Life-Cycle Assessment Tool Development for Flexible Pavement In-Place Recycling Techniques

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ABSTRACT: The Federal Highway Administration (FHWA) has partnered with research teams at the Illinois Center for Transportation (ICT) at the University of Illinois at Urbana–Champaign (UIUC), the University of California Pavement Research Center (UCPRC), and Rutgers, the State University of New Jersey, in developing a tool to assess the environmental impacts and to predict the performance of preservation and rehabilitation treatments on flexible pavements. This tool can be used on a national scale. The Life Cycle Inventory (LCI) database has been developed to assess the environmental impacts of the materials and construction stages. The performance evaluation was conducted using both deterministic performance models and a qualitative decision matrix to determine the expected treatment life. The importance of this study lies in analyzing the capacity of the tool to help in the preservation and rehabilitation treatments selection, especially in-place recycling treatments, in terms of performance evaluation, and environmental assessment under a range of traffic, climate, structure capacity, and existing pavement conditions.

1 INTRODUCTION

In 2011, the National Cooperative Highway Research Program (NCHRP) Synthesis 421 compiled an extensive summary of the use of in-place recycling (IPR) techniques in the United States (Stroup-Gardiner 2011). An online survey about IPR techniques was conducted and included responses from 45 states to collect information about usage extensiveness, traffic, treatment service life, cost, and work zone conditions (opening time, lane closure time, reduction percent in lane closure). It was found that CIR (cold in-place recycling) is the most used IPR technique.

CIR involves milling and pulverizing the existing asphalt surface, mixing the recycled material with additives (as needed), and laying and compacting the mix into a new pavement layer to replace the existing one. A hot-mix asphalt (HMA) overlay or surface treatment, such as a chip seal or cape seal, is then placed over the recycled pavement layer. The term *CIR* used in this study refers to a partial-depth recycling of only the existing HMA layers, while full depth reclamation (FDR) penetrates to layers beyond the HMA. Typically, CIR is used with milling depths of 50–100 mm and is used to address distresses in pavements that are structurally sound (ARRA 2015). Stabilizing agents used in CIR can be mechanical (e.g. compaction), chemical (e.g. Portland cement, fly ash, calcium chloride, magnesium, lime), or bituminous (e.g. engineered emulsion or foamed asphalt) (ARRA 2015). The expected service life for CIR is estimated at 6–10 years with a surface treatment and 7–20 years with an HMA overlay (ARRA 2015).

Energy consumption and limited environmental impact characterization of in-place recycling technique were done to compare these techniques to conventional alternatives and validate environmental benefits as claimed. Schvallinger (2011) compared various types of CIR practices to conventional paving methods, finding savings up to 69% in energy when compared to HMA overlay and 76% in energy when compared to mill-and-fill methods (Schvallinger 2011). Finally, Santos et al. (2014) used LCA to compare IPR, traditional reconstruction, and corrective maintenance strategies by considering the entire life cycle, including material production, construction, work zone effects, and the pavement use (Santos et al. 2014). The IPR-based strategies resulted in a reduction of 1.5% in energy, as compared to traditional reconstruction and 30% in energy as compared to a corrective maintenance strategy. It should also be noted that studies concerning GHG and other emissions related to CIR have also been conducted (Liu et al. 2014; Alkins et al. 2008). None of these studies followed a life-cycle framework.

The focus of this paper is to present the methodology used in developing a life-cycle assessment (LCA) tool to evaluate the energy consumption of in-place recycling techniques commonly used in the preservation program of flexible pavements and applying it in a case study. The tool analyzes techniques that local and state roadway agencies have been using as part of their preservation and rehabilitation programs, especially in-place recycling techniques, which include both hot-in-place recycling (HIR) and CIR. The research approach followed is based on the concepts of LCA and pavement life-cycle framework initiated by FHWA (FHWA 2016) that adheres to guidelines by the International Standards Organization (ISO) 14040:2006 standards for “Environmental management–Life-cycle assessment–Principles and framework” and the ISO14044:2006 standards for “Environmental Management–Life-Cycle Assessment–Requirements and Guidelines.”

2 METHODOLOGY

The guidelines recommend four steps when conducting a LCA: (1) goal and scope definition, (2) inventory analysis, (3) impact assessment, and (4) interpretation. The first three steps are discussed below, while the fourth step is presented in the “Case Study” section.

