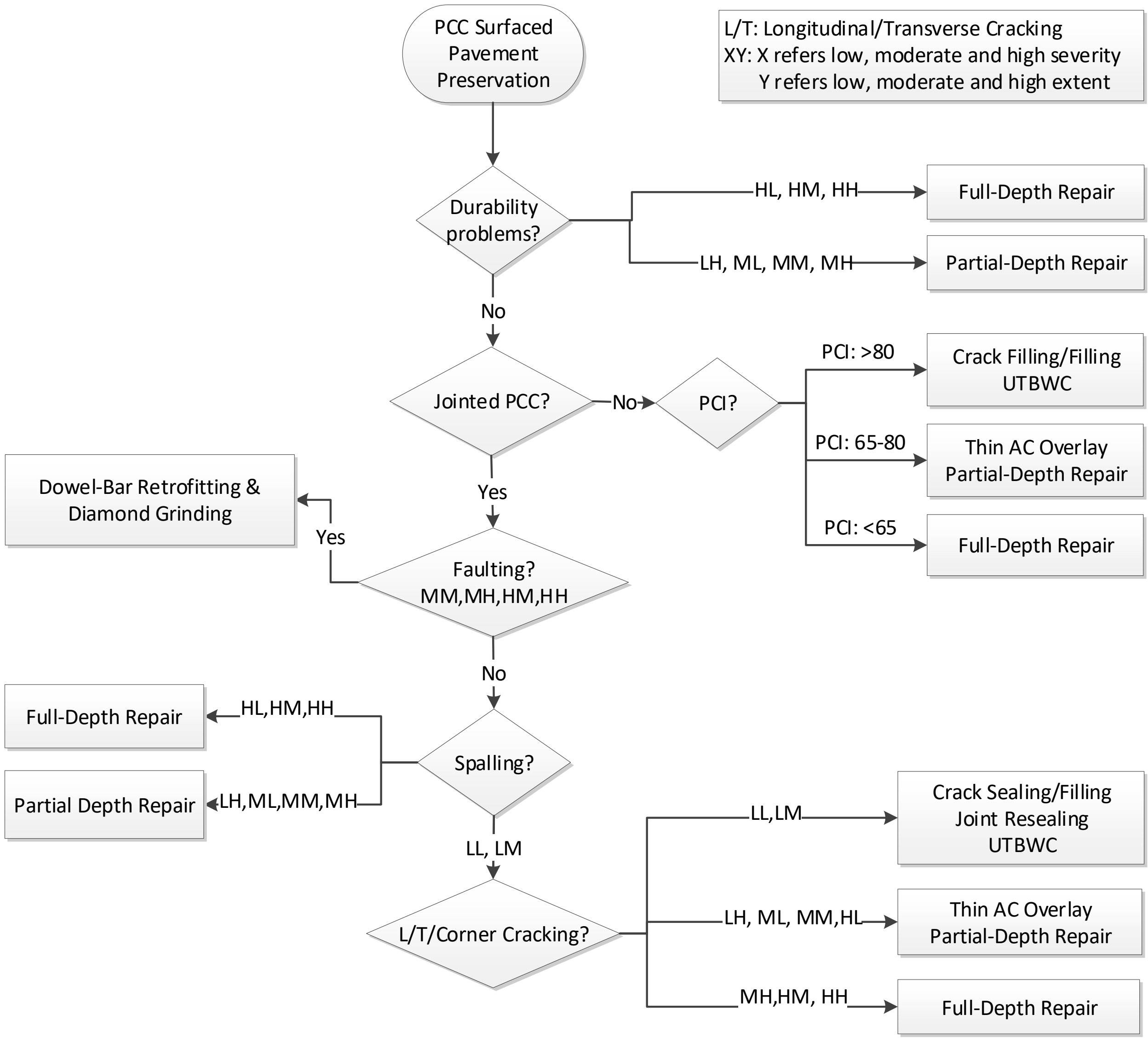


Figure 0.5 Decision tree for PCC-surfaced pavement preservation

5.3 PRESERVATION TREATMENT LIFETIME ESTIMATION

Lifetime estimation models were developed for different types of preservation activities using information collected in the questionnaires. The questionnaires were designed with a method that allowed for development of performance models based on expert opinion.

The analysis procedure to build a generalized lifetime-estimation framework starts with the selection of a basic linear model form. Major factors affecting the deterioration rate are then determined, and they include: traffic volume, truck percentage and existing pavement condition. Next, model coefficients were computed in terms of adjustments using the responses obtained through the questionnaires. Each step of the analysis procedure can be seen in Figure 5.6, and steps will be discussed in detail in the following subsections.

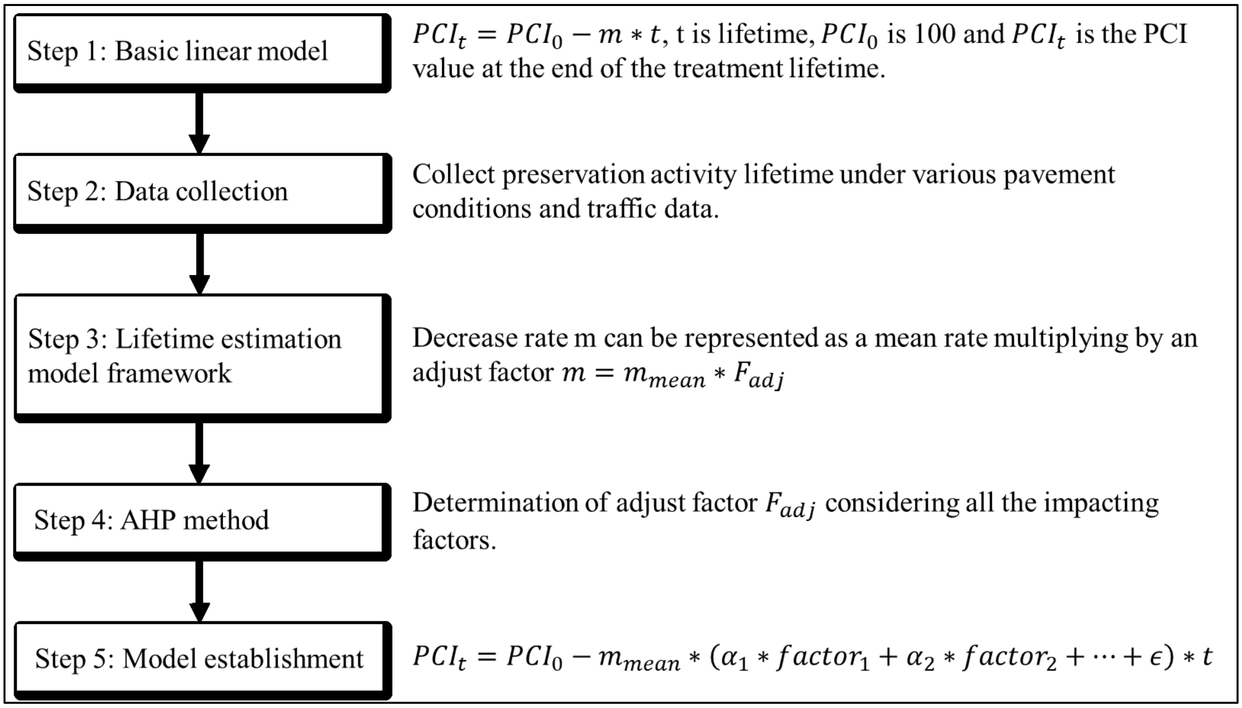


Figure 0.6 Lifetime-estimation model analysis procedure

5.3.1 Basic Linear Model

PCI was chosen as the pavement condition measure because it is a nationwide standard, even though some DOTs use customized condition indices (ASTM 6433-18). As with many other pavement condition measures, the PCI value will decrease with time. Deterioration can be linear or nonlinear depending on the window of analysis period, pavement type and other factors — such as traffic, environment, base conditions, etc. It is a common practice that preservation treatments are not recommended when the PCI is below 65.

A simple linear model was found to be appropriate for preservation treatments since the lifetime window is short and can be expressed accurately by fitting a linear model, as given in Equation 5.1. In addition, performance deterioration models are used only to predict the number of years it takes to reach a terminal condition index.

$$PCI_t = PCI_0 - m * t \tag{5.1}$$

PCI_0 is the PCI value right after the preservation treatment. PCI_t is the PCI value at that present year. The pavement condition deterioration rate after applying preservation treatment is m, and t is the time elapsed from PCI_0 to PCI_t.

PCI_0 is assumed to be 100 right after treatment. Terminal condition of the pavement at a time ($PCI_{terminal}$) is assumed to be 40 as a threshold for major rehabilitation or reconstruction. Thus, lifetime (t) can be calculated when the pavement condition deterioration rate after applying pavement treatment (m) value is known. The deterioration rate can be dependent on many different factors. Parameters to adjust the deterioration rate were determined through questionnaires.

5.3.2 Data Information

As discussed in Chapter 4.1, using collected data in question type (1), the three conditions for preservation activities were presented as follows:

- Poor condition: high AADT (95,000), high truck percentage (16%) and poor existing pavement condition (PCI = 65).
- Average condition: high AADT (50,000), high truck percentage (10%) and fair existing pavement condition (PCI = 75).
- Good condition: low AADT (5,000), low truck percentage (4%) and good existing pavement condition (PCI = 85).

Based on boundary conditions, an average condition can be determined with the average AADT (50,000), average truck percentage (10%) and fair existing pavement condition (PCI = 75).

In addition, agencies were asked in question type (3) to estimate the lifetime (L) (in years) that elapsed from the application of the preservation treatment to a major rehabilitation or reconstruction activity (see Table 0.3). Since PCI_0 and PCI_t in Equation 5.1 are set to be 100 and 40, respectively, the deterioration rates (m) (the PCI reduction per year) can be computed using Equation 5.2 (IDOT, 2012). The results are shown in Table 0.3.

$$m = \frac{PCI_t - PCI_0}{L} \tag{5.1}$$

Table 0.3 Lifetime and Deterioration Rate of Preservation Treatments

Treatment	Lifetime (L) (years)			Deterioration Rate (m) (PCI/year)		
	Poor	Good	Average	Poor	Good	Average
Microsurfacing	5.4	6.6	6.0	11.2	9.1	9.9
Thin AC overlay (< 2 in)	7.7	9.7	8.77	7.75	6.17	6.84
CIR+Thin AC overlays (< 2 in)	8.9	10.3	9.6	6.8	5.9	6.3
CIR+Medium AC overlays (2-4 in)	10.9	11.5	11.2	5.5	5.2	5.3
HIR+Thin AC overlays (< 2 in)	7.5	9.2	8.4	8.0	6.5	7.1
Slurry seal	4.1	5.4	4.8	14.5	11.0	12.5
Chip seal	5.8	7.4	6.6	10.3	8.1	9.1

Treatment	Lifetime (L) (years)			Deterioration Rate (m) (PCI/year)		
	Poor	Good	Average	Poor	Good	Average
UTBWC	7.1	8.7	7.9	8.4	6.9	7.6
Cape seals	5.4	7.7	6.5	11.0	7.8	9.2
Fog seals	3.4	3.8	3.6	17.9	16.0	16.9
Bonded-concrete overlays of asphalt pavement	12.7	13.8	13.3	4.7	4.3	4.5

The next step is to determine factors affecting deterioration rate. The three factors considered for modeling deterioration rate are traffic volume (AADT), truck percentage, and the existing pavement condition.

Agencies were asked in question type (5) about the comparative importance of AADT, truck percentage and the existing pavement condition on the lifetime of each activity. An example question is given in Figure 0.7. Importance factors were placed on a scale from one to nine with one being the least relatively important and nine being the most relatively important. Responses to these types of comparative questions are used to develop model coefficients.

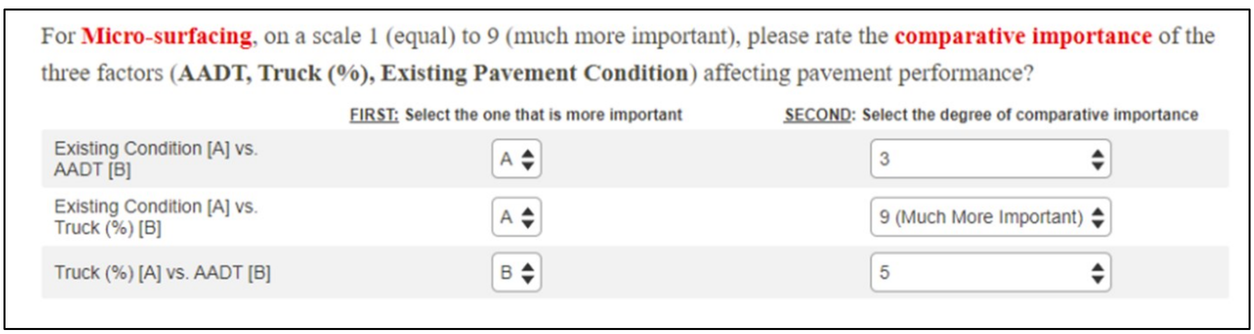


Figure 0.7 Example question of comparative importance

5.3.3 Preservation Lifetime-estimation Framework

After eliminating temperature, the focus of the modeling was to capture the effects of AADT, truck percentage and the existing pavement condition. The three critical conditions presented to the experts for comparative assessment were introduced as poor, medium and good conditions.

The deterioration rate (m) and lifetime (L) under poor, good and average conditions can be represented using $m_{condition}$ and $L_{condition}$, where $m_{condition}$ is either m_{poor}, m_{good} or $m_{average}$ and $L_{condition}$ is either L_{poor}, L_{good} or $L_{average}$.

There are three data points to fit into Equation 5.1 for each preservation activity. Thus, the relationship between time and the PCI can fit into Equation 5.3.

$$PCI_t = PCI_0 - m_{condition} \times L_{condition} \tag{5.2}$$

An overall deterioration rate ($m_{condition}$) must be determined to capture the effects of the three critical factors. The most straightforward way is to fit a linear combination of those three factors to $m_{condition}$, as shown in Equation 5.4. As shown in Table 0.3, the data points of $m_{condition}$, however, are close with respect to their magnitude, which will increase the error in fitting Equation 5.4.

$$m_{condition} = \alpha \times PCI_{existing} + \beta \times \ln(AADT) + \gamma \times Tr + \epsilon \tag{5.3}$$

Thus, an adjustment factor (F_{adj}) was proposed to consider the impacts of AADT, truck percentage and the existing PCI. The $m_{condition}$ can then be computed by multiplying $m_{average}$ with F_{adj}. For each treatment, the deterioration rate (m) under different conditions can be rewritten as Equations 5.5, 5.6 and 5.7. It is noted that F_{adj_ave} is always equals to 1.

$$m_{good} = m_{average} \times F_{adj\_good} \tag{5.4}$$
$$m_{poor} = m_{average} \times F_{adj\_poor} \tag{5.5}$$
$$m_{average} = m_{average} \times F_{adj\_ave} \tag{5.6}$$

The next task is to fit the data points $\{X = (PCI_{existing}, AADT, Tr), Y = F_{adj}\}$ into Equation 5.8. The values of AADT are transformed to logarithmic space to be on the same scale with other parameters.

$$F_{adj} = \alpha \times PCI_{existing} + \beta \times \ln(AADT) + \gamma \times Tr + \epsilon \tag{5.7}$$

As described in Table 0.3, m_{good}, $m_{average}$ and m_{poor} are available to compute F_{adj_good}, F_{adj_ave} and F_{adj_poor}. Once these adjustment factors are known, Equation 5.8 can be fitted to Equations 5.9, 5.10 and 5.11.

$$F_{adj\_good} = \alpha \times PCI_{existing\_good} + \beta \times \ln(AADT_{good}) + \gamma \times Tr_{good} + \epsilon \tag{5.8}$$
$$F_{adj\_ave} = \alpha \times PCI_{existing\_ave} + \beta \times \ln(AADT_{ave}) + \gamma \times Tr_{ave} + \epsilon \tag{5.9}$$
$$F_{adj\_poor} = \alpha \times PCI_{existing\_poor} + \beta \times \ln(AADT_{poor}) + \gamma \times Tr_{poor} + \epsilon \tag{5.10}$$

There are four unknowns in the given equations, but only three equations indicate the lack of a unique solution. Thus instead of solving this equation set, weights were assigned to each impacting factor with respect to the corresponding preservation treatment, and then each adjustment factor can be further decomposed to three linear equations.

For example, a weighting vector — $w = (w_{PCI}, w_{AADT}, w_{Tr})$ — is assigned to a specific treatment and $w_{PCI} + w_{AADT} + w_{Tr} = 1$. The parameters ($F_{adj\_good}$, F_{adj_ave} and F_{adj_poor}) can be computed for each treatment. For each adjustment factor (F_{adj}), the existing PCI contributes by $w_{PCI} \times 100\%$, AADT assists by $w_{AADT} \times 100\%$, and truck percentage takes part by $w_{Tr} \times 100\%$.

