DEVELOPMENT OF A LIFE-CYCLE ASSESSMENT TOOL FOR FLEXIBLE PAVEMENT IN-PLACE RECYCLING TECHNIQUES AND CONVENTIONAL METHODS

BY

MOUNA KRAMI SENHAJI

THESIS

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Advisers:

Professor Imad L. Al-Qadi
Dr. Hasan Ozer

ABSTRACT

The worldwide interest in using recycled materials in flexible pavements as an alternative to virgin materials has increased significantly over the past few decades. Therefore, recycling has been utilized in the pavement maintenance and rehabilitation activities. Three types of in-place recycling technologies have been introduced since the late 70's: hot-in-place recycling (HIR), cold-in-place recycling (CIR), and full-depth reclamation (FDR). The use of in-place recycling (IPR) have been evolving using new equipment trains, mix design specifications, and use of additives (e.g., engineered emulsion, lime, and cement). The advantages of using these evolving techniques include conservation of virgin materials, reduction of energy use and environmental impacts, reduction of construction time and traffic flow disruptions, reduction of number of hauling trucks, and improvement of pavement condition. The main objectives of this thesis are to develop a framework and a life-cycle assessment (LCA) methodology to evaluate maintenance and rehabilitation treatments, specifically in-place recycling and conventional paving methods; provide a fuel usage analysis of in-place recycling techniques during the construction stage; and develop a LCA tool utilizing Visual Basic for Applications (VBA) to help local and state highway agencies to evaluate environmental benefits and tradeoffs of in-place recycling techniques as compared to conventional rehabilitation methods at each life-cycle stage from the material extraction and production to the end of life. The ultimate outcome of this study is the development of a framework and a user-friendly LCA tool assesses the environmental impact of a wide range of pavement treatments, including in-place recycling, conventional methods, and surface treatments. The tool utilizes data, simulation, and models through all the stages of the IPR stages for the pavement LCA, including materials, construction, maintenance/rehabilitation, use, and end of life stages. The developed tool provides pavement industry practitioners, consultants and agencies the opportunity to complement their projects economic and social assessment with the environmental impacts quantification. In addition, the tool presents the main factors that impact produced emissions and energy consumed at every stage of the pavement life cycle due to pavement treatment. The tool provides detailed information such as fuel usage analysis of in-place recycling techniques based on field data. It shows that fuel usage is affected by pavement hardness, pavement width, air temperature, and horsepower of the equipment used.

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LIST OF ACRONYMS AND ABBREVIATIONS

General Terms

AADT	Annual Average Daily Traffic
AC	Asphalt Concrete
ADP	Acidification Potential
CH_4	Methane
CIR	Cold In-place Recycling
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CTUs	Comparative Toxicity Units
CY	Cubic Yard
DOT	Department of Transportation
eGRID	Emissions and Generation Resource Integrated Database
EIA	Energy Information Administration
EOL	End of Life
EPA	Environmental Protection Agency
ESAL	Equivalent Single Axle Load
FDR	Full-Depth Reclamation
FHWA	Federal Highway Administration
GWP	Global Warming Potential
HIR	Hot In-place Recycling
HMA	Hot Mix Asphalt
HP	Horsepower
IRI	International Roughness Index
ISO	International Organization of Standardization
LCA	Life-Cycle Assessment
LCCA	Life-Cycle Cost Analysis
LCIA	Life-Cycle Impact Assessment

M&R	Maintenance and Rehabilitation
MOVES	Motor Vehicle Emission Simulator
MPD	Mean Profile Depth
MSDS	Material Specification Data Sheet
NMHC	Non-Methane Hydrocarbons
NMVOC	Non-Methane Volatile Organic Compounds
NOx	Nitrogen Oxides
PADD	Petroleum Administration for Defense Districts
PCI	Pavement Condition Index
PCS	Pavement Condition Survey
PM	Particulate Matter
PMS	Pavement Management System
RAP	Recycled Asphalt Pavement
RSI	Roughness-Speed Impact Model
SO2	Sulfur Dioxide
SY	Square Yard
TRACI	Tool for Reduction and Assessment of Chemical and other environmental Impacts
VBA	Visual Basic Applications

CHAPTER 1: INTRODUCTION

In-place recycling (IPR) techniques, including hot-in-place recycling (HIR) and cold in-place recycling (CIR) methods, which have been used by local and state roadway agencies, are part of the preservation and rehabilitation techniques. The environmental impacts of IPR takes into consideration a large number of possible factors, including equipment operation, fuel consumption, transportation, materials production and handling, reusability of reclaimed aggregates, and expected longevity/durability of the pavement. The research approach followed in this work is based on the concepts of life-cycle assessment (LCA), and it includes the following interconnected deliverables:

- LCA framework/methodology.
- LCA decision-making tool.
- LCA comparative study.

The organizational structure of the goal and scope definition is based on “Chapter 3: Goal and Scope Definition of the Pavement Life-Cycle Framework” initiated by the FHWA (Harvey et al., 2016),which is consistent with the International Standards Organization (ISO) 14040:2006 for “Environmental Management – Life-Cycle Assessment – Principles and Framework” and the ISO14044:2006 for “Environmental Management – Life-Cycle Assessment – Requirements and Guidelines.” (ISO, 2006)

MOTIVATION

Roadway construction is a capital-intensive operation in which a vast amount of materials and various sets of equipment are used. The pavement industry is continually looking for more sustainable construction practices that can save costs and reduce environmental impacts. Since the increase of crude oil price in the 1970s, worldwide interest in using recycled materials in flexible pavements as an alternative to virgin materials has increased (IMF, 2000).

A plurality of design procedures and material selection frameworks were developed in the 1970s and 1980s primarily to reduce costs of construction and also improve sustainability. Such construction processes and material selection frameworks were tailed to the use of recycled asphalt concrete (AC) pavements (RAP) or IPR of the existing AC pavement. Therefore, recycling has played a significant role in pavement maintenance and rehabilitation activities. There are different types of recycling technologies: CIR, HIR, and hot in-plant recycling (HIPR). This report focuses on the three IPR techniques and their energy consumption and environmental impacts as categorized below:

- Cold in-place recycling (CIR)
- Full-depth reclamation (FDR)
- Hot-in-place recycling (HIR)
    - Surface recycling
    - Remixing

  - Repaving

In-place recycling methods have been evolving through the use of new equipment trains, mix design specifications, and use of additives (e.g., emulsion, lime, and cement). The advantages of using these evolving techniques reside in the following: (Stroup Gardiner, 2011)

- Conservation of virgin materials.
- Reduction of energy use and environmental impacts.
- Reduction of construction time and traffic flow disruptions.
- Reduction of number of hauling trucks.
- Improvement of pavement surface condition and sometimes structural capacity.

According to the online survey conducted by National Cooperative Highway Research Program (NCHRP), a total of 34 states reported having experience with IPR (Stroup Gardiner, 2011). Contractors reported in this survey that one of the factors limiting the use of IPR is the lack of project selection criteria. In addition, the increasing trend of using this technology raises questions about the level of efficiency of these technologies versus traditional conventional methods. Therefore, there is a need to develop a generalized methodology for IPR project selection through performance and environmental assessment.

This comparative study is the first to systematically apply LCA framework/methodology to compare IPR to conventional techniques. Figure 1.1 and 1.2 show, respectively, typical equipment set used for CIR and conventional mill and fill. The cases in the study cover a range of traffic, climatic, and structural conditions as well as pavement life expectancies and construction practices in various U.S. regions to develop a broad baseline assessment. Future users of the LCA framework/methodology and tool will be able to refer to this baseline when conducting their own environmental assessments.

Figure 1.1 (right). Photo. CIR equipment train.

Figure 1.2 (left). Photo. Conventional mill and fill train (Wirtgen Group)

OBJECTIVES

The main objectives of this study are to (1) develop a framework and a life-cycle assessment methodology to evaluate maintenance and rehabilitation treatments; specifically IPR and conventional paving methods; (2) provide a comprehensive fuel usage analysis of IPR techniques during the construction stage; and (3) develop a LCA tool utilizing Visual Basic for Applications (VBA) to help local and state highway agencies to evaluate environmental benefits and tradeoffs of IPR techniques as compared to conventional rehabilitation methods at each life-cycle stage from the material extraction and production to the end of life.

METHODOLOGY

The LCA methodology followed conforms to ISO 14044 standards as illustrated in Figure 1.3. The goal and scope focused on developing a LCA methodology to compare IPR and conventional methods along the life cycle of a project during the same analysis period that is defined based on FHWA LCA framework (Harvey et al, 2016). The inventory database covers materials and equipment used for the construction of IPR and conventional methods. Finally, the impact assessment is performed to compile the unit environmental emission and energy produced by each inventory item. The impacts are calculated using commercial and governmental software tools such as SimaPro and MOVES (EPA), respectively. The interpretation phase analyzes the final results of all phases and identifies the most significant factors and items though a sensitivity analysis.

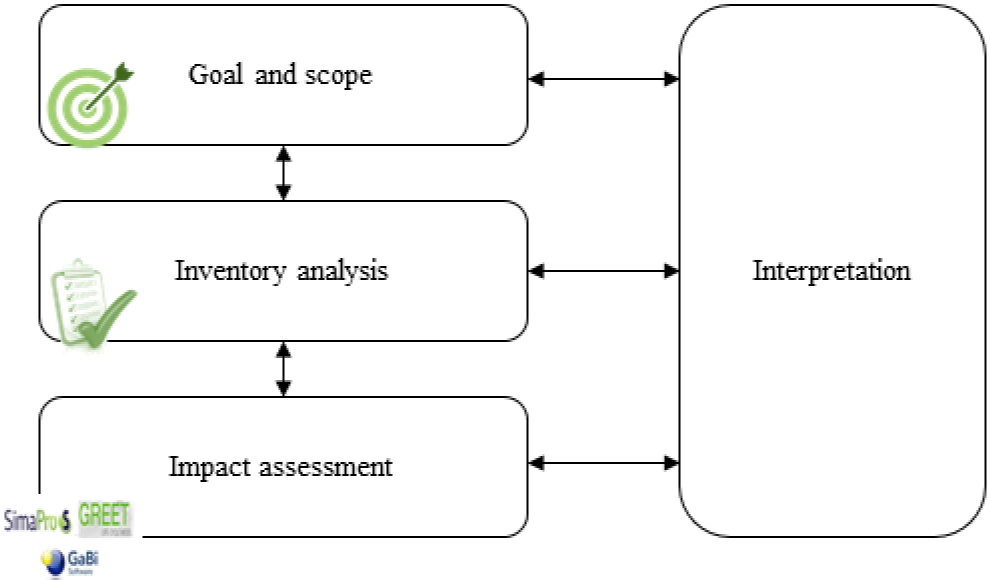

Figure 1.3. LCA methodology (ISO, 2006)

CHAPTER 2: REVIEW OF IN-PLACE RECYCLING TECHNIQUES

IN-PLACE RECYCLING TECHNIQUES

The chapter provides a synthesis of the literature surrounding the application and evaluation of CIR and HIR. The structure of this report is divided into two main sections for the two categories of IPR. Each section addresses the following nine topics for CIR and HIR: 1) construction process and materials, 2) applications in the U.S. and elsewhere, 3) project selection, 4) design and material characterization, 5) performance history and models, 6) consideration in pavement management systems (PMS), 7) cost effectiveness, 8) energy and emissions, and 9) life cycle assessment (LCA) studies.

Hot In-Place Recycling

Hot In-Place Recycling (HIR) is a sustainable pavement preservation/rehabilitation technique that is becoming more widely used in North America. It is a technique used to correct AC pavement surface distresses by "softening the existing surface with heat, mechanically removing the pavement surface, mixing it with asphalt binder, possibly adding virgin aggregate, and replacing the recycled material on the pavement without removing it from the original pavement site." There are three types of HIR: surface recycling (or heater scarification), repaving, and remixing.

The Asphalt Recycling and Reclamation Association (ARRA) defines surface recycling as a process that restores cracked, brittle, and irregular pavement in preparation for a final thin wearing course; this method has a scarification depth of up to 2 in, but typical thicknesses are ¾ to 1 in (FHWA, 1997).This method was originally developed by a contractor in Utah in the 1930s and the technology was advanced in the 1970s into a more complex system (Terrel et al., 1997). The repaving method is similar to the surface recycling method, but is combined with simultaneous AC overlay. It is expected to correct pavement distresses in the upper 1 to 2 in of an existing AC pavement (FHWA, 1997). This method is often referred to as the Cutler process, named after its inventor in the 1950s (FHWA, 1997). The third type of HIR technique is remixing, which consists of heating the surface to a depth of 1½ to 2 in, scarification and collection into a windrow, mixing with virgin aggregate, recycling agents and/or new AC in a pugmill, and laying the recycled mix (FHWA, 1997).

Construction Process and Materials

Chapter 9 of FHWA reference book describes the typical construction processes of HIR in four steps: (1) softening of asphalt pavement surface with heat, (2) scarification and mechanical removal of the surface material, (3) mixing with recycling agent, asphalt binder, or new mix, and (4) laydown and paving of the recycled mix. The three types of HIR (surface recycling, repaving, and remixing) use different sets of equipment (FHWA, 1997); typical sequence of construction equipment for each type of HIR is shown in Figure 2.1 to Figure 2.3.

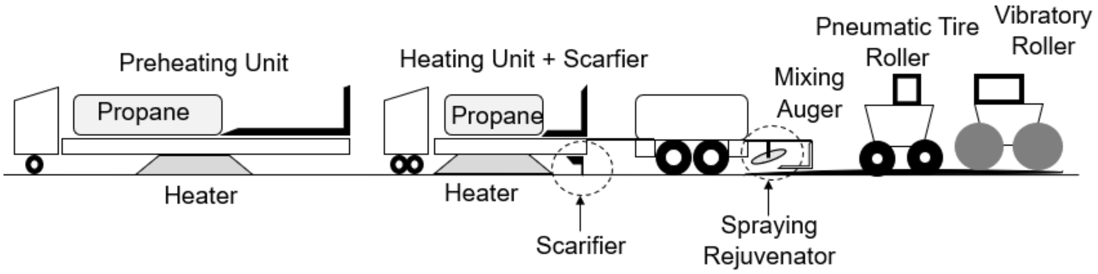

Figure 2.1 Typical sequence of equipment for HIR surface recycling

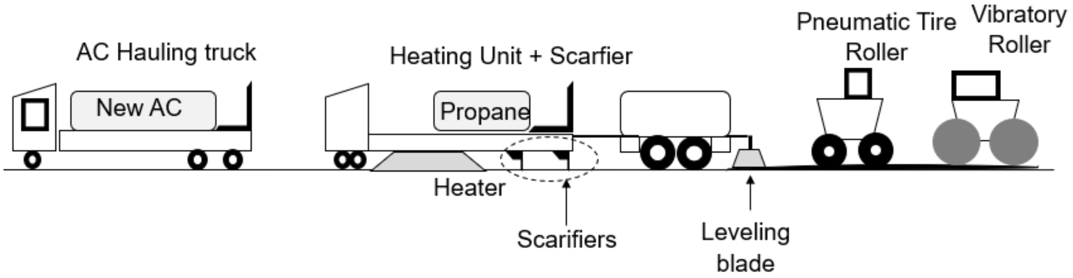

Figure 2.2. Typical sequence of equipment for HIR repaving

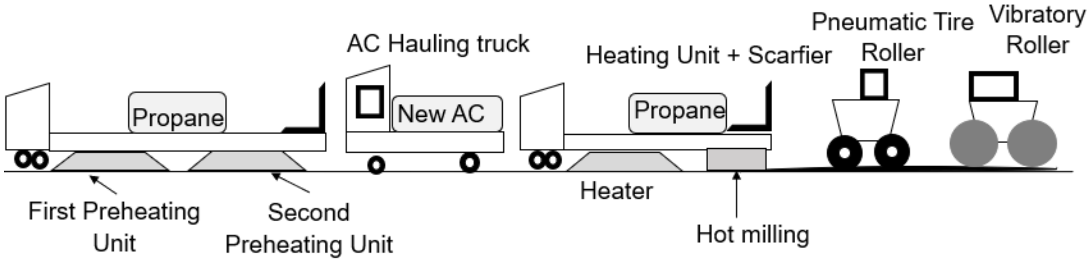

Figure 2.3. Typical sequence of equipment for HIR remixing

Energy Use and Emissions

Few studies document the energy and emissions associated specifically with the HIR processes. However, the energy and emissions associated with the production of virgin binder and aggregates as well as conventional AC plant operations are more readily available. The first study to estimate the energy required for HIR techniques is recorded in NCHRP report 214-19. Energy estimates for the production of pavement materials as well as for the operation of construction equipment were compiled in order to calculate the energy requirements for various initial roadway construction, maintenance, and rehabilitation techniques. For HIR treatments with a ¾ in thickness, the study reported energy consumption of 10,000–20,000 Btu/yd^2, with the range depending on the type of stabilization agent used (if any) (Epps et al., 1980).

In 2003, Colas Group released a study comparing energy and greenhouse gasses (GHGs) for various road construction techniques, including rehabilitation practices.The energy consumption and GHG emissions reported by the Colas Group for HIR are presented in Table 2.1 (Chappat; Bilal, 2003).

Table 2.1. Energy and GHG emissions for HIR (after Colas Group) (Chappat; Bilal, 2003)

Material	Amount (kg/ton)	Energy (MJ/ton)	GHG (kg/ton)	Data Source
Asphalt Binder	100	98	6	Eurobitume
Aggregates	200	4	1.0	Athena, IVL
Transportation	--	12	0.8	IVL
Laying	--	456	34.2	Colas Group
Total	1000	570	42	--

Cold In-Place Recycling

Cold in-place recycling (CIR) is an in-place rehabilitation technique that pulverizes the surface of the pavement, mixes the recycled material with new materials, compacts it, and places an overlay as a wearing surface. CIR starts with milling and pulverizing the surface of the distressed pavement to a predetermined depth. The pulverized materials are then mixed with or without additives and are graded, placed, and compacted back in place providing an improved base layer and a wearing hot mix asphalt (HMA) overlay or a surface treatment is typically added on top. There are two types of CIR practice: partial IPR which only pulverizes the materials in the HMA layer of the previous section and does not go through the layers underneath, and full depth reclamation (FDR) in which all of the HMA and at least 2 in of the base/sub-base materials are pulverized.

The benefits of IPR according to a study conducted by NCHRP in 2011 are as follows (Stroup-Gardiner, 2011):

- Reduction in use of natural resources
- Elimination of materials generated for disposal or landfilling
- Reduction in fuel consumption primarily due to reduction in transport of new materials
- Reduction in Greenhouse Gas (GHG) emissions between 50% to 85%
- Reduction in lane closure times
- Safety improvement by increasing friction, widening lanes, and eliminating overlay edge drop-off
- Reduction in costs of preservation, maintenance, and rehabilitation
- Improving base support with minimum overlay thickness

This section discusses cold in-place recycling in detail starting with the construction processes and the materials and additives that are used, then continues with examples of applications in the U.S. and other parts of the world. Project selection criteria are discussed afterwards, explaining suitable candidates for each cold in-place technique. The document then focuses on energy consumption and emission data collected from previous projects followed by a summary of performance evaluations for each technique and a discussion on cost effectiveness of the treatments. The section is wrapped up with a review and summary of available life cycle assessment (LCA) studies on CIR.

ARRA recommends that the equipment used for CIR be capable of the following: (ARRA, 2014)

- Milling of the existing roadway
- Sizing the resulting RAP
- Mixing the RAP with the additives designated in the mix design
- Meeting the required gradation and sizing with either the milling process or with additional sizing equipment
- Producing a homogenous and uniformly coated mixture (if emulsions) by mixing RAP and additives in the milling machine or in an additional mixing chamber
- Placement and compaction according to the specifications

These requirements can be achieved through a set of equipment consisting of (not all the equipment may be needed for every project):

- Pavement cold planer (milling machine) with a minimum 12.5 ft cutter and a means for controlling the depth of milling and the cross-slope or pulverization machine
- Crushing and sizing equipment
- Mixing and proportioning equipment
- Cement and asphalt emulsion or foamed asphalt storage and supply equipment
- Mixing and spreading equipment for dry cement
- Mixing and spreading equipment for corrective aggregate
- Paving equipment
- Water truck
- Compaction equipment
- Fog sealing and sand spreading equipment

The construction process starts with roadway preparation in which the contractor should identify the location of all utilities within the project site, clean and remove any dirt or obstacle, reference the profile and cross-slope, cold mill along cross walks and gutters to prepare for the final overlay, and correct all areas known to have soft or yielding subgrades.

CIR construction is recommended only when the existing pavement temperature is above 50°F and the previous overnight temperature is above 35°F. A control strip with a minimum length of 1000 ft should be constructed on the first day of the project to show that the construction process meets the specifications. The optimal rates of additives (if any) and the rolling pattern to achieve the optimum field density should be identified from the control strip.

The existing pavement should be milled to the depth required by the plan or the specifications and the recycled materials should be crushed and sized to the maximum particle size specified. Typical depths are 2 to 4 in. The incorporation of recycling additive or stabilizing agent can be in the form of applying mechanical, chemical, or bituminous additives or a combination of all (ARRA, 2014). Mechanical stabilization in the form of compaction is used for all treatments, and the addition of imported granular materials is used if the existing in-place materials do not provide a satisfactory gradation (Van Dam, et al. 2015). Chemical stabilization is achieved by adding one or a combination of Portland cement, fly ash, calcium chloride, magnesium chloride, and lime. Bituminous stabilization consists of adding asphalt emulsion or foamed asphalt. The common practice in many states is to use a combination of bituminous stabilization and chemical stabilization for partial-depth recycling. Cement or lime slurry may be directly added to the mixing chamber or sprayer over the cutting teeth of the milling machine (Van Dam et al., 2015). If dry cement or corrective aggregate is needed, it can be spread on the existing surface before milling. The CIR milling and mixing process can be accomplished with a single-unit machine or a multi-unit train (Van Dam et al., 2015).

The placement of the recycled materials is conducted either with conventional asphalt pavers or cold mix pavers followed by compaction. The time between material placement and start of compaction is determined by the contractor. Compaction (initial/breakdown, intermediate, and final compaction) is one of the main factors affecting the future performance of the section. The type and number of compactors depend on many factors such as the degree of compaction required, material properties of the pulverized mix, support capabilities of the underlying layers, and the needed productivity. In general, the characteristics of the recycled mix determine the type of roller needed and the thickness of the layer and the required compaction dictates the weight, amplitude, and frequency of the compactors (Van Dam et al., 2015).

For materials stabilized by some chemical and/bituminous materials, in a process similar to that shown in Figures 2.4 and 2.5, curing is a critical step and is needed to assure achieving adequate strengths before opening to traffic, prevent raveling, and facilitate placement of the final wearing course. The curing rate depends on multiple factors such as the nature of the stabilization particularly if asphalt emulsions are used, temperature, humidity, moisture content of the mix, compaction level, and drainage characteristics of the section.

ARRA requires CIR to cure for a minimum of three days and the moisture content to be less than 3% before proceeding to secondary compaction or opening to traffic. ARRA recommends secondary compaction if the recycling agent is emulsified asphalt. If secondary compaction is planned, a separate rolling pattern should be established during the control strip and the density of the recycled materials after secondary compaction should be checked to verify compliance (ARRA, 2014). ARRA suggests that secondary compaction be done with pneumatic and double drum vibratory at temperatures above 80 °F. As materials are better understood and contractors gain more experience, local governments in several locations with light vehicles moving at slow speeds often open within hours of construction and follow with re-compaction and overlay several days later.

In the final step, a wearing course is usually laid on top. For low-traffic roads, a single or double chip seal might be sufficient, but in sections with higher traffic levels, an AC overlay might be needed. The minimum recommended thickness for AC overlays is 1 in, depending on the specifics of the project, agency policies, anticipated traffic, climate, economics, stabilizing agent, and structural requirements. For AC or warm mix asphalt (WMA) overlays, ARRA recommends applying a tack coat of either CSS-1h or SS-1h emulsified asphalt at minimum rate of 0.05 gal/yd^2 before applying the wearing course.

The construction of CIR should always include field adjustments because these processes are variable in nature due to changes in the materials being recycled along the roadway, changes in the speed of the equipment and, therefore, the RAP gradation from milling, and changes in the ambient temperature and humidity conditions. Field observations and adjustments are, thus, needed to assure good coating of the materials and workability of the AC mixture and quality construction even though the optimum moisture, additive type and content, and other factors are determined through laboratory tests and are stated in the job mix formula. These modifications and adjustments should be conducted by experienced field personnel who are continuously engaged in observing the material being placed behind the recycling train. Table 2.2 lists some of the common early problems that are observed in sections with CIR and recommended mitigation for them.

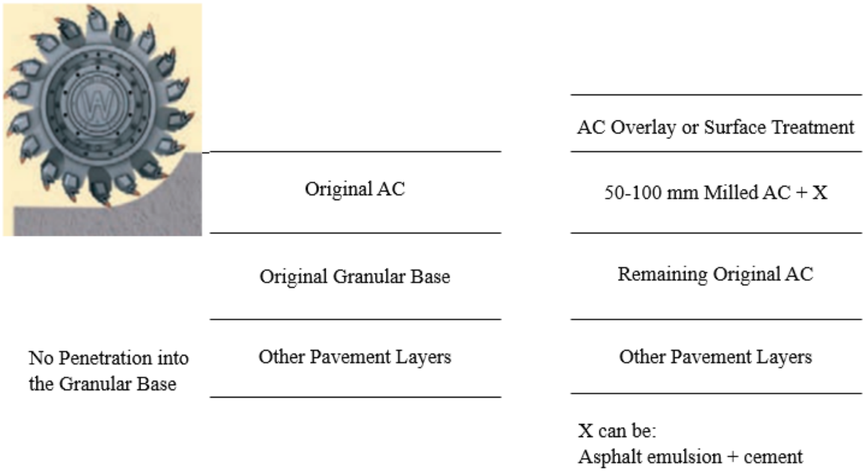

Figure 2.4. Diagram of CIR process. (Van Dam et al., 2015)

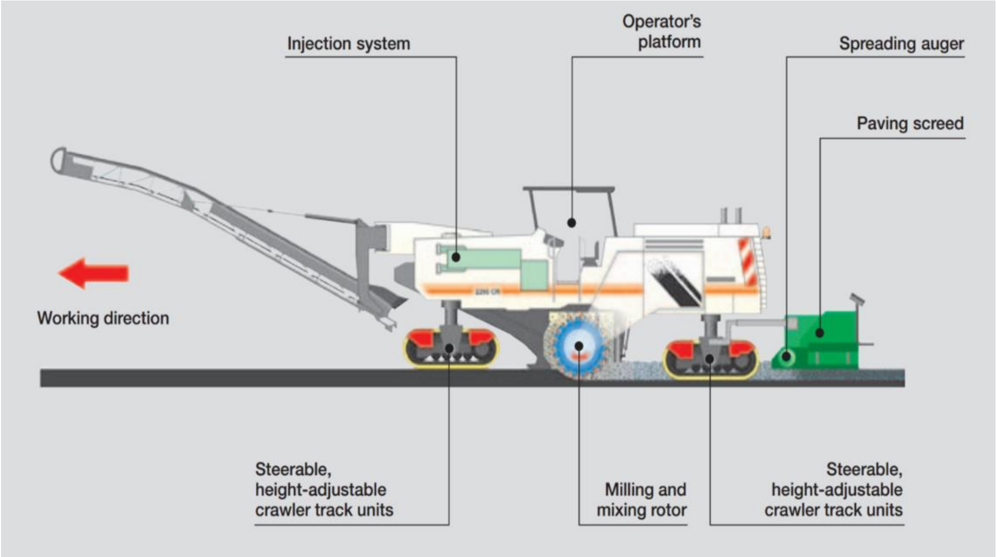

Figure 2.5. Diagram of CIR equipment (Wirtgen America Inc.)

Table 2.2 CIR early damage and mitigation (ARRA, 2014)

Distress	Mitigation
Isolated areas of minor raveling or scuffing.	Sweep and monitor. Determine if fog sealing or re-fog sealing is necessary to protect.
Isolated areas of major raveling, scuffing or tearing.	Maintain better traffic restrictions in areas that are not cured. Sweep and monitor. Determine if fog sealing or re-fog sealing is necessary to protect. Fill or remove and replace deep damaged areas with AC mixture (cold mix, recycled mix, WMA, or traditional AC) prior to surface course.
Large scale areas of raveling, scuffing or tearing in straight traffic areas.	Re-recycle or remove and replace with asphalt mixture (cold mix, recycled mix, WMA, or AC).
Dimpling due to parked vehicles or equipment.	Fill with AC mixture (cold mix, recycled mix, WMA, or traditional AC) prior to surface course.
Permanent deformation within wheel path areas due to secondary compaction by traffic.	If pavement temperatures permit, apply secondary compaction. Fill with AC mixture (cold mix, recycled mix, WMA, or traditional AC) or micro surfacing in the low areas or cold mill to provide a smooth surface.
Permanent deformation and shoving due to unstable mix.	Investigate pavement structure in conjunction with mix design lab. Depending on investigation, remove and replace affected areas with AC mixture (cold mix, recycled mix, WMA, or traditional AC) or re-recycle supplementing with uncoated coarse aggregate, additives and/or recycling agent as necessary.

Full-Depth Reclamation

The FDR construction process is similar to CIR, the only difference as stated earlier is that the whole thickness of the existing AC layer and a predetermined thickness of the underlying layer for at least 2 in are pulverized and mixed together (with water and with or without additives) into a homogenous mixture, as shown in Figures 2.6 and 2.7.

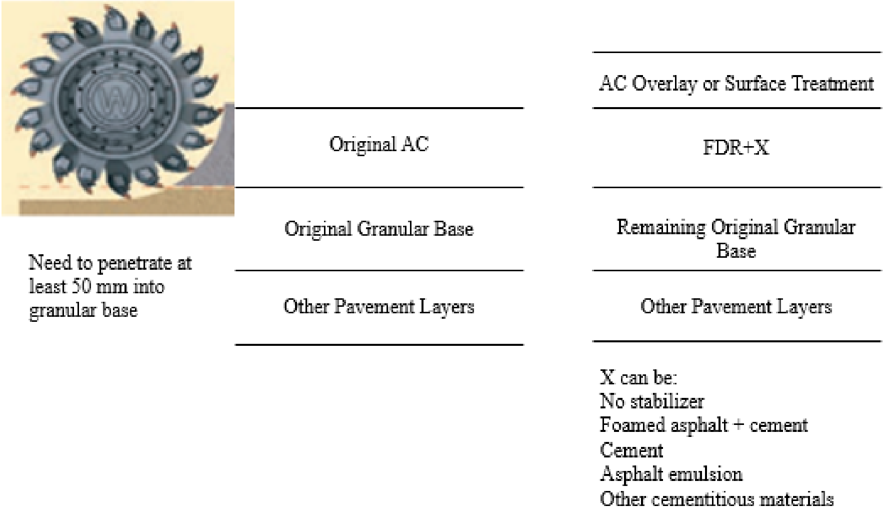

Figure 2.6. Diagram of FDR process (Van Dam et al., 2015)

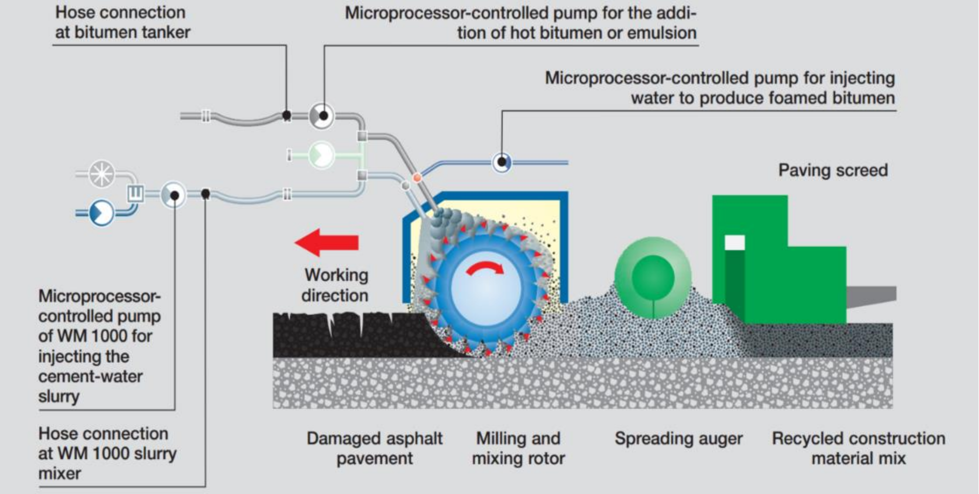

Figure 2.7. Diagram of FDR equipment (Wirtgen America Inc.).

FDR can recycle pavement depths up to 12 in. The FDR process can vary between projects depending on the project specifics, owner/agency needs, and the requirements of the section after recycling. The common practice for many agencies is to use a combination of foamed asphalt and chemical stabilization (typically cement) or only chemical stabilization or only asphalt emulsion stabilization with FDR (ARRA, 2013b).

ARRA has set the requirements shown in Table 2.3 on the gradation of the FDR pulverized material. When using asphalt emulsion, the maximum passing sieve no. 200 should not exceed 20% (ARRA, 2013a). Research conducted at University of California Pavement Research Center (UCPRC) recommends less than 12% passing the no. 200 sieve for stabilization with a combination of foamed asphalt and cement and up to 15% maximum with special consideration for binder content (Jones et al., 2009).

Table 2.3. ARRA requirements on FDR recycled materials gradation (ARRA, 2013a)

Sieve Size	Minimum Percent Passing
3 in. (75 mm)	100
2 in. (50 mm)	95
No. 4 (4.75mm)	55
No. 200 (0.075 mm)	5

For compaction of FDR with bituminous stabilization, ARRA requires the processed materials to be uniformly compacted in one layer (ARRA, 2013a). The moisture content at the start of the compaction should be within -1% to +2% of the specified optimum moisture. The initial compaction should not be more than 500 feet (160 m) behind the reclaimer unit and should be done by a padfoot or pneumatic roller. After the breakdown roller the materials should be spread using a motor grader until the desired shape and slope are achieved. After blading, a vibratory double drum steel roller and pneumatic roller should be used for intermediate and final compaction of the layer. Completed portions can be immediately opened to low speed local traffic. The overlay should follow within several days to protect the recycled layer from traffic wear.

For stabilization with cement, ARRA recommends that no more than 60 min pass between the first contact of cementitious stabilizer with water and application on the subgrade, and the time span between placement of the stabilizer and start of mixing not exceed 30 min. Compaction should begin no more than 20 min after mixing and all compaction operations should be completed within two hrs from start of the mixing process. There should be no grading or blading of the material after compaction has been completed. Curing is done by application of a bituminous or other approved sealing membrane or by using water spray to keep the section moist for three to five days. To help limit shrinkage cracking, micro-cracking can be done (optional) by using a 12 ton steel wheel vibratory roller. Completed portions of the section can be immediately opened to low speed local traffic (ARRA, 2013b).

The key for quality FDR construction as identified by a UCPRC report on guidelines for IPR is the following: (Jones et al., 2009)

- Contractor experience
- Traffic accommodation
- Pre-milling in cases where the asphalt layer is too thick (typically more than 10 in) or when precise surface levels need to be maintained
- Importing new material in case additional materials are needed to correct grades, increase layer thickness, and/or improve the bearing capacity of the section
- Equipment inventory
- Recycling train crew responsibilities
- Recycling train setup
- Test strip to check processes and determine compaction rolling pattern necessary to achieve specified density
- Ambient and pavement temperatures for asphalt emulsion additives (it is recommended to start the recycling when the ambient temperature is over 50 ºF and the temperatures of the road surface and pre-spread active filler are both equal of above 60 ºF)
- Recycling plan
- Recycling additive content and application rate
- Recycling depth and recycled material consistency
- Lateral joints
- Compaction moisture
- Initial compaction, final grades, and final compaction
- Curing
- Trafficking
- Surfacing
- Drainage

- Quality control

The FHWA has published checklists for CIR and FDR in collaboration with the ARRA and the National Center for Pavement Preservation. The checklists are comprehensive and include items for document review, project review, materials checks, preconstruction inspection responsibilities (preconstruction meeting, surface preparation, and equipment inspection), weather requirements, mix design, traffic control, project inspection responsibilities (milling, crushing, mixing, pickup machine and paver, rolling procedure, and quality assurance), opening to traffic, curing, and surface course (FHWA, 2013c; FHWA, 2013d) .