2.1 *Goal and Scope*

The goal of paper is to examine the upstream and downstream energy consumed by an IPR technique and the corresponding performance during the analysis period, using the LCA decision-making tool. This information is of interest to federal, state, and local transportation agencies that consider the environmental impacts of using IPR techniques in their pavement management strategies. The product system evaluated are IPR methods used in the United States. The functional unit is one lane-km of a flexible pavement upon application of a preservation treatment designed and expected to perform to satisfy average standards in the United States. A typical mainline lane of 3.65 m was assumed in the study, and only construction and materials related to the layers above the subgrade for the mainline pavement were included. Shoulders and supporting drainage, lighting, signage, and landscaping elements were not included and were assumed to be equivalent among alternatives.

Material production and hauling and construction stages of the pavement life cycle were considered, while the use phase, future maintenance or rehabilitation, and end-of-life stages were excluded. Thus, comparisons made between the alternatives assumed equal performance of the systems. Upstream materials and resources were considered for the major processes involved, including raw materials production, fuel production, and electricity generation.

As IPR techniques rely largely on recycled materials, a methodological choice for allocating recycled materials must be made. In this study, a cut-off allocation procedure was chosen for recycled asphalt pavement materials. Thus, only the processes related to the preparation of the previous pavement system were attributed to the recycled materials (i.e. scarifying, milling, crushing, and mixing of in-situ pavement); and processes related to the production of the original pavement were cut off.

2.2 *Life Cycle Inventory (LCI)*

In this LCA, a data-collection strategy has been developed using both primary and secondary data sources to build a comprehensive LCI database for the IPR preservation treatments, including material production, material hauling, and construction stages. The procedures described in the

FHWA's pavement LCA framework were followed to develop the inventory database. The primary data collected included mainly process activity data associated with the construction of IPR treatments, equipment train, use of fuel, or other energy sources, and productivity that can be used to estimate total energy consumption and environmental impacts for specific on-site conditions. To complement the primary data, the secondary data were collected using various sources, including commercial LCI databases (e.g. Ecoinvent, US-Ecoinvent (Earthshift 2013)), software (e.g., EPA MOVES 2014 (US EPA 2015), eGRID (US EPA 2013)), governmental reports, material safety data sheets, and manufacturers' specifications.

2.2.1 *Primary data*

For data-collection purposes, customary U.S. units were used for all LCI data per unit area (i.e., in square yards) or unit lane-miles. Survey data collected from relevant local contractors in each region were compared with values reported in the literature for validation. As an example, process activity data from the CIR and FDR operations (fuel consumption, productivity, etc) were collected to estimate energy consumption. If collected data were outside the expected range, follow-up questions were asked to clarify the source of the discrepancy. After the survey data were benchmarked, the data were averaged where possible to achieve a representative value for each relevant region and to preserve the confidentiality of individual contractors.

2.2.2 *Secondary data*

Secondary data sources were used in this study. Upstream data for raw materials, resources, and transportation inputs were collected from various datasets (such as the commercial LCI database, the literature, and simulations) using publicly available software. Regional LCI data corresponding to the U.S. East and Midwest were obtained and modeled. Whenever regional data were not available, national LCI data representing the whole United States were used. Major unit processes that can be modeled to represent specific U.S. regions are listed below:

- Asphalt-binder production
- Diesel-fuel production
- Electricity generation
- Hauling trucks
- Construction equipment
- Vehicle operations (for use phase)

2.3 *Impact Assessment*

The energy-use assessment in the case study was cumulative of all the energy consumed during material production, material hauling, and construction. Impact categorization was done using the EPA's TRACI method (Bare 2012).

2.4 *Interpretation*

The results of energy analysis and performance assessment are presented according to the life-cycle stages and major processes included in the scope. To allow for a comparative assessment, the results are presented for all alternatives. Interpretation of the final results are presented in the "Case Study" section.

2.5 *Performance Estimation*

A two-pronged approach to evaluate the performance of preservation and rehabilitation treatments was developed and implemented in the comparative assessment tool. The two approaches were the deterministic performance models and the multi-criteria performance estimation.

The two approaches were used for calculating specific parameters to evaluate the pavement performance under certain project conditions. These parameters were the treatment life (i.e., the number of years until the next major treatment for the same pavement segment) and IRI (international roughness index) progression. The deterministic performance models approach predicts the wheelpath and fatigue cracking and time to estimate treatment lifetime under specific climate condition, traffic volume, and overlay thickness. The deterministic models were also developed to estimate IRI progression as a function of pavement variables.