Thus, the impacts of the existing PCI under different conditions are formulated as in Equations 5.12, 5.13 and 5.14.

$$F_{adj\_good} \times \mathrm{w_{pci}} = \alpha \times PCI_{existing\_good} + \epsilon_{\mathrm{pci}} \quad (5.11)$$
$$F_{adj\_ave} \times \mathrm{w_{pci}} = \alpha \times PCI_{existing\_ave} + \epsilon_{\mathrm{pci}} \quad (5.12)$$
$$F_{adj\_poor} \times \mathrm{w_{pci}} = \alpha \times PCI_{existing\_poor} + \epsilon_{\mathrm{pci}} \quad (5.13)$$

With the three data points ($\mathrm{PCI_{existing}}, F_{adj}$) which are under poor, average and good conditions, Equation 5.12, 5.13 and 5.14 can be linearly fitted to extract α and ϵ_{pci}. Similar equation sets may also derive the AADT factors and truck percentages, as shown in Equations 5.15 to 5.20:

$$F_{adj\_AADT\_good} = F_{adj\_good} \times w_{AADT} = \beta \times \ln(AADT\_good) + \epsilon_{\mathrm{AADT}} \quad (5.14)$$
$$F_{adj\_AADT\_ave} = F_{adj\_ave} \times w_{AADT} = \beta \times \ln(AADT_{ave}) + \epsilon_{\mathrm{AADT}} \quad (5.15)$$
$$F_{adj\_AADT\_poor} = F_{adj\_poor} \times w_{AADT} = \beta \times \ln\left(AADT_{poor}\right) + \epsilon_{\mathrm{AADT}} \quad (5.16)$$
$$F_{adj\_Tr\_good} = F_{adj\_good} \times w_{Tr} = \gamma \times Tr_{good} + \epsilon_{\mathrm{Tr}} \quad (5.17)$$
$$F_{adj\_Tr\_ave} = F_{adj\_ave} \times w_{Tr} = \gamma \times Tr_{ave} + \epsilon_{\mathrm{Tr}} \quad (5.18)$$
$$F_{adj\_Tr\_poor} = F_{adj\_poor} \times w_{Tr} = \gamma \times Tr_{poor} + \epsilon_{\mathrm{Tr}} \quad (5.19)$$

Following the same procedure as above, parameters ($\beta, \epsilon_{\mathrm{AADT}}$ and γ, ϵ_{Tr}) can be determined by linear regression as long as w_{AADT} and w_{Tr} are known. Last, the ϵ in Equation 5.21 is the summation of $\epsilon_{\mathrm{pci}}, \epsilon_{AADT}$ and ϵ_{Tr}.

$$\epsilon = \epsilon_{\mathrm{pci}} + \epsilon_{AADT} + \epsilon_{Tr} \quad (5.20)$$

The modeling procedure presented herein relies on the assumption of the weighting vector (*w*) for the modeling variables. Since there is no deterministic method to find these weights, the AHP method was used to combine the experts' opinions with a mathematical framework to approximate the weights of factors.

5.3.4 Analytical Hierarchy Process (AHP)

Saaty (1990) introduced the AHP method to simplify decision making under complex settings. By reducing complex decisions to a series of pairwise comparisons and then synthesizing the results, the AHP method allows constructing an objective decision-making framework based on a collection of subjective opinions. Consistency of the decision maker's evaluation may be checked to reduce possible bias in the process. AHP weighting criteria can be implemented in three simple consecutive steps, which are as follows:

1) Creating a comparison matrix between different factors
2) Checking the consistency of the comparison matrix
3) Generating a weighing vector for all factors

In this particular case, the different factors of interest are the AADT, truck percentage and the existing pavement condition. Weights for these factors will be assigned to the respective preservation activities.

Comparison Matrix

Because only three factors are considered in this study, a comparison matrix of m (3×3 matrix) with each pairwise comparison was introduced as an entry. In each m_{jk} entry of the matrix, m represents the importance of the j^{th} factor relative to the k^{th} factor (j, k $\in\{1,2,3\}$). If $m_{jk} > 1$, then the j^{th} factor is more important than the k^{th} factor. If $m_{jk} < 1$, then the j^{th} factor is less important than the k^{th} factor.

If two factors have the same importance, then m_{jk} is 1. The entries m_{jk} and m_{kj} satisfy the following constraint:

$$m_{jk} \times m_{kj} = 1 \tag{5.21}$$

$m_{jj} = 1$ for all j. The relative importance between two factors is measured according to a numerical scale, from one to nine, as shown in Table 0.4.

Table 0.4 Relative Scores

Value of m_{jk}	Interpretation
1	*j* and *k* are equally important
3	*j* is slightly more important than *k*
5	*j* is more important than *k*
7	*j* is strongly more important than *k*
9	*j* is absolutely more important than *k*
2,4,6,8	Intermediate values between any of the above two interpretations

The questionnaire format collects the comparative importance of factors for each preservation treatment (see the example in Figure 0.7). The responses collected reflect the experts' opinion based on their experience with the treatments' field performance or expectations. A comparative matrix can be generated from each response to compute the weighting vector; however, an extra step, which follows, is required to check the matrix consistency to ensure the validity of responses.

Checking Consistency

A strictly consistent matrix should ensure $m_{jk} = m_{jl} \times m_{lk}$ $(j, k, l \in \{1,2,3\})$, which indicates that pairwise comparisons are always in agreement with each other. For example, if the comparative importance of factor 2 to factor 1 (m_{12}) is 2 and the comparative importance of factor 3 to factor 1 (m_{13}) is 3, then the comparative importance of factor 3 to factor 2 (m_{23}) can only be 3/2.

Checking consistency assures the rationality of the inputs from the surveys or questionnaires. It is unreasonable, however, to expect that a comparative matrix from surveys or questionnaires is always consistent, especially in cases with multiple pairwise comparisons. Allowing margin for error to account for slight inconsistencies without disregarding the entire matrix is necessary. This is achieved by calculating a consistency index (CI), see Equation 5.23.

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{5.22}$$

λ_{max} is the maximum eigenvalue, and n is the row/column number of the comparative matrix. For strictly convex matrices, the maximum eigenvalue (λ_{max}) should be equal to the row or column number of the matrix; thus the CI equals to zero.

As the CI increases, the matrix becomes more inconsistent. To determine a threshold, Saaty (1990) introduced a random value index (RI), which entails generating 500 comparative matrices at random that are bound to the same constraints and computing as the average CI value. For different comparative matrixes' sizes, the RI value was computed by Saaty as shown in Table 0.5.

Table 0.5 RI Value

n	1	2	3	4	5	6	7	8	9	10	11
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.19	1.51

Finally, if $\frac{CI}{RI} < 0.1$, the comparison matrix is assumed to be within the consistency limits; otherwise it should be disregarded (Saaty, 1990).

In this study, not all responses from questionnaires passed the consistency check. The total number of comparative matrix responses and the number of matrixes that passed the consistency check are listed in Table 0.6. As for those comparative matrixes which do not pass the consistency check, the information is discarded.

Table 0.6 Comparative Matrix Consistency Check

Treatment name	**Total number of matrices**	**Consistent matrices**
Microsurfacing	16	7
Thin AC overlays	21	9
CIR + Thin AC overlays	15	9
HIR + Thin AC overlays	14	5
Slurry seal	13	7
Chip seal	21	11
UTBWC	15	9
Cape seal	15	8
Fog seal	19	6
BCOAP	16	6

Weighting Vector

For consistent matrices, the weighting vector is the normalized eigenvector corresponding to the largest eigenvalue. Since each response gives a different weighting vector, the final weighting vector computes the average of responses for each treatment. Four valid weighting vector examples for the corresponding treatment are shown in Figure 0.8. The final weighting vectors for each treatment are presented in Figure 0.9. The weights assigned to each modeling variable indicate that the existing pavement condition is the most critical factor affecting the deterioration rate followed by the truck percentage.

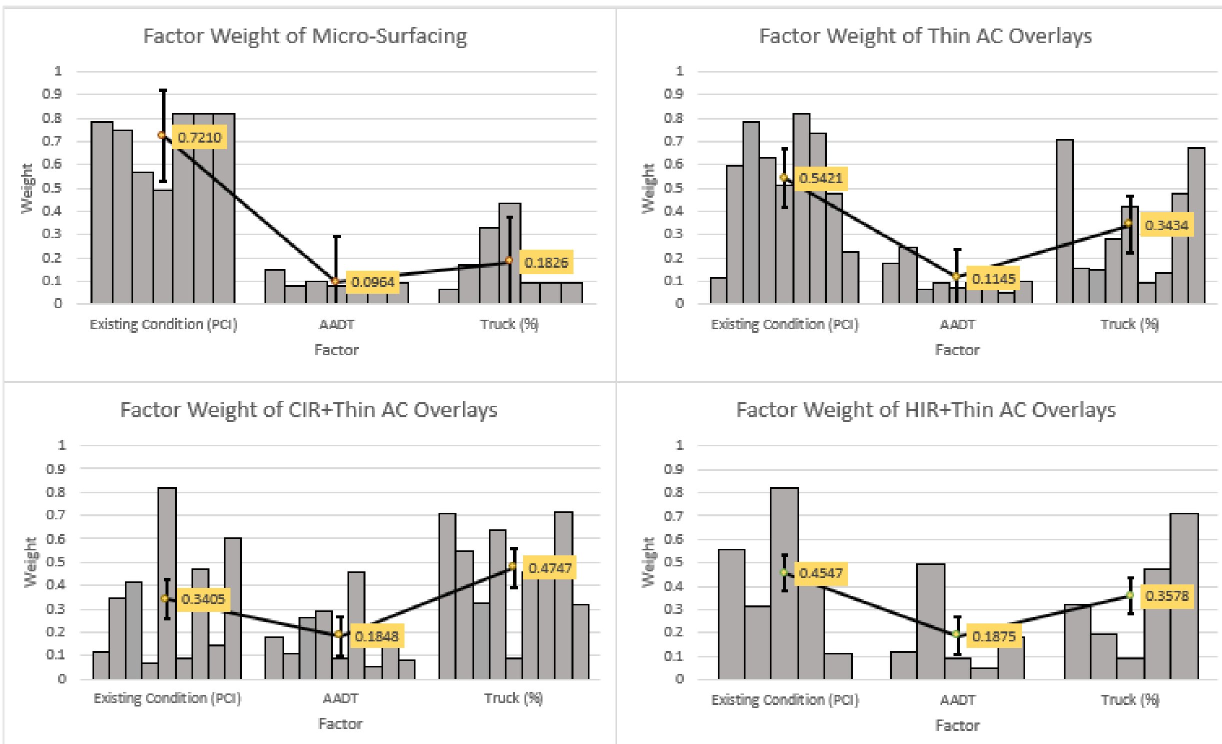


Figure 0.8 Example of four valid weighting vectors

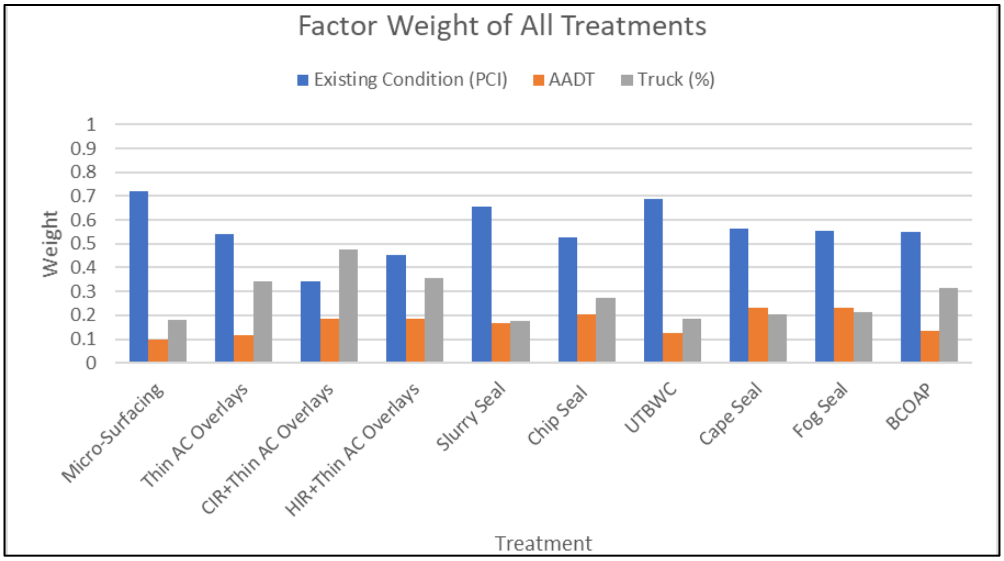


Figure 0.9 Three factors' weighting vectors for each preservation treatment

This procedure can be repeated for all preservation activities to calculate their corresponding model coefficients. In this study, due to insufficient responses for CIR+Medium AC overlay, the weighting vector for this treatment is assumed to be the same with CIR+Thin AC overlay. This is reasonable since these two treatments aim to solve similar problems. The lifetime estimation models for each treatment are summarized in Table 0.7.

Table 0.7 Lifetime Estimation Model for Asphalt Pavement Preservation Treatment

Treatment Type	**Lifetime Prediction Model**
Microsurfacing	PCI(t) = 100 – **9.93** × (**0.0044** * ln(AADT) – **0.0076** × PCI(0) + **0.0032** × Tr + **1.5105**) × t
Thin AC overlay (less than 2 inches)	PCI(t) = 100 – **6.84** × (**0.0058** * ln(AADT) – **0.0063** × PCI(0) + **0.0067** × Tr + **1.3668**) × t
CIR + Thin AC overlays (less than 2 inches)	PCI(t) = 100 – **6.27** × (**0.0058** * ln(AADT) – **0.0025** × PCI(0) + **0.0058** × Tr + **1.0801**) × t
CIR + Medium AC overlays (2 to 4 inches)	PCI(t) = 100 – **5.34** × (**0.0021** * ln(AADT) – **0.0009** × PCI(0) + **0.0021** × Tr + **1.0295**) × t
HIR + Thin AC overlays (less than 2 inches)	PCI(t) = 100 – **7.11** × (**0.0084** * ln(AADT) – **0.0047** × PCI(0) + **0.0062** × Tr + **1.2264**) × t
Slurry seal	PCI(t) = 100 – **12.54** × (**0.0098** * ln(AADT) – **0.009** × PCI(0) + **0.0041** × Tr + **1.557**) × t
Chip seal	PCI(t) = 100 – **9.09** × (**0.0108** * ln(AADT) – **0.0065** × PCI(0) + **0.0056** × Tr + **1.3425**) × t

Treatment Type	Lifetime Prediction Model
UTBWC	PCI(t) = 100 – **7.58** × (**0.0054*** ln(AADT) – **0.0070** × PCI(0) + **0.0031** × Tr + **1.451**) × t
Cape seals	PCI(t) = 100 – **9.21** × (**0.0176*** ln(AADT) – **0.0098** × PCI(0) + **0.0060** × Tr + **1.5325**) × t
Fog seals	PCI(t) = 100 – **16.9** × (**0.0107** * ln(AADT) – **0.0058** × PCI(0) + **0.0037** × Tr + **1.3175**) × t
Bonded-concrete overlays of asphalt pavement	PCI(t) = 100 – **4.52** × (**0.0024** * ln(AADT) – **0.0023** × PCI(0) + **0.0022** × Tr + **1.1314**) × t

Model Verification

The lifetime computed from the models are compared to the typical lifetime reported in literature for the corresponding treatments. The lifetime computed from the proposed models under two marginal conditions (poor and good) are considered as the bounds of each treatment's lifetime. Comparisons of the model bounds and literature review on the lifetime range are shown in Table 0.8.

An agreement exists between the literature and model bounds for most of the treatments; however, in general, the model bounds are tighter than the literature bounds. The literature bounds cover a wider range of AADT, PCI and truck percentage than the range reported by the experts in the survey.

Table 0.8 Model Results and Literature Review Data Comparison

Treatment type	Lifetime from model (years)		Lifetime from literature review (1)(2)(3)
	Poor condition	Good condition	
Microsurfacing	5.4	6.6	[5, 7]
Thin AC overlay (< 2 in)	7.7	9.7	[7, 11]
CIR+Thin AC overlays (< 2 in)	8.9	10.4	[10, 12]
CIR+Medium AC overlays (2-4 in)	10.9	11.5	[10, 18]
HIR+Thin AC overlays (< 2 in)	7.5	9.2	[10, 15]
Slurry seal	4.1	5.4	[3, 6]
Chip seal	5.8	7.4	[5, 7]
UTBWC	7.1	8.7	[7, 12]
Cape seals	5.4	7.7	[7, 10]
Fog seals	3.4	3.8	[1, 4]
Bonded-concrete overlays of asphalt pavement (BCOAP)	12.7	13.8	> = 20

(1) Wu et al., 2010

(2) Alan, 1999
(3) Peshkin et al., 2011

Lifetime of treatments can be calculated by changing the range of variables to extreme cases, as shown in Table 0.9 and Table 0.10. Despite the extreme conditions assigned, the lifetime model estimation did not vary significantly. For example, BCOAP's lifetime is still over 10 years — even if it is applied under extremely poor conditions — given that the questionnaire inputs used to build the lifetime models are limited to the range of conditions that do not represent some of the extreme cases.