Energy Use and Emissions

There are a few studies that have tried to estimate energy consumption and emissions of IPR techniques. Although the number of studies is limited, they all result in the same conclusion that CIR not only reduces consumption of virgin materials but also results in significant savings in energy consumption and emission compared to conventional methods of rehabilitation.

Thenoux compared the energy consumption during construction for three different structural pavement rehabilitation alternatives which included AC overlay, reconstruction and FDR-foamed asphalt. It was determined that the FDR technique is the least energy consuming in all the scenarios, resulting in energy savings between 20% to 50% compared to AC overlay and up to 244% compared to reconstruction (Thenoux et al., 2007).

Robinette and Epps conducted a literature survey for estimating energy consumption and emissions of IPR practices (Robinette, 2010). The results are presented in Table 2.4 and Table 2.5.

Table 2.4. Energy consumption (Btu/yd^2-in) for CIR processes (Robinette, 2010)

Operation	**NCHRP 214**	**Colas Group**	**PaLATE**	**Granite Construction**	**Representative Range**
CIPR—partial depth	--	6,400	24,600	3,100	3,000–24,000
CIPR—full depth	15,000–20,000	6,200	34,700	1,300–11,100	1,300–15,000

Table 2.5. GHG emissions (CO_2-eq. lb/yd^2-in) of different CIR processes (Robinette, 2010)

Operation	**Colas Group**	**Granite Construction**	**Representative Range**
Cold milling asphalt pavement	0.084	3.377	0.08-3.500
CIPR-partial depth	–	0.71	–
CIPR-full depth	1.082	0.932-4.017	0.900-4.100

CHAPTER 3: DEVELOPMENT OF THE LCA TOOL METHODOLOGY

In this chapter, the LCA methodology developed to analyze each life cycle phase is presented. This discussion includes goal and scope, life cycle inventory and life cycle phases modeling and

GOAL AND SCOPE

The goal of this study is to develop a LCA methodology to assess the environmental impacts and energy use of transportation projects that involve maintenance and rehabilitation treatments using IPR and conventional paving methods.

This study is related to a project sponsored by FHWA that aims to develop a life cycle assessment decision making tool for IPR techniques. The pavement LCA framework and tool developed in this thesis can be applied to various agencies and national roadway practitioners. The scoping elements include the methodological choices required at the Goal and Scope phase of LCA according to the ISO 14044 (ISO, 2006) and FHWA Pavement LCA Framework (Harvey et al., 2016).

System Boundary

The product systems included in the study are IPR methods recognized by federal and state transportation agencies in the U.S which will be compared with conventional hot mix asphalt (HMA) overlays. The LCA includes the following life-cycle stages: material production, construction, maintenance, use, and end of life. The material production and construction life cycles of the systems considered in this LCA are related to IPR or conventional mill/fill processes. Thus, any processes related to the production and construction of the initial pavement is not included. The system boundary for the product system is shown as the dashed line in Figure 1.3.

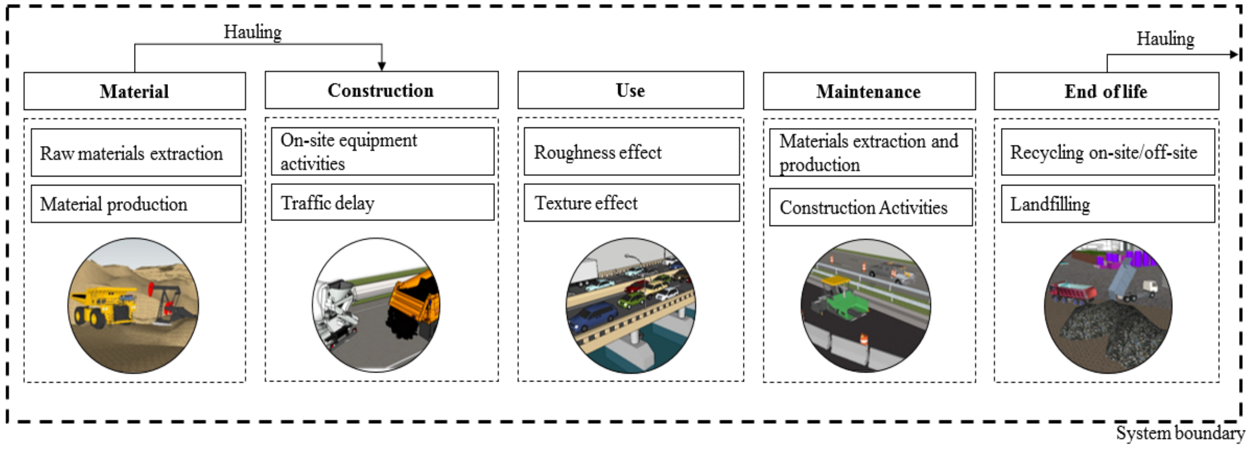

Figure 3.1. Life-cycle phases and system boundary of the LCA scope.

Functional Unit

The functional unit used in this LCA study is a one lane-mile over the analysis period. The analysis period depends on the treatments under comparison. The lane width is assumed to be equal to 12 ft.

Analysis Period

The analysis period is calculated following the method highlighted in the FHWA pavement LCA framework (Harvey et al., 2016). This method compares the life expectancy of treatments under study, defines the alternative treatment with the longest life expectancy, and adds it to the estimated life of the subsequent maintenance of the longest living treatment, as illustrated in Figure 3.2. It is important to assign a common analysis period in order to compare the pavement rehabilitation alternatives and to quantify the impacts of the use stage.

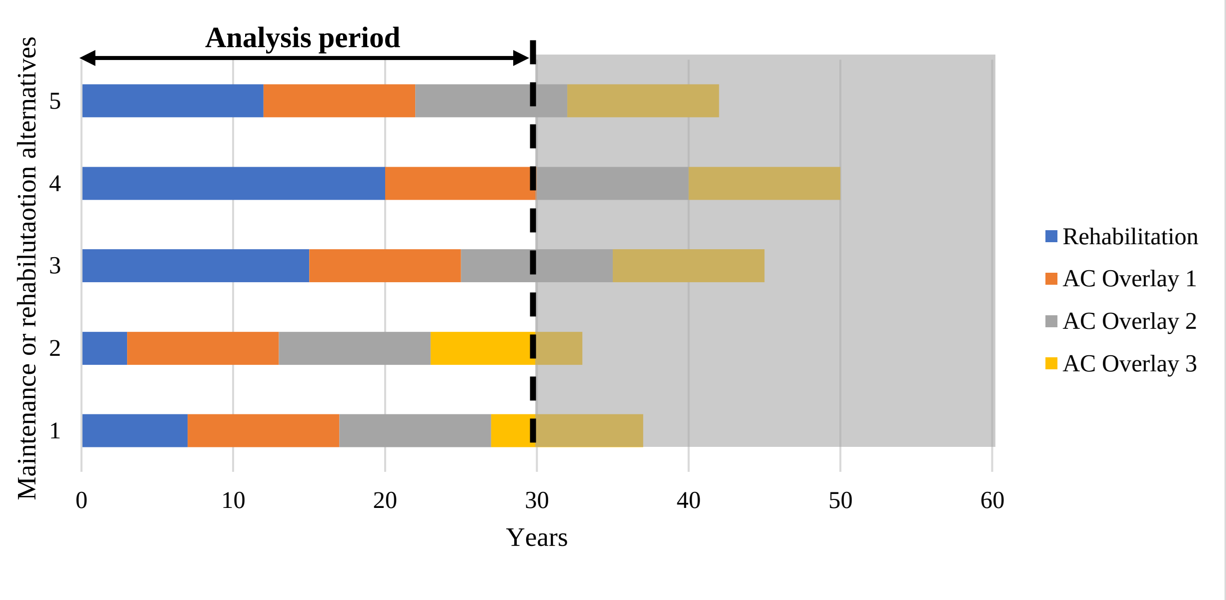

Figure 3.2. Analysis period strategy illustrating the first treatment's lifetime to be analyzed by the tool and subsequent overlays.

Allocation Method

The adopted allocation method is the cut-off or also known as recycled content methodology. The boundary of the analysis conducted is limited to the pavement system during the analysis period without accounting for the quantity of resources used in a subsequent system (Nicholson, 2009). The substitution allocation method is analyzed in the interpretation step of the LCA methodology to compare its effect to the cut-off method.

LIFE CYCLE INVENTORY

Data collection phase of the study included collecting primary and secondary data from various sources. Primary data refers to specific data collected for some of the IPR techniques from the contractors whereas secondary data refer to average and background data for processes like fuel and electricity production, emission due to equipment use. Data sources included agency and contractor questionnaires and interviews, commercial inventory databases, and publicly available data sources.

Primary Data

The primary data are the information collected from field projects and used for quantification of life-cycle inventory (LCI) impacts. Questionnaires have been distributed to contractors throughout the nation in 2016-2017. Data collection was undertaken at an early stage of the project in order to collect information and data about IPR techniques and construction methods. The project information and data were analyzed to assess the fuel usage of IPR techniques, especially CIR and FDR. Follow-up interviews were conducted with some of the contractors to collect additional data.

Figure 3.3 represents the distribution of agencies and contractors that responded to questionnaires and shared their IPR data from field projects.

Figure 3.3. Representative map of contractors and agencies contacted in the three main US regions.

Appendix A contains information collected from agencies regarding the HIR and CIR/FDR practices. The main conclusions extracted from the data collected are that IPR techniques are applied under specific project conditions. The selection of any IPR type requires a good understanding of the dynamic parameters (traffic level, truck percent, lane closures and openings, and climate) and static characteristics (road geometry, structural capacity, and existing pavement condition). It was found that HIR and CIR are commonly used at low traffic volume pavements, under a truck percent that varies from 5% to 10% for a pavement length of 100 lane-mi per year. According to agencies responses, CIR extends existing pavement service life to more than 11 years, whereas HIR is reported to extend service life from five to ten years. The difference in performance between CIR/FDR and HIR is due to the fact that CIR/FDR is a rehabilitation technique that enhances the structural capacity and treats a wide range of surface and deep distresses. On the other hand, HIR is classified as a maintenance treatment applied to a limited number of functional distresses.

Secondary Data

The secondary data complements the inventory items missing in the primary data collected. Various sources were used to compile a comprehensive inventory list which are (1) Commercial LCI databases (e.g. Ecoinvent 2.2/3.0 (Frischknecht, 2004; Wernet et al., 2016)), US-Ecoinvent 2.2 (EarthShift, 2013)), (2) software (e.g. EPA MOVES 2014 (EPA, 2015), eGRID 2010 (eGRID, 2015)), (3) governmental databases, (4) governmental reports, (5) material safety data sheets, and (6) equipment manufacturer specifications.

Other Data Collected from Questionnaires (States)

Apart from primary data collected from contractors, a set of questionnaire surveys was distributed to state/local transportation agencies (via online survey). There were two sets of questionnaire surveys: one for HIR, and the other for CIR. Each set contains similar questions inquiring agency experience in IPR, pavement management, construction details, performance, and specifications. A sample questionnaire survey and the detailed results of questionnaire surveys are attached in Appendix A. Some survey result highlights are summarized in Table 3.1 for HIR and CIR.

This information was also used to support the development of the decision matrix for the pavement performance estimation qualitative approach. Agencies were asked about the following information:

- Major items associated with the IPR practice.
- Most sensitive specification requirements pertaining to IPR.
- Safety concerns.
- Lane closure and opening strategies.
- Existing regulations regarding emissions associated with the construction practices such as dust, dirt, or smoke.
- Factors affecting the success of CIR/FDR project.
- Traffic condition.
- Pavement performance indicators used by the agency.
- Cost per square yard.

Table 3.1. Survey highlights for HIR and CIR.

Questionnaire Contents	Agencies Common Practices in HIR	Agencies Common Practices in CIR
IPR use	Less than 100 lane-mi/year	Less than 100 lane-mi/year
Traffic	Low volume roads below 10,000 AADT	Low volume roads below 10,000 AADT
Truck percent	Varies between 5 and 10%	Varies between 5 and 10%
Condition index	PCI, PDI, or in-house index	PCI, PDI, other in-house index (i.e., distresses)
What triggers?	The selected index	The selected index and others (i.e., IRI, distresses, etc.)
Index after IPR	> 50% improvement	> 26% improvement
Expected life	Varies but between 5 and 10 years	Varies but between 3 and 7 years
Cost	Varies between \$4 and \$7 per sq yd	Varies between \$3 and \$6 for CIR; \$9 and \$12 per sq yd
Lane closure	Mostly partial closure	Majority partial closures
Opening time	1 – 4 hours after treatment	1 – 4 hours after treatment

As seen in Table 3.1, the application of IPR is still limited to low-volume roads with relatively low traffic levels (less than 10,000 AADT). The condition index used varies greatly; among different indices, pavement condition index (PCI), pavement distress index (PDI), pavement quality index (PQI), and international roughness index (IRI) are the most commonly used ones. Most agencies trigger treatment based on the condition index in use. Upon the application of IPR, it is reported that the index improves more than 50% for HIR and more than 26% for CIR

INVENTORY ANALYSIS AND IMPACT CATEGORIZATION

Inventory database is compiled from primary and secondary sources with regionalized data collected from agencies and contractors from the three main US regions. Life cycle inventory analysis is performed using regionalized models for fuel and electricity.

The impact characterization is performed using TRACI categories. Four quantitative outcomes from the LCA study are:

- Global warming potential,
- Energy,
- Total energy with feedstock,
- Single score.

Global Warming Potential

"Global warming is an average increase in the temperature of the atmosphere near the Earth's surface and in the troposphere, which can contribute to changes in global climate patterns. Global warming can occur from a variety of causes, both natural and human induced. In common usage, "global warming" often refers to the warming that can occur as a result of increased emissions of greenhouse gases from human activities" (EPA, 2008). This impact is given in units of kg carbon dioxide equivalence (CO_2e). The 100-year GWP is calculated using the EPA's Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) 2.1.

Single Score

Other environmental impacts were reported in a condensed format though calculation of a unit-less parameter calculated based on the normalization and weighting for TRACI impacts using the coefficients presented in Table 3.2 (Lautier et al.,2010; Bare et al., 2006). This parameter is referred to as the Single Score, which is reported in "points." It must be noted that the weighting given to the Single Score is subjective, though the weighting values developed by National Institute of Standards and Technology (NIST) are specific to the context of the U.S.

Table 3.2. TRACI Impacts with Normalization and Weighting Factors

Impact category	Unit	Normalization	Weighting
Ozone depletion	kg CFC-11 eq	6.20	0.024
Smog	kg O3 eq	0.000718	0.048
Acidification	kg SO2 eq	0.0110	0.036
Fossil fuel depletion	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
Global warming	kg CO_2 eq	0.0000413	0.349

Energy Indicators

Two energy consumption indicators are included in the impact assessment: energy and total energy with feedstock. Energy refers to combusted or expended energy as fuel. Total energy with feedstock includes energy that is embodied as a fuel (e.g. diesel, natural gas) and energy that is embodied as a material (e.g. plastics, asphalt binder). As FHWA Pavement LCA guidelines recommend, two types of energy are reported to provide a more complete view of energy consumption over the life cycle (Harvey et al., 2016). For example, accounting feedstock energy for asphalt agents results in higher energy for asphalt concrete pavement life cycle due to the energy retained in the asphalt binder.

DATA QUALITY ASSESSMENT

Data Quality Requirements

Data quality assessment was conducted following ISO 14044 recommendations (ISO, 2006) and FHWA pavement LCA framework (Harvey et al., 2016). High-quality data is important to ensure an accurate LCA study and reliable results to use at the decision-making stage (Weidema; Wesnaes, 1996). Table 3.3 shows the quality goals description assessed in this study.

Table 3.3. List of data quality requirements.

Data Quality Indicator	Description
Time related coverage	Age of the data and the minimum length of time over which data should be collected.
Geographical coverage	Geographical area 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 of the data values for each data expressed.
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.

The commercial database Ecoinvent and other external software such as MOVES 2014, GREET and eGRID were used to develop the inventory of upstream and downstream processes. The missing data in materials inventory was addressed by using MSDS. In addition, other processes extracted from an external software are limited to downstream processes such as the emissions compiled using the NONROAD option of MOVES 2014 software. Therefore, appropriate upstream data from Ecoinvent was used to address the missing upstream data.

Data quality was evaluated based on Pavement LCA FHWA framework (Harvey et al., 2016) and scored based on the Greenhouse Gas Protocol developed by Weidema and Wesneas (Weidema; Wesneas, 1996). The score ranges from 1 to 5 to evaluate the reliability of data in life cycle inventory using the five independent indicators presented in Table 3.3. The results of data quality assessment are presented in Table 3.4.

Table 3.4. Data quality assessment of major modeled unit processes.

Process Type	Unit Process	Data Source	Data Collection Option[1]	Score
Fuel	Diesel	Public and government databases	4	Fair
Fuel	Propane	Public and government databases	4	Fair
Electricity	Electricity	Government and commercial database	4	Good
Construction	Equipment	MOVES 2014 simulations	4	Good
Hauling	Hauling trucks	EPA MOVES simulations and commercial database	4	Good
Hauling	Single-unit truck	EPA MOVES simulations and commercial database	4	Good
Hauling	Passenger car	EPA MOVES simulations and commercial database	4	Good

Data Validation

The data validation is conducted by comparing the trend of GWP and energy consumption to reveal any anomalies in the data. Figure 3.4 shows that GWP and energy have the same trend as expected, except for cement where the associated CO_2 emissions are the highest among many other materials and that is due to the additional CO_2 emissions arising from limestone calcination. Figures 3.5 and 3.6 show that the trend for GWP and energy is the same for construction equipment and hauling inventory.

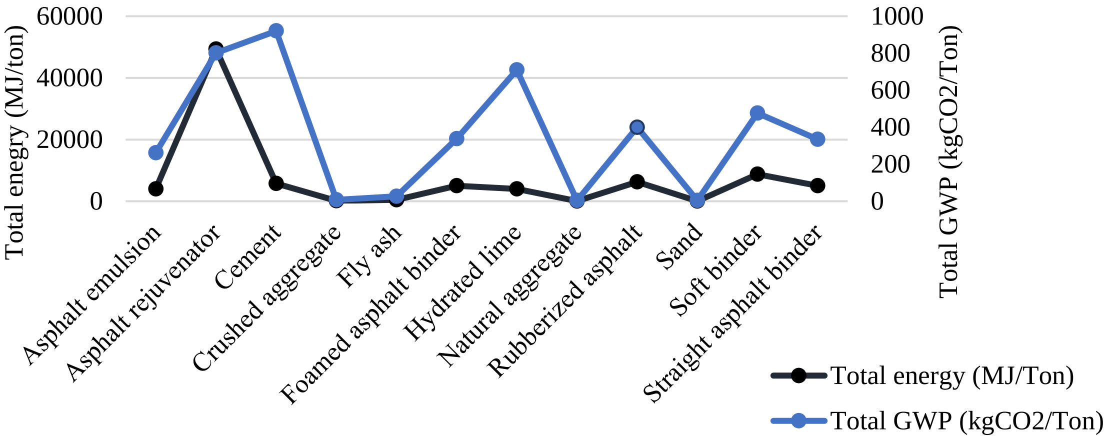

Figure 3.4. Data validation of material inventory.

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[1] Data collection options are defined in the FHWA LCA framework to describe the use of primary and secondary data.

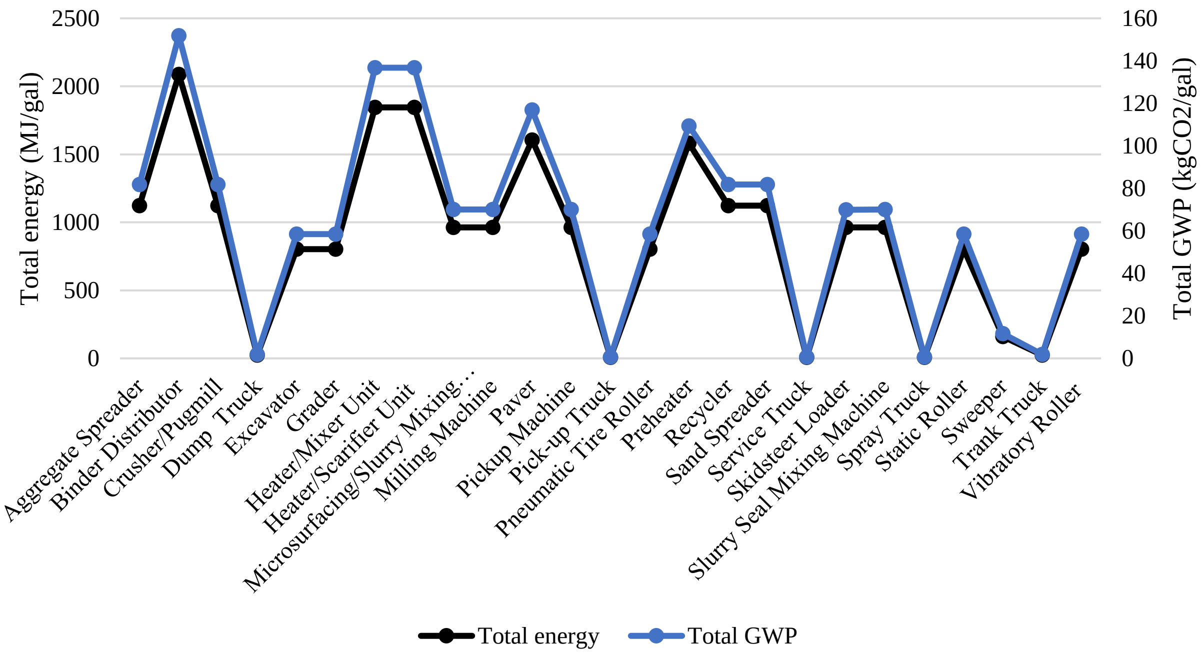


Figure 3.5. Data validation of equipment inventory.

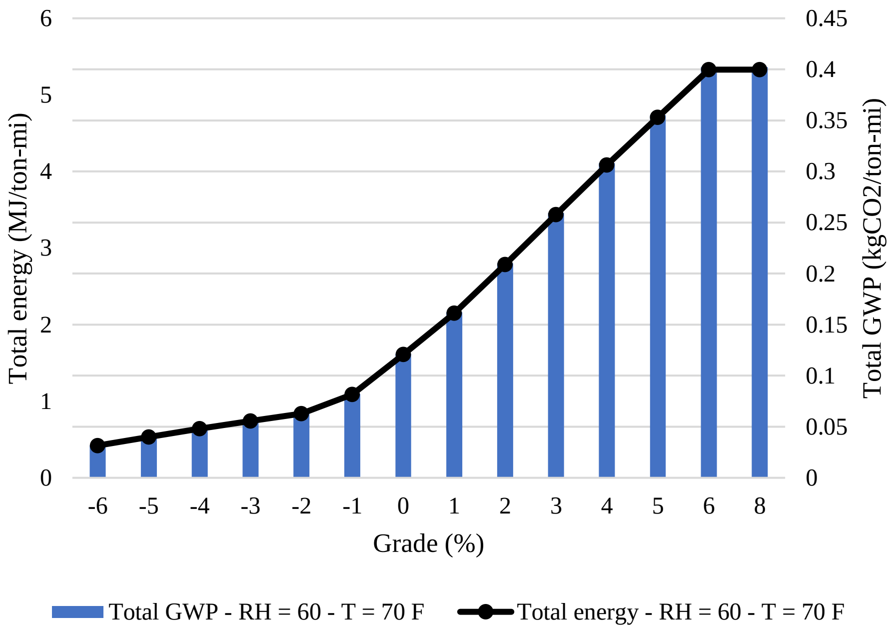


Figure 3.6 Data validation of hauling inventory.

MATERIAL PRODUCTION AND HAULING PHASE

This section discusses the regional models developed to assess the impacts of materials' production and hauling to site. A list of materials used for construction of pavement maintenance and rehabilitation was developed to allow running materials phase analysis.

Modeling procedure

Fuel and Electricity

The fuel and electricity inventory database was regionalized based on the Petroleum Administration for Defense Districts (PADD) and eGRID regions. The IPR tool is intended to be applied on a national scale. Therefore, fuel and electricity production unit processes inventory database was developed to cover all U.S. states. These processes are used to assess the impacts of materials production.

Figure 3.7 highlights the five PADD regions based on the U.S Energy Information Administration that help in analyzing open source data of regional petroleum product supplies (EIA, 2010a). A study by Yang et al. compiled life-cycle impact processes of crude oil production including extraction, flaring, and transportation (Yang et al., 2016). The results of this work allowed assessing the environmental impacts and energy use of asphalt binder production in the five PADDs. It was assumed that the same quantity of 1tn.sh of a processed crude oil is necessary to produce 1tn.sh of asphalt binder. Figures 3.8 and 3.9 shows the energy of asphalt products production in all PADDs.

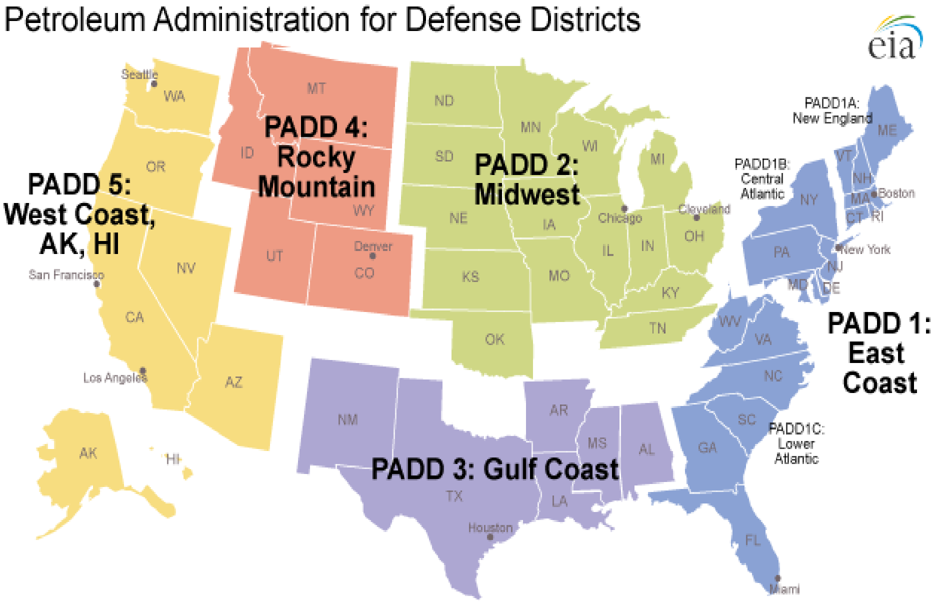


Figure 3.7. PADDs map from U.S. Energy Information Administration (EIA, 2010a)

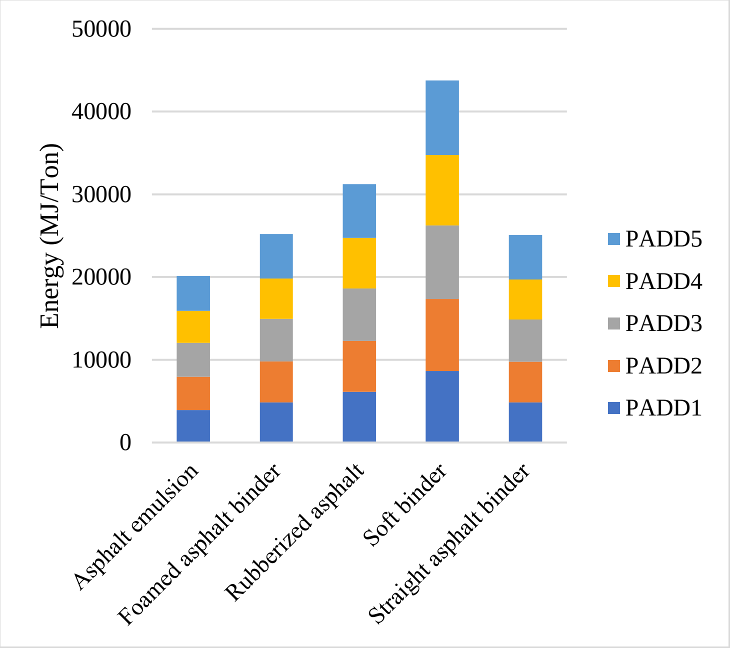


Figure 3.8 (left). Energy of different asphaltic materials production in the five PADD regions without feedstock. (Yang et al., 2016)

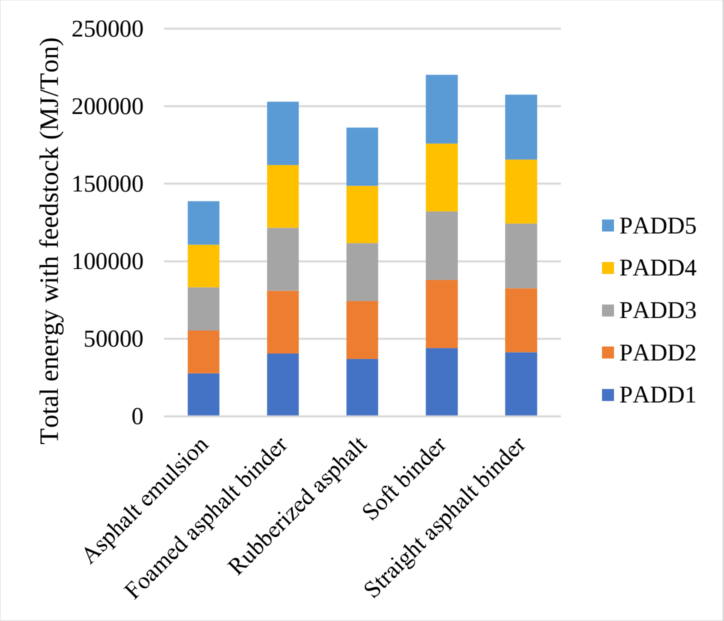


Figure 3.9 (right). Energy of different asphaltic materials production in the five PADD regions with feedstock. (Yang et al., 2016)

There are ten North American Electricity Reliability Corporation (NERC) regions in the U.S. as illustrated in Figure 3.10.Unlike PADDs district, NERC regions do not have clear boundaries because the region that electricity providers cover is not strictly divided by state (U.S. EPA, 2015). This implies that a state may belong to multiple NERC regions. For example, three NERC regions, Reliability First Corporation (RFC), Southeastern Reliability Council (SERC), and

Midwest Reliability Organization (MRO), provide electricity to the state of Illinois. Using eGRID 2012, type and percent contribution of NERC regions relevant to each state are calculated (U.S. EPA, 2015). Commercial life-cycle inventory (LCI) contains unit processes for electricity production with all NERC regions. Combining this information, the electricity production unit processes for each state are modeled in SimaPro, a commercial LCA software. It is assumed that NERC regions contributing less than 0.02% of state electricity are not considered. Primary energy demand (PED) and global warming potential (GWP) for producing 1 kWh of electricity for each state are illustrated in Figures 3.11 and 3.12.

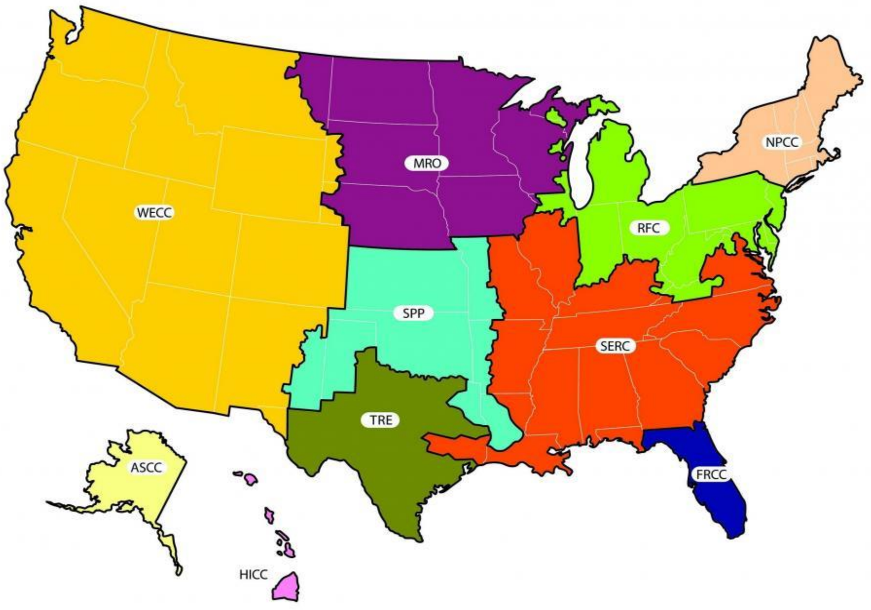


Figure 3.10. North American Electricity Reliability Corporation (NERC) regions in the U.S. (U.S. EPA, 2015)

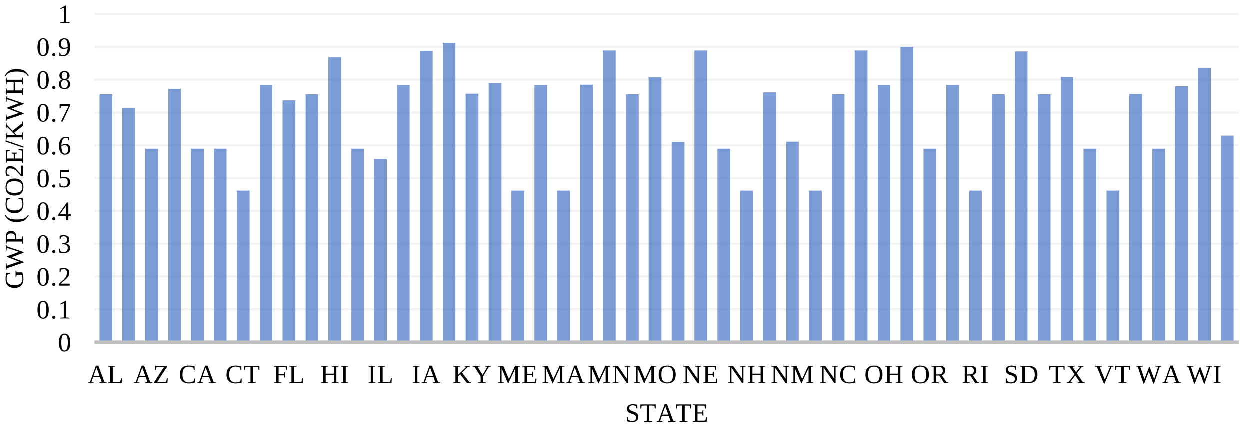


Figure 3.11. GWP for electricity generation of 1 kWh.

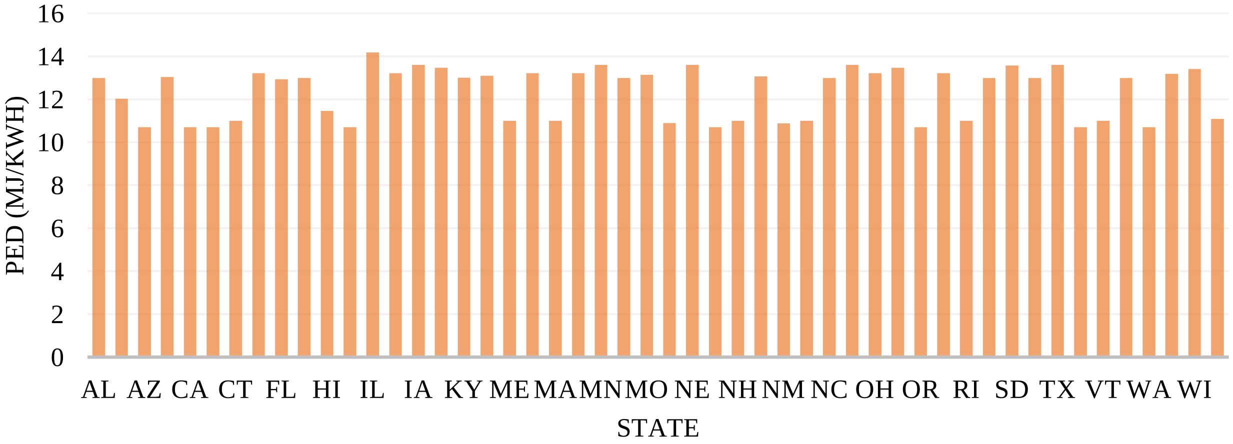


Figure 3.12. Primary Energy Demand (PED) for electricity generation of 1 kWh.