As for the multi-criteria performance estimation, it calculates a performance score that varies from 1 to 5 and determines the performance of all rehabilitation and preservation treatments under various conditions (i.e., traffic, climate, existing pavement conditions, soil properties, and material characteristics). Furthermore, this approach estimates the treatment life and, with a specified IRI threshold, indirectly provides the IRI progression rate to describe how fast the pavement deteriorates.

2.5.1 *Deterministic performance models*

These models are obtained at a network or project level and may be used to predict the international roughness index (IRI) progression and cracking distresses performance over the entire life of the pavement. The output from these models is a function of continuous and/or categorical variables. This approach can be used to predict the performance of IPR pavements. Distress criteria considered to estimate treatment life include the load-associated wheelpath cracking, fatigue cracking, and IRI.

2.5.2 *Multi-criteria performance estimation*

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 and 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 categories: climate, traffic, existing pavement condition, soil properties, and pavement material properties. The process of integrating these into the performance estimation process is as follows:

1. Collect site-specific conditions under each criterion for a given treatment candidate from the user (e.g. traffic: annual average daily traffic (AADT) or/ and equivalent single axle load (ESAL), % truck, road type; overall condition index representing existing pavement condition, distress severity and composition; soil properties; etc.)

2. Score the impact of each site-specific condition under each major category (or subcategory) by a 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, an HIR resurfacing treatment followed by a thin overlay of 50 mm or less is compared to a conventional treatment such as mill and overlay. 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 there is a high risk for the selected design, and it expected to perform poorly.

3. Evaluate the score for each criterion and determine the final rating score for the application.

4. Based on the rating score, calculate the 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 (1). It is assumed that all the factors are independent:

$$PS = \frac{\sum_{i=1}^{N_C} C_i + \sum_{i=1}^{N_T} T_i + \sum_{i=1}^{N_S} S_i + \sum_{i=1}^{N_E} E_i + \sum_{i=1}^{N_M} M_i}{N_C + N_T + N_S + N_B + N_M} \quad (1)$$

Where:

T_i : Rating for factor *i* related to each traffic

C_i: Rating for each climate condition *i*

S_i : Rating for each soil property *i*

E_i : Rating for factor *i* each existing pavement condition *i*

M_i: Rating for factor *i* related to material properties condition

N_C: Number of factors related to climate condition

N_T: Number of factors related to traffic

N_S: Number of factors related to soil properties

N_E: Number of factors related to existing conditions

N_M: Number of factors related to material properties

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

- PS is 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 part of the range.
- PS is 2 or 3: Conditions are fair, carrying medium risk for the performance of treatment. Treatment life can be expected to be in the medium area of the range of expectations.
- PS is 1: On-site conditions are not appropriate for the treatment, with very high risk. Treatment life may be predicted at the lower end of the range of expected values.

3 FRAMEWORK OF THE TOOL

Both of the aforementioned approaches are implemented in the tool currently being developed. Once the project input parameters are entered, the user is provided with a list of treatment alternatives. The user has the option to select one or more in-place recycling treatments and compare them to one or more conventional methods. 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, in-place recycling train), the user is warned. The selected treatments are evaluated by calculating treatment lifetime and developing IRI progression curves. Figure 1 presents a flowchart of the suggested tool, to illustrate the performance-estimation process integration to the overall flow of data and input flow.