Even though these models cannot always provide an accurate lifetime under all types of climatic conditions, they can be used as an initial estimate of the lifetime using three key variables. The user has the option to adjust the lifetime based on historical performance of the treatments in the selected region. The models could be improved with the incorporation of more collected responses; more data help increase the models' stability.

Table 0.9 Treatments' Lifetime under Extremely Poor Conditions

Treatment types	**Extremely poor conditions:**			
	AADT = 120,000 Tr = 20% PCI (0) = 20	AADT = 150,000 Tr = 25% PCI (0) = 10	AADT = 200,000 Tr = 40% PCI (0) = 10	AADT = 300,000 Tr = 80% PCI (0) = 5
	Lifetime (years)			
Microsurfacing	4.1	3.9	3.7	3.4
Thin AC overlay (< 2 in)	6.1	5.7	5.2	4.5
CIR+Thin AC overlay (< 2 in)	7.9	7.5	6.9	6.0
CIR+Medium AC overlays (2-4 in)	10.4	10.2	9.9	9.2
HIR+Thin AC overlays (< 2 in)	6.2	5.9	5.4	4.7
Slurry seal	3.0	2.8	2.7	2.4
Chip seal	4.6	4.3	4.0	3.5
UTBWC	5.5	5.2	5.0	4.6
Cape seals	3.9	3.6	3.4	3.0
Fog seals	2.5	2.4	2.3	2.1
BCOAP	11.5	11.1	10.7	10.0

Table 0.10 Treatments' Lifetime under Extremely Good Conditions

Treatment types	Extremely good conditions:			
	AADT = 1,000; Tr = 4% PCI(0) = 90	AADT = 500; Tr = 4% PCI(0) = 90	AADT = 500; Tr = 2% PCI(0) = 95	AADT = 150; Tr = 0% PCI(0) = 95
	Lifetime (years)			
Microsurfacing	7.0	7.0	7.4	7.5
Thin AC overlay (< 2 in)	10.3	10.3	10.9	11.0
CIR+Thin AC overlay (< 2 in)	10.6	10.6	10.9	11.0
CIR+Medium AC overlays (2-4 in)	11.6	11.6	11.7	11.8
HIR+Thin AC overlays (< 2 in)	9.7	9.7	10.1	10.3
Slurry seal	5.8	5.9	6.3	6.4
Chip seal	7.8	7.9	8.3	8.5
UTBWC	9.2	9.2	9.7	9.7
Cape seals	8.3	8.4	9.2	9.5
Fog seals	4.1	4.1	4.3	4.3
BCOAP	14.0	14.1	14.3	14.4

5.4. DO-NOTHING SCENARIO

An additional scenario was added to the comparative assessment to quantify the benefits and trade-offs of a preservation program. As shown in Figure 0.1 Pavement preservation schedule design schematic, preservation and maintenance schedules are comprised of a series of minor and major treatments; however, sometimes treatment application can be delayed due to various reasons. Therefore, do-nothing option was added to capture such a scenario and also allow the user to quantity the cost and benefit of timely applied preservation activities. When a do-nothing approach is selected, pavement deterioration will continue until a treatment is applied.

One needs to enter the rate of deterioration on the existing pavement when no treatment option is chosen. The PCI progression of a typical asphalt pavement under three types of deterioration rates is shown in Figure 0.10. As the green line shows, it takes 18 years for a typical asphalt pavement's PCI to drop from 70 to 40 under a high deterioration rate if nothing is done. Although the data used in this figure cannot represent realistic PCI progression in pavements at present time, it can be used as a user reference to estimate the PCI drop.

Since this is a hypothetical scenario that is used to calculate benefits of preservation, it is deemed sufficient to use deterioration rates proposed by Shahin and Starr (1981) as default. For example, when the existing pavement PCI is 70 at present and preservation is delayed for two years, then the PCI is estimated to drop to 66; the orange line in Figure 0.10 under the high deterioration rate shows this. In this study, the user can always adjust the pavement deterioration rate instead of referring to Figure 0.10 when no treatments are applied. Thus, the PCI value can be estimated at the end of the do-nothing period.

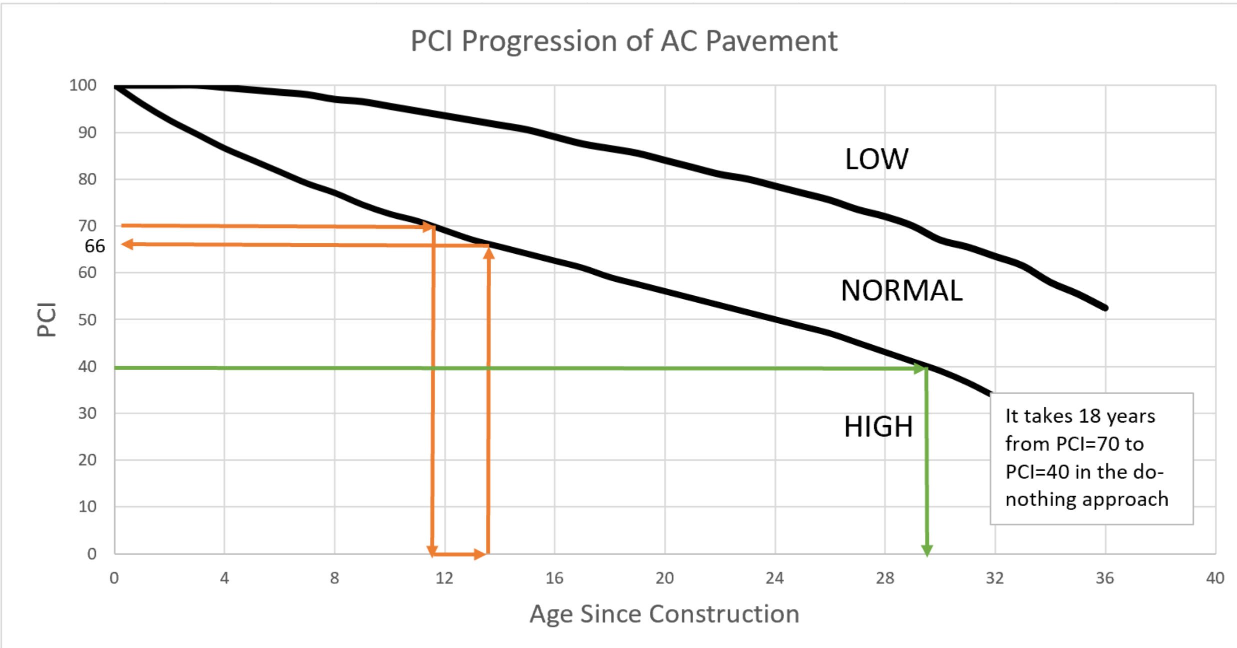


Figure 0.10 PCI progression of asphalt pavement (Shahin and Starr, 1981)

CHAPTER 6. TOOL DEVELOPMENT

6.1 OVERVIEW

The Preservation Sustainability Assessment Tool (PSAT) was developed with a user-friendly interface. The primary motivation of developing the PSAT tool is to provide data and necessary information to practitioners in the industry and programming engineers at state or local roadway agencies to make informed decisions on designing a preservation schedule considering sustainability impacts. The tool is equipped with a complete LCA with a regional inventory database for the entire U.S. to calculate environmental impact. The decision trees built into the tool can be used to design a schedule of activities and compare multiple preservation schedules for a given project location.

6.2 PROGRAMING PLATFORM

PSAT was developed using visual basic applications (VBA), an event-driven programming language in Microsoft® Excel. The front page of PSAT is shown in Figure 0.1. The tool is a series of user forms operated by macros — programmed instructions to automate a task. Macros allow modeling of the environmental impacts and performance of database-selected projects, which are built in Excel. The user form is a user-friendly, interactive platform to enter required data to compile the final outputs. Key terms of the software tool are defined in Table 0.1.

Table 0.1 Key PSAT Terms and Definitions

Key terms	Definitions
Worksheet	A single page in an Excel workbook
Table	A special object available in Excel that contains column headers and advanced properties
Form controls	An interactive button, checkbox or other visual control that is directly implemented on a worksheet
Command button	A user-form control used to run a macro
Checkbox	A user-form control used to indicate a Boolean choice
Combo box	A user-form control to create a dropdown list
Page	A control existing on userforms that contains different sections associated to different project aspects
List box	A user-form box containing a list of multi-column information

The main objective of using VBA is to ease PSAT use and access to inventory databases and performance models for all transportation project stakeholders. Features that highlight PSAT's user-friendliness are as follows:

- Worksheets used to report data and review results
- Worksheet interfaces that include form controls to guide the user in project analysis
- Error messages prompt invalid user inputs or questionable choices

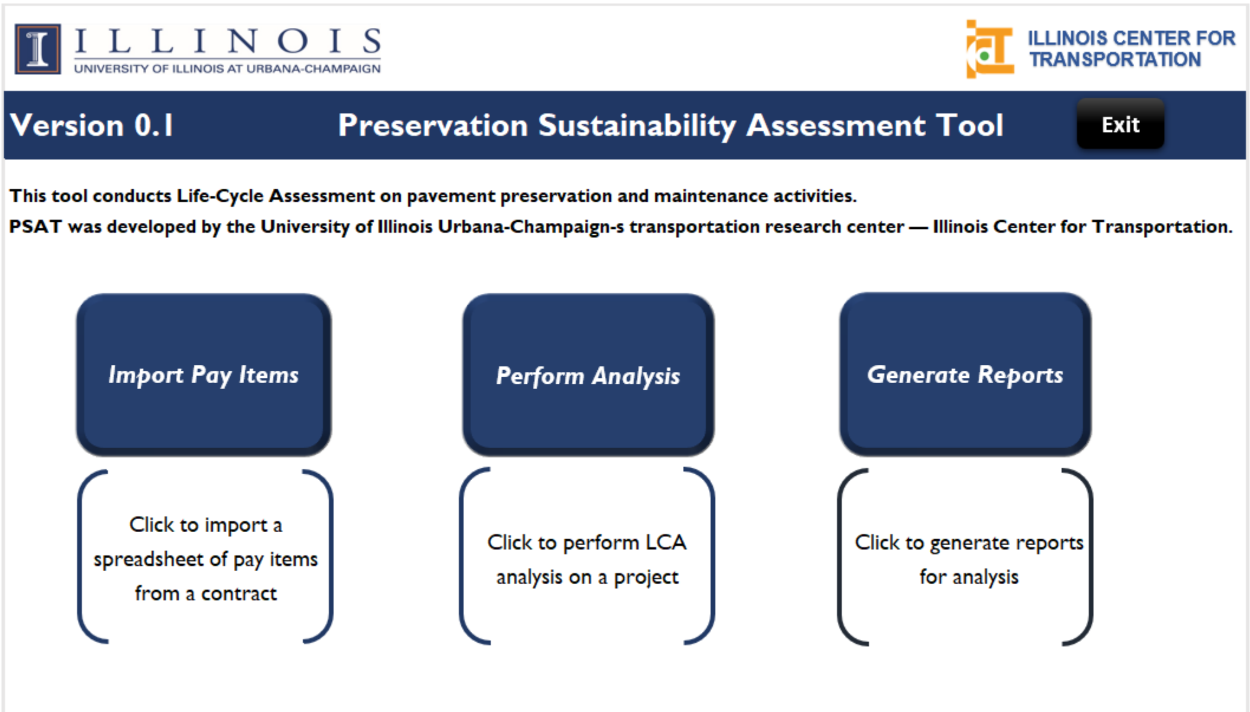


Figure 0.1 PSAT home page

6.3 MODULES

PSAT includes material production, construction, work zones and preservation and maintenance treatments' use stages. Users need to go through the steps shown in Figure 0.2 to conduct the LCA on the designed preservation and maintenance schedule.

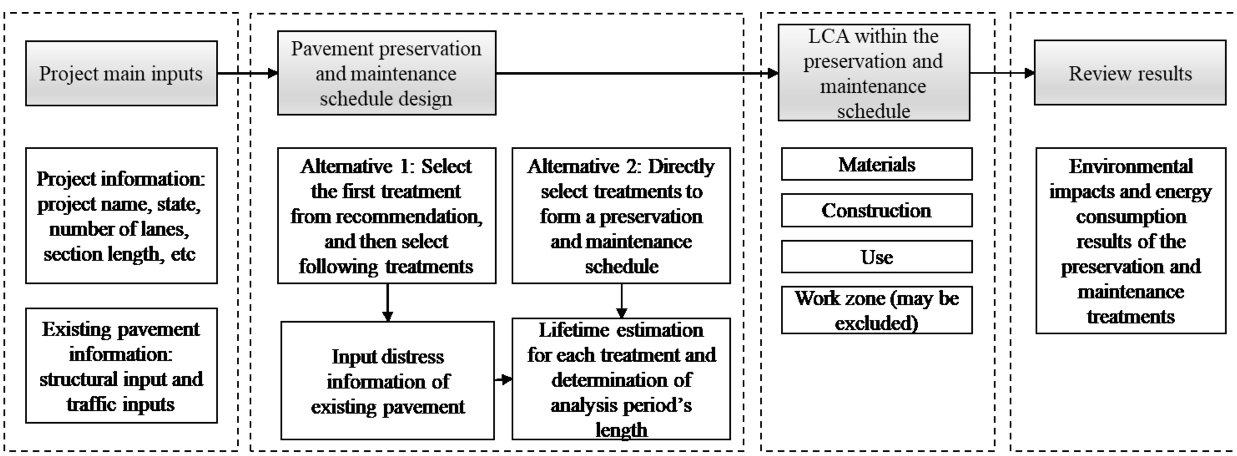


Figure 0.2 PSAT framework schematic

6.3.1 Initial Inputs

Each analyzed project should start with the projection information loading page, as shown in Figure 0.3. This page allows the user to enter or review project information. Additional and more specific inputs about pavement structure and traffic can be entered using the user forms, as shown in Figure 0.4.

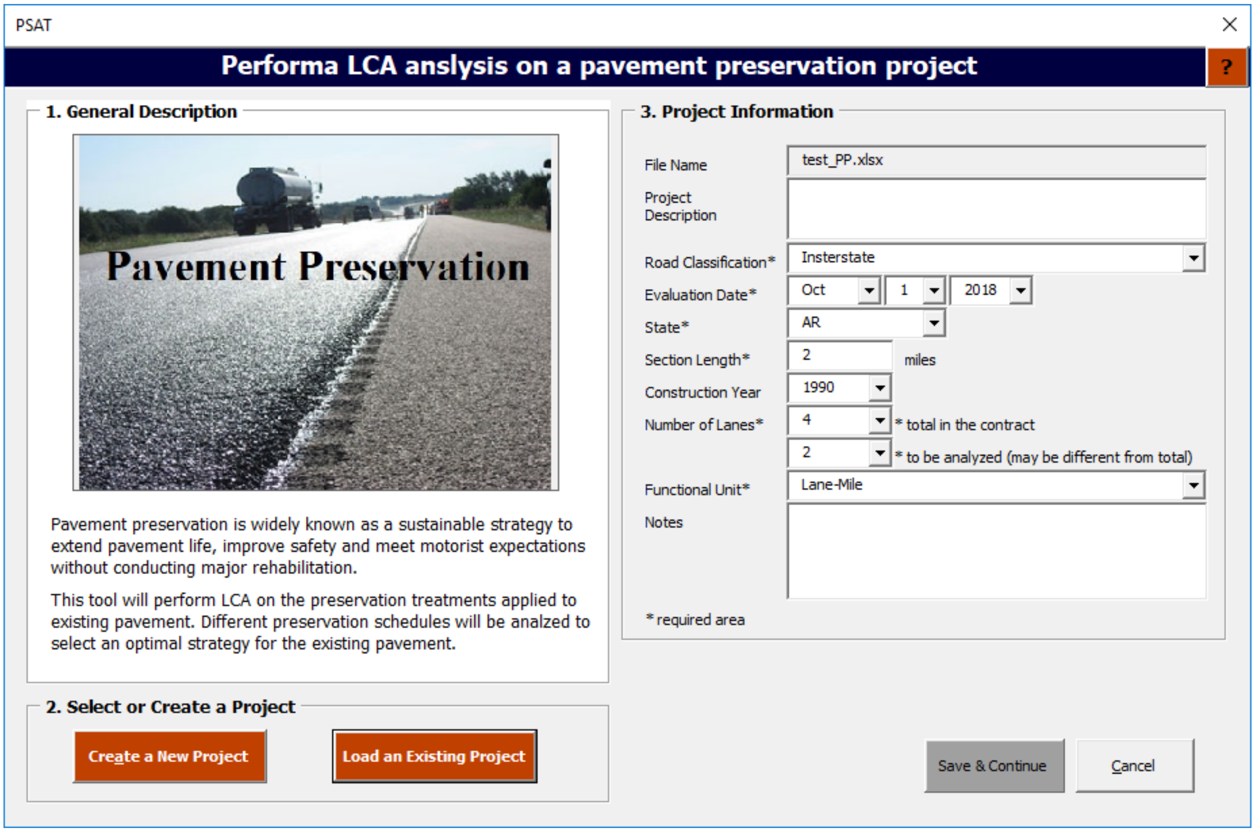


Figure 0.3 Project information loading page (user form)

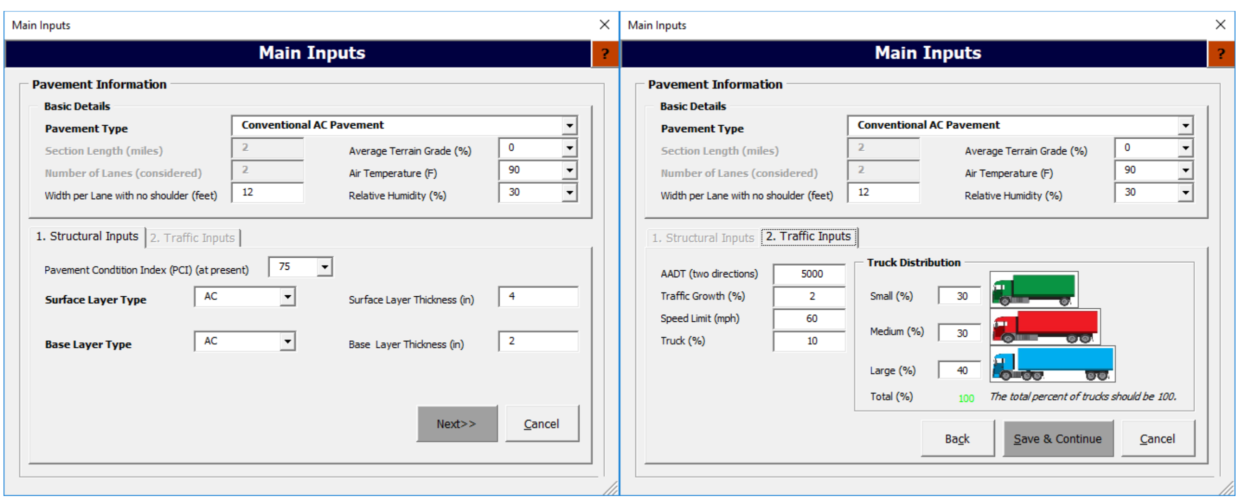


Figure 0.4 Main input page (user form)

Figure 0.5 illustrates the dependencies of project input and impact assessments. The tool was developed using the framework for each treatment or schedule of treatments.