Construction Materials

As IPR techniques are used on AC pavement, mineral aggregate, asphaltic materials, other (i.e., rejuvenating and stabilizing) materials, and plant operation are considered. The mineral aggregates considered include natural aggregate, crushed aggregate, and sand. Impacts associated with producing these materials are calculated using relevant unit processes in the U.S. Ecoinvent (US-EI) 2.2 database (EarthShift, 2013). Aggregate unit processes are then modified by replacing default electricity models with state electricity models developed to improve its regional proximity.

The production of asphaltic materials follows similar procedures as petroleum fuel production in the previous section because asphalt binder is a co-product obtained during petroleum refining processes. Therefore, the impacts of asphalt binder vary with regions (i.e., five PADDs) (Yang et al., 2016).Taking the asphalt binder model as the base, other asphaltic materials such as emulsion, ground tire rubber (GTR) binder, polymer modified binder, and foam asphalt are modeled in SimaPro (Simapro, 2014) . Additional information about material composition and fuel/electricity use is summarized in Appendix B.

Asphalt rejuvenator is a paraffinic material used during IPR techniques to restore binder properties. This material consists predominantly of aromatic hydrocarbon with carbon numbers in the range of C20 to C50 [paraffin wax] with 5% of C4 to C6 numbered aromatic hydrocarbons [benzene]. Impacts associated with these materials are obtained from US-EI 2.2 database. Hydrated lime can be used for stabilizing subgrade and the impact of producing hydrated lime is obtained from US-EI 2.2 database (U.S. EPA, 2017; NIH, 2016).

Asphalt plant operation involves various processes. The sources of fuel consumption include the use of electricity to operate mixing drums and conveyor belts, the use of fuel (i.e., natural gas) to dry aggregate and heat asphalt binder, and the use of diesel to operate loaders for in-plant transportation. Combining these processes based on data collected from questionnaires, commercial database (Kang et al., 2014), and literature, a base AC plant model is developed

(Young, 2007). By adopting different electricity models, the environmental impact associated with operating AC plants is computed for each state.

Hauling

One of the advantages of using IPR techniques over conventional rehabilitation methods is the significant reduction in material hauling. Mill and inlay is the most widely used rehabilitation technique in AC pavements. Deteriorated AC surface is milled to a certain depth and transported for recycling (mainly) or to a landfill; and new AC materials are transported to the site for the new surface course. IPR techniques typically do not require much new materials because scarified in-situ pavement materials are re-used on-site. Hence, material hauling is minimized; this is manifested by capturing environmental benefits when IPR techniques are used.

Environmental Protection Agency (EPA)'s Motor Vehicle Emission Simulator is used to compute the environmental impacts of hauling operations (U.S. EPA, 2016). Based on preliminary simulations, it is found that six parameters including truck speed, road grade, payload, year, temperature, and relative humidity affect emissions of heavy truck operations. Through numerous simulations, variable impact transportation (ICT-VIT) model was developed to compute the environmental impacts and energy associated with hauling activities (Franzese, 2011). Types and values of variables considered are summarized in Table 3.5. The results of preliminary simulations are illustrated in Figure 3.13 through Figure 3.16.

Table 3.5. Types and ranges of variables considered in MOVES simulations.

Variable	Quantity
Vehicle speed (mph)	Idling, 1, 2.5, 5, 10, 20, 30, 40, 50, 55, 60, 70
Vehicle weight (tn.sh)	9.07, 15.3, 24.6, 30.1, 33.4, 36.3
Road grade (%)	0, ±1, ±2, ±3, ±4, ±5, ±6, ±8
Temperature (°F)	0 - 110
Relative humidity (%)	30 - 100
Year	2015 - 2050

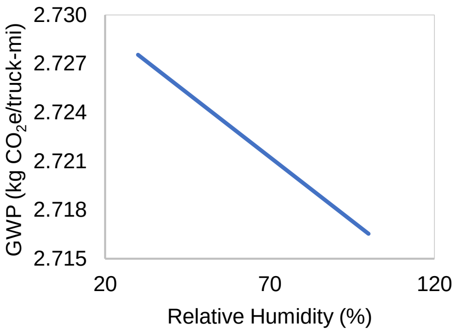


Figure 3.13 (top left). Effect of relative humidity on global warming potential (GWP) (T=temperature, RH=relative humidity, G=grade, M=payload).

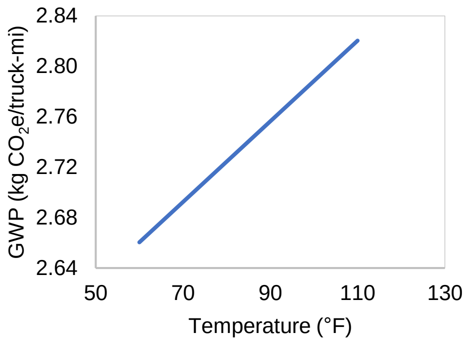


Figure 3.14 (top right). Effect of temperature on global warming potential (GWP) (Temp=temperature, RH=relative humidity, G=grade, M=payload).

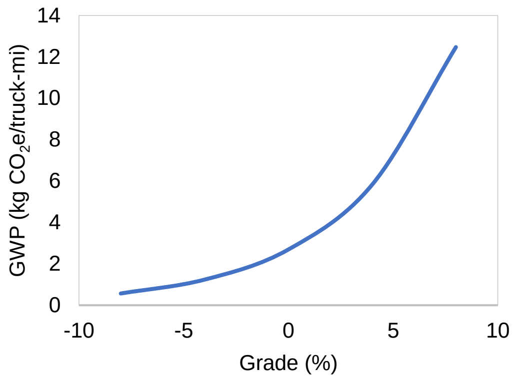


Figure 3.15 (bottom left). Effect of grade on global warming potential (GWP) (T=temperature, RH=relative humidity, M=payload).

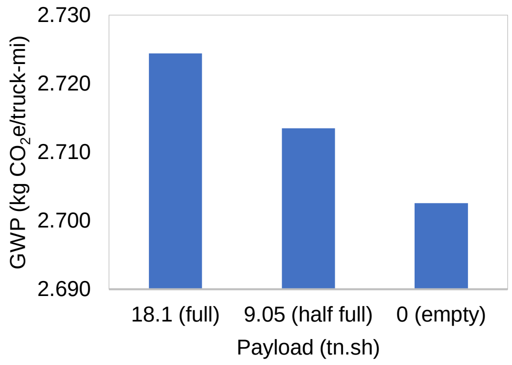


Figure 3.16 (bottom right). Effect of payload on global warming potential (GWP) (T=temperature, RH=relative humidity, G=grade).

CONSTRUCTION STAGE

The impacts resulting from the construction stage are associated to fuel usage of on-site equipment and additional emissions due to traffic delay. Construction equipment data was collected from contractors and agencies experienced with use of IPR techniques. Therefore, fuel usage models were modeled. Also, procedure was developed to assess the impacts of construction stage. The use of the existing pavement during the construction phase is governed by the work zone traffic control which is assessed based on the user traffic management strategy.

Fuel Usage Models for IPR Techniques

This section presents the various construction practices of IPR treatments and their energy analysis during the construction stage of life-cycle. In the construction stage, the processes are mainly associated with fuel usage of equipment used in construction. The main factors that affect energy use are discussed, evaluated, and quantified to measure their impact on the construction stage of each treatment. The construction processes modeled represent specific construction projects. The IPR techniques are introduced and discussed separately.

Hot In-Place Recycling

General HIR Process

In this study, the milling depth during HIR construction processes is assumed 1.5-1.75 in for resurfacing and 1-3 in for remixing and repaving. The construction information of the HIR treatments was based on data collected from projects in various locations. The total propane consumption ranges from 118.17 to 253.46 gal/hr for resurfacing and from 138.55 gal/hr to 1030.73 gal/hr for remixing and repaving. The equipment propane consumption was based on an average train speed of 18.5 ft/min. Figure 3.17 shows that most of the HIR projects consumed approximately 323 gal/hr of propane fuel.

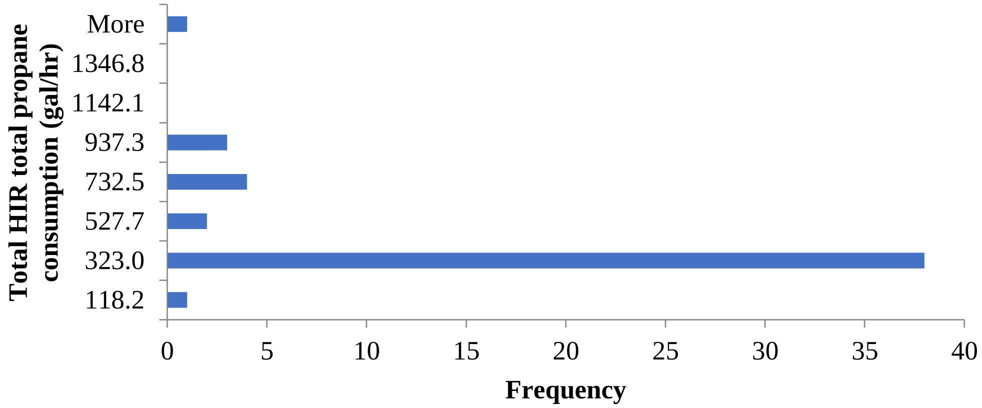


Figure 3.17. Graph. Histogram of HIR projects propane consumption.

According to the results in Table 3.6, the energy consumption of HIR resurfacing, HIR remixing, and HIR repaving construction operations were found to be 95.95GJ/lane-mi, 242.56GJ/lane-mi, 250.56 GJ/lane-mi, respectively.

Table 3.6. Details for the environmental assessment of HIR construction processes.

Activity	Equipment Type	Fuel Type	HP	Hourly Fuel Consumption (Gal/hr)	Speed (ft/min)	Total Energy (GJ/Lane
HIR Surface Recycling	Preheater	Diesel	99	3	18.5	95.95
HIR Surface Recycling	Heater/Scarifier Unit	Diesel	321	3	18.5	–
HIR Surface Recycling	Preheater	Propane	99	106	18.5	–
HIR Surface Recycling	Heater/Scarifier Unit	Propane	321	71	18.5	–
HIR Surface Recycling	Vibratory Roller	Diesel	150	8.1	25	–
HIR Remixing	Preheater	Diesel	99	3	18.5	242.56
HIR Remixing	Heater/Mixer Unit	Diesel	321	3	18.5	–
HIR Remixing	Preheater	Propane	99	286	18.5	–
HIR Remixing	Heater/Mixer Unit	Propane	321	190	18.5	–
HIR Remixing	Vibratory Roller	Diesel	150	8.1	25	–
HIR Repaving	Preheater	Diesel	99	3	18.5	250.65
HIR Repaving	Heater/Scarifier or Mixer Unit	Diesel	321	3	18.5	–
HIR Repaving	Preheater	Propane	99	286	18.5	–
HIR Repaving	Heater/Scarifier Unit	Propane	321	190	18.5	–
HIR Repaving	Vibratory Roller	Diesel	150	8.1	25	–
HIR Repaving	Paver	Diesel	250	10.6	18.5	–

The energy use results calculated for each HIR treatment are shown in Figure 3.18 separated by fuel type and equipment type. Repaving has the highest amount of energy use among all HIR treatments since it has an additional paving activity of an asphalt overlay. The equipment used to heat the pavement surface (preheater, heater/scarifier unit, and heater/mixer unit) contributes the most to energy consumption due to their high propane consumption. The heating machines contribute 90.45%, 96.22%, and 93.12% to overall energy consumption for resurfacing, remixing and repaving, respectively.

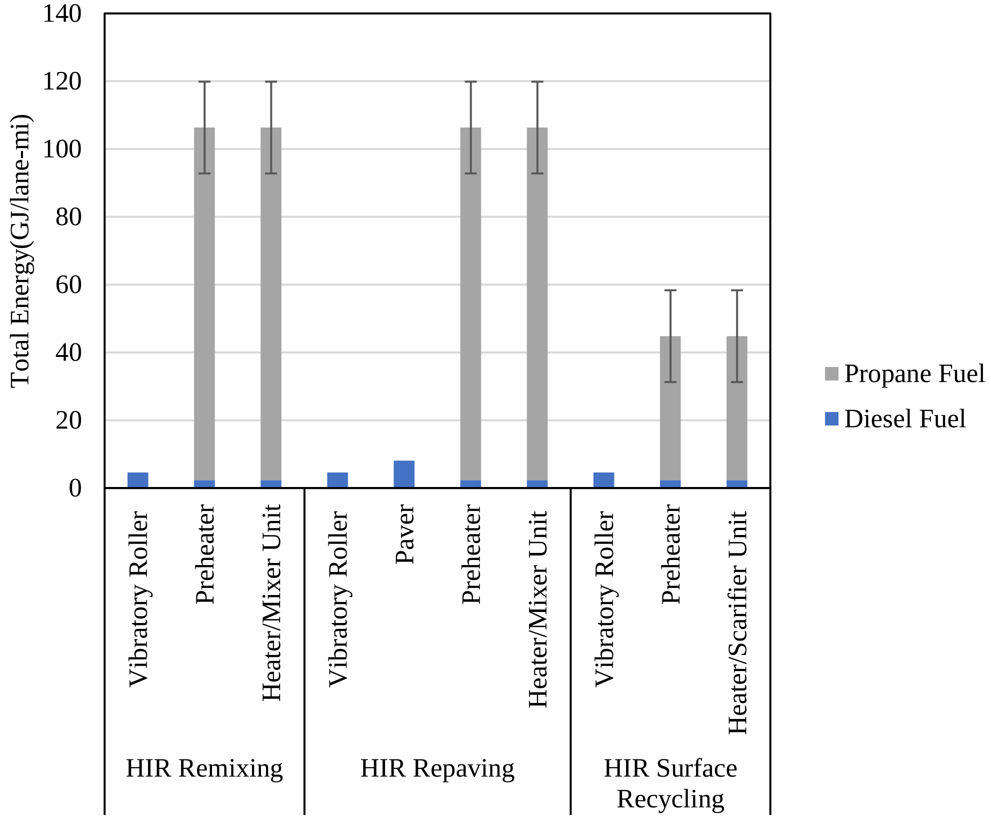


Figure 3.18. Construction energy consumption of HIR methods.

Effect of Air Temperature

The HIR projects analyzed were constructed in air temperature that ranges from 34°F to 87°F. The data analysis within this range showed that air temperature does not have any effect on propane consumption of the heating machines as it did not show any consistent trend. However, it was clear that the highest propane consumption rates were localized in the range between 68°F and 87°F which falls in the range of the construction season temperatures that usually start in April and end in October (Figure 3.19).

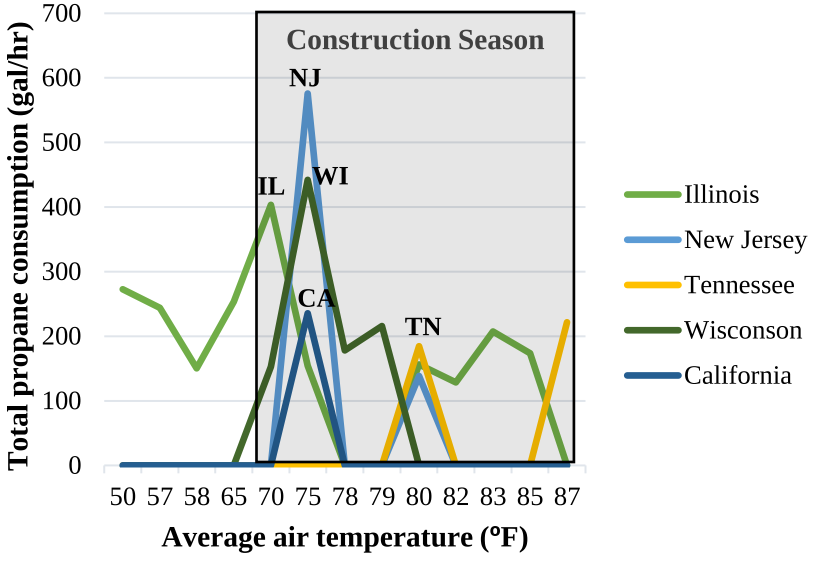


Figure 3.19. The HIR total propane consumption versus air temperature for different U.S. states.

Effect of Construction Year

According to the results presented in Figure 3.20, the data collected from contractors between 2012 and 2014 show that the average propane consumption of the projects analyzed decreases over the years. That decrease might be due to the use of a lower number of equipment units or change in the operation of trains. Propane consumption decreased 44.75% from 2012 to 2013 and 49.05% from 2013 to 2014.

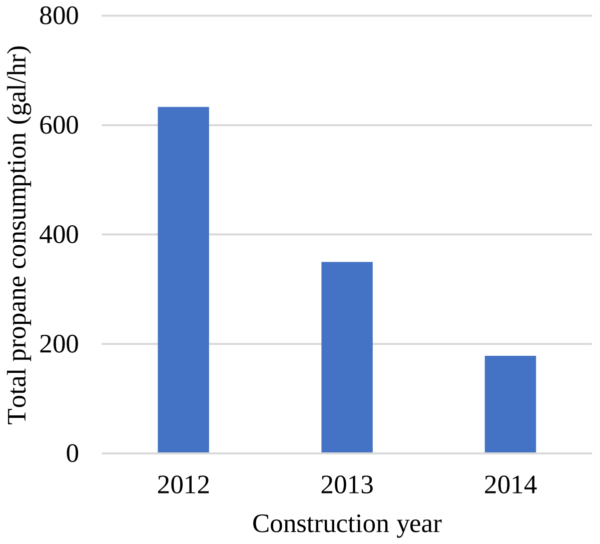


Figure 3.20. Total HIR propane consumption versus year of construction.

Effect of Equipment Type

In 2014, heater units used to operate HIR construction activities and the projects analyzed were either tractor pulled or self-propelled. The tractor-pulled set is an equipment train propelled by a tractor truck, thus the speed of the equipment train units depends on the speed of the tractor truck. The self-propelled or self-contained equipment is defined as “automobiles, motorcycles, aircraft, boats, snowmobiles, trucks, tractors, jet skis, lawn mowers, golf carts, etc., that convert their own energy supply into motive power used for propulsion.” (Fox, 1999). Figure 3.21 shows that in 2014, the self-propelled heater unit consumed 11.71% less propane than the tractor-pulled set. Therefore, it is more efficient to use self-propelled instead of tractor-pulled heating machine units.

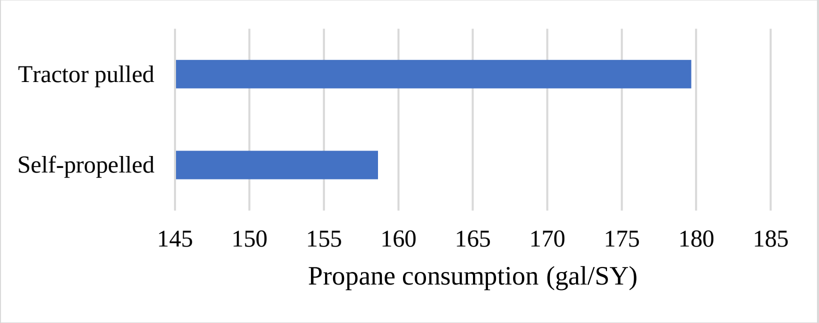


Figure 3.21. HIR propane consumption for two equipment sets.

Effect of Milling Depth

The first step in the HIR construction process is to heat the milling depth of the pavement surface in order to soften it before milling. Figure 3.22 shows that the higher the milling depth for both resurfacing and remixing, the greater the propane consumption. For remixing, propane consumption ranges from 154 gal/hr to 689 gal/hr for a milling depth varying from 1 to 2 in. Whereas, the propane consumption of resurfacing varies from 175 gal/hr to 206 gal/hr at milling depth of 1.5 in and 1.75 in, respectively.

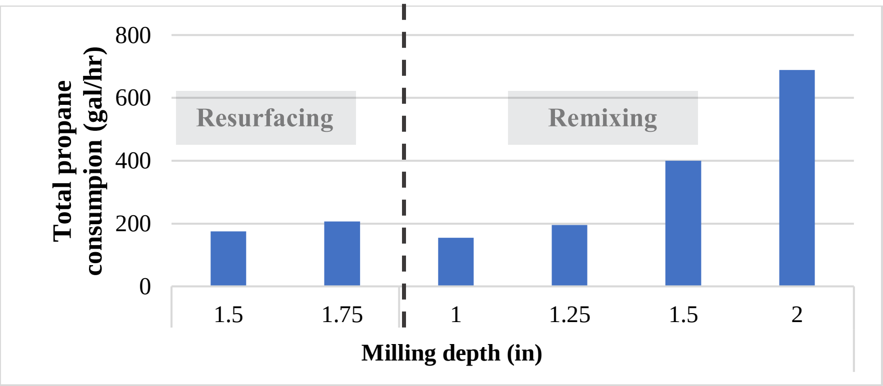


Figure 3.22. Total propane consumption of HIR resurfacing and HIR remixing versus milling depth.

Effect of Pavement Aggregate Hardness

Pavement aggregate hardness is one of the main factors that influence propane and diesel fuel consumption. This study considers the impact of pavement hardness on propane consumption because the propane usage has the highest contribution to the overall energy use. The impact of pavement hardness is mostly seen during the scarification or grinding of the existing HMA surface. Hardness can be attributed to aggregate type, temperature during heating, and asphalt binder type used in the surface layers. The project-specific data collected from the contractors were used to evaluate the effect of hardness with an intent to develop a model that is capable of predicting the relative hardness of the pavement based on project location.

Available data show propane consumption during the remixing process in different job locations in Georgia, Illinois, Massachusetts, New Jersey, Tennessee, and Wisconsin. In order to characterize the aggregate hardness at these locations, the average Moh's hardness (0-10) was defined for each state based on the predominant aggregate types found in these states according to a U.S. Geological Survey (USGS) study illustrated in Figure 3.23 (Langer, 2011). For instance, the predominant rock type in Illinois and Tennessee is limestone, so the average Moh's hardness associated to their job locations is 3.5. Granite and Limestone are the predominant rocks in Wisconsin and Georgia, so their associated average Moh's hardness is 5.5. Granite and sandstone are the predominant rocks in New Jersey and Massachusetts, and their average Moh's hardness is 6.5. Based on the primary data collected about HIR remixing job locations, the average propane consumption in Illinois, Tennessee, Wisconsin, Georgia, New Jersey and Massachusetts are 0.15 gal/SY, 0.16 gal/SY, 0.47 gal/SY, 0.56 gal/SY, 0.58 gal/SY and 0.86 gal/SY, respectively. The results summarized in Table 3.7 show that pavements containing harder aggregates result in higher propane consumption during the remixing process.

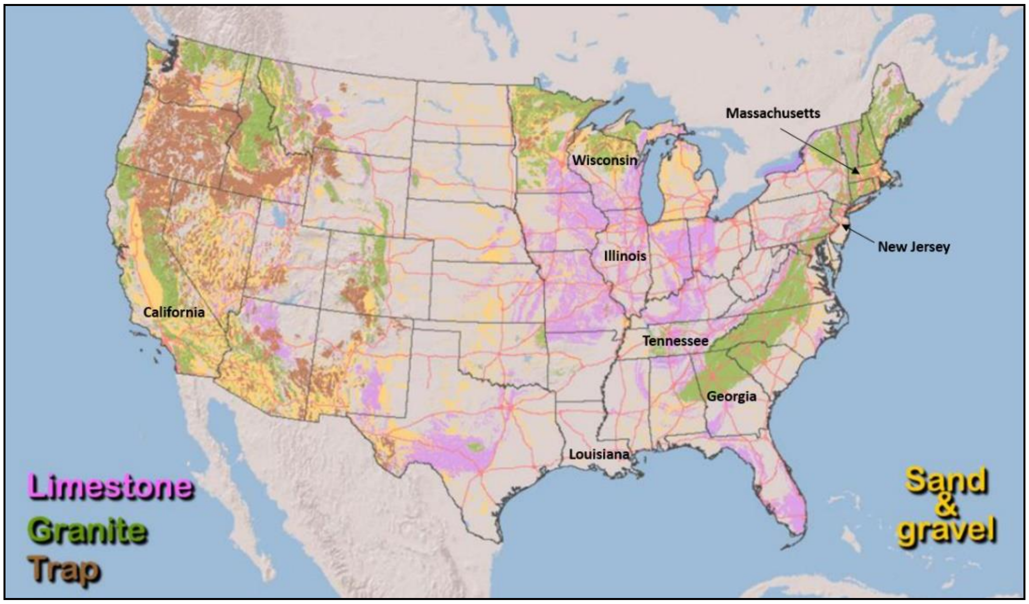


Figure 3.23. Generalized locations of aggregate resources (Langer, 2011)

Table 3.7. Average Moh's hardness of the available HIR remixing job locations.

State	Predominant rock types	Average Moh's hardness (0-10)	Propane consumption (Gal/SY)
Wisconsin	Granite, limestone	5.5	0.47
Georgia	Granite, limestone	5.5	0.56
New Jersey	Granite, sandstone	6.5	0.58
Massachusetts	Granite, sandstone	6.5	0.86
Illinois	Limestone	3.5	0.13
Illinois	Limestone	3.5	0.12
Illinois	Limestone	3.5	0.17
Illinois	Limestone	3.5	0.19
Illinois	Limestone	3.5	0.14
Tennessee	Limestone	3.5	0.16

A linear regression analysis is performed to predict the propane consumption of the heating machines set (Preheater + Heater/Mixer unit) during the remixing construction process based on the available data. The independent variable in this analysis is the relative Moh's hardness. Table 3.8 shows the results of the regression. The predictor variable has a high significance (p-value <0.001) and the model coefficient of determination (R^2) is 0.923. This best fit model is shown below and can be applied by different states to estimate the total propane consumption.

Table 3.8. HIR remixing propane consumption regression model results.

Regression parameters	Coefficients	Standard error	T-value	P-value
Intercept	-0.5072	0.0896	-5.657	0.0005
Average Moh's hardness	0.1879	0.0192	9.795	9.96e-06
$R^2 = 0.923$	-	-	-	-

The effect of aggregate hardness on propane consumption during the remixing construction process was analyzed in California and Illinois. The average Moh's hardness for the aggregates in California is 6.5 since the predominant rocks are Trap, Sandstone, and Granite; whereas, the average Moh's hardness for the aggregates in Illinois is 3.5, because the predominant rock is limestone. Therefore, based on the developed linear regression mode, the total energy resulting from propane consumption is 570.02 and 127.28 GJ/lane-mi in California and Illinois, respectively. As a result, it was found that that HIR treatment can be less efficient in California than in Illinois.

Cold In-Place Recycling

General CIR Process

According to the information collected from contractors in 2015. Two different construction methods are commonly used for CIR, namely, single machine and the single-pass equipment train.

The single machine method breaks, pulverizes, and adds recycling agents in a single pass. The advantages of a single machine include high production capacity and simplicity of operation. On the other hand, the single-pass equipment train consists of a cold milling machine, a portable crusher, a travel-plant mixer, and a laydown machine (FHWA, 2015). It provides better process control, more uniformity, and higher production rates (often more than two miles per day) (FHWA, 2015).

An environmental impact assessment is conducted for CIR operations. In this study, the milling depth during CIR construction processes ranges from 3 to 4 in. The construction information of CIR was based on the data collected from 24 projects located in Illinois, Indiana, Iowa, Massachusetts, and Nebraska, that used the single-pass equipment train method. The equipment fuel consumption was based on an average train speed of 22 ft/min. The fuel consumption of the equipment used in CIR processes is presented in Table 3.9. The milling operation contributes the most in the total energy of the CIR construction process with approximately 82.32%.

Figure 3.24 shows that most of the CIR projects consumed approximately 0.04 gal/SY of diesel, which also matches the total fuel consumption calculated for the CIR single-pass equipment train 0.036 gal/SY in Table 3.9, thus resulting in a total of 58.628 GJ/lane-mi energy use.

Table 3.9. Details for the Environmental Assessment of CIR.

Equipment type	**HP**	**Average fuel**	**CIR energy**
Milling machine	860	0.01966	48.260
Crusher/pugmill	375	0.00488	4.792
Oil pump	5	0.00005	0.002
Paver	150	0.00204	2.000
Pickup machine	90	0.00126	1.238
Skid steer	70	0.00019	0.186
Double steel drum roller	115	0.00128	1.255
Rubber tire roller	150	0.00081	0.802
Water truck	425	0.00027	0.011
Pickup truck	300	0.00448	0.061
Service truck	300	0.00154	0.021
Total	-	0.03646	58.628

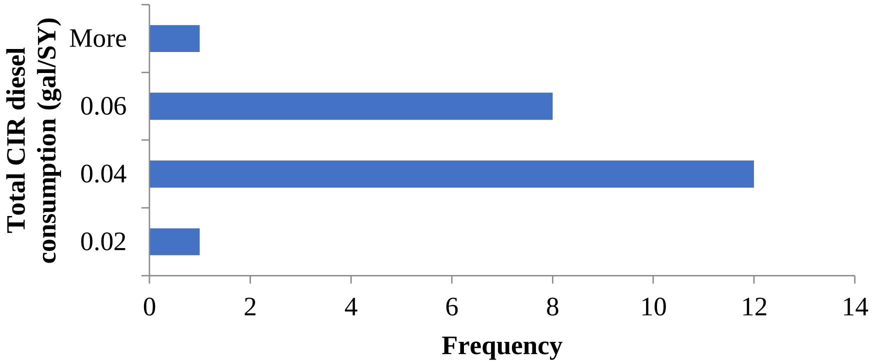


Figure 3.24. Graph. Histogram of CIR projects total diesel consumption.

Effect of Air Temperature

The University of Leeds conducted a study on the "impact of ambient temperatures on exhaust thermal characteristics during cold start." (Li et al., 2005). The study showed that ambient temperatures have an impact on fuel consumption and that 1.4% more fuel was consumed in cold winter (28.4°F) compared with hot summer (87.8°F) because of the higher heat losses caused by increased mechanical frictions in the vehicle engine. A study investigated the relationship of combustion efficiency of direct injection diesel engine as function of time cold and warm conditions. It was found that for warm start of the engine, the efficiency was over 98%; whereas, the efficiency did not exceed 95% at cold start (Bielaczyc et al., 2001). Figure 3.25 shows that the diesel consumption of the CIR projects analyzed has a decreasing trend with higher air temperatures. In addition, the cutting speed during the milling operation increases under warmer temperatures.

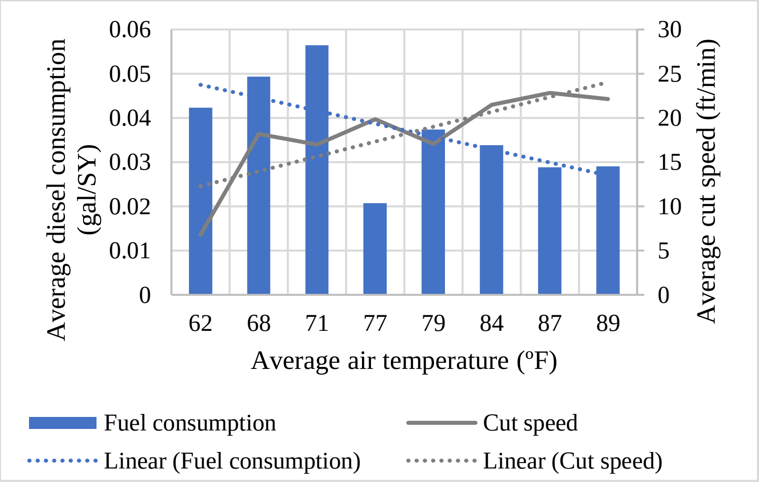


Figure 3.25. Effect of air temperature on diesel consumption and cutting speed during milling operation

Effect of Pavement Width

During the follow-up interviews with the contractors, it was found that pavement width is another factor affecting fuel consumption during the milling operation. The CIR contractors typically used a half-lane milling machine model characterized by a cut width of 12.5 ft. Figure 3.26 shows that the wider the pavement lane, the more diesel is consumed by the milling machine and the higher is the number of teeth per 100 ton used in the milling operation. In fact, the contractor needs to change the number of installed cutting teeth for different widths.

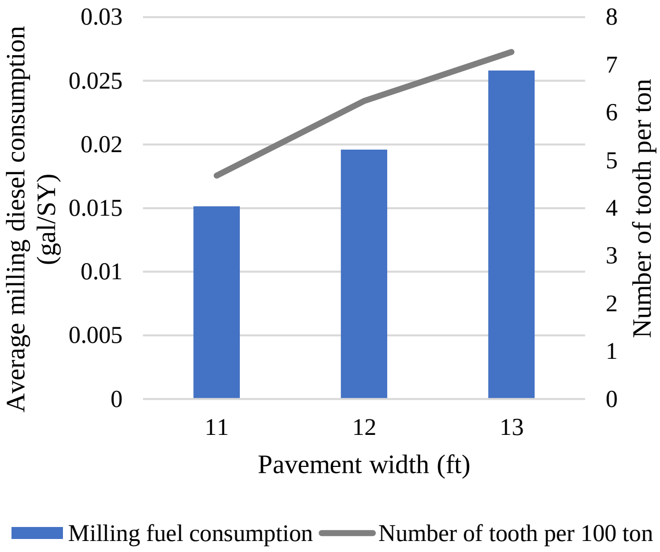


Figure 3.26. Total CIR fuel consumption versus width.

A multiple regression analysis was performed to predict the diesel consumption of the milling machines set (milling machine + crusher) during CIR construction process based on available data. The independent variables in this model are pavement width and the number of teeth per 100 tons. The predictor variable has a high significance (p-value <0.001) and the model R^2 is 0.81. The best fit model obtained is given in Table 3.10 and can be used to estimate the fuel consumption during the milling operation of CIR.

Table 3.10. CIR milling operation fuel consumption regression model.

Regression Parameters	**Coefficients**	**Standard Error**	**T-Value**	**P-Value**
Intercept	-0.0343	0.0482	-0.711	0.4949
Width	0.0039	0.0047	0.950	0.3668
Teeth per 100 tons	0.0017	0.0003	6.005	0.0002
$R^2 = 0.8063$	-	-	-	-

Effect of Milling Depth

The effect of milling depth on fuel consumption has been investigated. Figure 3.27 shows that the total fuel consumption increases with higher milling depth. However, there is no clear trend of crushing and milling fuel consumption rates with increasing milling depth. In the range from 3.5 to 5 in cut depth, the milling fuel consumption is clearly increasing, but the crushing contribution stays at approximately a constant rate from 3 to 5 in.