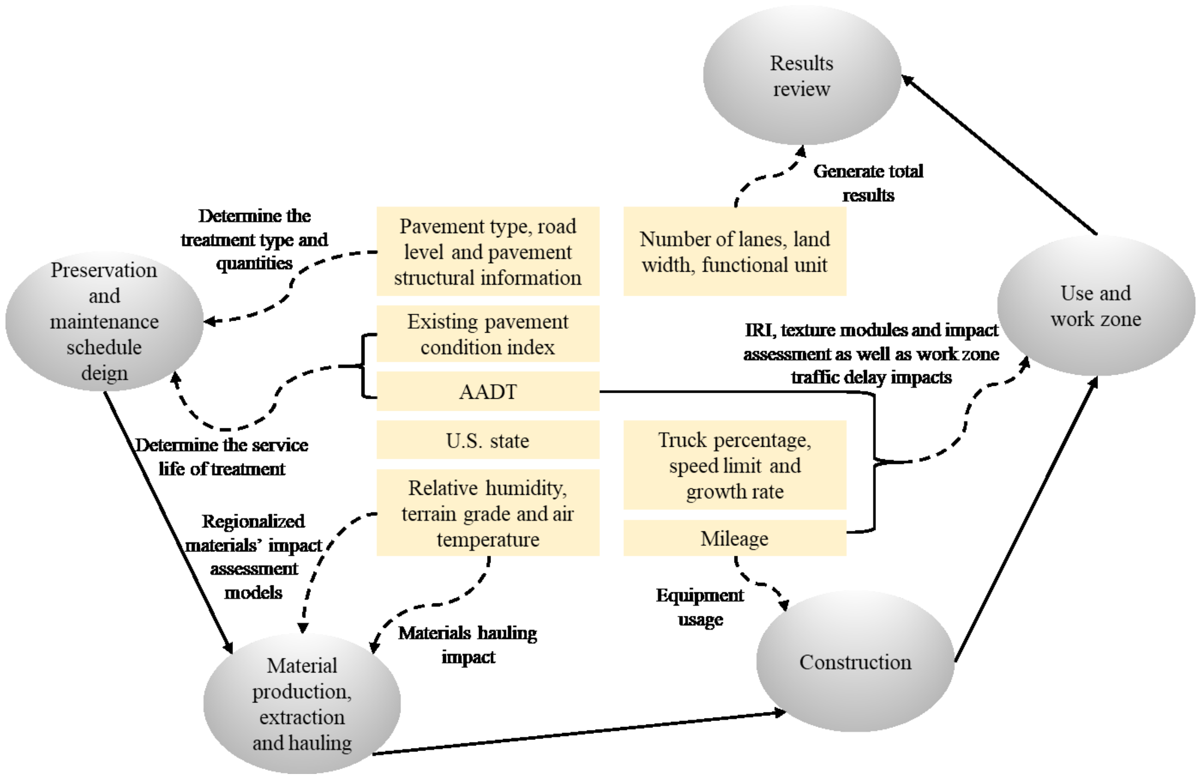


Figure 0.5 Impact assessment and project input dependencies

6.3.2 Preservation and Maintenance Schedule Design

There are two approaches to designing preservation and maintenance schedules:

- Approach No. 1: The user schedules treatments by adding them manually (see Figure 0.6). The lifetime will be calculated based on triggering the PCI value automatically.
- Approach No. 2: The user clicks the "Distress Inputs" option to select the first treatment, as shown in Figure 0.7. Available and recommended treatments will then be displayed. Alternatively, the user may select one of the appropriate treatments as the first treatment. Then, the user may click the "Add" option to select other treatments to set up a complete preservation and maintenance schedule. In the event that the user inputs a conflicting information, such as high PCI value and severe structural problems, the tool automatically gives a warning message and corrects it accordingly.

Each time a treatment is selected, related tasks and pay items need to be populated, as shown in Figure 0.6.

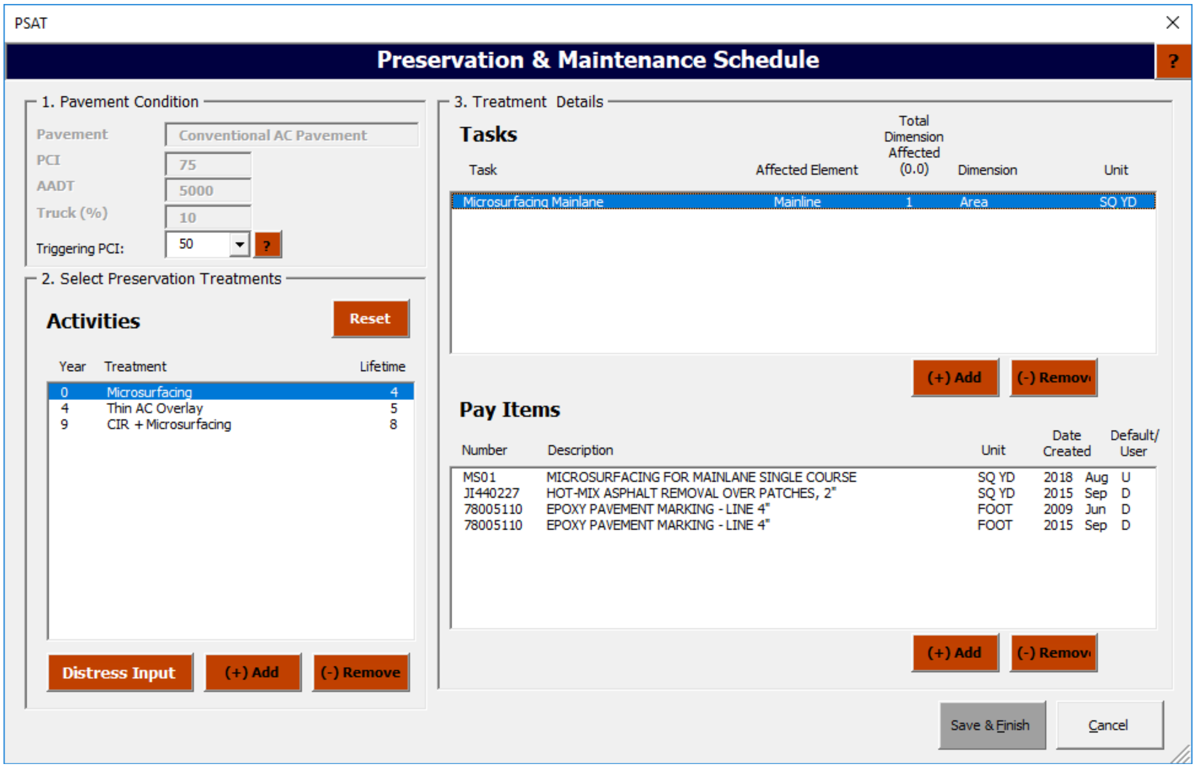


Figure 0.6 Preservation and maintenance schedule design

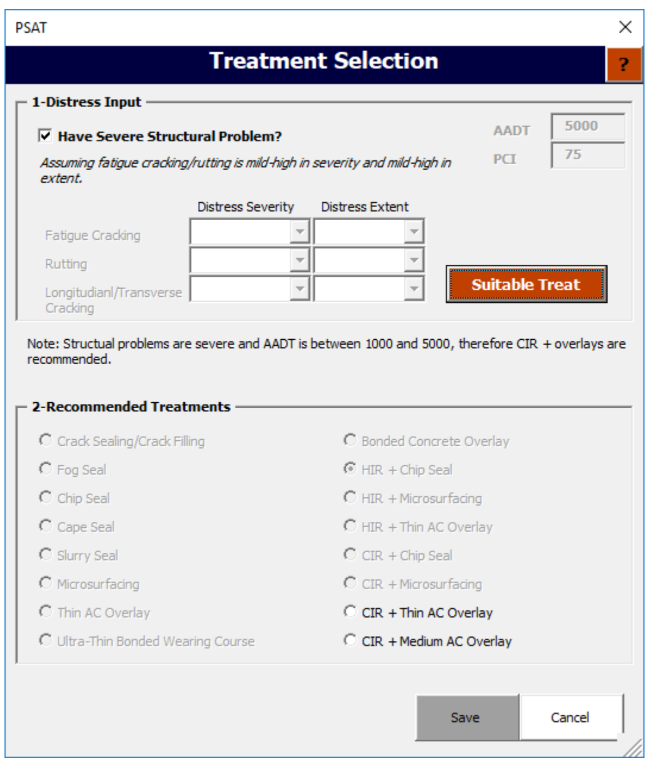


Figure 0.7 Treatment selection based on distress

6.3.3 Materials and Construction

After completing the treatment schedule design, the user is able to access all pay items added within that schedule (see Figure 0.8). These are default pay items populated for each treatment. The user may view, edit or add new pay items, as shown in Figure 0.8.

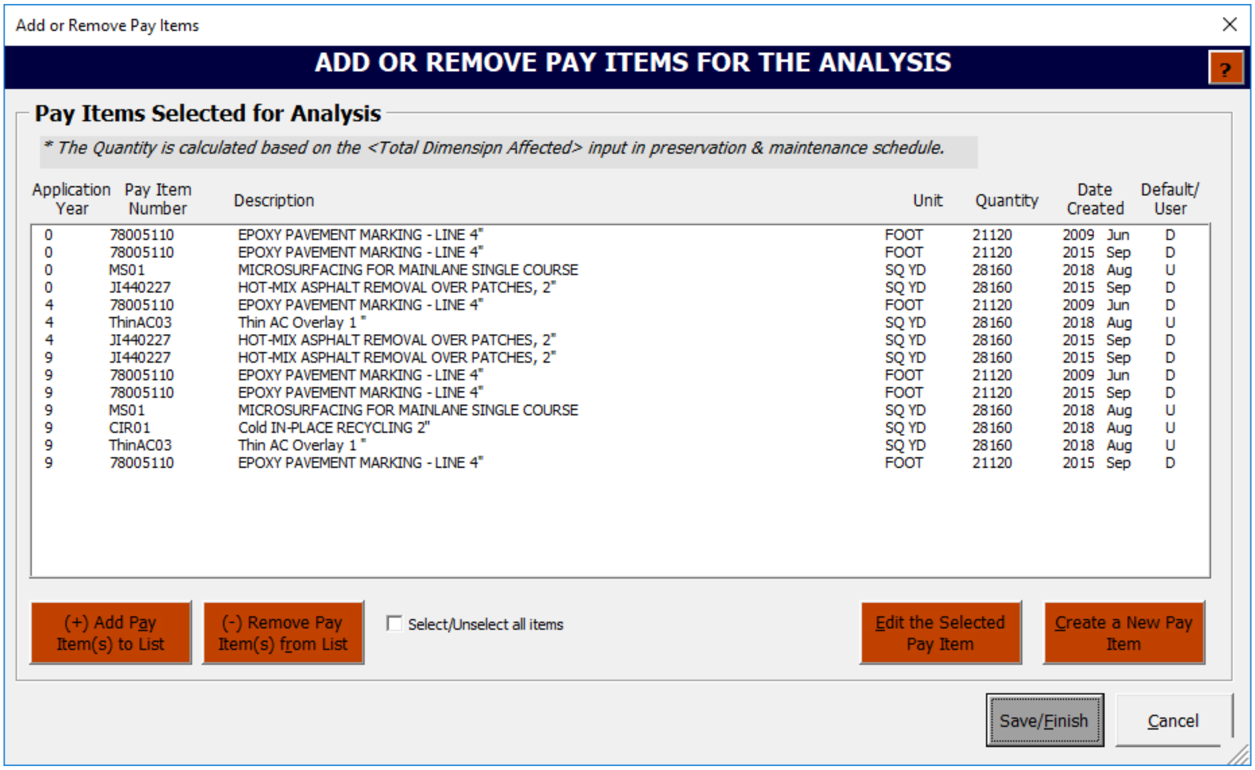


Figure 0.8 Pay items used in the project

The developed user forms for revising or creating a new pay item is illustrated in Figure 0.9 to Figure 0.12. The general page contains introductory information and inputs, such as name and description, units, productivity, cost, etc. In the material input page, the quantity of each material type and its hauling distance are entered.

All pay item materials are needed to be entered because the LCA is impacted by various material types. The equipment input page refers to the construction stage of the pay item. Each equipment used in the tasks has to be added. The impact calculation for the construction stage is due to number and type of equipment and fuel used as well as the fuel efficiency and mobilization distance.

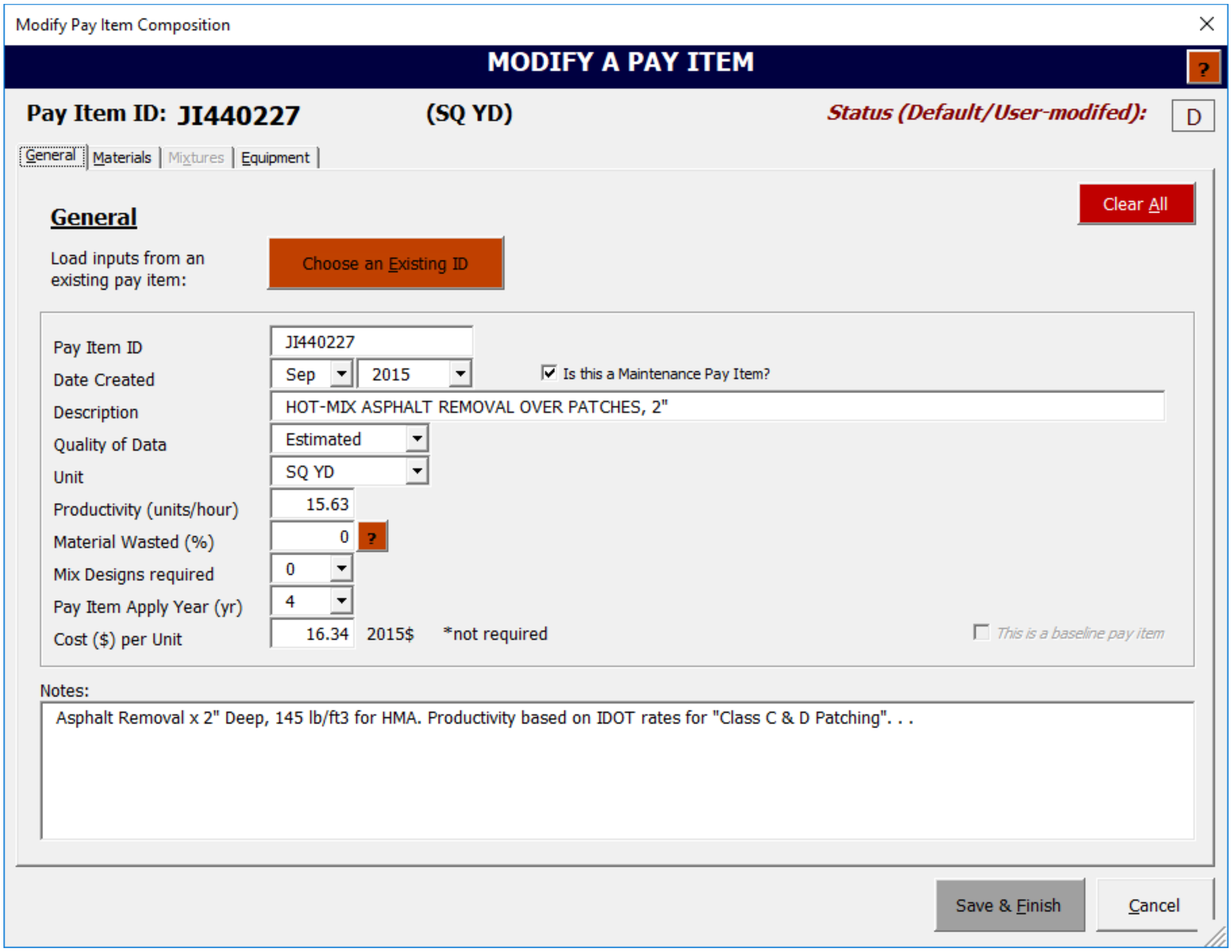


Figure 0.9 Pay item modification — general page

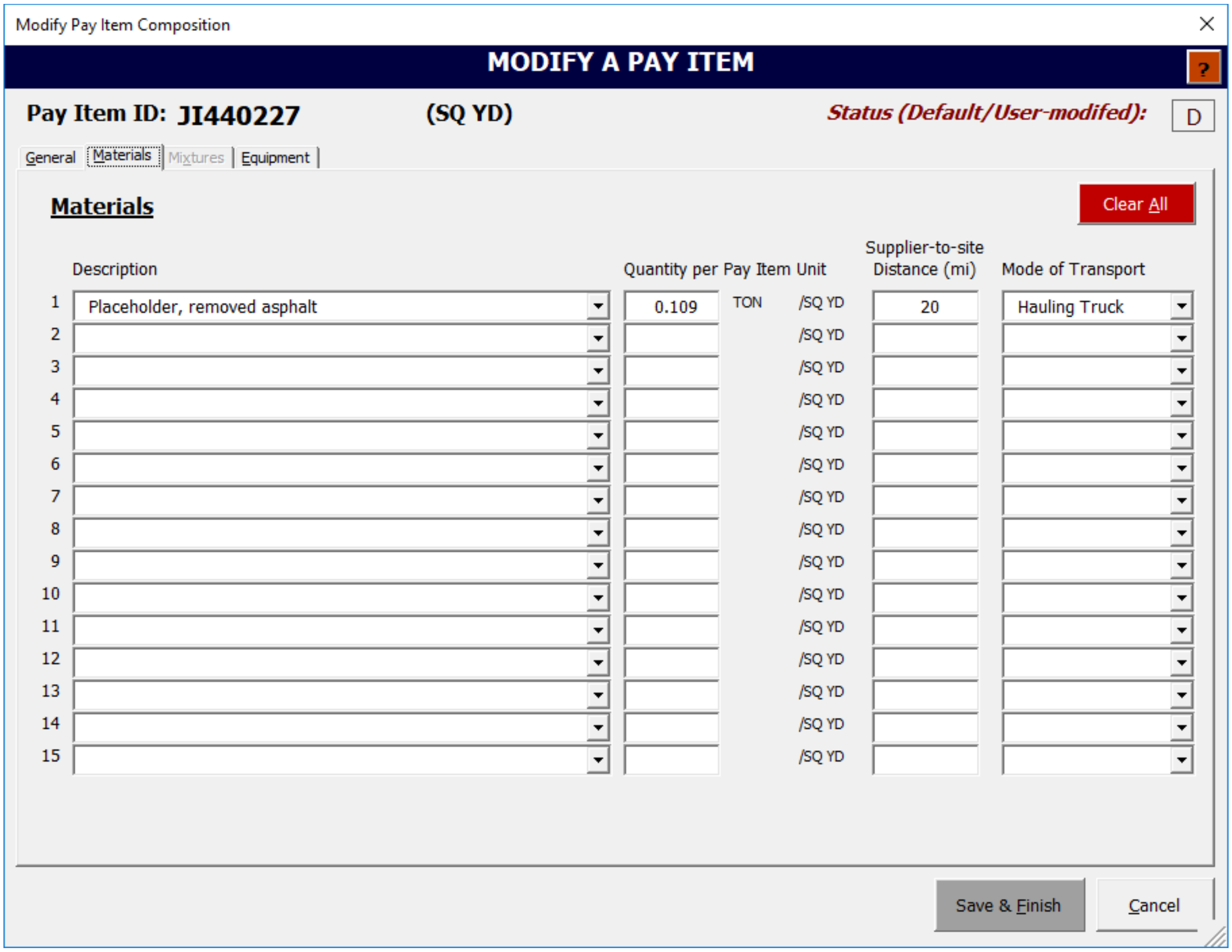


Figure 0.10 Modify a pay item — materials page

If the mix design is needed in the material input page, an extra user form should be completed, as shown in **Error! Reference source not found.**. Completing an extra user form allows the user to customize a mix design by presetting the air voids (percentage), asphalt content (percentage) and maximum specific gravity (G_{mm}) as well as select the material types used in the mix design.

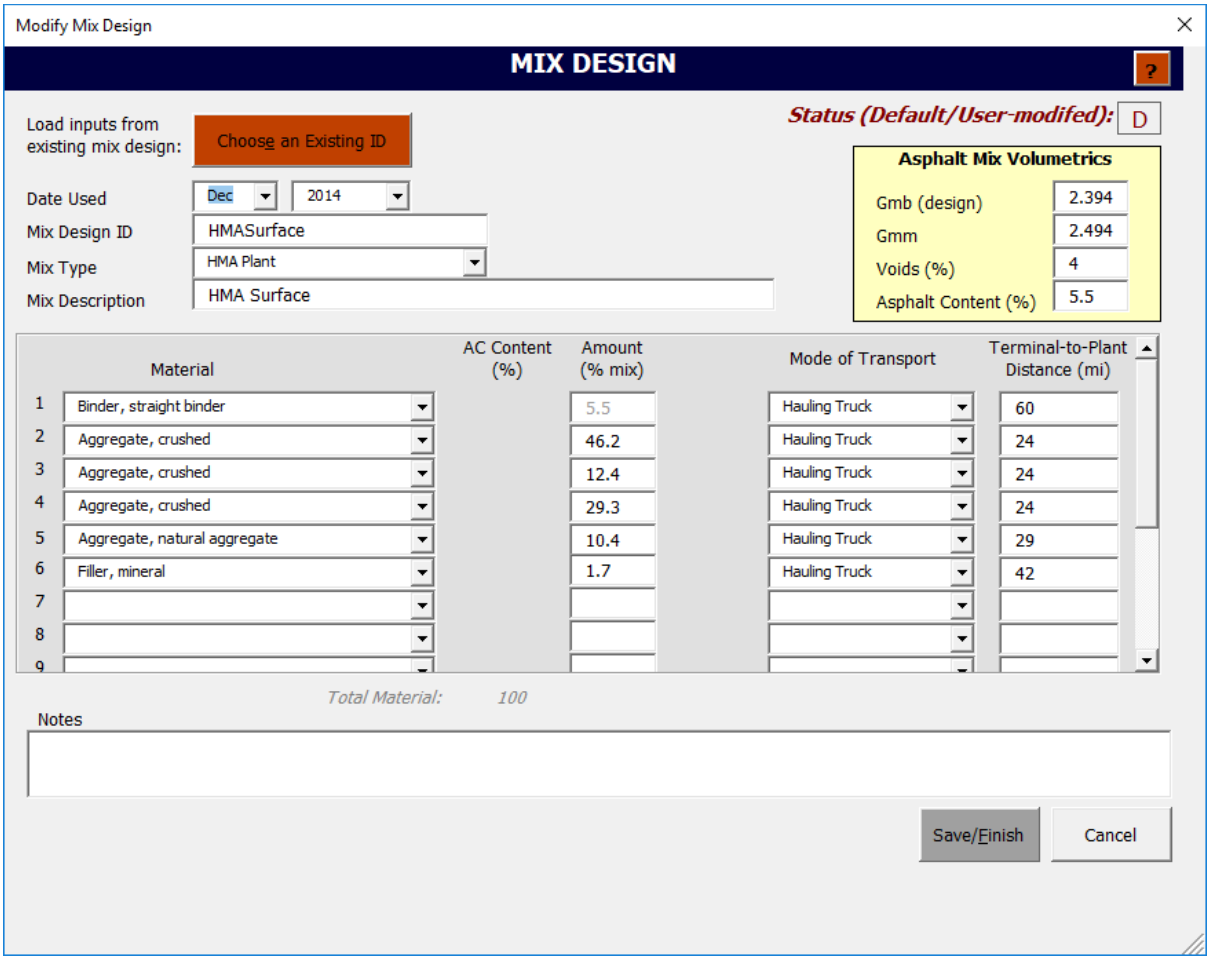


Figure 0.11 Pay item mix-design page

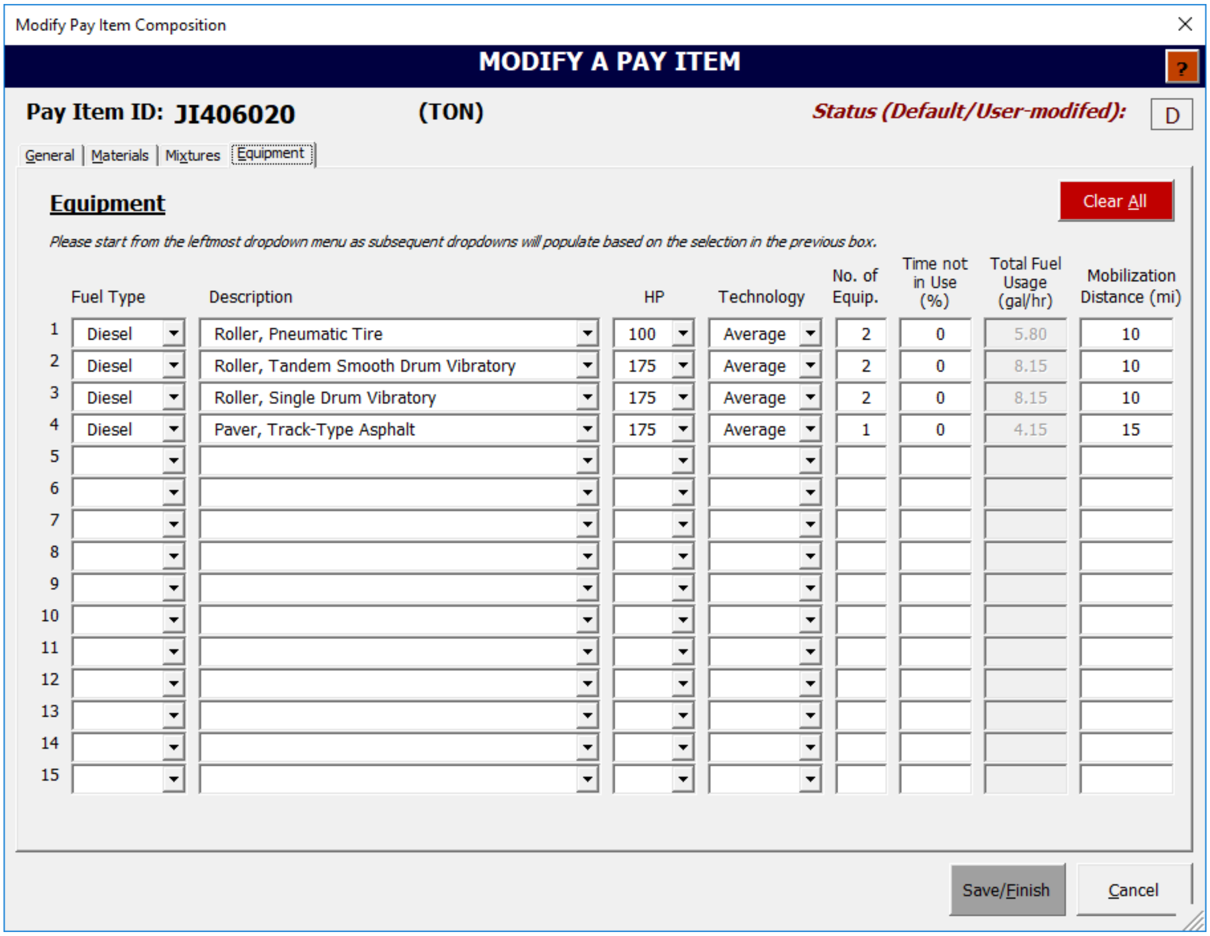


Figure 0.12 Modify a pay item — equipment page

6.3.4 Use Stage

Use-stage calculations include impacts due to heat island, roughness and texture-related rolling resistance. As shown in Figure 0.13, the heat island impacts considered in this study quantify the radiation reflection from a surface due to the sunlight. Because different surfaces absorb and reflect radiation differently, heat island impacts vary among different treatments. Heat island impacts were determined by geographical location, exposure surface type, and the amount of time the pavement is exposed to the sunlight. Details of the models used in calculating heat island impacts are discussed in Volume II.

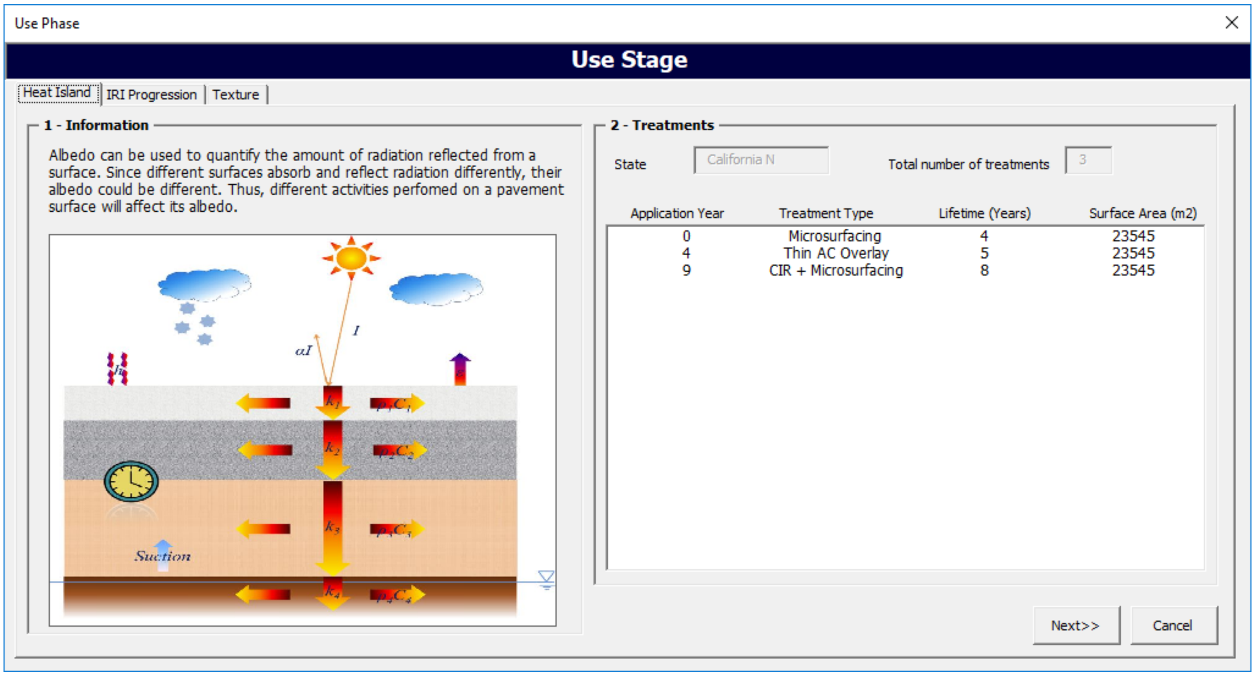


Figure 0.13 Use stage: Heat island page

The next component the user needs to enter is inputs for the calculation of rolling resistance-related impacts. Pavement roughness represented by IRI progression can cause additional vehicle fuel consumption; therefore, the first step is to develop an IRI progression to cover each treatment's lifetime. Three approaches to develop progression curves exist:

1) Default approach: The user must input the initial and threshold IRI values where a treatment is needed. The initial IRI is needed for each treatment. It is assumed that IRI progression is linear between the initial and terminal IRI values (see Figure 0.14).