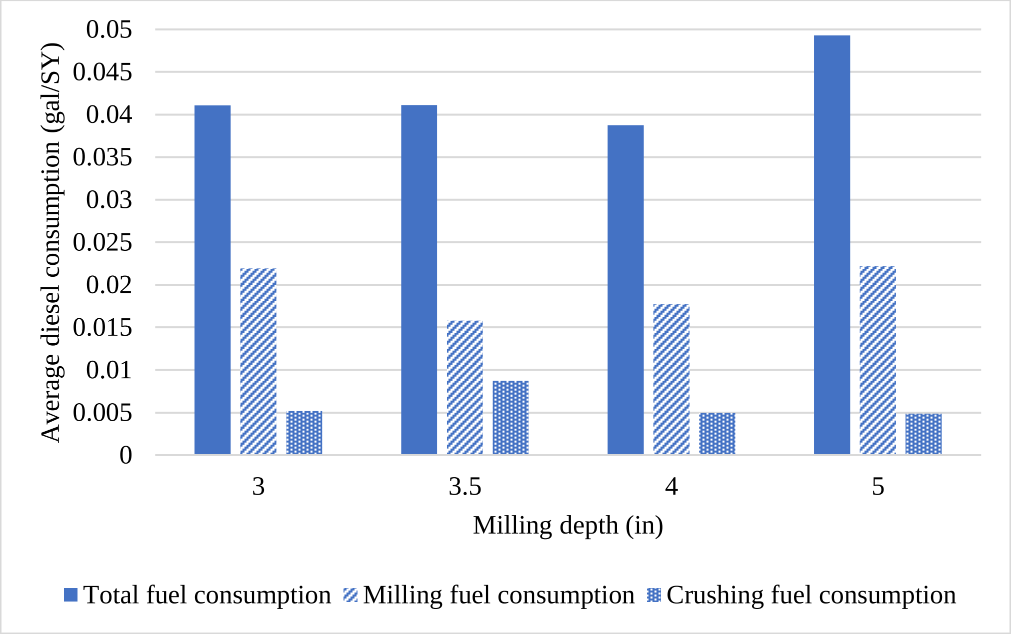


Figure 3.27. CIR Diesel consumption versus milling depth.

Effect of Equipment Technology

Higher horsepower results in higher fuel consumption (Suman, 2010). The CIR contractor used two types of equipment trains that differ in their milling machine horsepower (HP) (FHWA, 2015). Train 1 has a milling machine of HP equal to 800 and train 2 is characterized by a milling machine of HP equal to 860. Table 3.11 shows that HP of 860 results in a fuel consumption higher than HP of 800 with a difference of 4%.

Table 3.11. Summary of HP effect on fuel efficiency.

Train type	**Train 1 (Milling machine, HP= 800)**	**Train 2 (Milling machine, HP= 860)**
Diesel consumption (gal/SY)	0.0197	0.0205

Fuel Use for Conventional Overlay Methods

The fuel usage data for conventional overlays was extracted from Tollway pay items (Yang et al., 2017). According to results of Figure 3.28, HMA full-depth projects construction total consumption is higher than the HMA surface and base courses. In Figure 3.29, the contribution of equipment unit used in a HMA full depth of 12 in thickness was assessed and it was found that that the milling machine contributes the most to the overall construction processes fuel consumption followed by paver and then the different roller types.

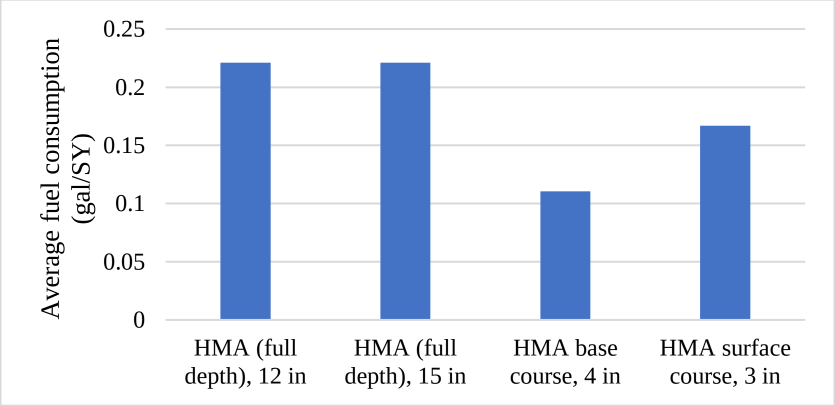


Figure 3.28. Fuel consumption of conventional overlay projects.

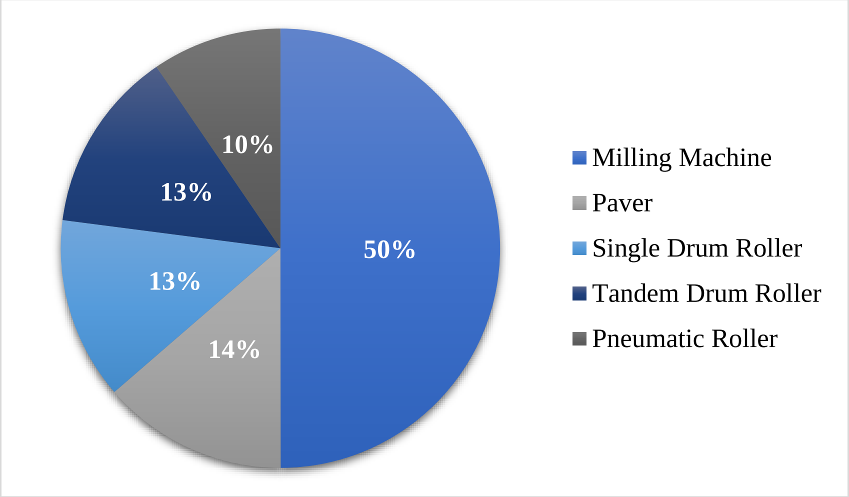


Figure 3.29. HMA full depth 12-in overlay equipment use contribution.

Modeling Procedure

EPA MOVES 2014 (NONROAD)

The equipment unit processes are compiled using the NONROAD 2008 model incorporated in MOVES 2014 software. NONROAD equipment are used to perform and help to operate construction activities on-site. Air pollution emission inventories are combined with TRACI impact assessment methodology to estimate the unit emission quantities per gallon of fuel consumed. TRACI 2.1 provides characterization factors for life-cycle impact categories rates: ozone depletion, GWP, acidification, eutrophication, smog formation, human health impacts, ecotoxicity, and fossil fuel depletion for fuel combustion (Bare, 2011). Figure 3.30 shows the methodology used to calculate TRACI impact categories rates from eight pollutant types included in MOVES 2014.

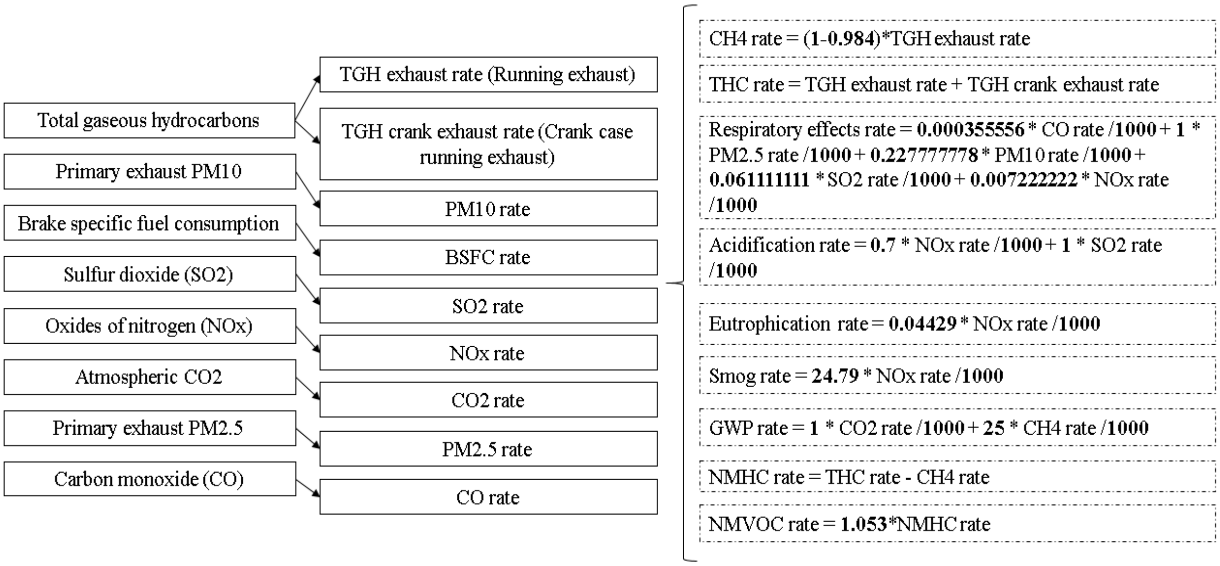


Figure 3.30. TRACI impacts rates calculation from pollutants emissions included in MOVES 2014.

NONROAD Model Development

Simulations have been performed using MOVES 2014 from 2015 to 2050 to allow for running LCIA of equipment for future projects, as shown in Figure 3.31.

The simulations run on MOVES 2014 software allowed developing a NONROAD model to assess the environmental impacts of on-site equipment. For a single equipment type, the unit emission of a substance depends on three main variables which are tier category, HP bin (range), and year of construction. NONROAD model inputs are geographic bound, time spans, NONROAD vehicle equipment type and pollutants/processes types. The outputs are the rates of the pollutants selected. These rates are then used to calculate the US-EI 2.2 unit processes of diesel combustion. The TRACI characterization of fuel production is used to quantify the unit processes of diesel upstream production.

The total per-gallon inventory quantities of diesel combustion and production shares represent the NONROAD equipment impact as illustrated in Figure 3.32.

Figure 3.33 shows GWP results of various types of equipment in three different counties: Champaign (Illinois), Yolo (California), and Middlesex (New Jersey). It was found that the environmental impacts of on-site equipment are not sensitive to the geographic location. Since results are not sensitive to location, Champaign County was used to run simulations.

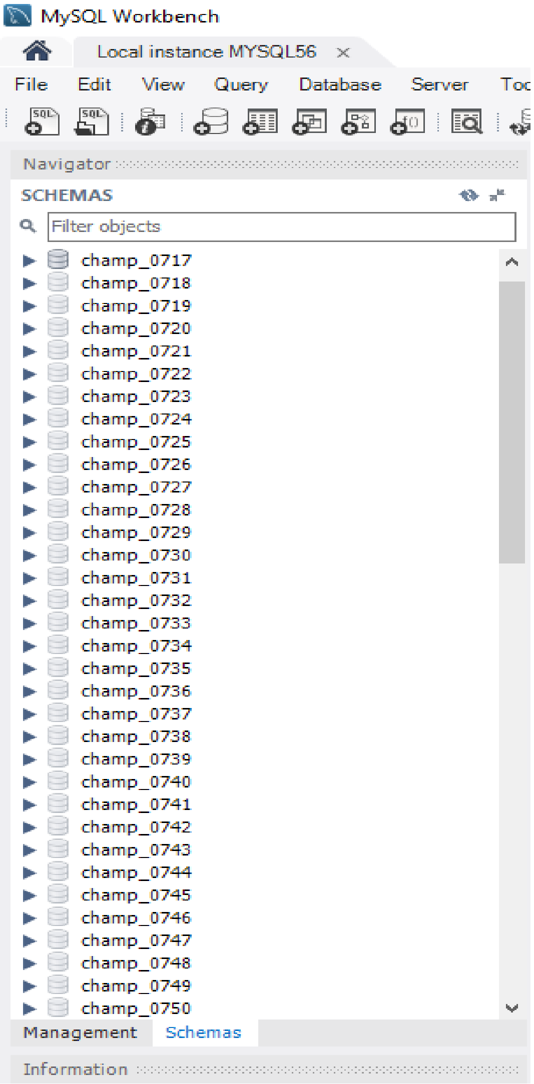


Figure 3.31. MOVES 2014 simulations from 2015 to 2050.

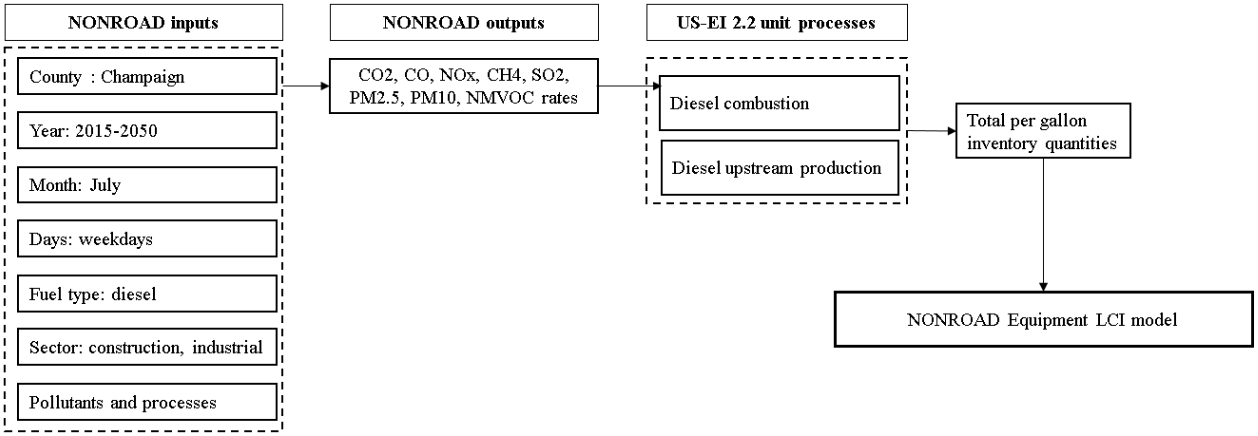


Figure 3.32. NONROAD equipment LCI model schematic.

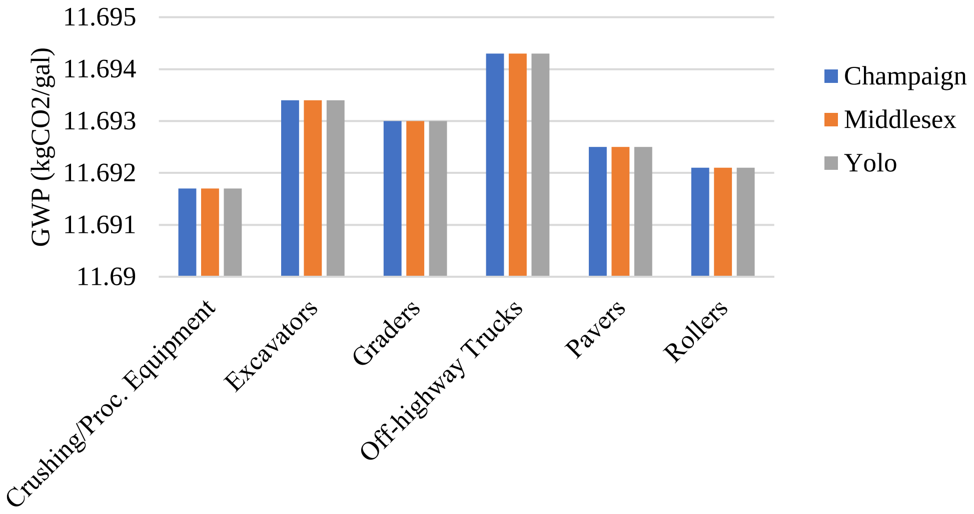


Figure 3.33. Sensitivity analysis of equipment GWP results to the geographic location.

The model accounts for four tier categories, which are the federal emission standards for compression ignition engines (diesel engines) used in most construction vehicles, resulting from five regulations as follows:

- "Determination of Significance for Nonroad Sources and Emission Standards for New Nonroad Compression Ignition Engines at or above 37 Kilowatts." This rule establishes "Tier 1" standards for compression ignition (CI) engines at or above 50 hp (37 kW). (EPA, 1994)
- "Control of Emissions from Nonroad Diesel Engines". This rule lists "Tier 1" and "Tier 2" standards for CI engines below 50 hp, and "Tier 2" and "Tier 3 " standards for engines of 50 hp and greater. (EPA, 1998)
- "Control of Emissions from Nonroad Large Spark-Ignition (SI) Engines and Recreational Engines (Marine and Land-Based)." This rule establishes "Tier 2" equivalent standards for recreational marine diesel engines over 50 hp. (EPA, 2002)
- "Control of Emissions from Nonroad Diesel Engines and Fuel." This rule establishes "Tier 4" standards for CI engines covering all hp categories and regulates diesel fuel sulfur content. (EPA, 2004)
- "Control of Emissions of Air Pollution from Locomotive Engines and Marine Compression Ignition Engines Less Than 30 Liters per Cylinder; Republication." This rule establishes "Tier 3" standards for recreational marine diesel engines. (EPA, 2008)

The objective of these regulations is to reduce NOx, NMHC, PM pollutant. Therefore, the impact categories such as smog, acidification, eutrophication, and respiratory effects will decrease over time. Figure 3.34 shows that respiratory effects impact decreases with the years and with the development of engine technologies through regulations mentioned above.

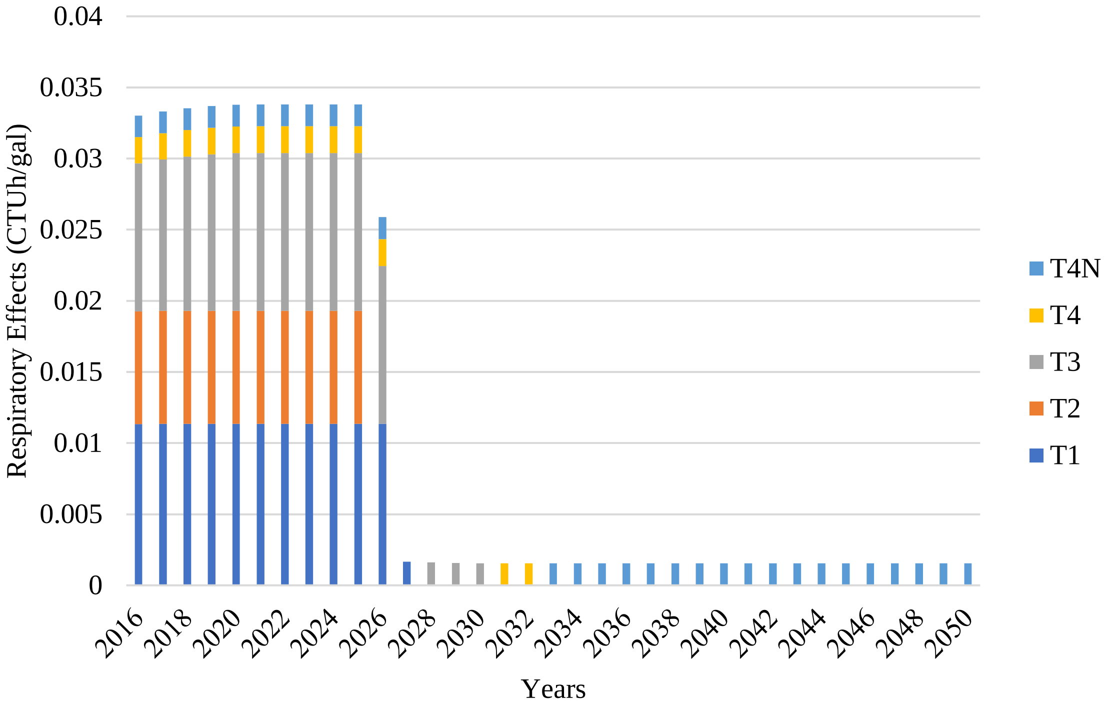


Figure 3.34. Respiratory effects variation and tier progression of pavers (100<HP<=175) over the years.

Contractors’ data were collected for Tier 2 equipment. Using the NONROAD model, other tier categories were evaluated to compare their impact on the environmental emissions. It was found that using a Tier 4 (T4) instead of Tier 2 (T2) for the CIR single-pass equipment train results in a reduction of 37% of the total respiratory effects as shown in Figure 3.35.

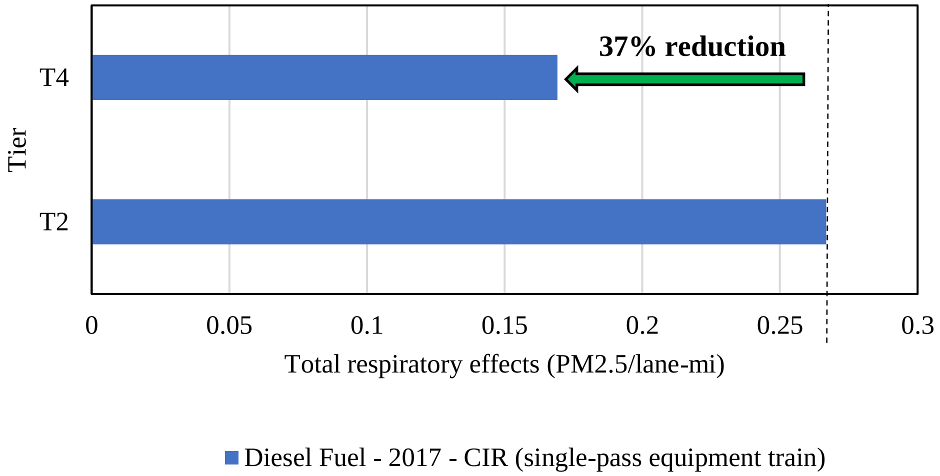


Figure 3.35. Comparison of total respiratory effects of a CIR single-pass equipment train Tier 2 versus Tier 4.

Work zone modeling

Many studies investigated methods to model work zone strategies. Governmental agencies and FHWA developed software tools (e.g., Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) (Rister; Graves, 2002), Kentucky user cost program (KyUCP) (Lee; Ibbs, 2005)) to select strategies for traffic delay management during the construction stage. A good traffic management plan prior to construction is important to provide a contractor with an optimal construction window and ensure a better flow of traffic through the work zone. The developed tool assumes that user has already set a traffic management plan and parameters to model the work zone. These parameters are represented in Table 3.12.

Table 3.12. Work zone parameters used for impact calculation.

Work Zone Parameters
Queue length (mi)
Work zone length (mi)
Queue speed (mi)
Work zone speed (mph)
Normal traffic speed (mph)
Passenger car (%)
Small truck (%)
Medium truck (%)
Large truck (%)

Virginia Department of Transportation (DOT) applied CIR and FDR on 3.66 mi of southbound I-81 in August County and monitored the road section performance for three-year service period. The results of the study showed that the IPR techniques were successfully constructed (Diefenderfer,2014). The traffic management plan of the project consisted of reducing two lanes to one lane for the entire length. A closure window was decided based on traffic data which reflected times when highest volumes occurred.

USE STAGE

The use stage is analyzed using roughness and texture related rolling resistance progression over the analysis period. This stage is the most significant among all life cycle stages and includes other components such as albedo and lighting (Santero et al., 2011) which are considered out of scope. During use phase, agencies tend to apply maintenance and rehabilitation activities in order to maintain the pavement in a good condition.

Impact of roughness on rolling resistance

The Roughness-Speed Impact Model (RSI) by Ziyadi et al. was used to calculate the environmental impacts and energy consumption of use stage (Ziyadi et al., 2017). The general form of the RSI model depends on the vehicle speed and IRI progression as equation 3.1 shows. A regression analysis was then conducted using MOVES simulations to define the model coefficients as it is shown in Table 3.13 and for different vehicle categories, as shown in Table 14.3.

$$RSI_{t=0}^{Energy}: \hat{E}(v, IRI) = \frac{p}{v} + (k_a.IRI + d_a) + b \times v + (k_c.IRI + d_c) \times v^2 \qquad (3.1)$$

This method uses the incremental rate of pollutants used in the TRACI impacts calculation. The incremental rate changes with speed and IRI using as equation 3.2 shows.

$$\Delta RSI_{t=0}^{Env}: \qquad \Delta\widehat{I_i}(v, IRI) = [q_{v_i}.\frac{\Delta IRI}{63.36}] \times I_i(v) \qquad (3.2)$$

where,

$I_i(v)$: is the incremental rate of environmental rate i at speed v

q_{v_i}: is the percent increment of the environmental impact i at a speed v and calculated as equation 3.3 shows.

$$q_{v_i} = k_{v_i}.v + d_{v_i} \qquad (3.3)$$

$\boldsymbol{k_{v_i}}, \boldsymbol{d_{v_i}}$: are the increment rate coefficients. Table 3.15 shows the model coefficients values for passenger cars per TRACI impact category. The list of environmental impacts do not include ozone depletion and fossil fuel depletion since the results of MOVES simulation showed that these two impacts are not affected by the pollutants used in the RSI model development**.**

Table 3.13. RSI model regression coefficients per vehicle type (Ziyadi et al., 2017)

Coefficients	Passenger Car	Small Truck	Medium Truck	Large Truck
k_a	6.70E-01	7.68E-01	9.18E-01	1.40E+00
k_c	2.81E-04	1.25E-04	1.33E-04	1.36E-04
d_c	2.1860E-01	3.0769E-01	9.7418E-01	2.3900E+00
d_a	2.1757E+03	7.0108E+03	9.2993E+03	1.9225E+04
b	-1.6931E+01	-7.3026E+01	-1.3959E+02	-2.6432E+02
p	3.3753E+04	1.1788E+05	1.0938E+05	8.2782E+04

Table 3.14. Vehicle classification used to develop the RSI model.

MOVES Classification	HDM-4 Classification	FHWA Classification	FHWA Truck Classification
Passenger car	Medium car	Class 1, 2, 3	--
Single-unit, long-haul truck	Medium truck	Class 4, 5	Class 1, 2, 3
Single-unit, short-haul truck	Medium truck	Class 6, 7, 8	Class 4, 5, 6
Combination long-haul truck	Articulated truck	Class 9, 10, 11, 12, 13	Class 7, 8

Table 3.15. Increment rate coefficients for passenger car. (Ziyadi et al., 2017)

Impact category i	k_{vi}	d_{vi}
Global warming	5.88E-04	3.51E-03
Smog	8.06E-04	1.42E-02
Acidification	7.83E-04	1.25E-02
Eutrophication	7.83E-04	1.27E-02
Carcinogenics	7.24E-04	-7.24E-03
Noncarcinogenics	7.59E-05	-9.25E-04
Respiratory effects	1.01E-03	2.80E-03
Ecotoxicity	1.80E-04	-2.05E-03

Texture-related rolling resistance

The texture model developed by Chatti and Zaabar was used to quantify the additional energy consumption due to texture (Equation 3.4). The model depends on the vehicle speed v (Chatti; Zaabar, 2012).

$$\delta E_{texture}(\%) = 0.02 - 2.5 \times 10^{-4} \times (v - 35) \qquad (3.4)$$

The tool conducts LCA for flexible pavements. The model developed by University of California Pavement Research Center (CPRC) for mean profile depth (MPD) progression of dense graded AC pavements was chosen to incorporate in the tool (Lu et al, 2009). This model is shown in equation 3.5.

$$MPD(micron) = -93.7089 - 4.2910 \times AirVoid(\%) + 47.8933 \times Age(\,year) + 283.2136 \times FinenessModulus - 9.9487 \times NMAS(mm) - 5.4209 \times Thickness\ (mm) - 0.7087 \times NumberOfDays > 30C - 0.0402 \times AADTTinCoringLane \qquad (3.5)$$

where NMAS: is the nominal maximum aggregate size.

Equation 3.6 is the calibrated version of CPRC model (equation 3.5) for use in Illinois. The coefficients shown below can be changed by the user in the tool and be replaced with numbers more representative for the state DOT specifications.

$$MPD(mm) = -0.055 \times \ln(age + 1) + 1.6604 \qquad (3.6)$$

Maintenance and rehabilitation schedule

Maintenance and rehabilitation (M&R) is an essential component in pavement management system (PMS) since it supports strategies to maintain a serviceable condition for pavements and extends pavement service life through various jumps at times of maintenance application. The deterministic performance models and multi-criteria estimation approach (presented in Chapter

4) were used to build M&R schedule that extends over the analysis period calculated based on the alternatives selected by the user. More information about the M&R schedule construction methods are presented in Chapter 6: Decision making Tool Development

The developed tool assumes thin AC overlay to be a default maintenance activity applied every time it is optimum to take an action to maintain the pavement in a good condition. However, in case IRI progression is triggered by cracking threshold then CIR with overlay is applied to enhance structural capacity of the pavement.

END OF LIFE STAGE

The end of life analysis depends on the approach used by the user to allocate the system resources. Figure 3.36 shows the chain of material life cycle from System 1 (original system) to System 2 (subsequent system) (Ekvall; Tillman, 1997). Nicholson showed that environmental impacts and energy resulting from materials production stage is sensitive to the allocation method choice. A 100% cut-off allocation was chosen to manage end of life burdens in this LCA study as illustrated in Figure 3.37. In fact, pavement construction materials (e.g., AC) may be recycled at the end of life. Therefore, the recycled materials can be either accounted as a burden when using cut-off or as a benefit to the original system using substitution.

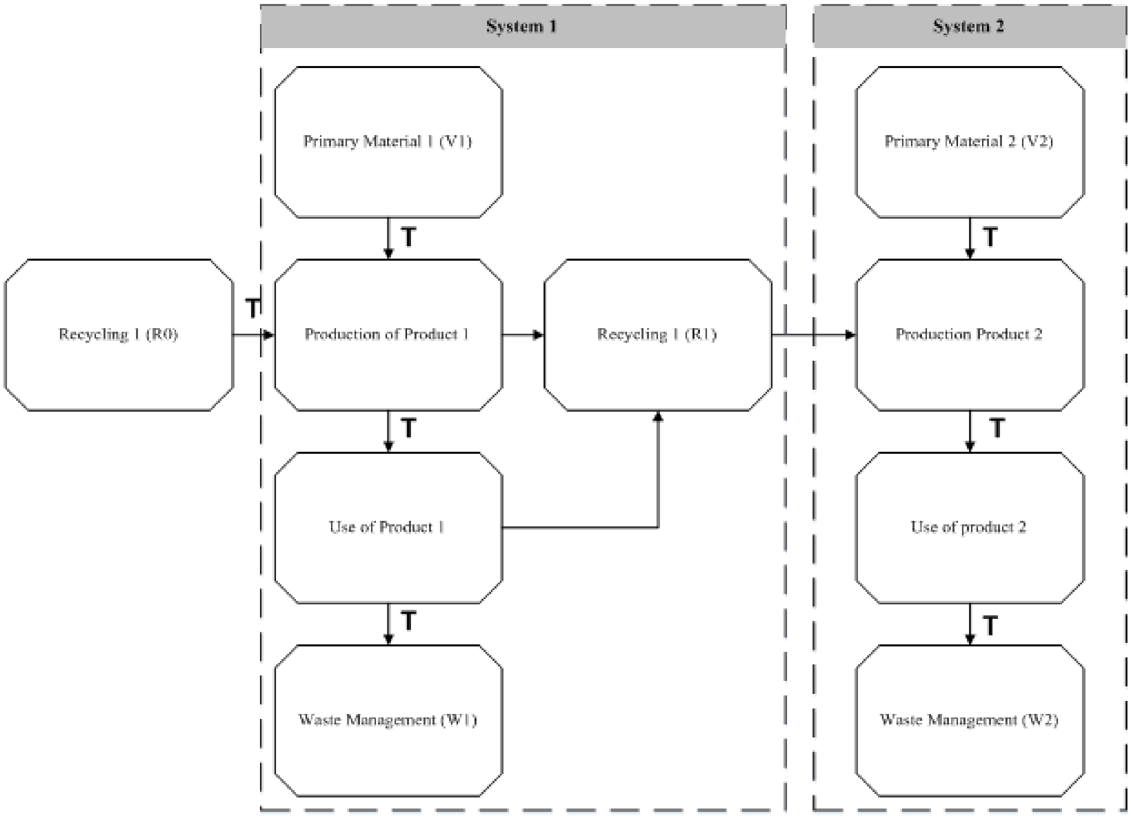


Figure 3.36. Cascade of System 1 and System 2 material life cycles (T = material transportation) (Ekvall; Tillman, 1997)

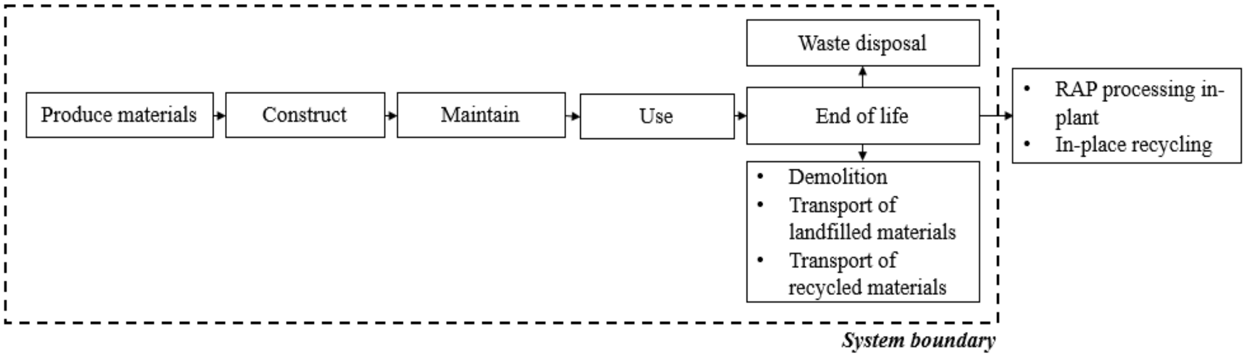


Figure 3.37. Cut-off allocation method system boundary.

Cut-Off Method

In the cut-off method, the recycling processing R_1 is not included in the impacts resulting from system 1 and is considered as a burden on System 2. The overall emissions resulting from System 1 materials life cycle is the summation of emissions due virgin material input V_1 production and hauling, disposal and hauling of waste to a landfill facility at the end of life of System 1 as equation 3.7 shows.

$$E_{Tot} = X_1 E_{v_1} + (1 - X_1)E_{R_0} + W_1 E_{W_1} \tag{3.7}$$

where,

X_1: proportion of material in the virgin input of System 1

R_0: proportion of material in the recycled input of System 0

V_1: proportion of material in the virgin input of System 1

W_1: proportion of waste material at the end of life of System 1

E_{V1}: emission arising from material in the virgin input of System 1

E_{R0}: emission arising from material in the recycled material of System 0

E_{W1}: emission arising from disposal of waste/landfill material of System 1

Substitution (Closed Loop Approximation)

The substitution method gives a credit to original system for producing RAP for the future system as a substitute for virgin materials. The impacts calculation for this method is shown in equation 3.8.

$$E_{Tot} = (1 - R_1)E_{V_1} + R_1 E_{R_1} + (1 - R_1)E_{W_1} \tag{3.8}$$

where,

R_1: proportion of material in the product recycled at the end of life of System 1

$E_{R1:}$ emission arising from material in the recycled input of System 1

CHAPTER 4: PAVEMENT PERFORMANCE MODELING

OVERVIEW OF METHODS

The performance and lifetime estimation play a critical role in evaluating life-cycle benefits of IPR treatments as compared with conventional treatments. The methodology to incorporate performance and lifetime estimation into the life-cycle comparative tool is introduced and a two-pronged approach is presented: Multi-criteria performance estimation and deterministic performance models. When deterministic models are not available for the selected treatments, a multi-criteria performance estimation approach is proposed to evaluate the selected treatments to make predictions.

- Deterministic performance models – The models in the tool were developed by University of California Davis using network level condition survey data from the California Department of Transportation and are used to predict the international roughness index (IRI) progression and wheelpath cracking performance over the life of pavement. The outputs from these models are estimates of the performance of conventional AC overlays, CIR, and FDR pavements in terms of wheelpath cracking (fatigue cracking) and IRI, which can be used to estimate the time to the next treatment. Similar models can be developed using information from other agencies.
- Multi-criteria performance estimation –This approach utilizes existing information in the literature (e.g., decision-making recommendations from various agencies, treatment lives, guidelines, best practices, expert opinion) to estimate the performance of a treatment considering specific on-site conditions. This approach relies on a process that calculates a "performance score" on a 1 to 5 scale indicating the level of risk of a selected treatment based on available on-site condition information regarding traffic, climate, existing pavement conditions, soil properties and material characteristics. The process then compares the performance score with on-site conditions and estimates a treatment life based on the recommendations and other information reported in the literature, which can be modified by the user. This approach also selects an estimated roughness progression rate based on the available information. This approach is used when deterministic performance models do not exist or those available are not considered applicable.

The two approaches determine IRI progression starting from the treatment application time at a trigger IRI value to an IRI threshold value input by the user. This enables the user to visualize the IRI progression and decide the timing of the next treatment. Figure 4.1 presents the IRI progression for two different treatments A and B that start, respectively, from IRI_a and IRI_b and reach the corresponding thresholds $IRI_{threshold}$.Both performance prediction approaches are utilized in the developed tool. Once the project input parameters are entered, the user would be provided with a list of treatment alternatives. The user would have the option to select one or more IPR treatments and compare them to one or more conventional AC overlay treatments. The selected treatments are initially screened for their applicability for the project conditions. If there are obvious and clear barriers against application of the selected treatment (e.g., geometric features impeding application of using a long IPR train), the user would be warned. After this, the user can decide to use either one of the performance modeling approaches to evaluate the selected treatments and calculate treatment lifetime and develop IRI progression curves. In the following schematic (Figure 4.2), a flowchart of the developed tool illustrates the performance estimation process integration to the overall flow of data and input flow.