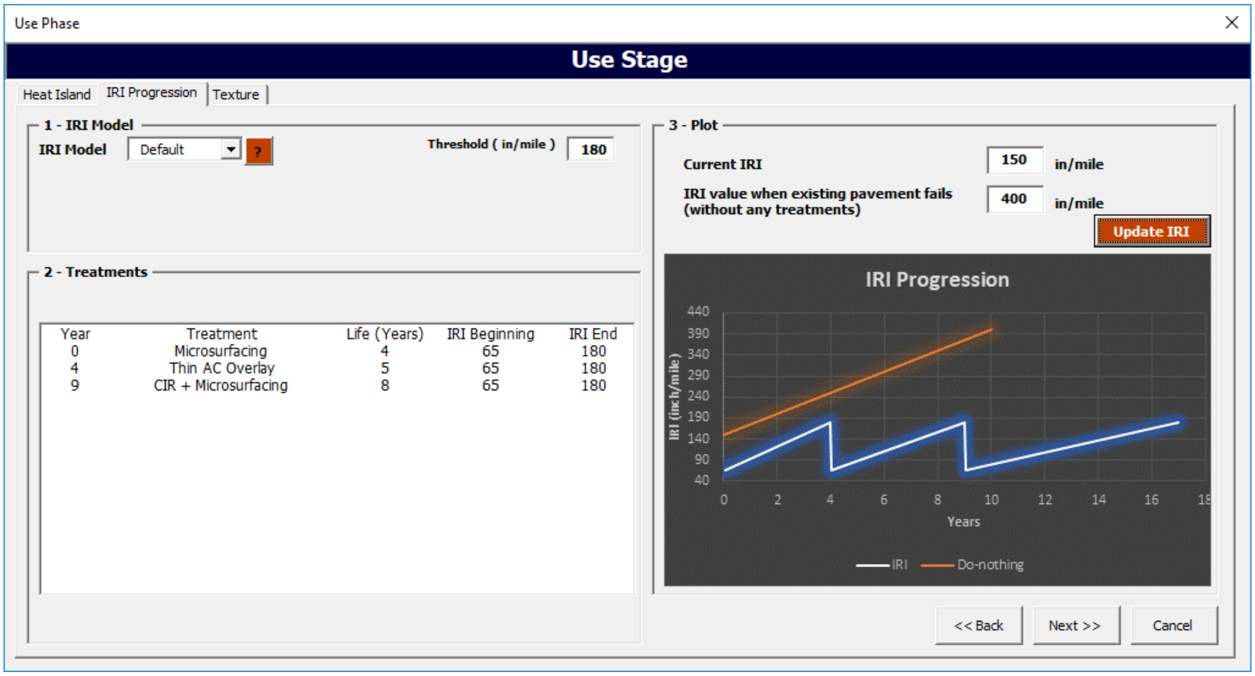


Figure 0.14 Use stage: IRI progression page (default progression)

2) Coefficients: The second approach involves entering coefficients for a selected progression model form. At this point, there is only a linear model available in the tool. The user is required to input an initial IRI and IRI progression rate (IRI change per year) for each treatment. Based on the linear assumption of the IRI progression, IRI changes along the service life can be viewed (see Figure 0.15).

3) Advanced progression models: The third approach involves the use of more advanced progression models. It is expected that there may be some projects where the user has access to a historical IRI progression model developed as a function of traffic, pavement thickness or some other critical input parameters. After entering the initial IRI, the user may input required parameters of the IRI progression model and IRI drop model under *Input Advanced Parameters* (see Figure 0.16). The advanced parameters for the IRI progression model and IRI drop model are shown in Figure 0.17.

   Because these models are expected to be customized, no default parameters are attached to this form. Thus, it is important for the user to understand the models to provide reliable parameters. If the equivalent single axel load's (ESAL) information is unknown, the ESAL's calculation can be done by inputting values as shown in Figure 0.18.

   Texture information needs also to be entered. The input flow is similar to the IRI progression. Texture progression curves need to be developed as shown in Figure 0.19.

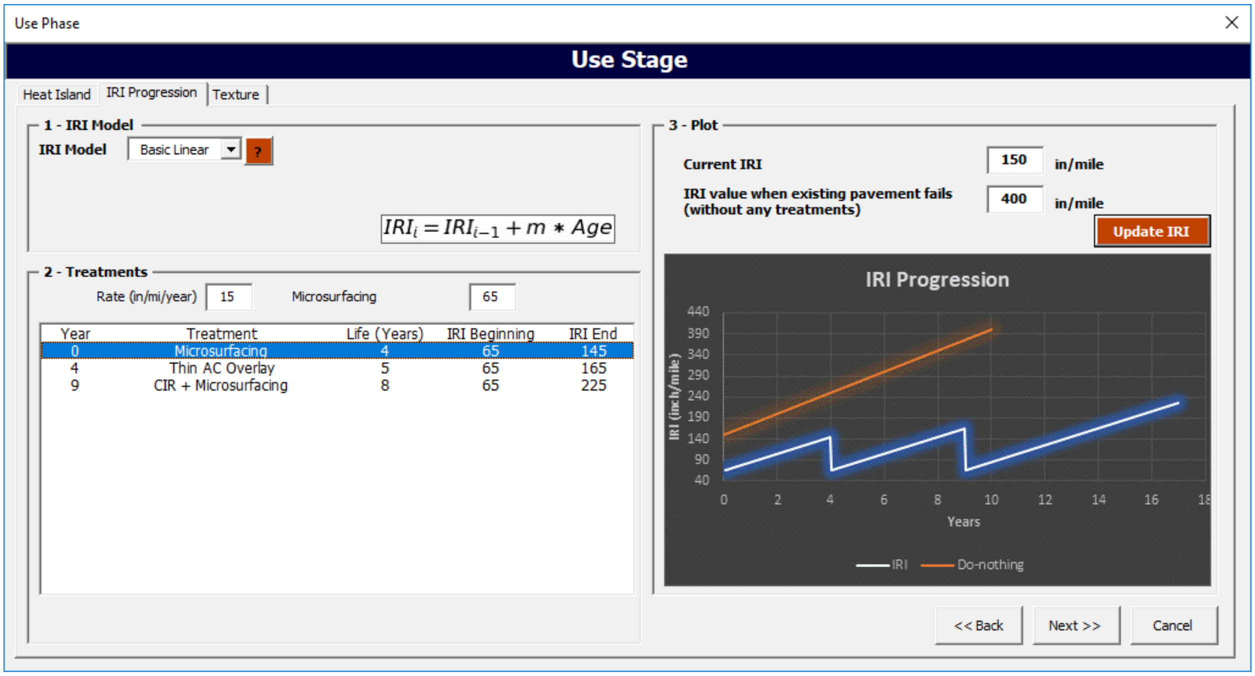


Figure 0.15 Use stage: IRI progression page (basic linear progression)

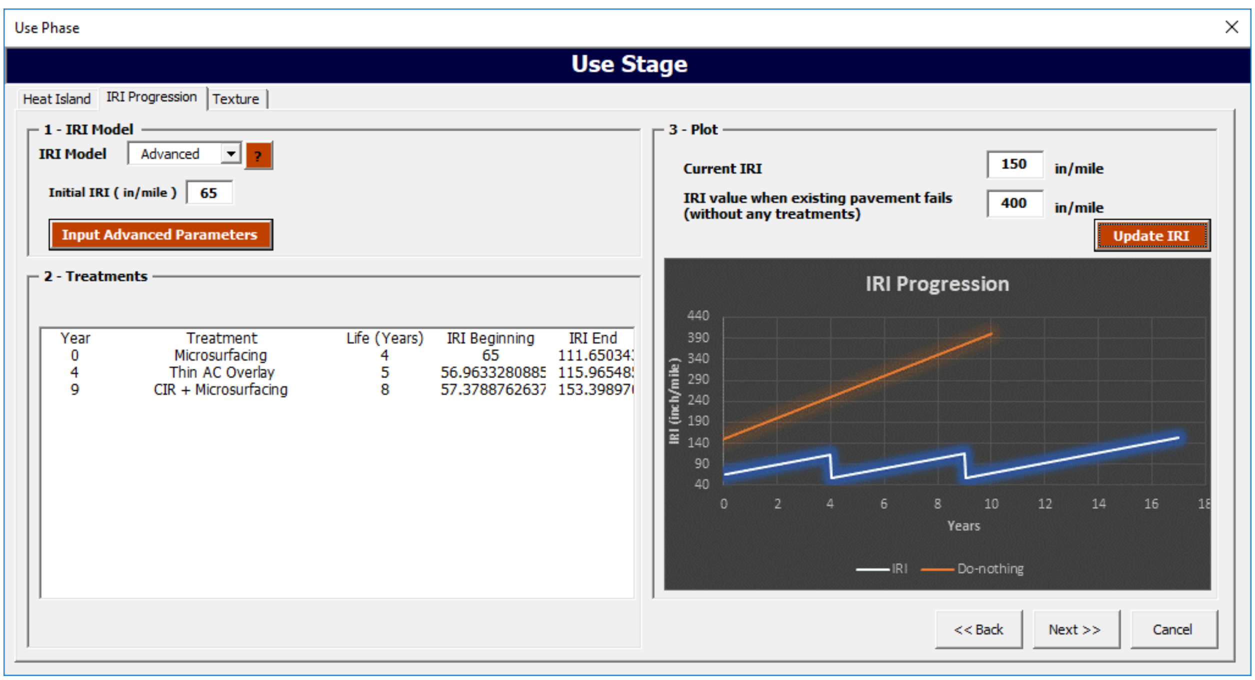


Figure 0.16 Use stage: Advanced IRI progression page

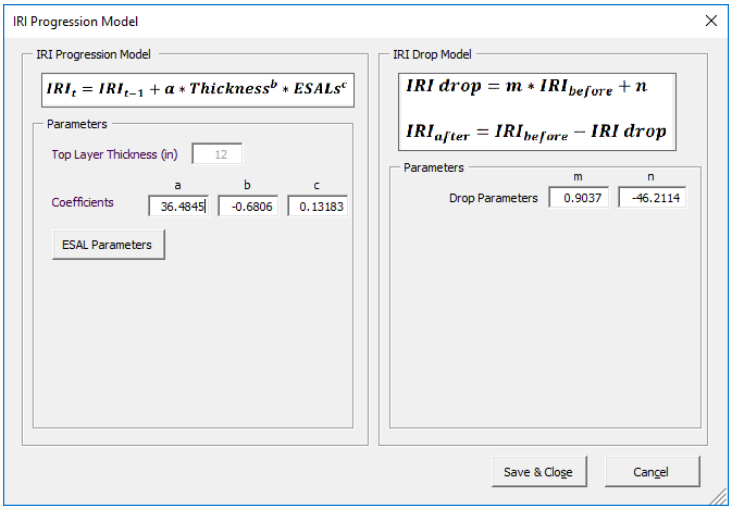


Figure 0.17 Parameters for advanced IRI progression and drop models

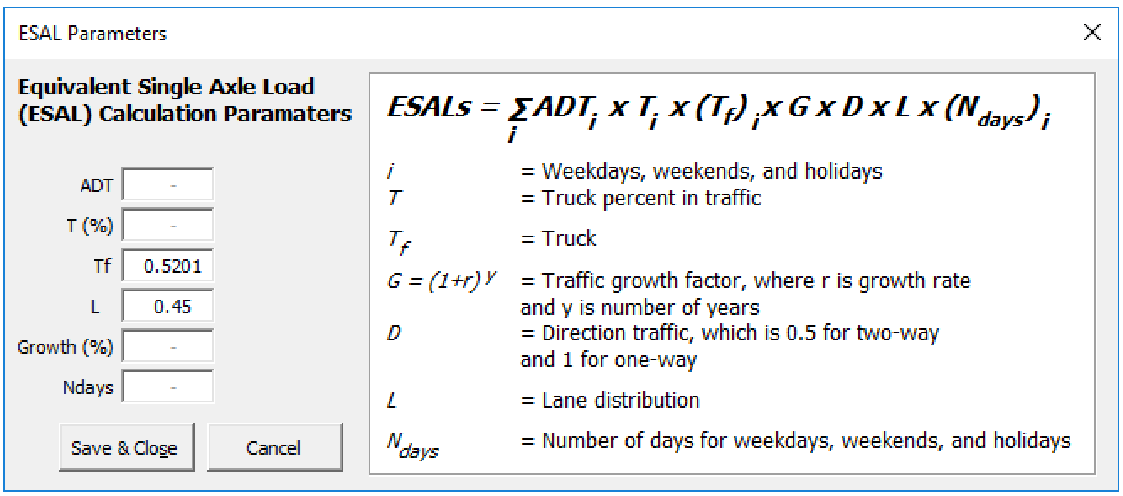


Figure 0.18 Parameters for ESAL calculation

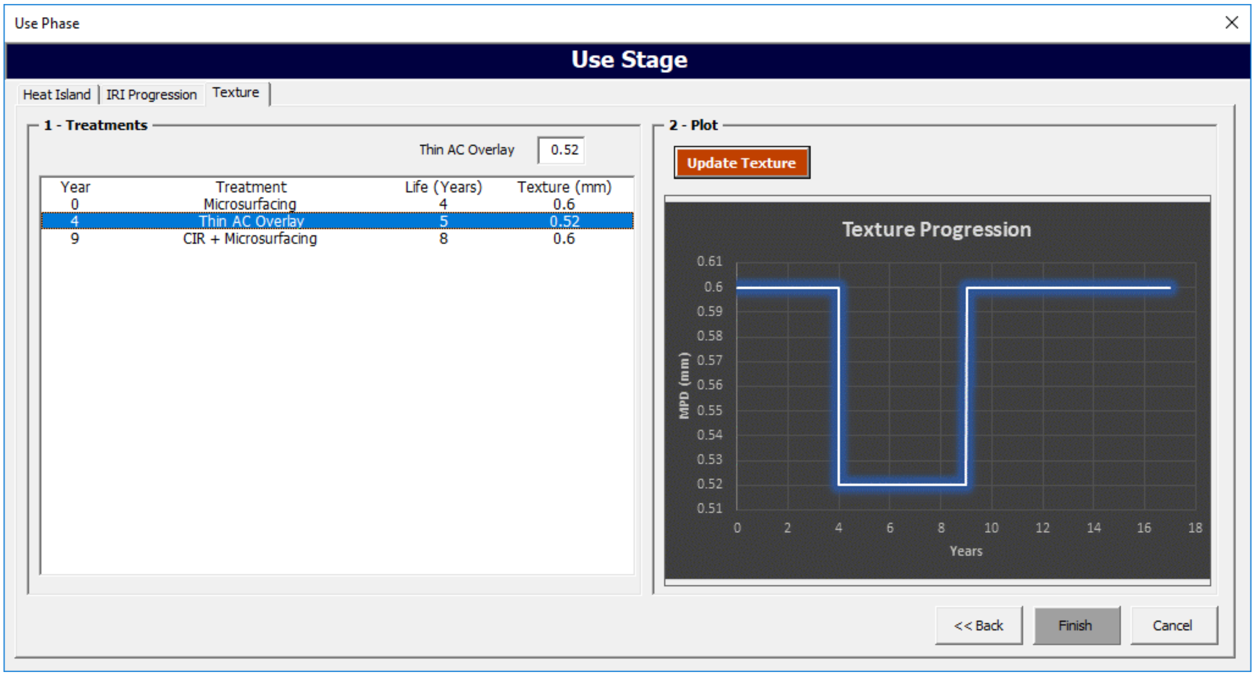


Figure 0.19 Use Stage: Texture progression page

6.3.5 Work Zone

The last component of use stage user forms is to calculate work-zone-related impacts when traffic may be congested during construction activities; this component is optional. If the user decides to evaluate the work zone impacts, two possible scenarios are available. First, if the congested queue exists, the user should also input the work zone speed as well as the queue speed and length. While this scenario is expected to be common, it is not easy to correctly input the information because the traffic flow is dynamic. Second, if no congested queue exists, then only the work zone speed is required, and it is assumed to be 10 mph below the speed limit.

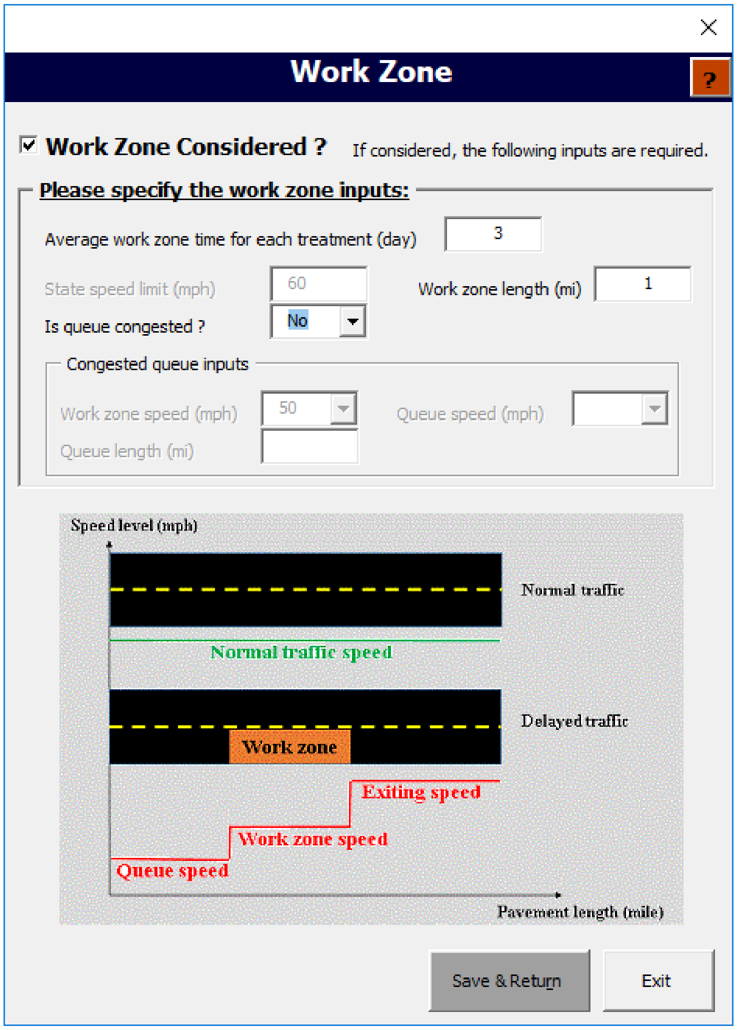


Figure 0.20 Work zone page

6.4 OUTCOME CALCULATIONS

6.4.1 Materials: Extraction and Production

Material extraction and production impacts of each pay item are the summation of the quantity of each type of material included in the pay item multiplied by its unit impact.

$$E_{PItem_j\_mat_i} = unit\ process\ E_{mat_i} * Q_{PItem_j\_mat_i} \tag{6.1}$$

$$Env_{PItem_j\_mat_i} = unit\ process\ Env_{mat_i} * Q_{PItem_j\_mat_i} \tag{6.2}$$

E_{mat_i} and Env_{mat_i} are the unit energy consumption (EC) and environmental impacts (EI) of material i. $Q_{PItem_j\_mat_i}$ is the quantity of material i included in pay item j. $E_{PItem_j\_mat_i}$ and $Env_{PItem_j\_mat_i}$ are the EC and EI of material i in pay item j.

If mix design is considered, the EC and EI of mixture k in pay item j are $E_{PItem_j\_mix_k}$ and $Env_{PItem_j\_mix_k}$ (see below). $E_{PItem_j\_mixmat_i}$ and $Env_{PItem_j\_mixmat_i}$ are the EC and EI of material *i* used in mixture *k*, and *m* is the total number of material type used in mixture *k*. $Q_{PItem_j\_mixmat_i}$ is the quantity of material *i* used in mixture *k* of pay item *j*.

$$E_{PItem_j\_mix_k} = \sum_{i=1}^{m} E_{PItem_j\_mixmat_i} * Q_{PItem_j\_mixmat_i} \quad (6.3)$$

$$Env_{PItem_j\_mix_k} = \sum_{i=1}^{m} Env_{PItem_j\_mixmat_i} * Q_{PItem_j\_mixmat_i} \quad (6.4)$$

The total EC and EI of pay item *j* are $E_{PItem_j\_mat}$ and $Env_{PItem_j\_mat}$.

$$E_{PItem_j\_mat} = \sum_{i=1}^{N} E_{PItem_j\_mat_i} + \sum_{k=1}^{K} E_{PItem_j\_mix\_k} \quad (6.5)$$

$$Env_{PItem_j\_mat} = \sum_{i=1}^{N} Env_{PItem_j\_mat_i} + \sum_{k=1}^{K} Env_{PItem_j\_mix\_k} \quad (6.6)$$

N is the total number of different material types used in pay item *j*, except mixture, and *K* is the total number of mixtures in pay item *j*.

6.4.2 Hauling

The materials hauling impact assessment uses a model that calculates environmental emissions and energy use during the hauling stage at various geometric and environmental hauling trip conditions using the following formula:

$$E_{Haul} = Unit\ process\ E(grade, temperature, RH, hauling\ mod) * quantity * hauling\ distance \quad (6.7)$$

$Unit\ process\ E(grade, temperature, RH, hauling\ mod)$ is the fuel consumption energy of hauling a ton of materials to 1 mi distance. The parameters' description of the unit hauling impact is shown in Table 0.2. A specific environmental impact of hauling can be converted from the E_{Haul} value by multiplying the unit environmental impact of fuel.

Table 0.2 Information Required for Hauling Impact Computation

Key Items	Description	User Form Name
Grade	User selects grade from an [-8%, 8%] range.	"Main Inputs"
Temperature	User selects the average temperature of the hauling trip in this range [0 ºF, 110 ºF].	"Main Inputs"
RH	User selects relative humidity rate of hauling trip in this range [0%, 100%].	"Main Inputs"
Supplier-to-site distance (mi)	Distance traveled for selected processed material to site (mi).	"Material/Mix Design" page
Supplier-to-plant distance (mi)	Distance traveled for selected raw material to plant (mi).	"Material/Mix Design" page

6.4.3 Construction

User is asked to input information about the equipment used on-site to perform the construction activities; up to 27 equipment types may be selected. The on-site equipment impacts are calculated using Equation 6.8, and user inputs are listed in Table 0.3.

$$E_{PItem_{j\_}Equip_i} = \left\{ \begin{matrix} Unit\ process\ E_{Equip}(fuel\ type, tier, equipent\ type) \\ * \frac{fuel\ consumption}{speed} * number\ of\ passes \end{matrix} \right\}_i \quad (6.8)$$

Table 0.3 User input for construction page

Key Item	Description
Fuel type	User selects a fuel (i.e. diesel, propane) in the fuel-type dropdown menu
Equipment type	User selects an equipment type that filters the possible horse power (HP) in the next input
HP bin	Possible HP ranges for the equipment selected. Once selected, it filters the applicable tier categories.
Tier category	Set of emissions regulations established by EPA (base, T0, T1, T2, T3, T3B, T4, T4A, T4N)
Fuel consumption	Hourly equipment productivity (in gal/hr)
Speed	Off-highway and trucks' speed on-site (in ft/min)
Number of passes	The number of passes that the equipment performs during the construction phase.

Then the total construction EC equation for pay item j is $E_{PItem_{j\_}Equip} = \sum_{i=1}^{N} E_{PItem_{j\_}Equip_i}$, where N is the total number of various equipment used in pay item j. Similarly, construction EIs of pay item j still can be converted from E_{PIem_j} by multiplying the unit impact of diesel, which is used to run the equipment.

6.3.4 Work Zone

Work zone impacts are defined by the difference in fuel consumption of vehicles using the work zone between regular-, free flow, and delayed-traffic flow due to work zone activities. Figure 0.21 shows an example of a traffic delay model for a typical work zone (i.e., pavement rehabilitation, maintenance project).

The roughness speed impact (RSI) model, developed by Ziyadi et al. (2018), quantified the work zone impacts. The same model was also used in calculating rolling resistance-related impact, which is discussed in greater detail in Volume II. This model has two main variables — IRI and speed. The unit processes are categorized by vehicle type (i.e. passenger car, small truck, medium truck, large truck). The RSI model requires inputs from IRI progression and speeds of normal and delayed traffic due to work zones. The work zone impact is calculated as follows:

$$\Delta E_{WZ} = E_{queue} + E_{WZ} - E_{normal} \quad (6.9)$$

ΔE_{WZ} is the additional impact due to work zone, and E_{queue} and E_{WZ} are the impacts resulting from queue and work zone traffic. E_{normal} is the impacts resulting from normal traffic without a work zone.

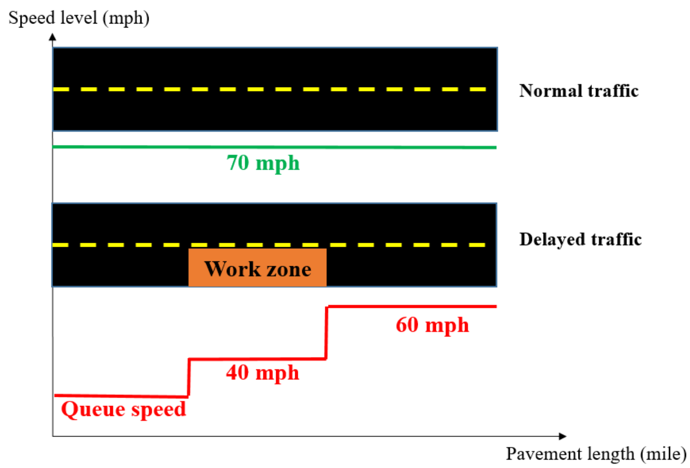


Figure 0.21. Work zone schematic

CHAPTER 7. LIFE-CYCLE ANALYSIS AND INTERPRETATION

7.1 RESULTS OVERVIEW

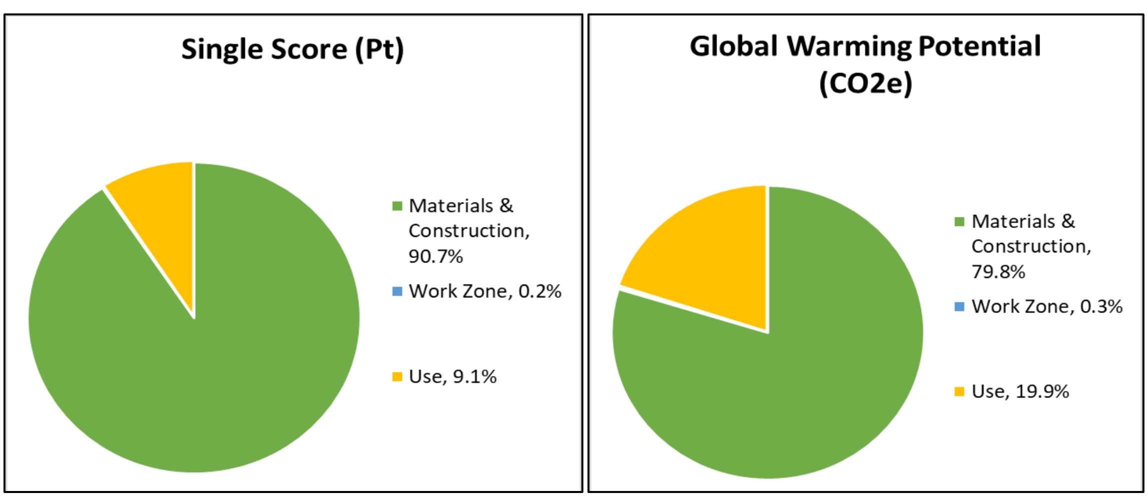
The results from the LCA are presented in tabular and graphical forms, as shown in Figure 0.1 and Figure 0.2, respectively. The final results are characterized for each stage and impact category.

Calculate Results

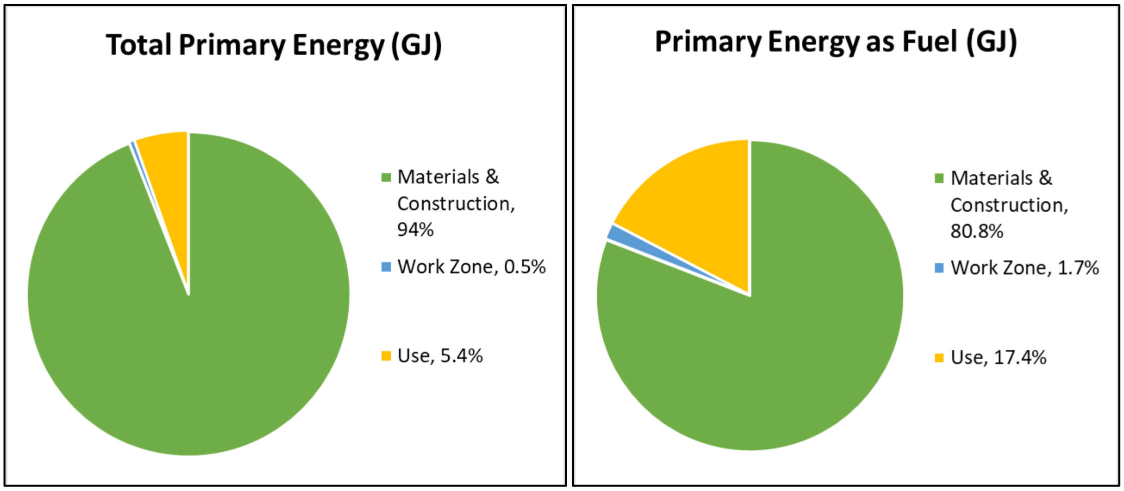
Full Results per Project- Analysis Period

Tabulated Results (per project-analysis period)	Entire Project	Materials & Construction	Work Zone	Use
Present Cost ($)	$ 2,579,921	$ 2,579,921	$ -	$ -
Single Score (Pt.)	3.82E+02	3.47E+02	6.18E-01	3.48E+01
Global Warming Potential (tonnes CO2e)	1.52E+03	1.21E+03	4.22E+00	3.02E+02
Total Primary Energy (GJ)	7.74E+04	7.28E+04	4.20E+02	4.20E+03
Primary Energy as Fuel (GJ)	2.41E+04	1.95E+04	4.20E+02	4.20E+03

Figure 0.1 Project-based results



a) b)



c) d)

Figure 0.2 Results' characterization

A number of major assumptions are used is this LCA study, many of which have been noted in the goal and scope. A summary of the key assumptions are the following: No time gap between two treatments; PCI value is 100 right after a treatment application; and queue speed is 10 mph below the normal speed limit in work zones

Some of the limitations in this study have already been referred to in the goal and scope and/or previous chapters. A summary of major limitations is as follows:

1) The lifetime estimation model may not exactly represent the situation under extreme conditions, where the AADT is very high or the existing PCI value is very low.
2) The decision tree is only based on previous experience, and it is only used for the guidance of selecting the first treatment. For other treatment in the preservation schedule, it is decided by the user.
3) The PCI progression under the do-nothing scenario is undetermined, and the user should be able to identify the possible PCI drop when no action is taken for a certain period.
4) The lifetime estimation model was only developed for asphalt surfaced pavements, while the preservation lifetime for rigid pavements uses literature data as default.

7.2 CASE STUDIES

Two case studies are presented to demonstrate the capabilities of this study's developed tool and highlight benefits of a planned preservation schedule. The first case study quantifies the impact of delayed treatment by selecting a do-nothing scenario at the beginning of the planned schedule. In the second case study, use-stage factors are evaluated, including the heat island among different states and under different traffic conditions.

Case I – Delayed application of major rehabilitation

Four treatment schedules were designed to have comparable life extensions to existing pavement.

The first schedule is comprised of various preservation treatments while others schedules include major rehabilitation after a period of the do-nothing approach. The goal of this case study is to quantify benefits of a planned preservation treatment schedule as compared to a schedule with delays in treatment and rehabilitation activities.

Project and Traffic Inputs

General project inputs are shown in Table 7.1. The project is a typical low-volume traffic road. The applicable PCI for pavement preservation is limited above 65. The current pavement condition is favorable for preservation (PCI > 65).

Table 0.1 Basic information input of Case I

Pavement Type	Conventional AC Pavement
Surface depth	4 in
Mileage	2 mi
Lane number	2 (12-ft-wide lanes)
Present PCI	70
AADT	3,000
Traffic growth	2
Speed limit	60 mph
Truck percent	10
Small-truck percent	30
Medium-truck percent	30
Large-truck percent	40

Preservation Schedules and Other Inputs

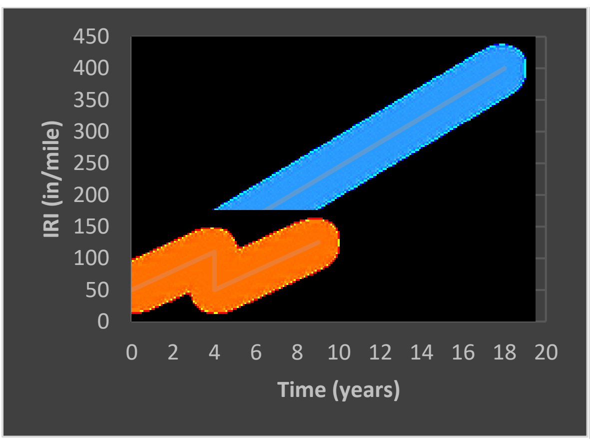
The scenarios for preservation schedules are shown in Table 7.2. The LCA for each scenario was performed using the developed tool. The material stage includes raw material acquisition, plant production and transporting raw materials to the job site. The hauling distance between an asphalt plant and the project site is assumed to be 50 mi. The construction processes of CIR with thin AC overlay includes milling and application of the prime coat and paving after in-place recycling. The depth of recycling is taken as 2 in. The amount of emulsion and cement applied to stabilize is 4% and 1%, respectively. As for the thin AC overlay, the design parameters are: 4% air void, 6% asphalt content and the maximum specific gravity of 2.500 g/cm^3.

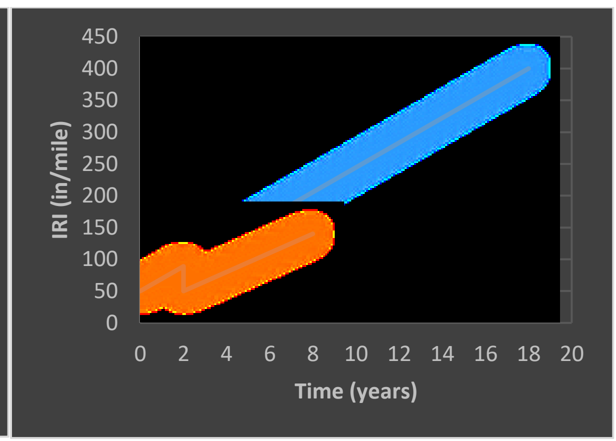
Results and Analysis

The progression of IRI was calculated and shown in Figure 7.3. The blue line is the IRI progression when there is no treatment applied (do-nothing scenario). It is assumed that the terminal IRI value of 400 in/mi is reached at year 18. Under the first schedule (a), two successive treatments are applied at years 0 and 4. In Figure 7.3, the deterioration rate (orange line) is slower than the blue line. For the other three schedules (b, c and d), blue and orange lines coincide in the first section because no treatment was applied. In the second section after treatment is applied, the IRI drops to the same value as at the beginning of the treatment. The IRI progression in schedule (a) is slowest to reach the lowest IRI value at the end of the analysis period.