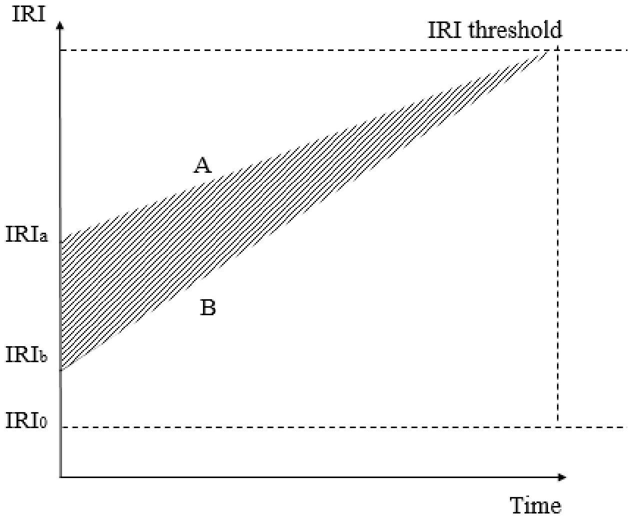


Figure 4.1. A schematic of IRI progression curves with significant model parameters obtained by the performance estimating methods.

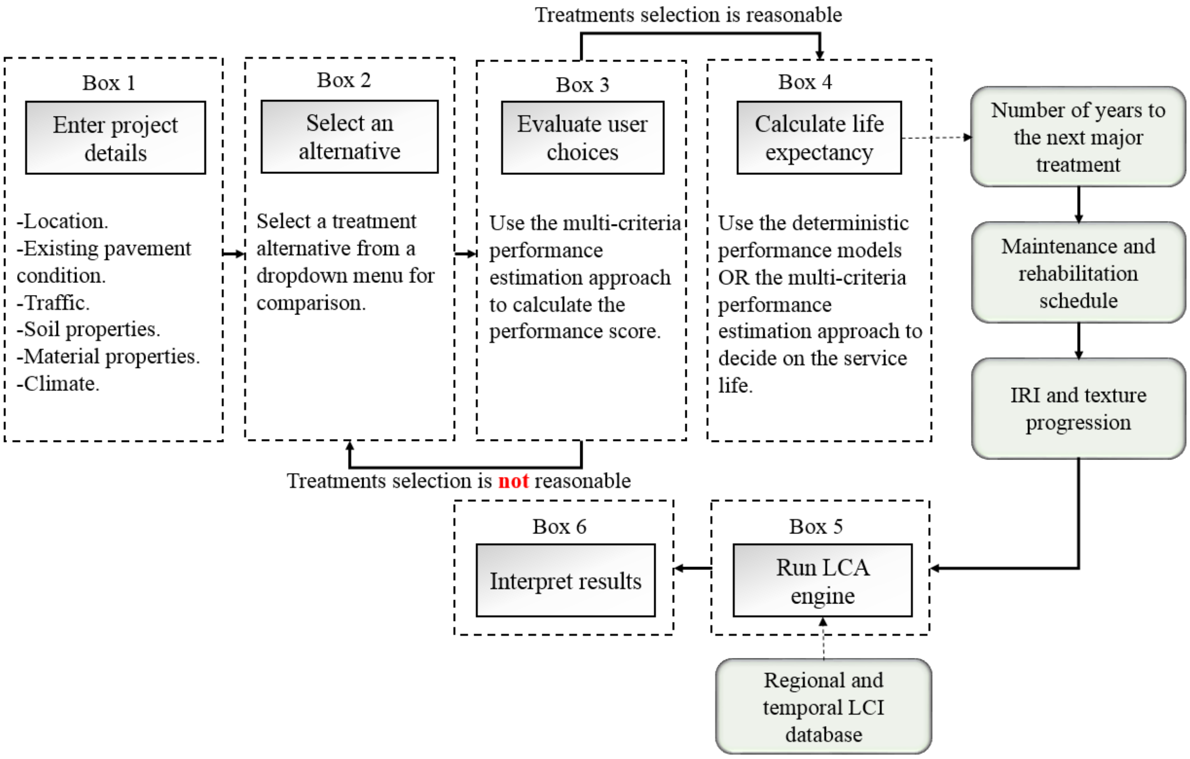


Figure 4.2. Flowchart of the treatments selection, evaluation, and life-cycle analysis.

MULTI-CRITERIA PERFORMANCE ESTIMATION APPROACH

Concept

When there is no performance model available, the multi-criteria performance estimation approach could be used. The multi-criteria performance estimation process is used to estimate treatment life by collecting information related to various site-specific conditions and evaluating this information through a rating system to determine an expected treatment performance. This approach provides an estimate of treatment life based on reported lifespans in the literature or observed by the user in the region of interest adjusted for site-specific conditions. The relationship of various site-specific factors to expected performance is compiled from multiple sources. These include existing literature for best practices and experimental data, agency and contractor surveys, decision trees adopted by local and state highway agencies, and expert opinions.

The performance estimation process is based on five major categories of information: climate, traffic, existing pavement condition, soil properties, and pavement material properties. The process of integrating these into the performance score calculation, treatment suitability and performance estimation process is as follows:

- Collect site-specific condition information for each major category for a given treatment candidate from the user (traffic, including average daily traffic (ADT), % truck, and road type, existing pavement condition, including overall condition index and distress level of severity, soil properties, climate type, and materials properties, including mix design if performed)
- Score the site-specific condition under each major category as a risk of poor performance rating score from 1 to 5. The interpretation of each rating score of a treatment under a certain condition is as follows:

  1: High risk; 2: Medium-high risk; 3: Medium risk; 4: Medium-Low risk; 5: Low or no risk.
- For example, a HIR resurfacing treatment followed by a thin overlay of 2 in or less. If a high traffic level of >30,000 AADT is used, a score of 1 is assigned; the literature widely agrees that this treatment type is not suitable for high traffic levels. Assigning a rating of "1" in this case means that there is a high risk that the selected design may perform poorly.
- Evaluate score for each category and determine the final rating score for the application.
- Based on the rating score, calculate expected treatment life based on lifetime estimates compiled from the literature and surveys.

The treatment overall performance score (PS) is calculated based on the following formulation (equation 4.1). It is assumed that all the factors are independent:

$$PS = \frac{\sum_{i=1}^{N_C} C_i + \sum_{i=1}^{N_T} T_i + \sum_{i=1}^{N_S} S_i + \sum_{i=1}^{N_E} E_i + \sum_{i=1}^{N_D} D_i}{N_C + N_T + N_S + N_E + N_D} \quad (4.1)$$

where,

T_i : rating for each traffic related factor i

C_i : rating for each climate condition i

S_i : rating for each soil property i

E_i : rating for each existing pavement condition related factor i

D_i : rating for material properties condition related factor i

N_C : number of climate condition related factors

N_T : number of traffic related factors

N_S : number of soil properties related factors

N_E : number of existing conditions related factors

N_D : number of structural design properties related factors

The interpretation of PS and resulting impact on treatment life is explained as follows:

- 4 or 5: Ideal on-site conditions for treatment; indicating very low risk for performance. Treatment life can be expected to be at the highest range.
- 2 or 3: Conditions are fair carrying medium risk for the performance of treatment. Treatment life can be expected to be at medium range of expectations.
- 1: On-site conditions are not appropriate for the treatment with very high risk. Treatment life may be predicted at lower range of expected values.

Development of Performance Estimation

Population of the Treatments List

The first step of the development process is to populate a list of anticipated in-place, conventional, and surface treatments. The list of treatments considered in the tool were classified into five categories with their associated expected life range as shown in Table 4.1. Tables 4.2 to 4.6 show the expected service life of treatments under each category. The information reported is based on the literature review and surveys collected from contractors and agencies for IPR treatments application. Agencies questionnaire feedback reflects the percent of agencies that applied various IPR treatments under different life ranges.

Table 4.1. Treatment categories expected life range.

Treatment Category Type	Expected Life Range (year)
Category 1	3-5
Category 2	4-10
Category 3	7-15
Category 4	12-20
Category 5	15-25

Table 4.2. Compiled list of treatment life estimates obtained of category 1 from various literature sources.

Treatment Type	Expected life range (year)	Literature Data Source
Fog seal	1-3	(Peshkin, 2011)
Sand seal	3-4	(Peshkin, 2011)
Slurry seal	3-6	(Peshkin, 2011)
Microsurfacing Single course	3-6	(Peshkin, 2011)
Chip seal Single course	3-7	(Peshkin, 2011)

Table 4.3. Compiled list of treatment life estimates obtained of Category 2 from various literature sources and surveys.

Treatment Type	Expected life range (year)	Literature Data Source	Agency Questionnaire Feedback
Cape seal	4-7 years	(Peshkin, 2011)	–
Microsurfacing Double course	4-7 years	(Peshkin, 2011)	–
Chip seal Double course	5-10 years	(Peshkin, 2011)	–
HIR resurfacing	6-10 years	(ARRA, 2015)	3-5 years (17%), 5-8 years (50%), 8-10 years (33%)
Thin HMA overlay (2 in or less)	6-12 years	(Peshkin, 2011)	–
HIR remixing	3-15 years	–	3-5 years (17%), 5-8 years (50%), 8-10 years (33%)

Table 4.4. Compiled list of treatment life estimates obtained of Category 3 from various literature sources and surveys.

Treatment Type	Expected life range (year)	Literature Data Source	Agency Questionnaire Feedback
CIR	6-10 years	(ARRA, 2015)	1-5 years (7%), 6-10 years (29%), 11-15 years (36%), 16-20 years (21%), >25 years (7%)
CIR + cape seal	6-10 years	(ARRA, 2015)	1-5 years (7%), 6-10 years (29%), 11-15 years (36%), 16-20 years (21%), >25 years (7%)
CIR + chip seal	6-10 years	(ARRA, 2015)	1-5 years (7%), 6-10 years (29%), 11-15 years (36%), 16-20 years (21%), >25 years (7%)
HIR remixing + thin overlay (2in or less)	7-20 years	(ARRA, 2015)	3-5 years (17%), 5-8 years (50%), 8-10 years (33%)
HIR remixing + medium overlay (between 2 and 4	7-20 years	(ARRA, 2015)	3-5 years (17%), 5-8 years (50%), 8-10 years (33%)
HIR remixing + thick overlay (over 4 in)	7-20 years	(ARRA, 2015)	3-5 years (17%), 5-8 years (50%), 8-10 years (33%)
HIR repaving	7-20 years	(ARRA, 2015)	3-5 years (17%), 5-8 years (50%), 8-10 years (33%)
CIR + thin overlay (2 in or less)	7-20 years	(ARRA, 2015)	1-5 years (7%), 6-10 years (29%), 11-15 years (36%), 16-20 years (21%), >25 years (7%)

Table 4.5. Compiled list of treatment life estimates obtained of Category 4 from various literature sources and surveys.

Treatment Type	Expected life range (year)	Literature Data Source	Agency Questionnaire Feedback
Cold milling + medium overlay (between 2 and 4 in)	6-17	(Peshkin, 2004)	–
CIR + medium overlay (between 2 and 4 in)	7-20	(ARRA, 2015)	1-5 years (7%), 6-10 years (29%), 11-15 years (36%), 16-20 years (21%), >25 years (7%)
FDR	7-10	(ARRA, 2015)	6-10 years (8%), 11-15 years (42%), 16-20 years (33%), 21-25 years (8%), >25 years (8%)
FDR +Chip Seal	7-10	(ARRA, 2015)	6-10 years (8%), 11-15 years (42%), 16-20 years (33%), 21-25 years (8%), >25 years (8%)
FDR +Cape Seal	7-10	(ARRA, 2015)	6-10 years (8%), 11-15 years (42%), 16-20 years (33%), 21-25 years (8%), >25 years (8%)

Table 4.6. Compiled list of treatment life estimates obtained of Category 5 from various literature sources and surveys.

Treatment Type	Expected life range (year)	Literature Data Source	Agency Questionnaire Feedback
CIR + thick overlay (over 4 in)	7-20 years	(ARRA, 2015)	6-10 years (8%), 11-15 years (42%), 16-20 years (33%), 21-25 years (8%), >25 years (8%)
Cold milling + thick overlay (over 4 in)	17-30 years	(Peshkin, 2004)	6-10 years (8%), 11-15 years (42%), 16-20 years (33%), 21-25 years (8%), >25 years (8%)
FDR + thin overlay (2 in or less)	More than 20 years	(ARRA, 2015)	6-10 years (8%), 11-15 years (42%), 16-20 years (33%), 21-25 years (8%), >25 years (8%)
FDR + medium overlay (between 2	More than 20 years	(ARRA, 2015)	6-10 years (8%), 11-15 years (42%), 16-20 years (33%), 21-25 years (8%), >25 years (8%)
FDR + thick overlay (over 4 in)	More than 20 years	(ARRA, 2015)	6-10 years (8%), 11-15 years (42%), 16-20 years (33%), 21-25 years (8%), >25 years (8%)

Performance Estimation Process and Integration into the Tool

The information provided by the user under five major criterion categories are used to assess the performance of any treatment selected by the user. This section introduces the major criteria categories and the information requested specifically by the user. The traffic and soil properties inputs are used to generate the pavement design candidates that meet the required structural capacity. Follows are the five major criteria:

- Traffic: The criteria to be evaluated under this category include: traffic level (AADT or/and ESALs), truck volume (%), and road type (urban, rural). Traffic conditions are used to evaluate suitability of different treatments. For example, treatments such as CIR are generally used and recommended for lower volume roads whereas FDR can be designed to serve adequately for higher volume roads.

- Existing pavement conditions: This category is evaluated by criteria related to drainage adequacy, ride quality, and either overall pavement condition index or composition of critical distresses present in the pavement. The existing conditions of a pavement are vital for evaluating the relevance of treatment types. For example, the severity and type of distresses may limit the usefulness of some treatments (e.g., HIR surface recycling) which cannot address structural distresses.
- Soil properties: Characterization of the structure and soil type helps in determining which designs are more likely to satisfy structural capacity requirements. The user is asked to input a value of the California Bearing Ratio (CBR) to evaluate the support of pavement. This input is also used in the pavement design criteria that is introduced later.
- Material properties: The tool evaluates mix designs as part of this approach if provided. It is assumed that the use of a mix design reduces risks and accounts for the use of additives and their dosages that affect pavement performance.
- Climate: The climate may have an impact on the performance of some of the treatments. Normally, one should expect that the designs should be adjusted according to the climate conditions. However, (4) there may be some treatments performing favorably under certain climatic conditions such as micro-surfacing under warmer climates. Another factor is the curing time required when additives are used along with IPR techniques. Therefore, the different climate conditions considered in this study are cold/wet, cold/dry, hot/dry, and hot/wet.

The overall performance score value defines the risk factor that should be applied on the treatment. This process is applied on all the treatments selected by the user and directly influences the treatment life expectancy. The major category criteria are scored for each treatment considered in the tool using previous studies (e.g., (Peshkin, 2011), (ARRA, 2015), (Stroup-Gardiner, 2011), (IDOT, 2012), (Wu et al., 2010), and (Hicks et al., 1999)) where decision matrices were developed to help in decision making at the network level. Appendix C shows the “IPR Decision Matrix” for rehabilitation and preservation treatments selection and evaluation matrix.

Some of the limitations of this approach include the fact that rating of on-site conditions classified under five categories relies on information available in the literature and expert opinion without supporting data. Therefore, a validation step was conducted to support the design lives estimated by this approach. The validation step includes case studies with performance data available and vetting by internal and external experts. Case studies were chosen primarily from the following sources:

- Local and state highway pavement management databases (CalTrans, IDOT, and others) NCHRP study 09-51.

- LCA studies conducted to assess the environmental impacts and to evaluate the performance of preventive maintenance treatments.
- INDOT Study that show models to measure short and long effectiveness of Highway pavement maintenance.

Table 4.7 shows the five main criterion categories and conditions considered under each category in the decision matrix. The selected treatment score points ranges from 1 to 5 for each one of these conditions. These values are used to assess the treatments overall performance.

Table 4.7. List of main components of the performance evaluation categories.

Criteria Category	Conditions (Subcategories)	Possible Values/Ranges
Traffic	Traffic level (AADT and/or ESALs)	Low, Medium, High
Traffic	% Truck volume	<10% or >=10%
Traffic	Road type	Rural, Urban
Existing pavement conditions	PCI or an Equivalent Overall Condition Index	Good, Satisfactory, Fair, Poor
Existing pavement conditions	Raveling	Low, Medium, High
Existing pavement conditions	Potholes	Low, Medium, High
Existing pavement conditions	Bleeding	Yes/No
Existing pavement conditions	Low Skid Resistance	Yes/No
Existing pavement conditions	Shoulder Drop-Off	Yes/No
Existing pavement conditions	Rutting-Wear	Low, Medium, High
Existing pavement conditions	Corrugations	Low, Medium, High
Existing pavement conditions	Shoving	Low, Medium, High
Existing pavement conditions	Fatigue Cracking	Low, Medium, High
Existing pavement conditions	Edge Cracking	Low, Medium, High
Existing pavement conditions	Slippage	Low, Medium, High
Existing pavement conditions	Block Cracking	Low, Medium, High
Existing pavement conditions	Longitudinal Cracking	Low, Medium, High
Existing pavement conditions	Transverse Cracking	Low, Medium, High
Existing pavement conditions	Rough Ride Quality	Yes/No
Existing pavement conditions	Drainage Adequacy	Yes/No
Soil properties	CBR	Good (CBR >=10), Fair (3<CBR<10), Poor (CBR>=3)
Structural design	Pavement design performed	Yes/No
Climate	Type	Dry/Cold (-20F/14F), Wet/Cold (14F-50F),Wet/Hot (50F/64F), Dry/Hot (>64F)

Example: Case study

Suppose the user selects CIR with thin AC overlay and inputs the criteria in Table 4.8. In the performance score calculation, either the rating of existing pavement conditions is calculated through PCI or by considering the average of rating scores of all the structural and non-structural distresses. This distinction comes from the fact that PCI calculation considers the extent of distresses and level of severity. Therefore, if PCI is considered in the existing pavement condition evaluation, PS would be equal to 3, as shown in equation 4.2 which comprises the rating for traffic conditions, PCI, soil properties, material properties, and climate type.

$$PS = \frac{(!+1+5)+(5)+(1)+(5)+(5)}{7} = 3.29 \sim 3 \qquad (4.2)$$

Otherwise, if the rating of the different distresses is considered, then PS calculation is shown in equation 4.3.

$$PS = \frac{(1+1+5)+\left(\frac{5+5+3+5+5+4+5+5+5+4+5+5+3+5+5}{15}\right)+(1)+(5)+(5)}{7} = 3.23 \sim 3 \qquad (4.3)$$

The conditions are fair, indicating medium risk for the performance of the treatment. Treatment life can be expected to be at medium range of expectations which is 6 to 10 years (Peshkin, 2011).

Table 4.8. Example of PS criteria.

Criteria category	Conditions	Possible values/ranges	PS
Traffic	Traffic level AADT	40000	1
Traffic	% Truck Volume	20%	1
Traffic	Road type	Rural	5
Existing pavement conditions	PCI	Good	5
Existing pavement conditions	Raveling	High	5
Existing pavement conditions	Potholes	Low	5
Existing pavement conditions	Bleeding	Yes	3
Existing pavement conditions	Skid Resistance	Low	5
Existing pavement conditions	Shoulder Drop-off	No	5
Existing pavement conditions	Rutting-Wear	Low	4
Existing pavement conditions	Corrugations	High	5
Existing pavement conditions	Fatigue cracking	Low	5
Existing pavement conditions	Edge cracking	Low	5
Existing pavement conditions	Slippage	Medium	4
Existing pavement conditions	Block cracking	Low	5
Existing pavement conditions	Longitudinal cracking	Low	5
Existing pavement conditions	Transverse cracking	Low	3
Existing pavement conditions	Rough ride quality	Yes	5
Existing pavement conditions	Drainage adequacy	Yes	5
Soil properties	CBR (%)	7	1
Structural design	Pavement design performed	Yes	5
Climate	Climate condition	Wet/Hot	5

CHAPTER 5: ANALYSIS AND INTERPRETATION

The developed tool allows comparing energy use and emissions arising during various maintenance and rehabilitation treatments life cycle. Additionally, the performance progression over the analysis period is provided. In this chapter, a sensitivity analysis is conducted for various project-level factors.

SENSITIVITY ANALYSIS

Each life-cycle stage is assessed through analyzing the sensitivity of LCIA over the analysis period, considering allocation method, end of life scenarios, hauling distance, and pavement hardness.

Analysis Period

The analysis period is calculated following the approach explained in the pavement LCA framework as the duration from the longest living first major rehabilitation to the end of its subsequent rehabilitation application (Harvey et al., 2016).

The study is applied on a pavement in a good condition. The sensitivity of the M&R schedule to rehabilitation and maintenance alternatives selection is conducted through two rehabilitation alternatives which are conventional mill and fill (12 years) and CIR (15 years) and three maintenance scenarios:

- Scenario 1: P_1, thin overlay (8 years) (from 3 to 13 years when IRI is used). (Labi; Sinha, 2005)
- Scenario 2: P_2, bituminous surface treatment (BST) (7 years). (Braun Intelec Incorporation, 2016)
- Scenario 3: P_1P_2, thin overlay + BST.

The goal of this study is to show the impact of the analysis period on the use stage energy for the traffic characteristics presented in Table 5.1. Table 5.2 shows the analysis period calculation for the M&R scenarios considered. Since CIR service life is longer compared to mill and fill, AP calculation is based on the time of its subsequent rehabilitation; it is assumed same as the first major rehabilitation.

Figure 5.1 shows the M&R schedule, involving more maintenance applications, results in greater annualized energy and higher analysis period at low and high traffic. Furthermore, it is clear that the use energy is more sensitive to ADT than to analysis period value.

Table 5.1. Traffic assumptions.

ADT	Truck Percent (%)	Small Truck (%)	Medium Truck (%)	Large Truck (%)	Growth Factor (%)	Average Speed (mph)
2000/8000	10	35	40	25	2	55

Table 5.2. Analysis period sensitivity analysis scenarios.

M&R Scenario	Analysis Period (years)
RP$_1$R	15+8+15 = 38
RP$_2$R	15+7+15 = 37 s
RP$_1$P$_2$R	15+8+7+15 = 45

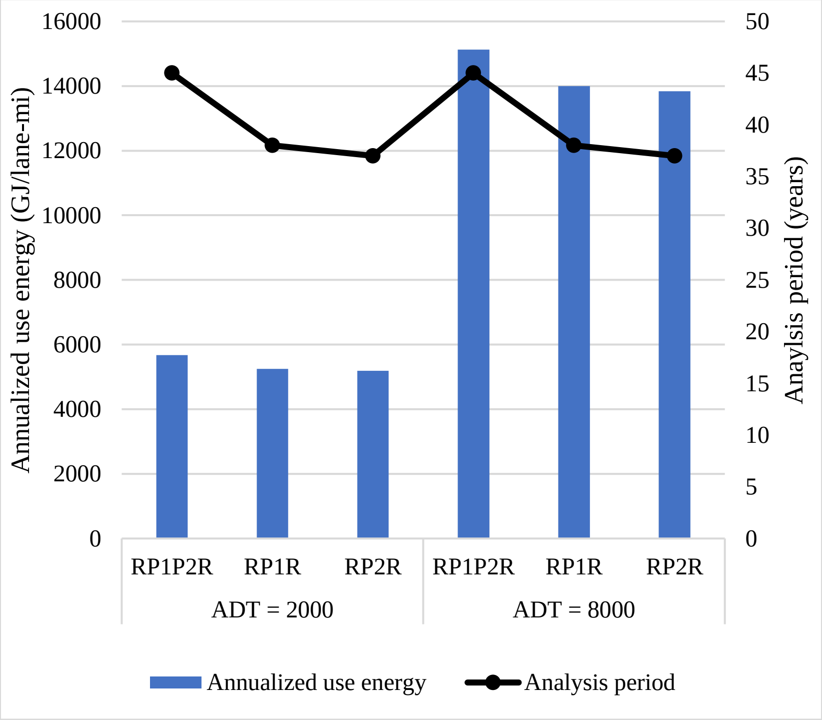


Figure 5.1 Annualized energy at use stage and analysis period for various M&R schedules.

End of Life

This section assesses the sensitivity of life-cycle total impacts to allocation method selection, to the recycling rate at end of life, to hauling road type, and to end of life recycling scenario. The analysis was applied on CIR/OL which is a combination of CIR and 2.5-in AC overlay treatment for an existing pavement surface of 4 in. The impacts of each life-cycle stage of the CIR/OL project are assessed and Table 5.3 presents the processes involved at each stage. The traffic information and AC materials quantities are presented in Tables 5.4 and 5.5, respectively. The analysis schematic is depicted in Figure 5.2.

Finally, an end-of-life comparative study of two equivalent IPR and conventional method designs was conducted to study the effect of end of life factors on different treatment types for the same pavement structure.

It was assumed that AC materials are all virgin and do not contain any RAP content and that the only recyclable materials are AC materials and be used as RAP for the future system.

Table 5.3. Life-cycle processes of CIR/OL treatment.

Material Production/Hauling	Construction	Use	Maintenance
• Asphalt straight binder • Crushed aggregate • Natural aggregate • AC operation • Cement • Asphalt emulsion	• Milling machine • Crusher/ pugmill • Paver • Pneumatic roller • Vibratory roller • Grader • Water truck • Service truck • Dump truck • Pickup machine • Work zone	• Roughness • Texture	• Asphalt straight binder production • Crushed aggregate production • Natural aggregate production • Hauling AC raw material to plant • Hauling AC, cement, asphalt emulsion to site • Milling machine • Paver • Sweeper • Vibratory roller

Table 5.4. Traffic assumptions.

ADT	IRI Threshold (in/mi)	Passenger Car (%)	Small Truck (%)	Medium Truck (%)	Large Truck (%)	Growth Factor (%)	Average Speed (mph)
2000	300	80	4	1	15	4	70

Table 5.5. Asphalt concrete overlay material quantities.

Material Type	Quantities (ton)
Asphalt binder	57.2
Crushed aggregate	705.5
Natural aggregate	213.2
AC	985.1

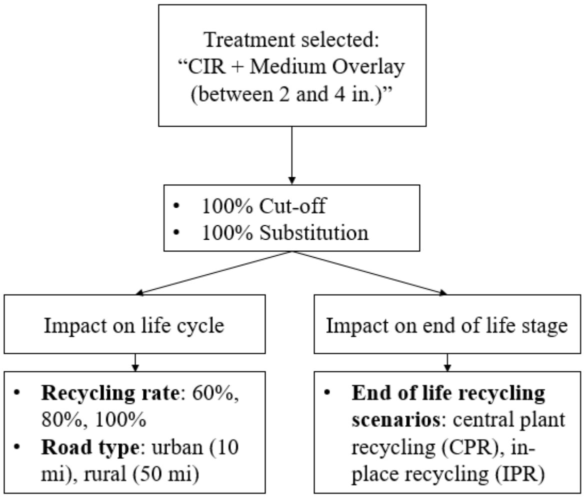


Figure 5.2. EOL sensitivity analysis schematic.

EOL Allocation Methods

Cut-off and substitution methods were evaluated to assess the impact of allocation method selection in an urban area where all material hauling distances are assumed to be 10 mi and where the pavement is totally recycled on plant at the end of life. Figures 5.3 and 5.4 shows that using 100% cut-off results in higher energy and GWP compared to 100% substitution. The total life-cycle energy and GWP show 8.3% and 3.5% reduction, respectively, when using substitution versus cut-off since cut-off allocates all burden of the pavement at end of life to the original pavement; whereas, substitution rewards the original system for producing recyclable materials for the future system.

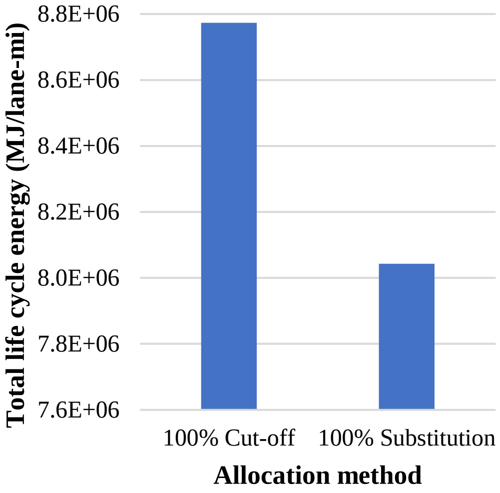


Figure 5.3. Total life-cycle energy for using 100% substitution versus 100% cut-off (at CPR = central plant recycling).

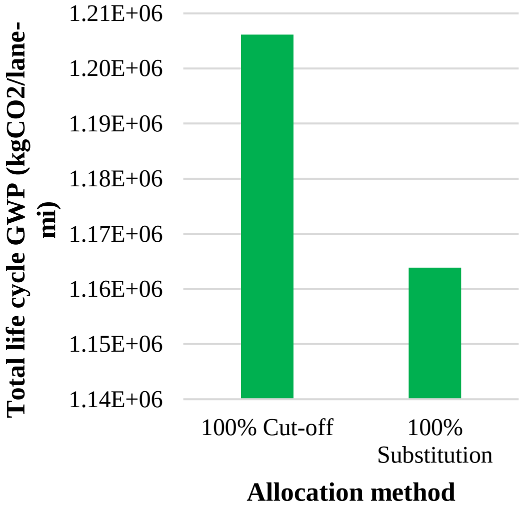


Figure 5.4. Total life-cycle GWP for using 100% substitution versus 100% cut-off (at CPR = central plant recycling).

Recycling Rate

At the end of life, the recycling rate decision has effect on the total life-cycle impacts. The higher the recycling rate, the more reward is allocated to the original system and the lower the impacts. Figure 5.5 shows a lower recycling rate at the end of life results in higher environmental impacts when using both cut-off and substitution. However, the cut-off method is less sensitive to the end-of-life recycling rate than substitution since the difference percent of using recycling rates of 80% and 60% versus 100% are 1.0% and 2.1%, respectively. However, substitution impacts at recycling rates of 80% and 60% versus 100% increase by 5.0% and 10.0%, respectively. Therefore, it is recommended to use the substitution method when part of the pavement is recycled. The cut-off method considers the pavement at the end of life as an isolated system responsible for all the burden generated during the life cycle.

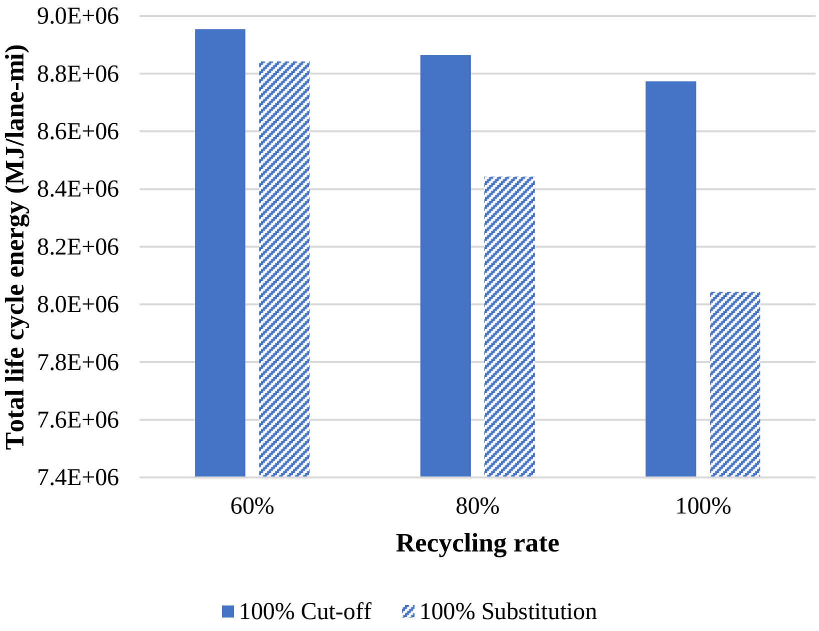


Figure 5.5. Total life-cycle energy and GWP versus different 100% substitution recycling rates.

Recycling EOL Scenarios

Three scenarios are usually considered at the end of life to manage the use of pavement materials: CPR, IPR, and landfilling. For a case presented herein, a pavement is located in an urban area and is totally recycled at end of life. When using the substitution method, Figure 5.6 shows that using IPR reduces end-of-life energy by 74.5%; however, it is 10.6% when allocating resources using the cut-off method. Therefore, cut-off is less sensitive to recycling EOL scenarios selection.

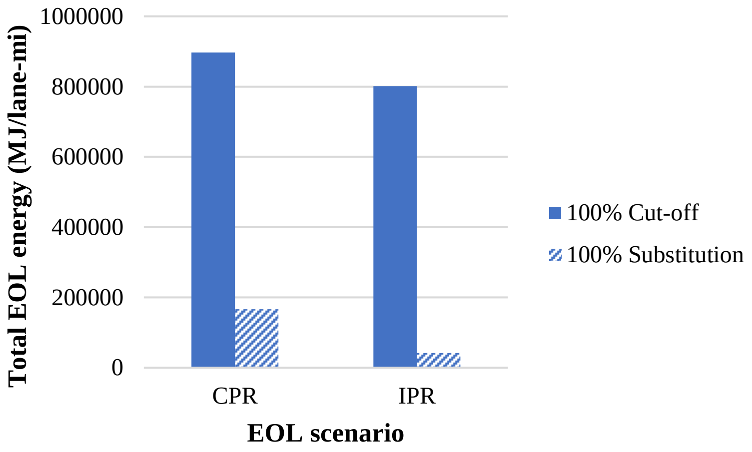


Figure 5.6. Total EOL energy using IPR versus CPR at 100% substitution and cut-off criteria.

Road Type

The effect of road type is assessed by calculating the impacts of hauling materials on an urban road (10 mi) versus a rural road (50 mi) when the pavement is recycled at different rates 60%, 80% and 100% using the CPR scenario. Figure 5.7 shows that the longer the hauling distance, the larger the impacts. At a hauling distance of 50 mi, the life-cycle energy calculated using substitution is higher than the one calculated with the cut-off method at 60% and 80% recycling rates. In addition, cut-off method is less sensitive to hauling distances from pavement location to central plant and landfill facilities; whereas, substitution is more sensitive to the road type since it accounts for hauling of virgin materials of the original system and hauling of RAP or waste to future systems.

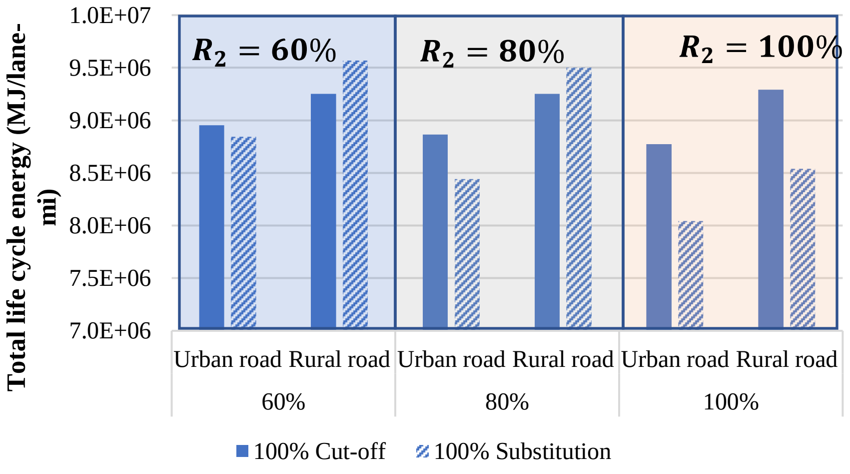


Figure 5.7. Sensitivity of energy to cut-off and substitution methods for different road types.