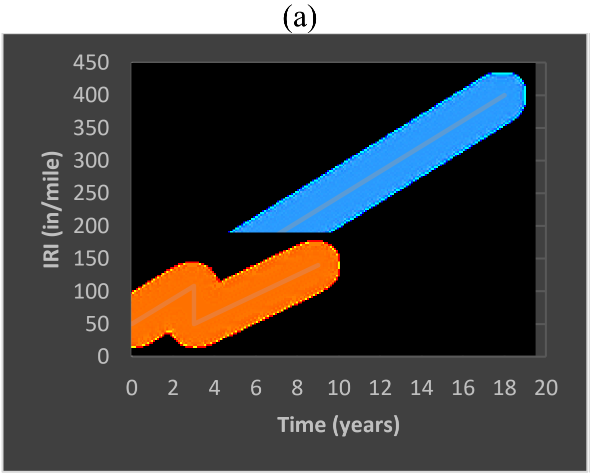
Table 0.2 Four types of asphalt-pavement preservation schedules

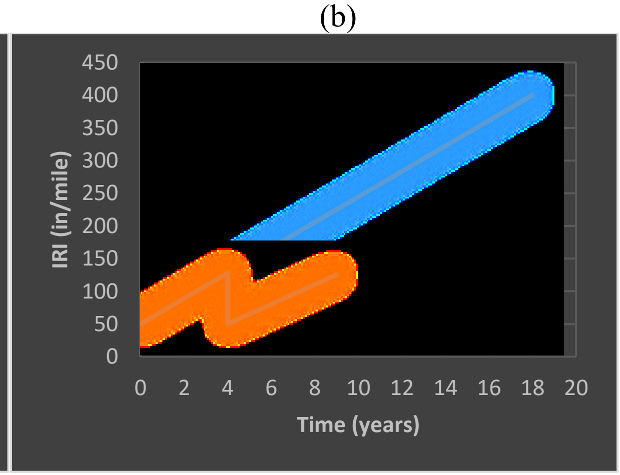
No.	Schedule	Total lifetime (year)
a	1) Microsurfacing — 4 yrs 2) Thin AC overlay 1 in (5 yrs)	9
b	1) Do–nothing — 2 yrs 2) CIR+Thin AC overlay 1 in (6 yrs)	8
c	1) Do–nothing — 3 yrs 2) CIR+Thin AC overlay 1 in (6 yrs)	9
d	1) Do nothing — 4 yrs 2) CIR+Thin AC overlay 1 in (5 yrs)	9





(a) (b)





(c) (d)

Figure 0.3 IRI progression of the planned treatment schedules in the case study

The GWP and primary energy results are shown in Table 0.3 and

Table 0.4 Primary Energy of Four Schedules

Primary Energy (GJ)	Entire Project	Materials and Construction	Work Zone	Use	Annualized
a	4.60E+04	4.84E+03	6.93E+01	4.11E+04	5.11E+03
b	4.85E+04	2.87E+03	4.66E+01	4.56E+04	6.06E+03
c	5.74E+04	2.87E+03	4.66E+01	5.45E+04	6.38E+03
d	5.92E+04	2.87E+03	4.66E+01	5.63E+04	6.58E+03

. The total project and annualized impacts are lowest for the schedule (a). The savings are due to lower use-stage impacts despite of the impact increase in material and construction stages due to the higher treatment frequency and resource consumption.

Table 0.3 GWP Impacts of Four Schedules

GWP (tons)	Entire Project	Materials & Construction	Work Zone	Use	Annualized
a	3.17E+03	2.16E+02	6.96E+00	2.95E+03	3.52E+02
b	3.38E+03	1.32E+02	4.63E+00	3.24E+03	4.22E+02
c	4.03E+03	1.32E+02	4.63E+00	3.89E+03	4.48E+02
d	4.15E+03	1.32E+02	4.63E+00	4.01E+03	4.61E+02

Table 0.4 Primary Energy of Four Schedules

Primary Energy (GJ)	Entire Project	Materials and Construction	Work Zone	Use	Annualized
a	4.60E+04	4.84E+03	6.93E+01	4.11E+04	5.11E+03
b	4.85E+04	2.87E+03	4.66E+01	4.56E+04	6.06E+03
c	5.74E+04	2.87E+03	4.66E+01	5.45E+04	6.38E+03
d	5.92E+04	2.87E+03	4.66E+01	5.63E+04	6.58E+03

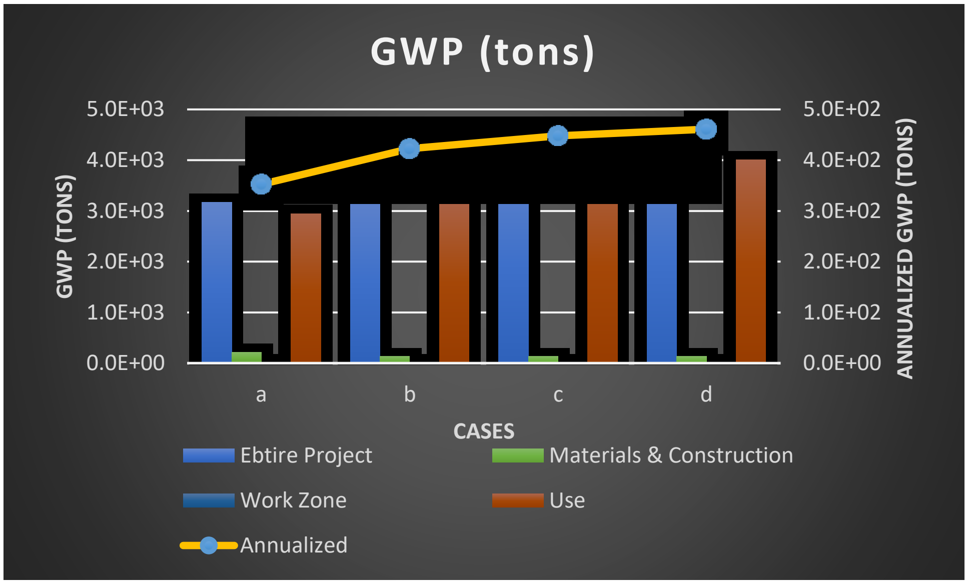


Figure 0.4 GWP results comparison

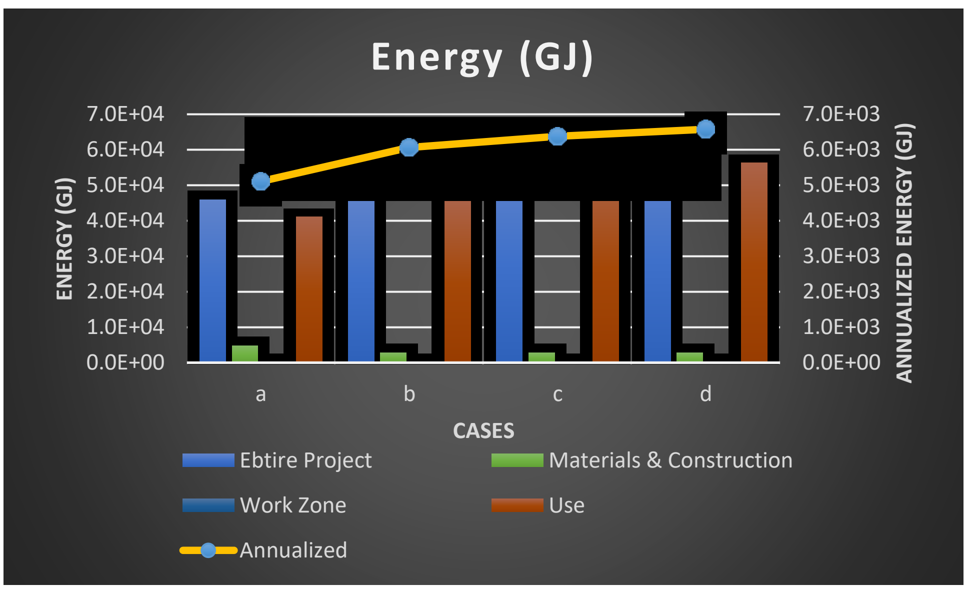


Figure 0.5 Primary energy results comparison

Case II – Use-stage impacts

The second case study evaluates use-stage impacts contributing the pavement heat island to the whole project's GWP results. The case study evaluates the varying contribution of heat island impact to the overall project GWP when traffic volume is changing. The results are presented for the selected regions throughout the nation.

Project and Traffic Inputs

The major inputs of pavement structure and traffic are presented in Table 0.5.

Table 0.5 Project and Traffic Inputs for Case II

Pavement Type	Conventional AC Pavement
Surface depth	4 in
Mileage	2 mi
Lane number	2 (12-ft-wide lanes)
Present PCI	70
Reference AADT	3,000
Traffic growth	2
Speed limit	60 mph
Truck percentage	10
Small-truck percentage	30
Medium-truck percentage	30
Large-truck percentage	40

Preservation Schedules and Other Inputs

The following preservation schedule was used in the case study. The lifetime of each treatment is estimated as shown in Table 0.6. The same preservation schedule was applied in different regions to evaluate the heat island's contributions and other use-stage factors. It is assumed that lifetime does not vary regionally.

Table 0.6 Preservation Schedule for Case II

Year applied	Treatment	Lifetime (year)
0	Microsurfacing	4
4	Thin AC overlay	5
9	CIR + Microsurfacing	8

Results and Analysis

The results are shown for a selected region in Table 0.7. Heat-island-impact results remained the same while the total GWP increased with AADT increases. The primary reason for the GWP increase is due to rolling resistance-related excess fuel consumption. When traffic increased, the contribution of the heat island to the project GWP decreased from 91% to 13%, as shown in Figure 0.6.

Table 0.7 Heat Island GWP Contribution to Total GWP under Different AADT

AADT	1,000	5,000	50,000	100,000	200,000
Heat Island (CO_2-eq in tons)	6,299	6,299	6,299	6,299	6,299
Other (CO_2-eq in tons)	640.33	1,485.57	10,994.51	21,560.00	42,690.97
Total (CO_2-eq in tons)	6,939.33	7,784.57	17,293.51	27,859.00	48,989.97

Percentage of Heat Island	91	81	36	23	13

The same analysis was repeated in different regions to evaluate the extent of heat island contribution and the AADT was assumed to be 5000. The variation of the heat island contribution is shown with a map in Figure 0.7. The southern regions have contributions as high as 50% while the contribution reduces to 30% in the northern states. In addition, the states in the west coast have higher impacts compared to those in the east coast area at the same latitude. The exception, however, is Pennsylvania, which is at a relatively high impact area.

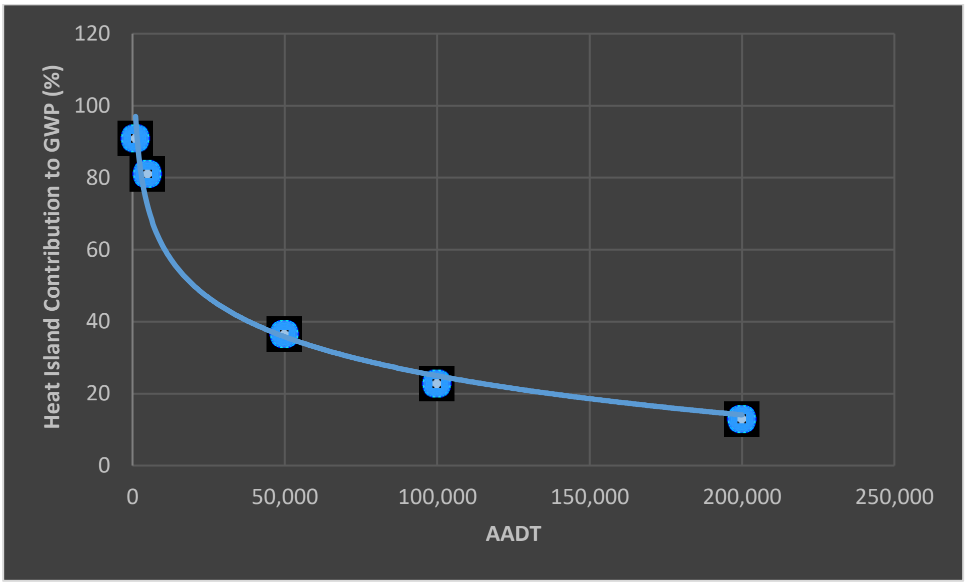


Figure 0.6 Heat island contribution to the project GWP

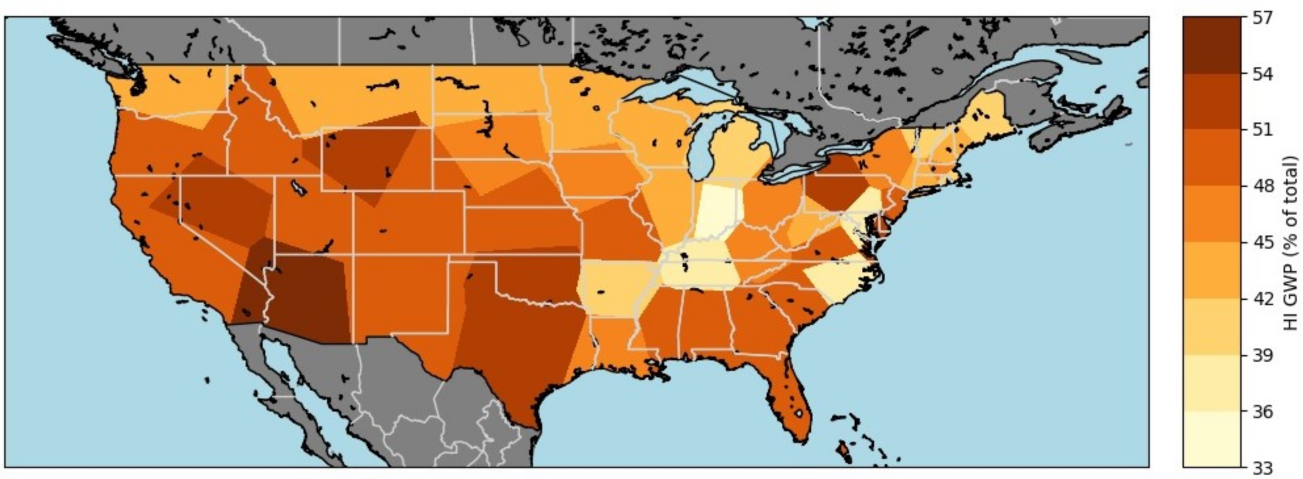


Figure 0.7 U.S. heat island impact

CHAPTER 8. SUMMARY AND CONCLUSIONS

A complete LCA methodology was developed to quantify sustainability impacts of preservation activities for asphalt and concrete surfaced pavements. The LCA models and methodology were implemented in a software tool to support making project-level decisions in between various preservation and rehabilitation activities and build a long-term preservation schedule. The key components of the development are the inventory analysis used in the LCA calculations, treatment lifetime models and decision trees for preservation treatment selection. A nationwide survey was conducted through questionnaires. Questionnaires were designed specifically to obtain agency experiences and practices and collect data to build lifetime models. Decision trees were developed to guide decision makers to select among various preservation and rehabilitation options for a given existing pavement condition and traffic information. Data for the LCA, to determine the impacts of various preservation and maintenance schedules, were obtained also from the literature and other publicly and commercially available databases.

The main outcome of this study is an LCA tool (PSAT), which was developed with user-friendly interfaces in the VBA platform and pay items as the building block for the ease of future implementation. The tool is intended for public use to assess the environmental impacts of pavement preservation and maintenance alternatives for highway pavements. Abovementioned data, models, decision trees, and other relevant information were incorporated in the tool for a standalone application. The tool can be used to perform LCA calculations considering materials, construction, maintenance/rehabilitation and use stages of LCA. The tool is intended for the engineers in state and local agencies, practitioners in the industry, and contractors. A sustainability analysis is presented to compare individual treatments or a schedule of treatments. The followings are the accomplishments of this study:

- Field application of different preservation and maintenance activities were collected from DOTs nationwide and representative schedules were built in the tool as default practices.
- Lifetime estimation models were developed to predict a treatment's lifetime service life using existing pavement condition and traffic information.
- Decision trees were developed for asphalt and concrete surfaced pavements. The trees were built in the tool to guide the user making the right selection for a given project.
- Pay items were developed and categorized for each treatment. Pay items were used as the major unit process in the LCA to calculate environmental impacts.
- Life-cycle inventory analysis were performed to develop a database of environmental impacts for various pay items used in the construction of preservation treatments. In addition, inventory analysis was performed for critical unit processes such as hauling.
- Use-stage models were developed to quantify the impact of rolling resistance (considering roughness and texture effect) and heat island.

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