Comparative Study

The following case study was employed to make a comparative energy assessment between the use of CIR/OL and conventional mill and fill (MF). Major factors affecting the comparative energy consumption such as pavement hardness, pavement width, AC hauling distance and hauling road grade were changed to perform a sensitivity analysis. When all major factors are considered for realistic CIR and overlay designs, such sensitivity analysis would allow for evaluation of the range of energy savings.

The existing structure consists of 4 in AC, 8 in crushed aggregate base coarse layer, and 4 in crushed granular material on top of a subgrade soil having a California Bearing Ratio (CBR) value of 6%. Both designs were conducted based on Chapter 46 of Illinois Department of Transportation Bureau of Local Roads and Streets (IDOT BLRS) manual for pavement rehabilitation. The design procedure for both alternatives assumes typical values of structural coefficients for each material and calculates a remaining structural number (SN_R) and a final structural number (SN_F) for each layer, which are calculated based on inputs for traffic levels, subgrade strength, and existing layer thicknesses. The required thickness of the overlay is then calculated based on the difference between the two structural numbers (IDOT, 2012).

The design was used for a low-volume road with a traffic factor of 0.65, equivalent to an average daily traffic of 2041 vehicles/day with 7.5% single-unit trucks and 2.5% multiple unit trucks. For the CIR with an overlay design alternative, the existing 4 in AC was recycled. The SN_R and SN_F were calculated to be 2.24 and 3.25, respectively, which requires an additional overlay thickness of 2.5 in on top of the recycled AC. For the mill and fill design alternative, on the other hand, the top 2 in of AC was milled, thus resulting in calculated values of 1.84 and 3.25 for SN_R and SN_F, respectively, and an additional overlay thickness of 4 in.

Figure 5.8 shows that MF produces higher life-cycle energy compared with CIR/OL: Approximately 19.2 million MJ/lane-mi using a 100% cut-off and 18.01 million MJ/lane-mi using 100% substitution. CIR/OL method results in 54.3% and 55.4% less energy than MF when cut-off and substitution were used, respectively. Hence, allocation methods are independent if in-place and conventional designs.

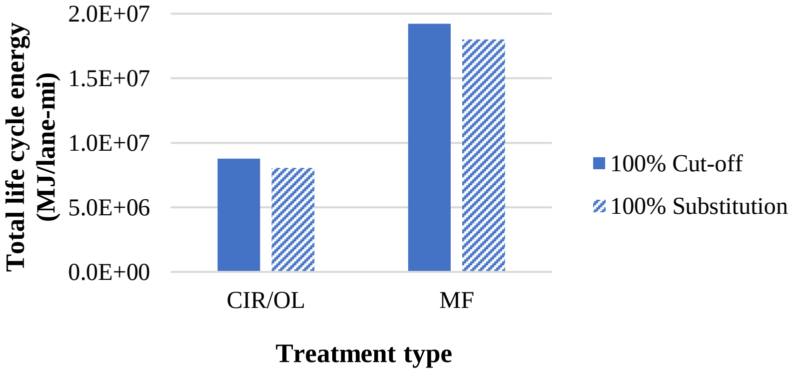


Figure 5.8. Comparison of CIR and MF life-cycle energy at 100% cut-off and 100% substitution methods.

MAJOR ASSUMPTIONS AND LIMITATIONS

The followings are limitations of the tool:

- More M&R realistic schedule is needed to better trigger performance over the analysis period.
- LCCA is not considered in the study.
- Deterministic models are limited to one region.
- The tool generates results that have embedded uncertainties. Therefore, a quantitative uncertainty should be considered.
- Use stage is limited to roughness and texture; hence, albedo and pavement deflection should be considered.
- The equipment inventory should be updated regularly.

CHAPTER 6: DECISION MAKING TOOL DEVELOPMENT

PROGRAMMING PLATFORM

The IPR tool is developed using visual basic applications (VBA) in Microsoft® excel. VBA is an event-driven programming language from Microsoft. The VBA allows the use of the tool by all transportation project stakeholders and access inventory databases and performance models. The developed tool is a series of linked user forms operated by macros (programmed instructions to automate a task) that allow modeling the environmental impacts and performance of projects selected through databases built in the tool excel file worksheets. The user form is a user-friendly interactive platform to enter data required to compile the final outputs. The tool key terms as they are used in this report are defined in Table 6.1.

Table 6.1. Tool key terms definition.

Key Term	Definition
Worksheet	A MS excel worksheet or sheet is a single page in a MS excel workbook.
Table	A MS table is a special object available in MS excel that contains column headers and advanced properties.
Form controls	A MS excel form control is 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.
Combobox	A user-form control to create a dropdown list.
Page	A control existing on user-forms that contain different sections associated to different project aspects.
Default button	Form control that is clicked to generate data extracted from primary data collected.

The features that highlight the user-friendly quality of the developed tool are listed below:

- Worksheets are used as a platform to report data and review results.
- The worksheet interfaces include form controls to guide the user in the project analysis.
- Invalid user inputs or questionable user choices are checked by displaying an error message.
- Projects results reports can be downloaded in pdf format.

MODULES

The tool includes five modules which are materials, construction, work zone, use and end of life. The user can select up to five maintenance or rehabilitation treatments candidates, from the list reported in Table 6.2, as alternatives for analyses.

Table 6.2. List of maintenance and rehabilitation treatments considered for project selection.

Maintenance Treatments	Rehabilitation Treatments
Cape seal	CIR
Chip seal double course	CIR + cape seal
Chip seal single course	CIR + chip seal
Fog seal	CIR + medium overlay (between 2 and 4 in)
HIR remixing	CIR + thick overlay (over 4 in)
HIR remixing + medium overlay (between 2 and 4 in)	CIR + thin overlay (2 in or less)
HIR remixing + thick overlay (over 4 in)	Cold milling + medium overlay (between 2 and 4 in)
HIR remixing + thin overlay (2in or less)	Cold milling + thick overlay (over 4 in)
HIR repaving	Cold milling + thin overlay (2 in or less)
HIR resurfacing	FDR
HIR resurfacing + medium overlay (between 2 and 4 in)	FDR + medium overlay (between 2 and 4 in)
HIR resurfacing + thick overlay (over 4 in)	FDR + thick overlay (over 4 in)
HIR resurfacing + thin overlay (2 in or less)	FDR + thin overlay (2 in or less)
Microsurfacing double course	FDR + Chip Seal
Microsurfacing single course	FDR + Chip Seal
Sand seal	
Slurry seal	
Thin AC overlay (2 in or less)	
Ultra-thin bonded wearing course	

The user inputs required data in the five modules for environmental impacts and energy use calculation, which are summarized in a worksheet and a breakdown chart as shown in Figure 6.1.

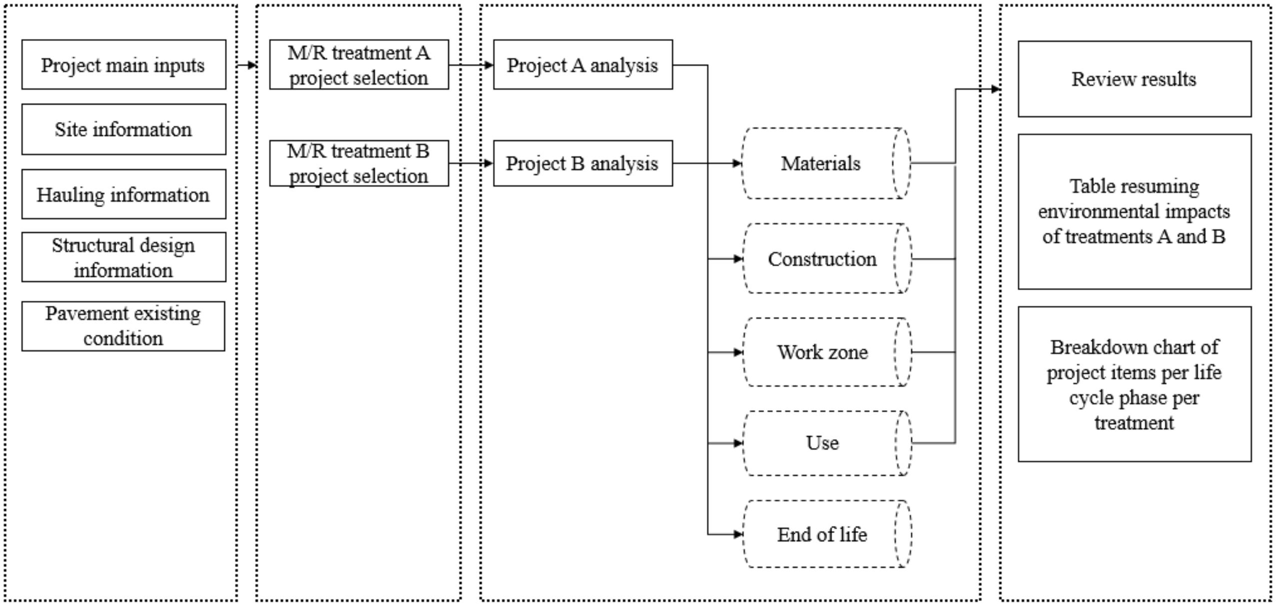


Figure 6.1. Projects selection process schematic (M/R = maintenance or rehabilitation).

General Inputs

The "Main Inputs" user form has key items to perform life-cycle analysis as illustrated in Figure 6.2. These inputs are entered in user form presented in Figure 6.3 before the treatment selection. All general inputs entered by the user are automatically reported in “Main Inputs” spreadsheet shown in Figure 6.4.

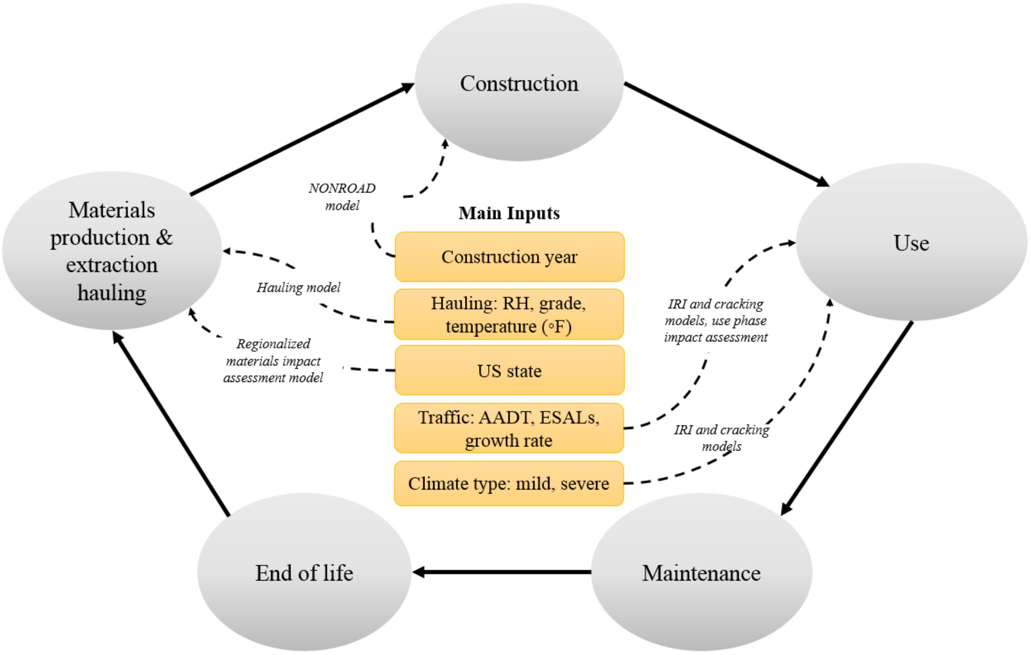
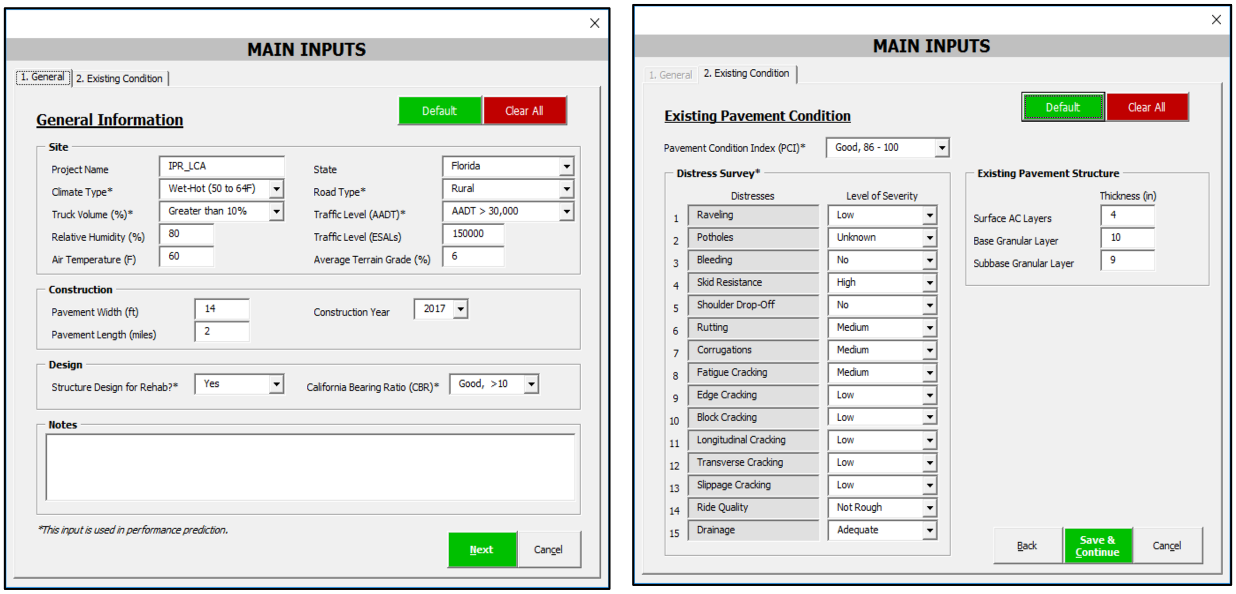


Figure 6.2. Impact assessment and project main inputs dependencies



General Information

Site

Project Name	IPR_LCA	State	Florida
Climate Type*	Wet-Hot (50 to 64F)	Road Type*	Rural
Truck Volume (%)*	Greater than 10%	Traffic Level (AADT)*	AADT > 30,000
Relative Humidity (%)	80	Traffic Level (ESALs)	150000
Air Temperature (F)	60	Average Terrain Grade (%)	6

Construction

Pavement Width (ft)	14	Construction Year	2017
Pavement Length (miles)	2		

Design

Structure Design for Rehab?*	Yes	California Bearing Ratio (CBR)*	Good, >10

Notes

*This input is used in performance prediction.

Existing Pavement Condition

Pavement Condition Index (PCI)* Good, 86 - 100

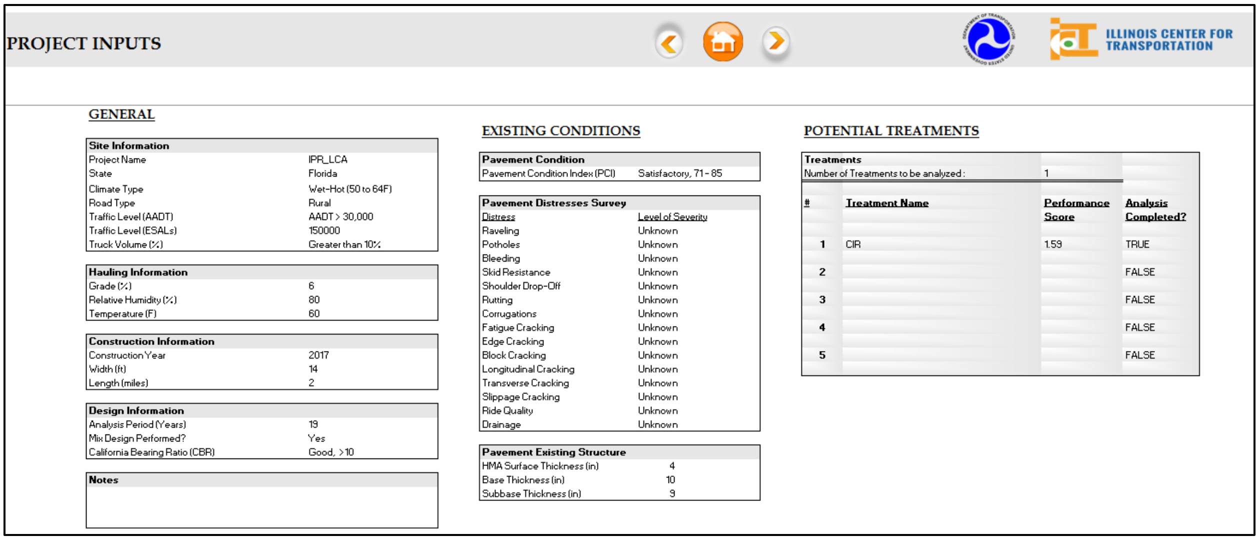
Distress Survey*

	Distresses	Level of Severity
1	Raveling	Low
2	Potholes	Unknown
3	Bleeding	No
4	Skid Resistance	High
5	Shoulder Drop-Off	No
6	Rutting	Medium
7	Corrugations	Medium
8	Fatigue Cracking	Medium
9	Edge Cracking	Low
10	Block Cracking	Low
11	Longitudinal Cracking	Low
12	Transverse Cracking	Low
13	Slippage Cracking	Low
14	Ride Quality	Not Rough
15	Drainage	Adequate

Existing Pavement Structure

	Thickness (in)
Surface AC Layers	4
Base Granular Layer	10
Subbase Granular Layer	9

Figure 6.3. “Main Inputs” user form pages.



PROJECT INPUTS

ILLINOIS CENTER FOR TRANSPORTATION

GENERAL

Site Information	
Project Name	IPR_LCA
State	Florida
Climate Type	Wet-Hot (50 to 64F)
Road Type	Rural
Traffic Level (AADT)	AADT > 30,000
Traffic Level (ESALs)	150000
Truck Volume (%)	Greater than 10%

Hauling Information	
Grade (%)	6
Relative Humidity (%)	80
Temperature (F)	60

Construction Information	
Construction Year	2017
Width (ft)	14
Length (miles)	2

Design Information	
Analysis Period (Years)	19
Mix Design Performed?	Yes
California Bearing Ratio (CBR)	Good, >10

Notes

EXISTING CONDITIONS

Pavement Condition	
Pavement Condition Index (PCI)	Satisfactory, 71 - 85

Pavement Distresses Survey	
Distress	Level of Severity
Raveling	Unknown
Potholes	Unknown
Bleeding	Unknown
Skid Resistance	Unknown
Shoulder Drop-Off	Unknown
Rutting	Unknown
Corrugations	Unknown
Fatigue Cracking	Unknown
Edge Cracking	Unknown
Block Cracking	Unknown
Longitudinal Cracking	Unknown
Transverse Cracking	Unknown
Slippage Cracking	Unknown
Ride Quality	Unknown
Drainage	Unknown

Pavement Existing Structure	
HMA Surface Thickness (in)	4
Base Thickness (in)	10
Subbase Thickness (in)	9

POTENTIAL TREATMENTS

Treatments

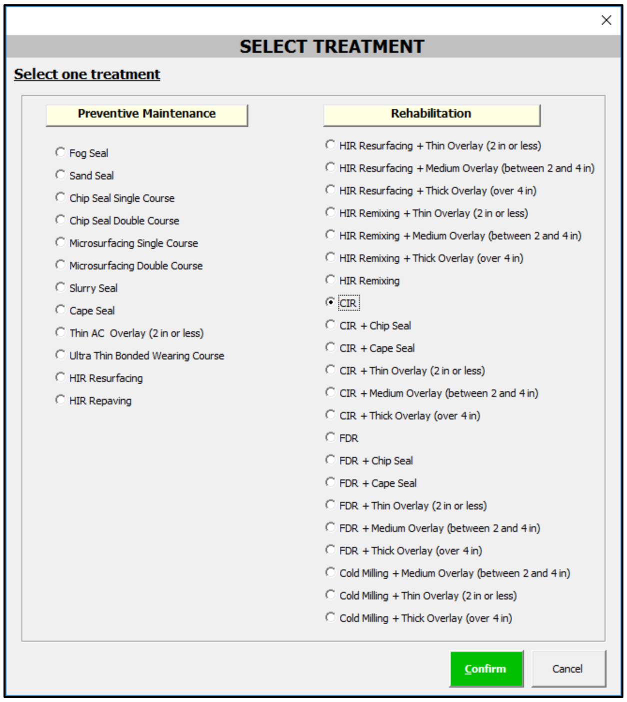
Number of Treatments to be analyzed : 1

#	Treatment Name	Performance Score	Analysis Completed?
1	CIR	1.59	TRUE
2			FALSE
3			FALSE
4			FALSE
5			FALSE

Figure 6.4. "Main Inputs" spreadsheet.

Treatment Selection

The treatment selection follows entering a project main inputs. Figure 6.5 shows an example of "CIR + Medium Overlay (between 2 to 4 in)" selection from the list of treatments displayed in "Treatment Selection" user form. The number of treatments selected can be up to five and listed in "Treatments for Analysis" user form with their corresponding performance score and risk level on performance as illustrated in Figure 6.6.



SELECT TREATMENT

Select one treatment

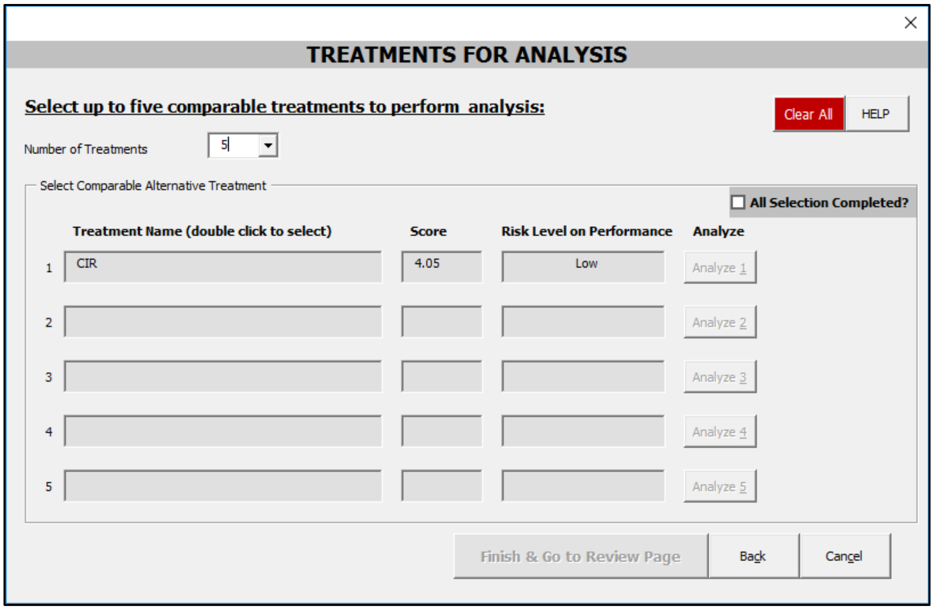
Preventive Maintenance

○ Fog Seal
○ Sand Seal
○ Chip Seal Single Course
○ Chip Seal Double Course
○ Microsurfacing Single Course
○ Microsurfacing Double Course
○ Slurry Seal
○ Cape Seal
○ Thin AC Overlay (2 in or less)
○ Ultra Thin Bonded Wearing Course
○ HIR Resurfacing
○ HIR Repaving

Rehabilitation

○ HIR Resurfacing + Thin Overlay (2 in or less)
○ HIR Resurfacing + Medium Overlay (between 2 and 4 in)
○ HIR Resurfacing + Thick Overlay (over 4 in)
○ HIR Remixing + Thin Overlay (2 in or less)
○ HIR Remixing + Medium Overlay (between 2 and 4 in)
○ HIR Remixing + Thick Overlay (over 4 in)
○ HIR Remixing
● CIR
○ CIR + Chip Seal
○ CIR + Cape Seal
○ CIR + Thin Overlay (2 in or less)
○ CIR + Medium Overlay (between 2 and 4 in)
○ CIR + Thick Overlay (over 4 in)
○ FDR
○ FDR + Chip Seal
○ FDR + Cape Seal
○ FDR + Thin Overlay (2 in or less)
○ FDR + Medium Overlay (between 2 and 4 in)
○ FDR + Thick Overlay (over 4 in)
○ Cold Milling + Medium Overlay (between 2 and 4 in)
○ Cold Milling + Thin Overlay (2 in or less)
○ Cold Milling + Thick Overlay (over 4 in)

Figure 6.5. Example of a selected treatment in the "Treatment Selection" user form.



Select up to five comparable treatments to perform analysis:

Number of Treatments: 5

Select Comparable Alternative Treatment

☐ All Selection Completed?

	Treatment Name (double click to select)	Score	Risk Level on Performance	Analyze
1	CIR	4.05	Low	Analyze 1
2				Analyze 2
3				Analyze 3
4				Analyze 4
5				Analyze 5

Figure 6.6. “Treatment for Analysis” user form.

Pavement Performance

The pavement performance analysis is important to present the expected life of the treatment and expected change in condition after applying a rehabilitation or a maintenance treatment over the analysis period. There are various descriptors that can be used to assess pavement performance such as IRI, wheel path cracking percent, pavement condition index, etc. In the tool, the performance models used in California were utilized. Since the tool is designed to be applied on a national scale, two options were provided to the user to estimate life expectancy of the treatment selected. First, the life expectancy range [L_{min}, L_{max}] of all treatments considered in the scope the project is estimated using data from literature. Performance score (PS) is evaluated using multi-criteria performance estimation approach and then used to estimate the treatment life expectancy as follows:

1. PS is 4 or 5: ideal on-site conditions for selected treatment; indicating very low risk for performance. Treatment life can be expected to be at the highest range, L_{max}.
2. PS is 2 or 3: conditions are fair carrying medium risk for the performance of selected treatment. Treatment life can be expected to be at medium range of expectations, $(L_{max} + L_{min})/2$.
3. PS is 1. on-site conditions are not appropriate for the selected treatment with very high risk. Treatment life may be predicted at lower range of expected values, L_{min}.

The estimated service life using the first approach is used to produce a default M&R schedule that the user visualizes on the “Life Expectancy” user form, as shown in Figure 6.7.

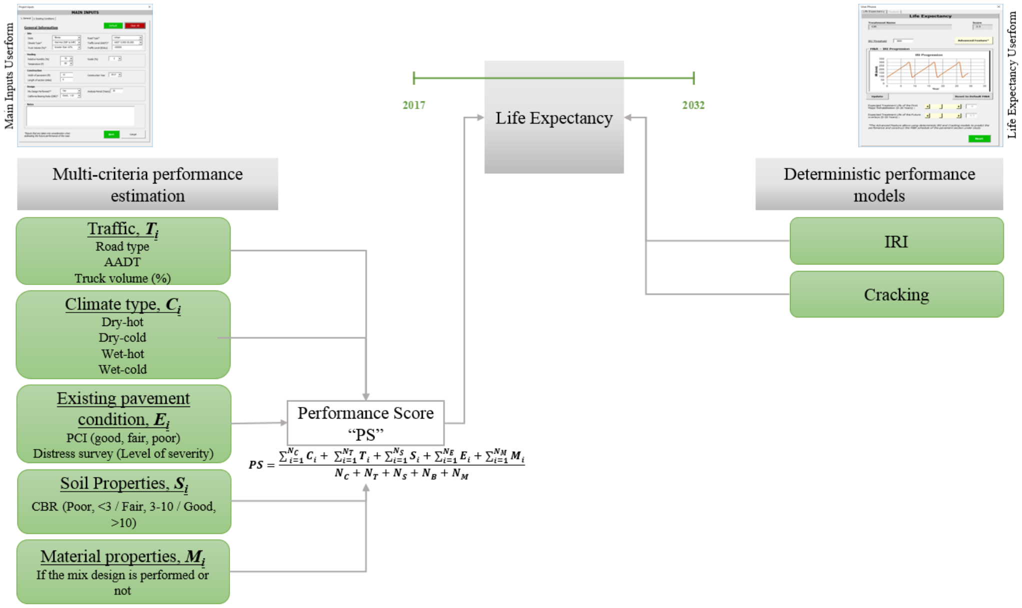
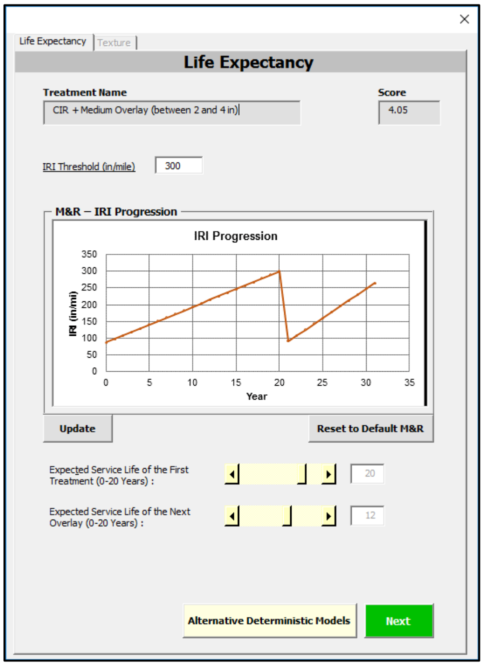


Figure 6.7. Life expectancy estimation approaches flowchart.

The second option is using deterministic performance models to predict the performance progression. The service life is triggered by default IRI threshold; if cracking model is selected, the performance is further triggered by cracking threshold. The cracking model is a good option to trigger the performance when the pavement has severe structural problems.



Treatment Name: CIR + Medium Overlay (between 2 and 4 in)

Score: 4.05

IRI Threshold (in/mile): 300

Expected Service Life of the First Treatment (0-20 Years) : 20

Expected Service Life of the Next Overlay (0-20 Years) : 12

Figure 6.8. "Life Expectancy" user form.

The pavement management plan of a project requires building a M&R schedule to model the timings when maintenance or rehabilitation actions are applied on the pavement during the analysis period. According to Figure 6.9, the tool provides two different options to build a M&R schedule. The first uses a simple linear IRI progression that depends on IRI threshold and life estimated for the treatment selected and the future maintenance actions. The user can change the IRI threshold and the treatment life using a slider in "UF_Use" userform. The second method allows building the M&R schedule using at most four criteria: maximum treatment life, IRI threshold, cracking threshold, and routine maintenance interval. The final M&R schedule can be visualized on the "Information_Treatment" worksheet.

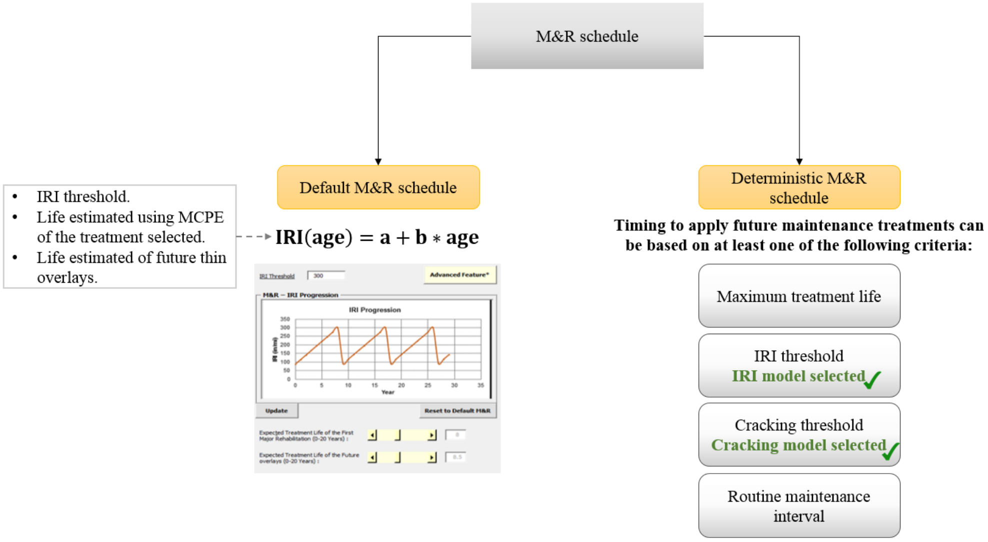


Figure 6.9. M&R schedule construction options flowchart.

The future maintenance activities are decided by the tool based on the predicted cracking performance of the pavement. Therefore, whenever the cracking performance is triggered by the wheel path cracking threshold, CIR + thin overlay is applied as an emergency maintenance; otherwise, thin overlay is applied as a preventive maintenance as illustrated in Figure 6.10.

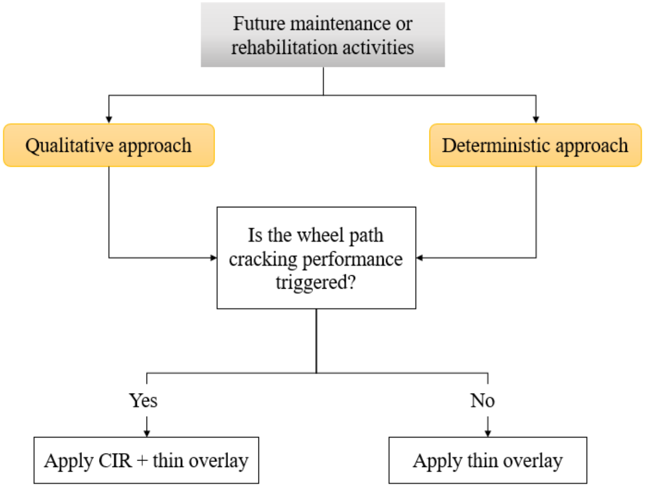
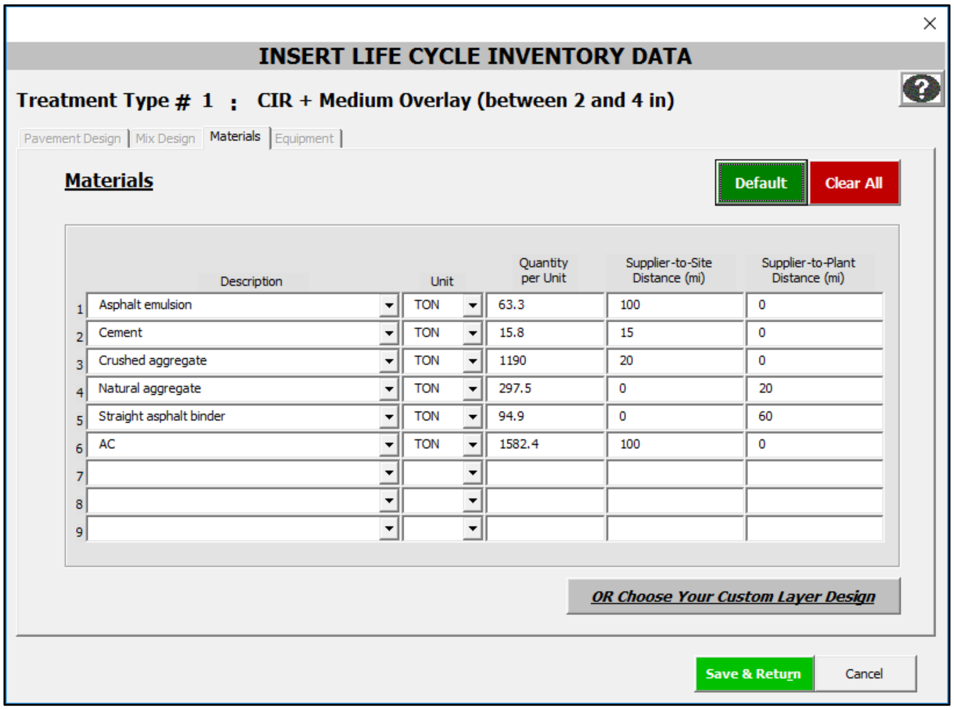


Figure 6.10. Future maintenance and rehabilitation strategy schematic.

Materials Extraction, Production and Hauling Stage

The user is shown the "Materials" page of "Life-Cycle Inventory" user form (Figure 6.11) upon clicking "Open LCIA Module" command button. In this page, the user either selects materials and enters the corresponding quantities or uses default materials list and quantities upon clicking "Default" command button.



INSERT LIFE CYCLE INVENTORY DATA

Treatment Type # 1 : CIR + Medium Overlay (between 2 and 4 in)

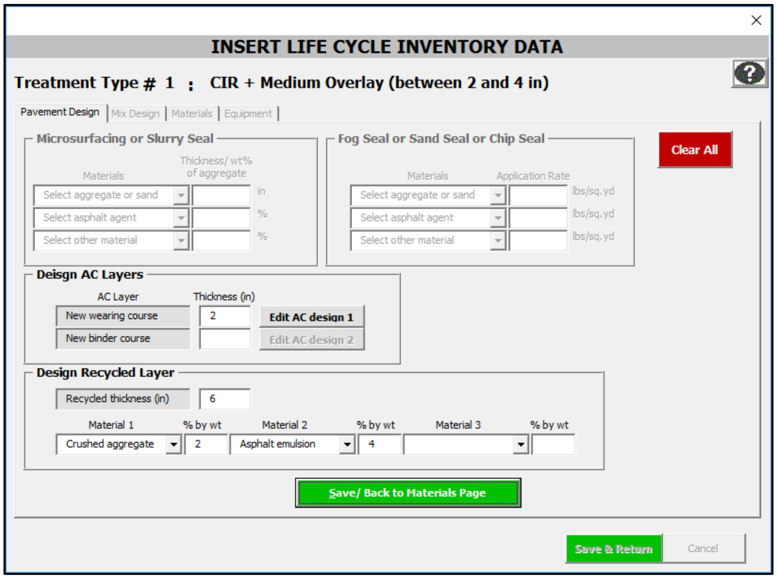
Materials

	Description	Unit	Quantity per Unit	Supplier-to-Site Distance (mi)	Supplier-to-Plant Distance (mi)
1	Asphalt emulsion	TON	63.3	100	0
2	Cement	TON	15.8	15	0
3	Crushed aggregate	TON	1190	20	0
4	Natural aggregate	TON	297.5	0	20
5	Straight asphalt binder	TON	94.9	0	60
6	AC	TON	1582.4	100	0
7					
8					
9					

Figure 6.11. "Life-Cycle Inventory" user form, "Materials" page.

In addition, the user can specify pavement design materials by clicking "OR Checking Your Custom Layer Design" as illustrated in Figure 6.11 and then the user is shown the "Pavement Design" page, shown in Figure 6.12. For example, if the user selects a combination of a major rehabilitation and microsurfacing or slurry seal, then "Microsurfacing and Slurry Seal" frame is enabled and it is required to input the thickness of aggregate or sand application as well as the application rate (by weight% of aggregate) of asphalt products (e.g., asphalt binder, emulsion). Whereas, if fog seal, sand seal or chip seal is selected, then "Fog Seal, Sand Seal and Chip Seal" frame is enabled and it is required to input the application rate of each material for the surface treatment by lbs/sq.yd unit. Finally, if cape seal is selected, both "Microsurfacing and Slurry Seal" and "Fog Seal, Sand Seal and Chip Seal" framed are enabled since cape seal is a combination of slurry seal or microsurfacing and chip seal.

In addition, the user is asked to input material information necessary for the construction of the treated pavement layers. If any of the IPR treatments is selected then the user need to input the pavement recycled thickness. Furthermore, if AC operation is selected in one of the materials list, then "Edit AC design" command button to enter mix design characteristics and mix materials types and proportions, as Figure 6.13 shows.



INSERT LIFE CYCLE INVENTORY DATA

Treatment Type # 1 : CIR + Medium Overlay (between 2 and 4 in)

Microsurfacing or Slurry Seal

Materials	Thickness/ wt% of aggregate	
Select aggregate or sand		in
Select asphalt agent		%
Select other material		%

Fog Seal or Sand Seal or Chip Seal

Materials	Application Rate	
Select aggregate or sand		lbs/sq.yd
Select asphalt agent		lbs/sq.yd
Select other material		lbs/sq.yd

Deisgn AC Layers

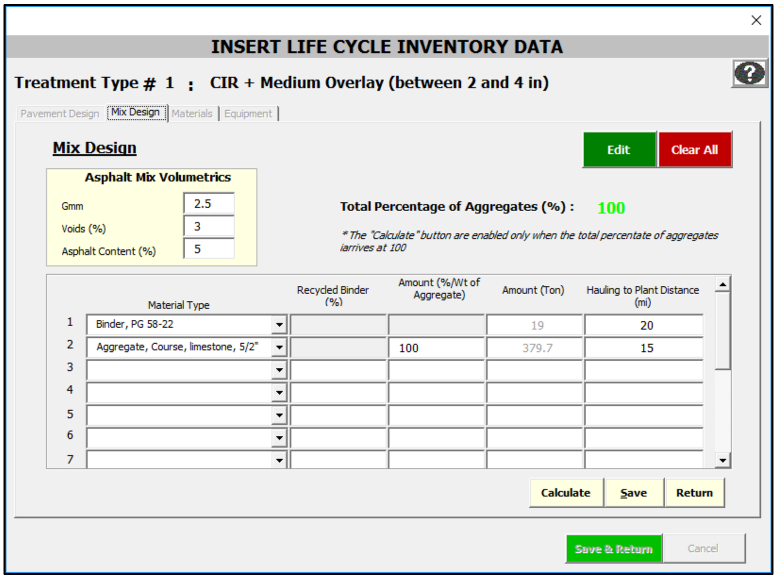
AC Layer	Thickness (in)
New wearing course	2
New binder course	

Design Recycled Layer

Recycled thickness (in) 6

Material 1	% by wt	Material 2	% by wt	Material 3	% by wt
Crushed aggregate	2	Asphalt emulsion	4		

Figure 6.12. “Life-Cycle Inventory” user form, “Pavement Design” page.



INSERT LIFE CYCLE INVENTORY DATA

Treatment Type # 1 : CIR + Medium Overlay (between 2 and 4 in)

Mix Design

Asphalt Mix Volumetrics

Gmm	2.5
Voids (%)	3
Asphalt Content (%)	5

Total Percentage of Aggregates (%) : 100

* The "Calculate" button are enabled only when the total percentate of aggregates iarrives at 100

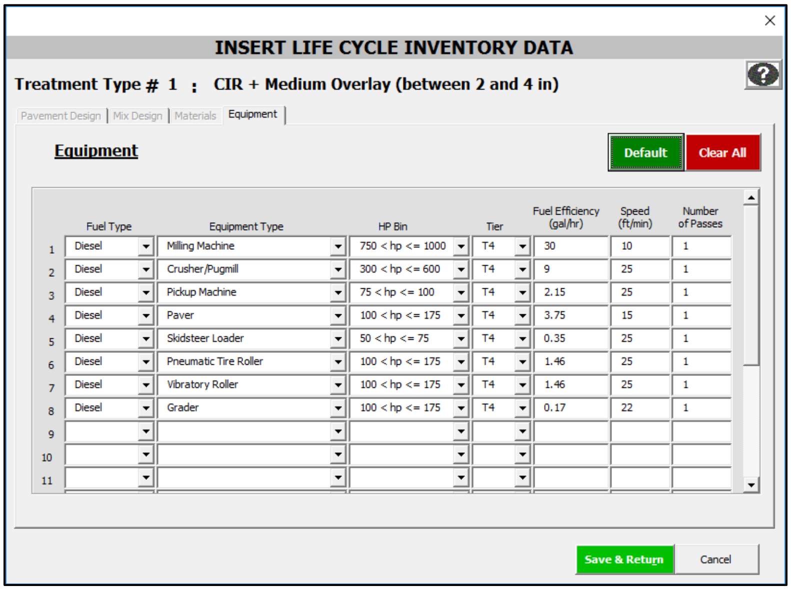
	Material Type	Recycled Binder (%)	Amount (%/Wt of Aggregate)	Amount (Ton)	Hauling to Plant Distance (mi)
1	Binder, PG 58-22			19	20
2	Aggregate, Course, limestone, 5/2"		100	379.7	15
3					
4					
5					
6					
7					

Figure 6.13. “Life-Cycle Inventory” user form, “Mix Design” page.

The final stage in the “Materials” page should be filling hauling distances for the selected materials, as shown in Figure 6.11. The hauling distance can be either to plant or to site. If the user selects the customization option then AC raw materials hauling distances to plant are entered in “Mix Design” page, as shown in Figure 6.13, while the AC hauling to site is entered in the “Materials” page, shown in Figure 6.11.

Construction Stage

At the construction stage, the user should select the equipment used to operate the construction activities in the “Equipment” page of “Life-Cycle Inventory” user form, which is visible upon clicking “Open LCIA Module” command button, shown in Figure 6.14. The inputs required to enter are fuel type, equipment type, HP bin, tier category, fuel efficiency, speed and number of passes. These inputs can also be generated upon clicking “Default” command button. The default equipment units represent the equipment data collected from contractors.



INSERT LIFE CYCLE INVENTORY DATA

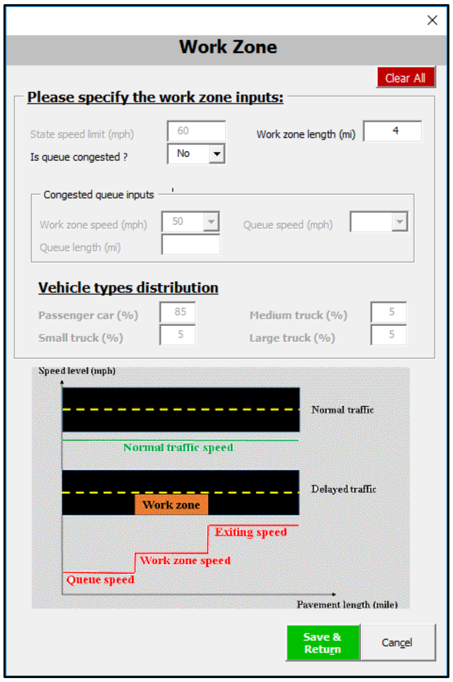
Treatment Type # 1 : CIR + Medium Overlay (between 2 and 4 in)

Equipment

	Fuel Type	Equipment Type	HP Bin	Tier	Fuel Efficiency (gal/hr)	Speed (ft/min)	Number of Passes
1	Diesel	Milling Machine	750 < hp <= 1000	T4	30	10	1
2	Diesel	Crusher/Pugmill	300 < hp <= 600	T4	9	25	1
3	Diesel	Pickup Machine	75 < hp <= 100	T4	2.15	25	1
4	Diesel	Paver	100 < hp <= 175	T4	3.75	15	1
5	Diesel	Skidsteer Loader	50 < hp <= 75	T4	0.35	25	1
6	Diesel	Pneumatic Tire Roller	100 < hp <= 175	T4	1.46	25	1
7	Diesel	Vibratory Roller	100 < hp <= 175	T4	1.46	25	1
8	Diesel	Grader	100 < hp <= 175	T4	0.17	22	1
9							
10							
11							

Figure 6.14. “Life-Cycle Inventory” user form, “Equipment” page.

The construction stage accounts for the work zone as well. The user enters work zone inputs in “Work Zone” user form, shown in Figure 6.15 upon clicking “Open Work Zone Module” command button.



Work Zone

Please specify the work zone inputs:

State speed limit (mph) 60
Work zone length (mi) 4
Is queue congested ? No

Congested queue inputs

Work zone speed (mph) 50
Queue speed (mph)
Queue length (mi)

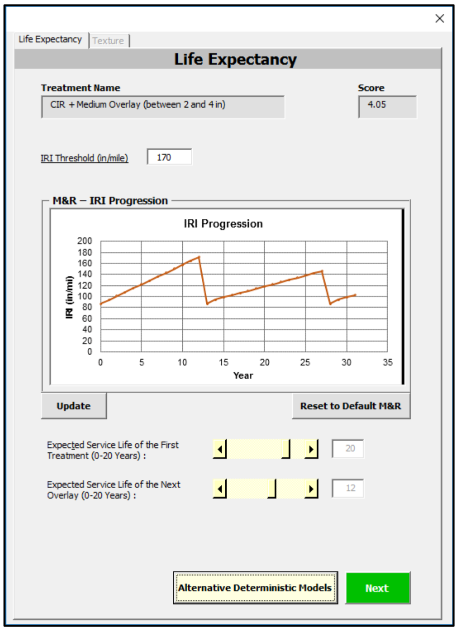
Vehicle types distribution

Passenger car (%) 85
Medium truck (%) 5
Small truck (%) 5
Large truck (%) 5

Figure 6.15. “Work Zone” user form.

Maintenance and Rehabilitation Stage

The ultimate outcome from “Life Expectancy” user form is to obtain a M&R schedule. M&R schedule is necessary to compile use and maintenance stages’ impacts. Figure 6.8 shows example of a default M&R schedule for a threshold of 300 in/mi and service life estimated to be 20 years, and a deterministic M&R schedule that shows when IRI progression is triggered by rehabilitation interval (Figure 6.16 and 6.17). The deterministic M&R schedule is obtained using up to five criteria and displayed in “Create Schedule” user form, shown in Figure 6.18.



Treatment Name: CIR + Medium Overlay (between 2 and 4 in)

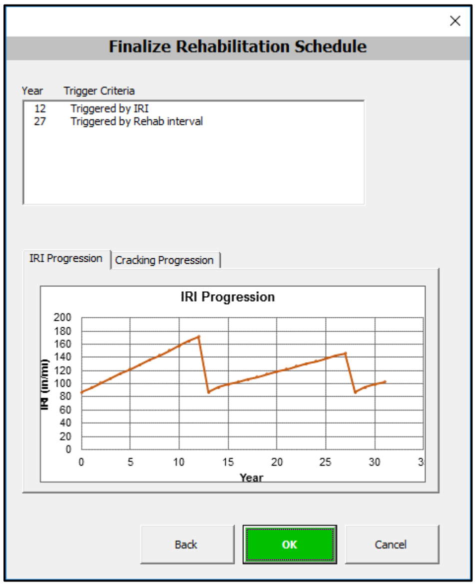
Score: 4.05

IRI Threshold (in/mile): 170

Expected Service Life of the First Treatment (0-20 Years) : 20

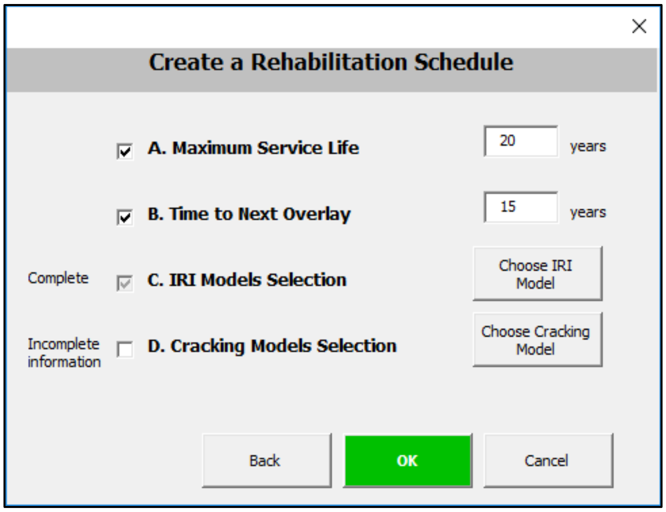
Expected Service Life of the Next Overlay (0-20 Years) : 12

Figure 6.16. Deterministic M&R schedule.



Year	Trigger Criteria
12	Triggered by IRI
27	Triggered by Rehab interval

Figure 6.17. M&R built using deterministic models.



Create a Rehabilitation Schedule

☑ A. Maximum Service Life: 20 years

☑ B. Time to Next Overlay: 15 years

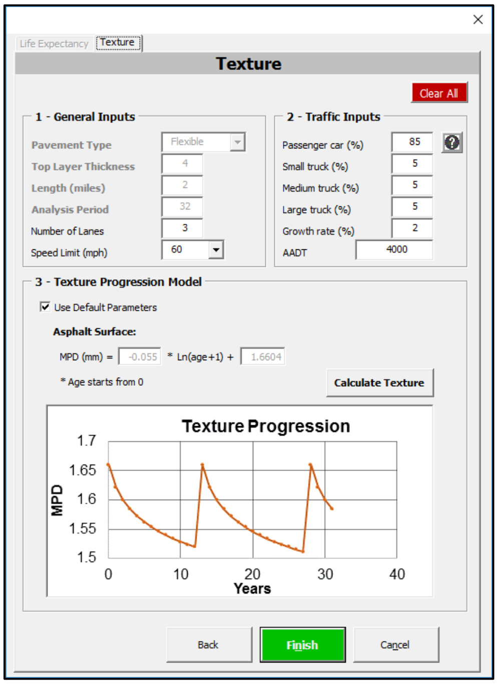
Complete ☑ C. IRI Models Selection

Incomplete information ☐ D. Cracking Models Selection

Figure 6.18. “Create Schedule” user form.

Use Stage

Roughness and texture are the elements considered in the use stage analysis. Figure 6.19 shows the main inputs of use stage in terms of general and traffic inputs. Most of the general inputs are greyed out since they have been already entered in the “Main Inputs” userform, shown in Figure 6.3except for the number of lanes and speed limit that should be input in the user form along with all traffic inputs including vehicle type distribution, growth rate and AADT in addition to the IRI and texture models selection.



Texture

1 - General Inputs

Pavement Type: Flexible
Top Layer Thickness: 4
Length (miles): 2
Analysis Period: 32
Number of Lanes: 3
Speed Limit (mph): 60

2 - Traffic Inputs

Passenger car (%): 85
Small truck (%): 5
Medium truck (%): 5
Large truck (%): 5
Growth rate (%): 2
AADT: 4000

3 - Texture Progression Model

☑ Use Default Parameters

Asphalt Surface:

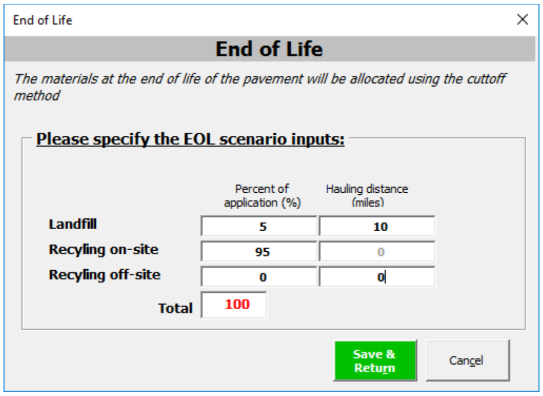
MPD (mm) = -0.055 * Ln(age+1) + 1.6604

* Age starts from 0

Figure 6.19. “Use Stage” user form, “Texture” page.

End of Life Stage

At the end of life stage, various scenarios can be considered namely landfilling, recycling on- and off-site. The user is shown "End of Life" user form, shown in Figure 6.20, upon clicking "Open End of Life Module" where the percent of application of each end of life scenario is entered, as well as the hauling distances to landfill facility and central plant recycling.



End of Life

End of Life

The materials at the end of life of the pavement will be allocated using the cuttoff method

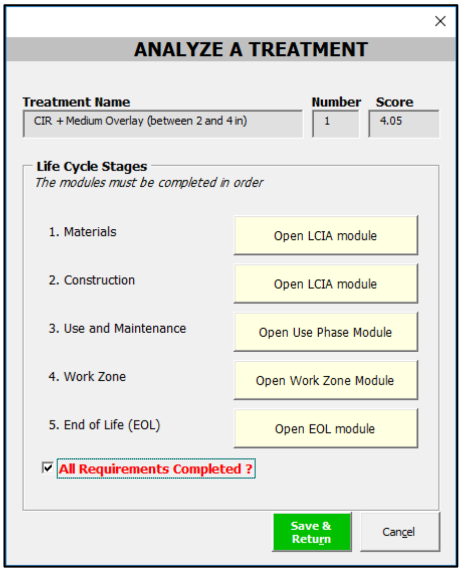
Please specify the EOL scenario inputs:

	Percent of application (%)	Hauling distance (miles)
Landfill	5	10
Recyling on-site	95	0
Recyling off-site	0	0
Total	100	

Figure 6.20. "End of Life" user form.

Review and Results

The results can be reviewed upon completing all requirements of the tool modules in "Modules Analysis" user form, as shown in Figure 6.21. Then, the "Treatments for Analysis" user form is shown (Figure 6.22) where the user clicks "Finish/ Go to Review Page" to visualize the results of the energy or emission selected by the user from a dropdown list in the "Review Results" spreadsheet (Figure 6.23). In the interpretation step of the LCA study, the user can check aggregate results of items involved in each stage in "Chart" spreadsheet (Figure 6.24).



ANALYZE A TREATMENT

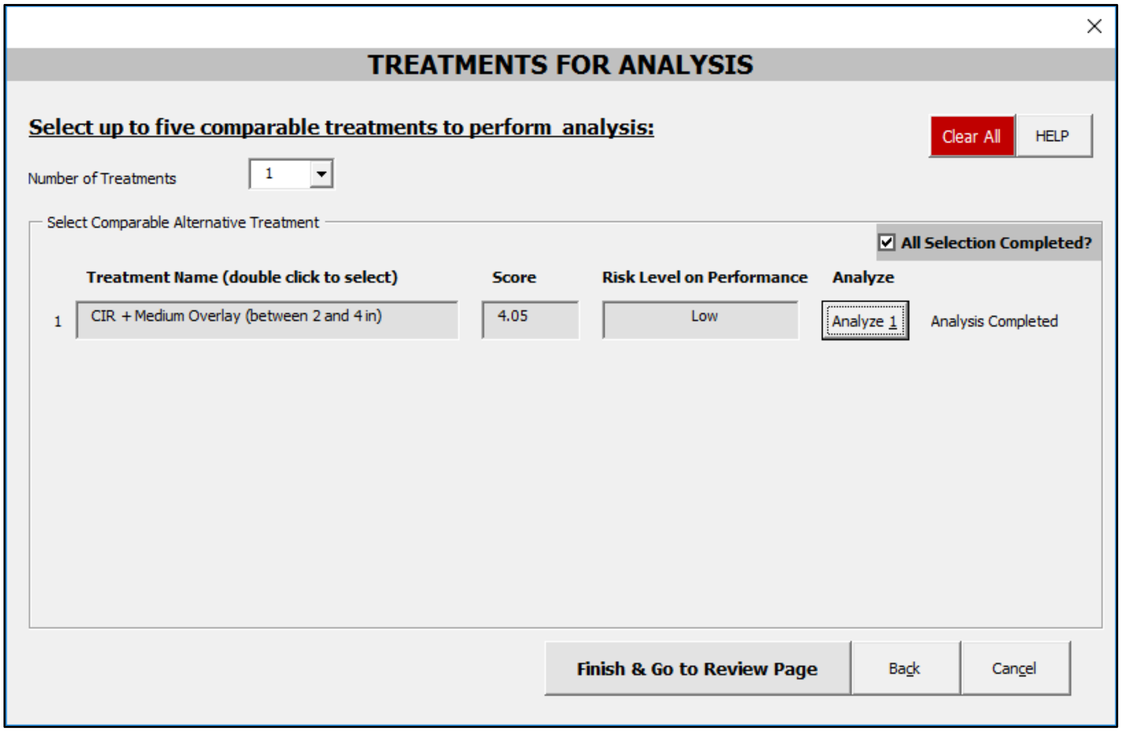
Treatment Name	**Number**	**Score**
CIR + Medium Overlay (between 2 and 4 in)	1	4.05

Life Cycle Stages
The modules must be completed in order

1. Materials
2. Construction
3. Use and Maintenance
4. Work Zone
5. End of Life (EOL)

☑ All Requirements Completed ?

Figure 6.21. Requirements completed before reviewing final results.



TREATMENTS FOR ANALYSIS

Select up to five comparable treatments to perform analysis:

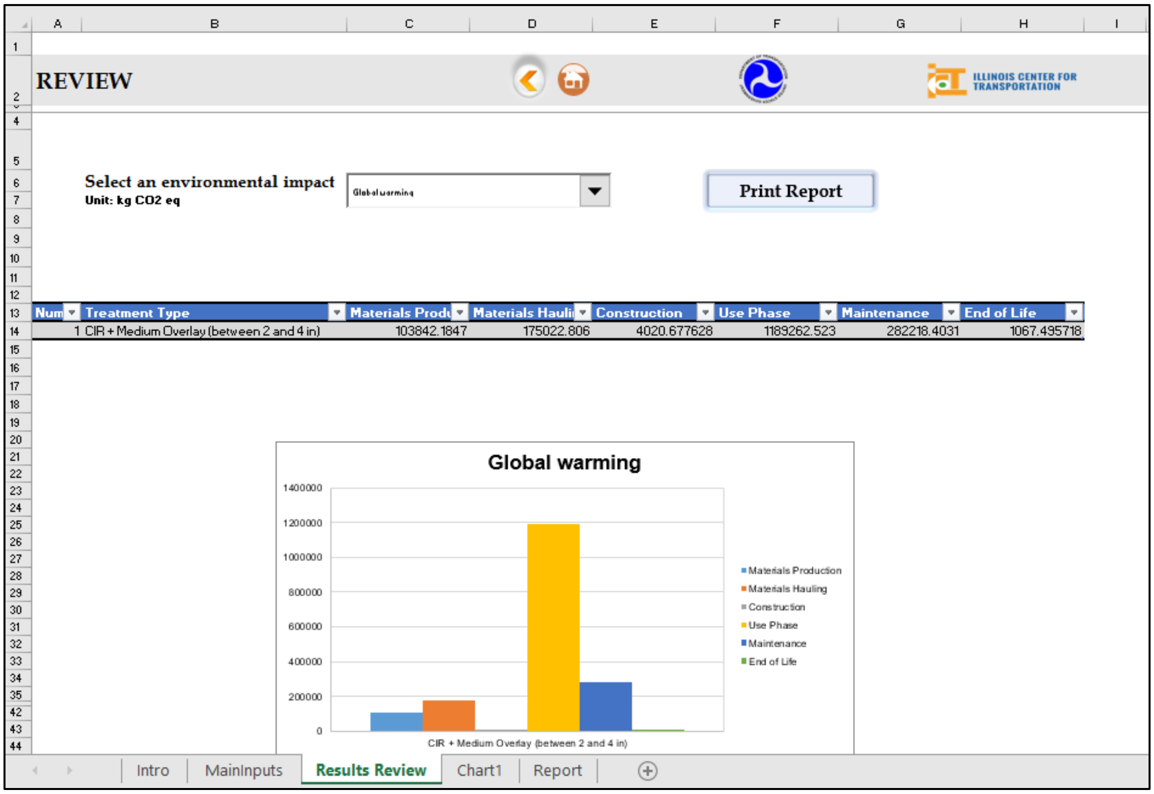
Number of Treatments: 1

Select Comparable Alternative Treatment

☑ All Selection Completed?

	Treatment Name (double click to select)	Score	Risk Level on Performance	Analyze	
1	CIR + Medium Overlay (between 2 and 4 in)	4.05	Low	Analyze 1	Analysis Completed

Figure 6.22. Completed analysis prior to clicking Finish/Go to Review Page button.



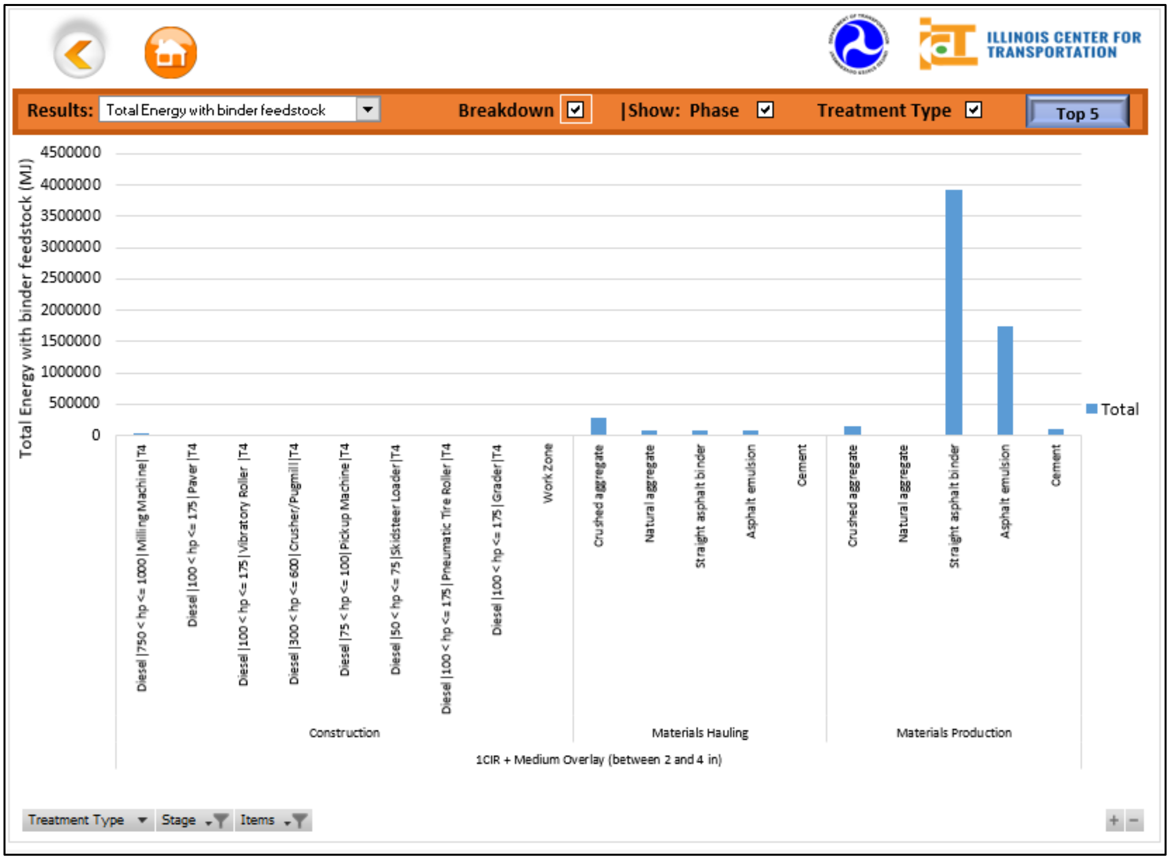
REVIEW

Select an environmental impact
Unit: kg CO2 eq

Global warming

Num	Treatment Type	Materials Produ	Materials Hauli	Construction	Use Phase	Maintenance	End of Life
1	CIR + Medium Overlay (between 2 and 4 in)	103842.1847	175022.806	4020.677628	1189262.523	282218.4031	1067.495718

Figure 6.23. Review of total results of each life-cycle stage.



Results: Total Energy with binder feedstock

Breakdown ☑ |**Show: Phase** ☑ **Treatment Type** ☑

Figure 6.24. Breakdown chart of final results for CIR + Medium Overlay (between 2 to 4 in).

CHAPTER 7: SUMMARY, FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

SUMMARY

The thesis aims to develop a new LCA methodology to evaluate maintenance and rehabilitation treatments, conduct a fuel usage analysis of in-place recycling techniques during the construction stage, and develop a tool to help highway agencies in comparing the environmental impacts of pavement maintenance and rehabilitation treatments. Construction data about IPR projects were collected from contractors and agencies to support the user selection during construction stage and to conduct fuel usage analysis of IPR techniques.

This study develops a LCA tool for pavement IPR that provides pavement industry practitioners, consultants and agencies the opportunity to complement their projects economic and social assessment with the environmental impacts quantification.

FINDINGS

The followings are findings of this study:

- Propane and diesel consumption are sensitive to project-level factors such as pavement hardness, pavement width, air temperature, and horsepower of the equipment used during pavement M&R treatments' construction activities and specifically for in-place recycling techniques.
- Analysis period is shown to be sensitive to the number of maintenance applications applied on the pavement system. The more maintenance activities involved, the longer is the analysis period and thus the higher is the energy consumed during the pavement life cycle.
- End of life stage is found to be sensitive to the allocation method selected. Substitution method resulted in reduced environmental impacts compared to the cut-off method. Also, the higher the recycling rate at the end of life, the less is the energy resulting from the system under analysis.
- In-place recycling techniques are found to be a more optimal alternative to use at the end of life stage compared to the central plant recycling scenario.
- Operating end of life stage activities in a rural road resulted in higher environmental impacts since hauling distances are higher compared to an urban area.

CONCLUSIONS

The followings are the conclusions of this study:

- An equipment inventory model was developed to evaluate the impacts of pavement M&R treatments during the construction stage.
- Regional fuel usage models for in place recycling techniques was developed based on regional factors such as average Moh's Hardness, to predict the fuel efficiency under various project level conditions.

- A decision matrix was built to estimate pavement performance based on multiple criteria (traffic, climate, pavement condition, structural design, and soil capacity). The performance estimation is important since it helps in building a M&R schedule and to quantify use stage impacts.
- A LCA tool, using VBA, was developed and intended for public use to assess the environmental impacts of pavement maintenance and rehabilitation alternatives for highway pavements including IPR techniques. The developed tool utilizes data, simulation, and models through all the LCA stages of the pavement IPR, including materials, construction, maintenance/rehabilitation, use, and end of life.

RECOMMENDATIONS

A future work can combine the environmental assessment with socio-economic impact assessment and pavement design in order to provide agencies with a comprehensive evaluation of pavement projects' alternatives.

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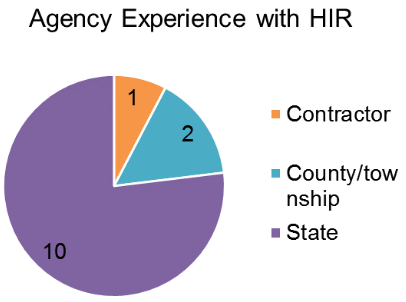
APPENDIX A: AGENCY QUESTIONNAIRE SURVEY SUMMARY



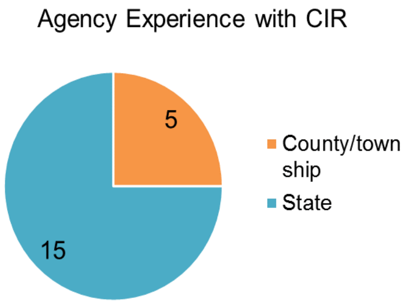
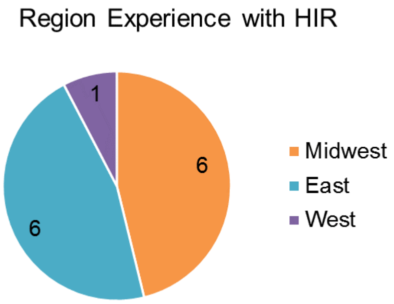


Figure A.1 (left). Agency experience with hot in-place recycling (HIR).

Figure A.2 (right). Agency experience with cold in-place recycling (CIR).



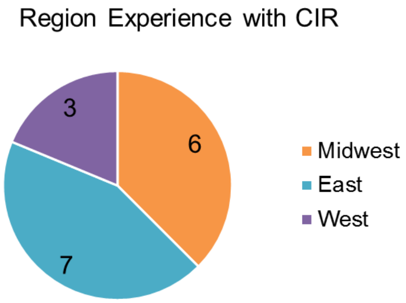
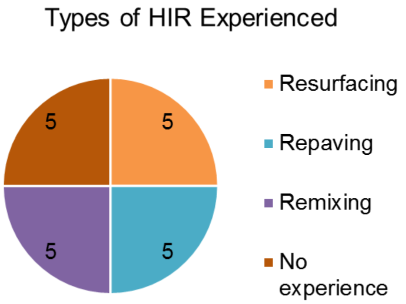


Figure A.3. (left). Agency experience with hot in-place recycling (HIR) by region.

Figure A.4. (right). Agency experience with cold in-place recycling (CIR) by region.



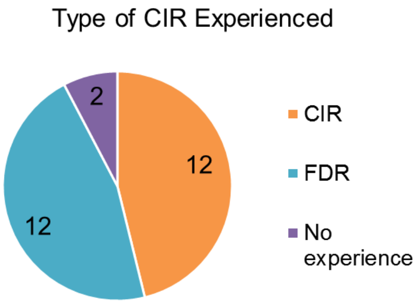
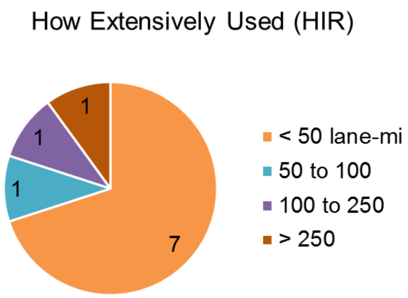


Figure A.5. (left). Types of hot in-place recycling (HIR) that agency experienced.

Figure A.6. (right). Types of cold in-place recycling (CIR) that agency experienced.



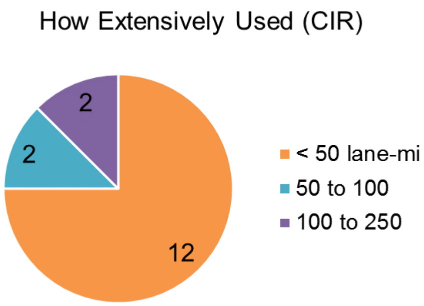
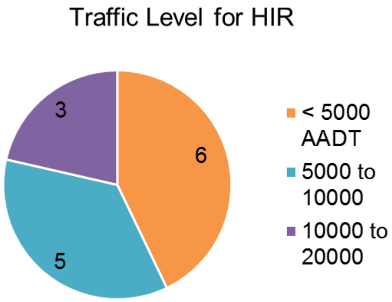


Figure A.7. (left). State of application of hot in-place recycling (HIR) by agency.

Figure A.8. (right). State of application of cold in-place recycling (CIR) by agency.



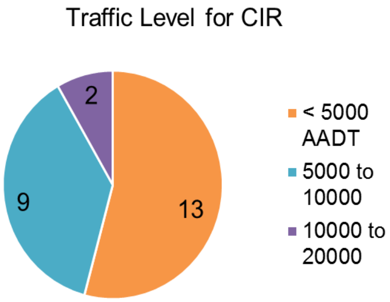
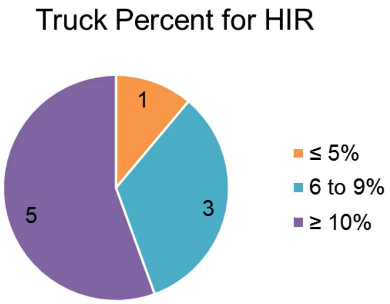


Figure A.9. (left). Traffic levels of pavement in which hot in-place recycling (HIR) is applied.

Figure A.10. (right). Traffic levels of pavement in which cold in-place recycling (CIR) is applied.



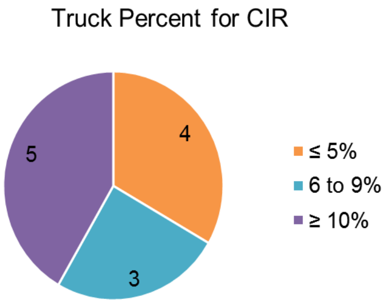
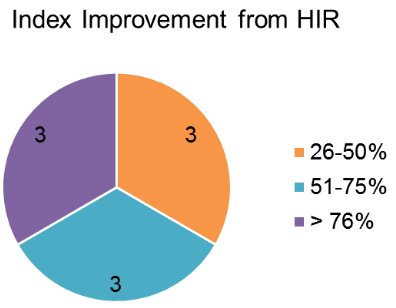


Figure A.11. (left). Truck percent of pavement in which hot in-place recycling (HIR) is applied.

Figure A.12. (right). Truck percent of pavement in which cold in-place recycling (CIR) is applied.



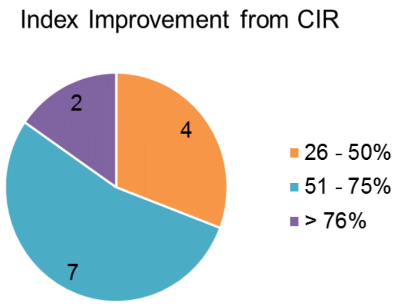
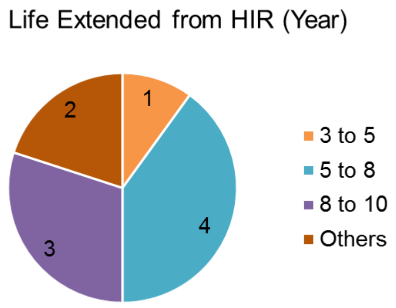


Figure A.13. (left). Improvement of pavement condition index after applying hot in-place recycling (HIR).

Figure A.14. (right). Improvement of pavement condition index after applying cold in-place recycling (CIR).



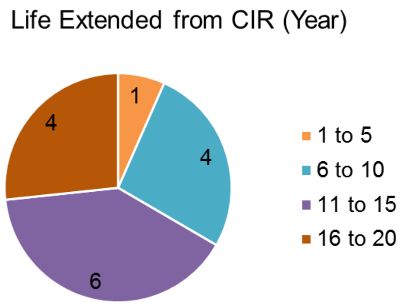
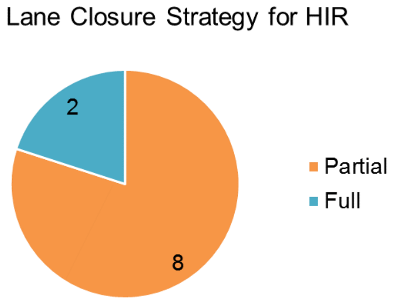


Figure A.15. (left). Pavement life extended from hot in-place recycling (HIR) application.

Figure A.16. (right). Pavement life extended from cold in-place recycling (CIR) application.



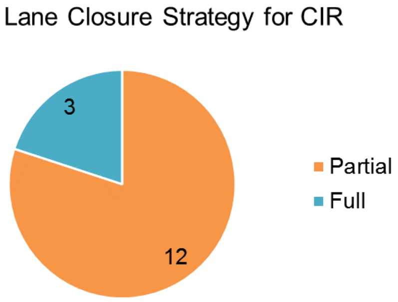
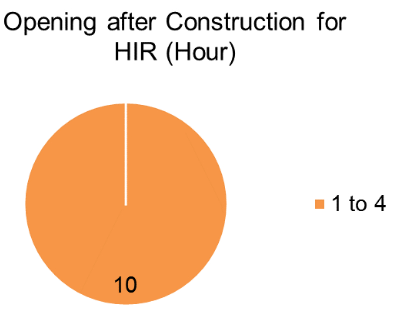


Figure A.17. (left). Type of lane closure strategy used during hot in-place recycling (HIR).

Figure A.18. (right). Type of lane closure strategy used during cold In-place recycling (CIR).



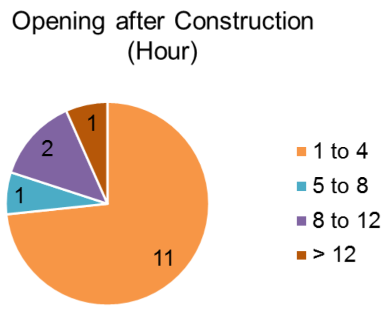
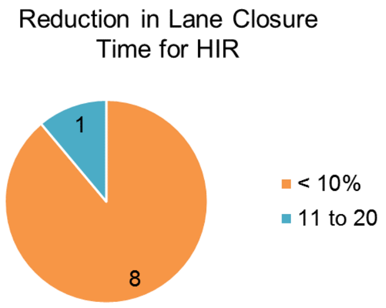


Figure A.19. (left). Opening time (in hour) after hot in-place recycling (HIR) application.

Figure A.20. (right). Opening time (in hour) after cold in-place recycling (CIR) application.



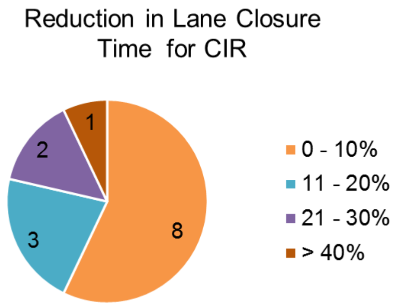
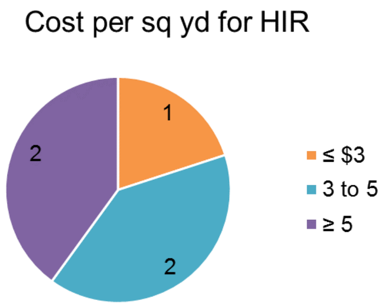


Figure A.21. (left). Reduction in lane closure time for hot in-place recycling (HIR) compared with conventional rehabilitation.

Figure A.22. (right). Reduction in lane closure time for cold in-place recycling (CIR) compared with conventional rehabilitation.



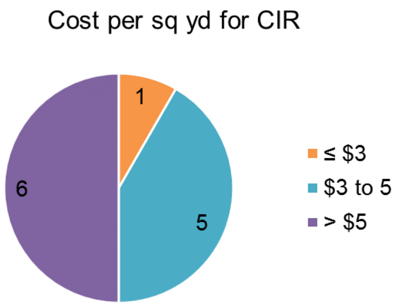


Figure A.23. (left). Cost per yd^2 of hot in-place recycling (HIR) application.

Figure A.24. (right). Cost per yd^2 of cold in-place recycling (CIR) application.

APPENDIX B: MAJOR UNIT PROCESSES MODELED

Table B.1. Type and percent contribution of NERC regions for each state (eGRID, 2015)

State	NERC Region	Contribution (%)	State	NERC Region	Contribution (%)
AK	ASCC	100	NC	SERC	100
AL	SERC	100	ND	MRO	100
AR	SERC	89.6585	NE	MRO	100
AR	SPP	10.3415	NH	NPCC	99.9959
AZ	WECC	100	NJ	NPCC	6.93202
CA	WECC	100	NJ	RFC	93.068
CO	WECC	100	NM	SPP	6.64509
CT	NPCC	100	NM	WECC	93.3549
DC	RFC	100	NV	WECC	100
DE	RFC	100	NY	NPCC	100
FL	FRCC	95.5426	OH	RFC	99.4508
FL	SERC	4.45744	OH	TRE	0.549153
GA	SERC	100	OK	SERC	4.15301
HI	HICC	100	OK	SPP	90.226
IA	MRO	99.1633	OK	TRE	5.621
IA	RFC	0.836656	OR	WECC	100
ID	WECC	100	PA	RFC	100
IL	MRO	0.0255141	RI	NPCC	100
IL	RFC	65.7789	SC	SERC	100
IL	SERC	34.1956	SD	MRO	99.0926
IN	RFC	100	SD	WECC	0.907452
KS	SPP	100	TN	SERC	99.9592
KY	RFC	6.77734	TN	WECC	0.0408408
KY	SERC	93.2227	TX	SERC	5.98278
LA	SERC	78.1378	TX	SPP	10.7096
LA	SPP	21.8622	TX	TRE	82.6485
MA	NPCC	100	TX	WECC	0.659124
MD	RFC	100	UT	WECC	100
ME	NPCC	100	VA	RFC	2.73803
MI	MRO	0.976683	VA	SERC	97.262
MI	RFC	99.0233	VT	NPCC	100
MN	MRO	99.9999	WA	WECC	100
MO	MRO	0.394321	WI	MRO	49.9817
MO	SERC	66.9628	WI	RFC	50.0183
MO	SPP	32.6429	WV	RFC	88.3757
MS	SERC	100	WV	SERC	11.6243
MT	MRO	6.83667	WY	MRO	13.6308
MT	WECC	93.1633	WY	WECC	86.3692

Table B.2. Unit processes adopted from US-EI 2.2 in material stage.

Materials	Unit Processes from US-EI 2.2
Crushed aggregate	Gravel, crushed, at mine/US* US-EI U
Natural aggregate	Gravel, round, at mine/US* US-EI U
Sand	Sand, at mine/US* US-EI U
Asphalt rejuvenator	Paraffin, at plant/US- US-EI U, Benzene, at plant/US- US-EI U
Hydrated lime	Lime, hydrated, loose, at plant/US* US-EI U

Table B.3. Unit processes information of asphalt binder products used in the materials database.

Asphalt Binder Product	Unit Processes
Emulsion	• 65% binder, transported 200 mi by rail • 1.5% hydrochloric acid, transported 200 mi by truck • 0.2% emulsifier (ethylene diamine), transported 200 mi by truck • 33 kWh (65.32 + 53.5 MJ) electricity • 83.1 gal water
GTR binder	• 85% binder, transported 200 mi by rail • 15% GTR, transported 200 mi by train • 15.9 kWh electricity • 6.29E5 KJ heat, light fuel oil, at industrial furnace, US-EI
SBS polymer modified binder	• 96.5% binder, transported 200 mi by rail • 3.5% Styrene butadiene rubber, transported 200 mi by truck • 35.45 ft^3 natural gas, combusted in industrial equipment • 0.0936 gal diesel, combusted in industrial boiler • 0.0021 tn.sh coal, combusted in industrial boiler
Foamed asphalt	• 97.5% binder, transported 200 mi by rail • 2.5% water

APPENDIX C: DECISION MATRIX

Table C.1. Decision matrix (1/4)

Treatment Type	AADT < 5000	AADT 5000-30000	AADT >30000	AADT Unknown	Rural Road	Urban Road	Road Type Unknown	Truck <10%	Truck>10%	Truck Volume Unknown	PCI 86 to 100	PCI 71 to 85	PCI 56 to 70	PCI <56	PCI Unknown	Low Raveling	Medium Raveling	High Raveling	Raveling Unknown
Cape seal	5	5	5	1	5	5	1	5	5	1	5	5	1	1	1	5	5	5	1
Chip seal double course	5	5	1	1	5	5	1	5	5	1	5	5	1	1	1	5	5	5	1
Chip seal single course	0	0	0	1	5	5	1	5	5	1	5	5	1	1	1	5	5	5	1
CIR	5	5	1	1	5	5	1	5	1	1	5	5	5	1	1	5	5	5	1
CIR + cape seal	5	5	1	1	5	5	1	5	1	1	5	5	5	1	1	5	5	5	1
CIR + chip seal	5	5	1	1	5	5	1	5	1	1	5	5	5	1	1	5	5	5	1
CIR + thin overlay (2 in or less)	5	5	1	1	5	5	1	5	1	1	5	5	5	1	1	5	5	5	1
CIR + medium overlay (between 2 and 4 in)	5	5	1	1	5	5	1	5	1	1	5	5	5	1	1	5	5	5	1
CIR + thick overlay (over 4 in)	5	5	1	1	5	5	1	5	1	1	5	5	5	1	1	5	5	5	1
FDR	5	5	5	1	5	5	1	5	5	1	5	5	5	5	1	5	5	5	1
FDR + cape seal	5	5	5	1	5	5	1	5	5	1	5	5	5	5	1	5	5	5	1
FDR + chip seal	5	5	5	1	5	5	1	5	5	1	5	5	5	5	1	5	5	5	1
FDR + thin overlay (2 in or less)	5	5	5	1	5	5	1	5	5	1	5	5	5	5	1	5	5	5	1
FDR + medium overlay (between 2 and 4 in)	5	5	5	1	5	5	1	5	5	1	5	5	5	5	1	5	5	5	1
FDR + thick overlay (over 4 in)	5	5	5	1	5	5	1	5	5	1	5	5	5	5	1	5	5	5	1
Fog seal	5	5	1	1	5	5	1	5	3	1	5	5	1	1	1	5	5	5	1
HIR remixing	5	5	5	1	5	5	1	5	1	1	5	5	5	1	1	5	5	5	1
HIR remixing + thin overlay (2 in or less)	5	5	5	1	5	5	1	5	1	1	5	5	5	1	1	5	5	5	1

Table C.1. Decision matrix (1/4) (cont)

HIR remixing + medium overlay (between 2 and 4	5	5	5	1	5	5	1	5	1	1	5	5	5	1	1	5	5	5	1
HIR remixing + thick overlay (over 4 in)	5	5	5	1	5	5	1	5	1	1	5	5	5	1	1	5	5	5	1
HIR repaving	5	5	5	1	5	5	1	5	1	1	5	5	5	1	1	5	5	5	1
HIR resurfacing	5	5	1	1	5	5	1	5	1	1	5	5	5	1	1	5	5	5	1
HIR resurfacing + thin overlay (2 in or less)	5	5	1	1	5	5	1	5	1	1	5	5	5	1	1	5	5	5	1
HIR resurfacing + medium overlay (between 2 and 4	5	5	1	1	5	5	1	5	1	1	5	5	5	1	1	5	5	5	1
HIR resurfacing + thick overlay (over 4 in)	5	5	1	1	5	5	1	5	1	1	5	5	5	1	1	5	5	5	1
Microsurfacing double course	0	0	0	1	5	5	1	5	5	1	5	5	1	1	1	5	5	5	1
Microsurfacing single course	5	5	5	1	5	5	1	5	5	1	5	5	1	1	1	5	5	5	1
Cold Milling + Thin Overlay (2 in or less)	5	5	5	1	5	5	1	5	5	1	5	5	5	1	1	5	5	5	1
Cold Milling + Medium Overlay (between 2 and 4	5	5	5	1	5	5	1	5	5	1	5	5	5	1	1	5	5	5	1
Cold Milling + Thick Overlay (over 4 in)	5	5	5	1	5	5	1	5	5	1	5	5	5	5	1	5	5	5	1
Sand seal	5	5	1	1	5	3	1	5	3	1	5	5	1	1	1	5	5	5	1
Slurry seal	5	5	5	1	1	5	1	5	3	1	5	5	1	1	1	5	5	5	1
Thin HMA Overlay (2 in or less)	5	5	5	1	5	5	1	5	5	1	5	5	5	1	1	5	5	5	1
Ultra thin bonded wearing course	5	5	5	1	5	5	1	5	5	1	5	5	5	1	1	5	5	5	1

Table C.2. Decision matrix (2/4).

Treatment Type	Low Potholes	Medium Potholes	High Potholes	Potholes Unknown	Bleeding	No Bleeding	Bleeding Unknown	Low Skid Resistance	High Skid Resistance	Skid Resistance Unknown	Shoulder Drop-Off	No Shoulder Drop-Off	Shoulder Drop-off Unknown	Low Rutting	Medium Rutting	High Rutting	Rutting Unknown	Low Corrugations	Medium Corrugations	High Corrugations	Corrugations Unknown	Low Fatigue	Medium Fatigue	High Fatigue	Fatigue Unknown
Cape seal	5	3	3	1	1	5	1	5	5	1	1	5	1	4	3	1	1	3	3	1	1	3	3	1	1

Table C.2. Decision matrix (2/4) (cont)

Chip seal double course	5	3	1	1	1	5	1	5	5	1	1	5	1	4	3	1	1	3	3	1	1	3	3	1	1
Chip seal single course	5	3	1	1	1	5	1	5	5	1	1	5	1	4	1	1	1	4	3	1	1	3	3	1	1
CIR	5	5	5	1	3	5	1	5	5	1	1	5	1	4	5	5	1	4	5	5	1	5	4	4	1
CIR + cape seal	5	5	5	1	3	5	1	5	5	1	1	5	1	4	5	5	1	4	5	5	1	5	4	4	1
CIR + chip seal	5	5	5	1	3	5	1	5	5	1	1	5	1	4	5	5	1	4	5	5	1	5	4	4	1
CIR + thin overlay (2 in or less)	5	5	5	1	3	5	1	5	5	1	1	5	1	4	5	5	1	4	5	5	1	5	4	4	1
CIR + medium overlay (between 2 and 4 in)	5	5	5	1	3	5	1	5	5	1	1	5	1	4	5	5	1	4	5	5	1	5	4	4	1
CIR + thick overlay (over 4 in)	5	5	5	1	3	5	1	5	5	1	1	5	1	4	5	5	1	4	5	5	1	5	4	4	1
FDR	5	5	5	1	5	5	1	5	5	1	1	5	1	5	5	5	1	5	5	5	1	5	5	5	1
FDR + cape seal	5	5	5	1	5	5	1	5	5	1	1	5	1	5	5	5	1	5	5	5	1	5	5	5	1
FDR + chip seal	5	5	5	1	5	5	1	5	5	1	1	5	1	5	5	5	1	5	5	5	1	5	5	5	1
FDR + thin overlay (2 in or less)	5	5	5	1	5	5	1	5	5	1	1	5	1	5	5	5	1	5	5	5	1	5	5	5	1
FDR + medium overlay (between 2 and 4 in)	5	5	5	1	5	5	1	5	5	1	1	5	1	5	5	5	1	5	5	5	1	5	5	5	1
FDR + thick overlay (over 4 in)	5	5	5	1	5	5	1	5	5	1	1	5	1	5	5	5	1	5	5	5	1	5	5	5	1
Fog seal	1	1	1	1	1	5	1	1	5	1	1	5	1	1	1	1	1	1	1	1	1	1	1	1	1
HIR remixing	5	5	3	1	3	5	1	5	5	1	1	5	1	0	0	0	1	4	5	5	1	5	4	4	1
HIR remixing + thin overlay (2 in or less)	5	5	3	1	3	5	1	5	5	1	1	5	1	4	5	5	1	4	5	5	1	5	4	4	1

Table C.2. Decision matrix (2/4) (cont)

HIR remixing + medium overlay (between 2 and 4	5	5	3	1	3	5	1	5	5	1	1	5	1	4	5	5	1	4	5	5	1	5	4	4	1
HIR remixing + thick overlay (over 4 in)	5	5	3	1	3	5	1	5	5	1	1	5	1	4	5	5	1	4	5	5	1	5	4	4	1
HIR repaving	5	5	3	1	3	5	1	5	5	1	1	5	1	4	5	5	1	4	5	5	1	5	4	4	1
HIR resurfacing	5	5	3	1	3	5	1	5	5	1	1	5	1	4	5	5	1	4	4	3	1	4	4	3	1
HIR resurfacing + thin overlay (2 in or less)	5	5	3	1	3	5	1	5	5	1	1	5	1	4	5	5	1	5	4	3	1	4	4	3	1
HIR resurfacing + medium overlay (between 2 and 4	5	5	3	1	3	5	1	5	5	1	1	5	1	4	5	5	1	5	4	3	1	4	4	3	1
HIR resurfacing + thick overlay (over 4 in)	5	5	3	1	3	5	1	5	5	1	1	5	1	4	5	5	1	5	4	3	1	4	4	3	1
Microsurfacing double course	5	3	3	1	1	5	1	5	5	1	1	5	1	5	4	3	1	3	3	1	1	3	3	1	1
Microsurfacing single course	5	3	3	1	1	5	1	5	5	1	1	5	1	4	3	1	1	3	1	1	1	3	3	1	1
Cold Milling + Thin Overlay (2 in or less)	5	5	5	1	3	5	1	5	5	1	1	5	1	4	5	4	1	5	5	5	1	4	4	3	1
Cold Milling + Medium Overlay (between 2 and 4	5	5	5	1	3	5	1	5	5	1	1	5	1	5	5	5	1	5	5	5	1	4	4	4	1
Cold Milling + Thick Overlay (over 4 in)	5	5	5	1	3	5	1	5	5	1	1	5	1	5	5	5	1	5	5	5	1	4	4	4	1
Sand seal	5	3	1	1	0	0	1	5	5	1	1	5	1	1	1	1	1	1	1	1	1	1	1	1	1
Slurry seal	5	3	3	1	1	5	1	5	5	1	1	5	1	3	1	1	1	1	1	1	1	1	1	1	1
Thin HMA Overlay (2 in or less)	5	5	5	1	3	5	1	5	5	1	1	5	1	4	5	4	1	5	4	3	1	5	5	3	1
Ultra thin bonded wearing course	5	1	1	1	1	5	1	5	5	1	1	5	1	4	3	1	1	4	3	1	1	3	3	1	1

Table C.3. Decision matrix (3/4).

Treatment Type	Low Edge Cracking	Medium Edge Cracking	High Edge Cracking	Edge Cracking	Low Slippage	Medium Slippage	High Slippage	Slippage Unknown	Low Block Cracking	Medium Block Cracking	High Block Cracking	Block Cracking Unknown	Low Longitudinal Cracking	Medium Longitudinal Cracking	High Longitudinal Cracking	Longitudinal Cracking Unknown	Low Transverse Cracking	Medium Transverse Cracking	High Transverse Cracking	Transverse Cracking Unknown
Cape seal	3	3	1	1	3	3	1	1	5	3	1	1	3	3	1	1	5	3	1	1
Chip seal double course	4	4	3	1	3	3	1	1	5	4	3	1	4	4	3	1	5	4	3	1
Chip seal single course	5	4	4	1	3	3	1	1	5	4	4	1	5	4	4	1	5	4	4	1
CIR	5	3	1	1	5	4	4	1	5	5	4	1	5	3	1	1	3	3	1	1
CIR + cape seal	5	3	1	1	5	4	4	1	5	5	4	1	5	3	1	1	3	3	1	1
CIR + chip seal	5	3	1	1	5	4	4	1	5	5	4	1	5	3	1	1	3	3	1	1
CIR + thin overlay (2 in or less)	5	3	1	1	5	4	4	1	5	5	4	1	5	3	1	1	3	3	1	1
CIR + medium overlay (between 2 and 4 in)	5	3	1	1	5	4	4	1	5	5	4	1	5	3	1	1	3	3	1	1
CIR + thick overlay (over 4 in)	5	3	1	1	5	4	4	1	5	5	4	1	5	3	1	1	3	3	1	1
FDR	5	5	5	1	5	5	5	1	5	5	5	1	5	5	5	1	5	5	5	1
FDR + cape seal	5	5	5	1	5	5	5	1	5	5	5	1	5	5	5	1	5	5	5	1
FDR + chip seal	5	5	5	1	5	5	5	1	5	5	5	1	5	5	5	1	5	5	5	1
FDR + thin overlay (2 in or less)	5	5	5	1	5	5	5	1	5	5	5	1	5	5	5	1	5	5	5	1
FDR + medium overlay (between 2 and 4 in)	5	5	5	1	5	5	5	1	5	5	5	1	5	5	5	1	5	5	5	1
FDR + thick overlay (over 4 in)	5	5	5	1	5	5	5	1	5	5	5	1	5	5	5	1	5	5	5	1
Fog seal	3	1	1	1	1	1	1	1	3	1	1	1	3	1	1	1	3	1	1	1
HIR remixing	5	3	1	1	5	4	4	1	5	4	4	1	5	3	1	1	3	3	1	1
HIR remixing + thin overlay (2 in or less)	5	3	1	1	5	4	4	1	5	4	4	1	5	3	1	1	3	3	1	1

Table C.3. Decision matrix (3/4) (cont)

HIR remixing + medium overlay (between 2 and 4 in)	5	3	1	1	5	4	4	1	5	4	4	1	5	3	1	1	3	3	1	1
HIR remixing + thick overlay (over 4 in)	5	3	1	1	5	4	4	1	5	4	4	1	5	3	1	1	3	3	1	1
HIR repaving	5	3	1	1	5	4	4	1	5	4	4	1	5	3	1	1	3	3	1	1
HIR resurfacing	5	3	1	1	4	4	3	1	5	4	3	1	5	3	1	1	3	3	1	1
HIR resurfacing + thin overlay (2 in or less)	5	3	1	1	4	4	3	1	5	4	3	1	5	3	1	1	3	3	1	1
HIR resurfacing + medium overlay (between 2 and 4 in)	5	3	1	1	4	4	3	1	5	4	3	1	5	3	1	1	3	3	1	1
HIR resurfacing + thick overlay (over 4 in)	5	3	1	1	4	4	3	1	5	4	3	1	5	3	1	1	3	3	1	1
Microsurfacing double course	5	4	3	1	3	3	1	1	5	3	1	1	5	4	3	1	5	4	3	1
Microsurfacing single course	4	3	1	1	3	3	1	1	5	3	1	1	4	3	1	1	5	3	1	1
Cold Milling + Thin Overlay (2 in or less)	5	3	1	1	4	4	3	1	5	5	4	1	5	3	1	1	5	3	1	1
Cold Milling + Medium Overlay (between 2 and 4 in)	5	4	4	1	4	4	4	1	5	5	4	1	5	4	4	1	5	3	3	1
Cold Milling + Thick Overlay (over 4 in)	5	5	4	1	4	4	4	1	5	5	5	1	5	5	4	1	5	3	3	1
Sand seal	4	1	1	1	1	1	1	1	5	1	1	1	4	1	1	1	5	1	1	1
Slurry seal	3	1	1	1	1	1	1	1	5	3	1	1	3	1	1	1	3	1	1	1
Thin HMA Overlay (2 in or less)	5	3	1	1	5	5	3	1	5	5	4	1	5	3	1	1	5	3	1	1
Ultra thin bonded wearing course	4	4	3	1	3	3	1	1	3	1	1	1	4	4	3	1	3	1	1	1

Table C.4. Decision matrix (4.4)

Treatment Type	Rough Ride Quality	Not Rough Ride Quality	Rough Ride Quality Unknown	Adequate Drainage	Not Adequate Drainage	Drainage Unknown	CBR<3	CBR 3-10	CBR>10	CBR Unknown	Mix Design Performed	Mix Design Not Performed	Mix Design Unknown	Dry-Cold Climate	Wet-Cold Climate Wet-Hot Climate	Wet-Hot Climate	Dry-Hot Climate Climate Unknown	Climate Unknown
Cape seal	3	5	1	5	1	1	1	1	5	1	5	1	1	0	0	0	0	0
Chip seal double course	3	5	1	5	1	1	1	1	5	1	5	1	1	5	5	5	5	1
Chip seal single course	3	5	1	5	1	1	1	1	5	1	5	1	1	5	3	3	3	1
CIR	5	5	1	5	1	1	1	1	5	1	5	1	1	5	3	3	5	1
CIR + cape seal	5	5	1	5	1	1	1	1	5	1	5	1	1	5	3	3	5	1
CIR + chip seal	5	5	1	5	1	1	1	1	5	1	5	1	1	5	3	3	5	1
CIR + thin overlay (2 in or less)	5	5	1	5	1	1	1	1	5	1	5	1	1	5	3	3	5	1
CIR + medium overlay (between 2 and 4 in)	5	5	1	5	1	1	1	1	5	1	5	1	1	5	3	3	5	1
CIR + thick overlay (over 4 in)	5	5	1	5	1	1	1	1	5	1	5	1	1	5	3	3	5	1
FDR	5	5	1	5	1	1	5	5	5	1	5	1	1	5	5	5	5	1
FDR + cape seal	5	5	1	5	1	1	5	5	5	1	5	1	1	5	5	5	5	1
FDR + chip seal	5	5	1	5	1	1	5	5	5	1	5	1	1	5	5	5	5	1
FDR + thin overlay (2 in or less)	5	5	1	5	1	1	5	5	5	1	5	1	1	5	5	5	5	1
FDR + medium overlay (between 2 and 4 in)	5	5	1	5	1	1	5	5	5	1	5	1	1	5	5	5	5	1
FDR + thick overlay (over 4 in)	5	5	1	5	1	1	5	5	5	1	5	1	1	5	5	5	5	1
Fog seal	1	5	1	5	1	1	1	1	5	1	5	1	1	0	0	0	0	1
HIR remixing	5	5	1	5	1	1	1	1	5	1	5	1	1	3	5	5	3	1
HIR remixing + thin overlay (2 in or less)	5	5	1	5	1	1	1	1	5	1	5	1	1	3	5	5	3	1

Table C.4. Decision matrix (4/4) (cont)

HIR remixing + medium overlay (between 2 and 4 in)	5	5	1	5	1	1	1	1	5	1	5	1	1	3	5	5	3	1
HIR remixing + thick overlay (over 4 in)	5	5	1	5	1	1	1	1	5	1	5	1	1	3	5	5	3	1
HIR repaving	5	5	1	5	1	1	1	1	5	1	5	1	1	3	5	5	3	1
HIR resurfacing	5	5	1	5	1	1	1	1	5	1	5	1	1	3	5	5	3	1
HIR resurfacing + thin overlay (2 in or less)	5	5	1	5	1	1	1	1	5	1	5	1	1	3	5	5	3	1
HIR resurfacing + medium overlay (between 2 and 4 in)	5	5	1	5	1	1	1	1	5	1	5	1	1	3	5	5	3	1
HIR resurfacing + thick overlay (over 4 in)	5	5	1	5	1	1	1	1	5	1	5	1	1	3	5	5	3	1
Microsurfacing double course	3	5	1	5	1	1	1	1	5	1	5	1	1	5	5	5	3	1
Microsurfacing single course	3	5	1	5	1	1	1	1	5	1	5	1	1	5	5	5	5	1
Cold Milling + Thin Overlay (2 in or less)	5	5	1	5	1	1	1	1	5	1	5	1	1	5	5	5	5	1
Cold Milling + Medium Overlay (between 2 and 4 in)	5	5	1	5	1	1	1	1	5	1	5	1	1	5	5	5	5	1
Cold Milling + Thick Overlay (over 4 in)	5	5	1	5	1	1	1	1	5	1	5	1	1	5	5	5	5	1
Sand seal	1	5	1	5	1	1	1	1	5	1	5	1	1	0	0	0	0	1
Slurry seal	5	5	1	5	1	1	1	1	5	1	5	1	1	5	5	5	5	1
Thin HMA Overlay (2 in or less)	5	5	1	5	1	1	1	1	5	1	5	1	1	5	5	5	5	1
Ultra thin bonded wearing course	5	5	1	5	1	1	1	1	5	1	5	1	1	5	5	5	3	1

APPENDIX D: HMA QUANTITY CALCULATION

Assuming that all the aggregate types (including RAP) selected in the design are put in a batch, the amount of aggregate type i ($Q_{agg,i}$,) by the total weight of a batch (Q_{Batch}) should verify the equation shown in equations D.1 and D.2.

$$P_{i,Batch}(\%) = \frac{Q_{agg,i}}{Q_{Batch}} \times 100 \tag{D.1}$$

$$\sum P_{i,Batch} = 100 \tag{D.2}$$

When RAP is used, the amount of recycled binder in the batch depends on the amount of recycled binder in aggregate type i ($Q_{recycled\ binder,i}$) as shown in equation D.3; $\delta_{i,Batch}$=0 when aggregate type i is virgin aggregate. Therefore, the recycled binder in the batch is calculated as follows:

$$Binder_{Batch}^{recycled}(\%) = \sum \frac{\delta_{i,Batch}}{100} \times \frac{P_{i,Batch}}{100} \times 100 \tag{D.3}$$

The aggregate content $Q_{agg,\ no\ binder}$ (does not include the weight of recycled binder in the batch) is calculated using the formula shown in equation D.4.

$$Agg_{Batch}(\%) = 100 - \sum \frac{\delta_{i,Batch}}{100} \times \frac{P_{i,Batch}}{100} \times 100 \tag{D.4}$$

Since asphalt content (%) of the AC mix (it includes the virgin binder and recycled binder contained in RAP) is known, the aggregate content in the AC mix is (equation D.5):

$$Agg_{AC}(\%) = \frac{Q_{agg,no\ binder}}{Q_{AC}} \times 100 = \frac{Q_{AC} - Q_{total\ binder}}{Q_{AC}} \times 100 = 100 - Asphalt\ content\ (\%) \tag{D.5}$$

The percent of AC by the weight of batch should be (equation D.6):

$$AC_{Batch}(\%) = \frac{Q_{AC}}{Q_{Batch}} \times 100 = \frac{Agg_{Batch}(\%)}{1 - \frac{Asphalt\ content\ (\%)}{100}} \tag{D.6}$$

And the amount of virgin binder by the weight of AC is calculated as follows (equation D.7):

$$Binder_{AC}^{virgin}(\%) = Asphalt\ content\ (\%) - \frac{Binder_{Batch}^{recycled}(\%)}{AC_{Batch}(\%)} \times 100 \tag{D.7}$$

The amount of aggregate type i by the weight of AC is (equation D.8)

$$Agg_{i,AC}(\%) = \frac{P_{i,Batch}}{AC_{Batch}(\%)} \times 100 \tag{D.8}$$

The bulk specific gravity (G_{sb} (g/cm^2) is used in AC quantity calculation and is expressed as follows (equation D.9):

$$G_{sb} = (1 - \frac{Air\ voids}{100}) \times G_{mm} \tag{D.9}$$