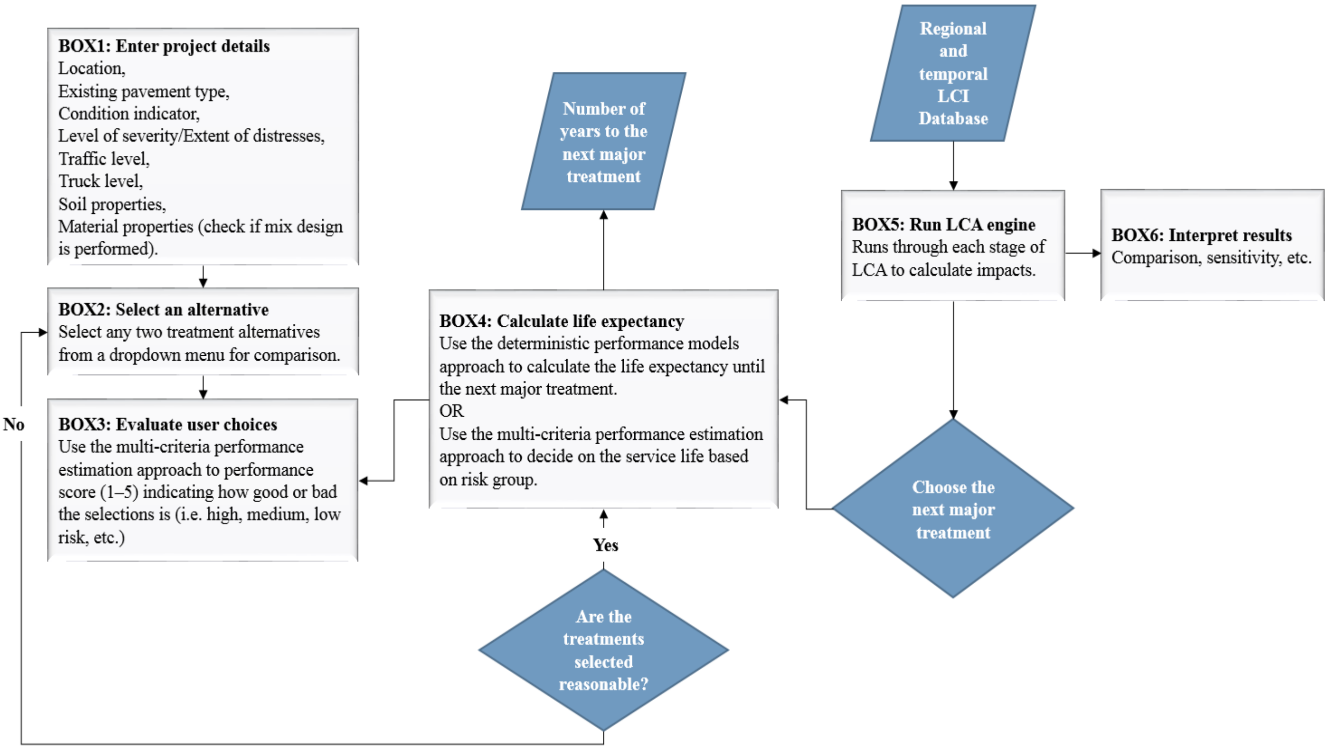

Figure 1. Flowchart of the comparative tool, illustrating the integration of the two performance-estimation approaches.

4 CASE STUDY

The following case study was employed to make a comparative energy and performance assessment between the use of CIR and conventional mill-and-fill.

4.1 *Structural Designs*

Two treatments were considered in the case study, namely, CIR with overlay (CIR/OL) and mill-and-fill. The existing structure consists of 100 mm of HMA, 200 mm of crushed aggregate base coarse layer, and 100 mm of crushed granular material on top of a subgrade soil having a California Bearing Ratio (CBR) value of 6%. The design was conducted based on chapter 46 of the Illinois Department of Transportation Bureau of Local Roads and Streets (IDOT BLRS) manual for pavement rehabilitation (IDOT 2012). 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.

In this study, the pavement design was carried out for a low-volume road with a traffic factor of 0.65, which is equivalent to an average daily traffic of 2,041 vehicles/day, with 7.5% single-unit trucks and 2.5% multiple-unit trucks. For the CIR with an asphalt concrete (AC) overlay design alternative, the existing 100 mm of HMA is recycled. The SN_R and SN_F were calculated to be 2.24 and 3.25, respectively, requiring an additional AC overlay thickness of 60 mm on top of the recycled asphalt. For the mill-and-fill design alternative, by contrast, the top 50 mm of HMA is milled, which resulted in calculated values of 1.84 and 3.25 for SN_R and SN_F, respectively, and an additional overlay thickness of 100 mm.

4.2 *Materials*

The design involved the use of 1% cement, 2.5% emulsion, and water for the cold in-place recycled-pavement surface course, and hot-mix asphalt (HMA) for the overlay applied on the CIR and conventional paving methods. HMA was used for the conventional method overlay layer. The material inventory database described in the methodology section was used to calculate the energy use of the material production phase. Materials-hauling conditions were assumed to be 26°C for the air temperature, 60% for the relative humidity, and 0% grade (flat).

4.3 *Construction*

The CIR and conventional method treatments considered in the design used the same aforementioned single-pass equipment train and paving equipment set described in the construction-phase analysis. The number of teeth used in the CIR milling operation was estimated to be 15 per 100,000 kg. To evaluate the effect of pavement hardness on total energy savings, a harder pavement is considered by looking at the impact of using 30 teeth instead of 15 teeth per 100,000 kg. Pavement width was also varied from 3.65 to 4 m to assess its impact on energy savings using the aforementioned regression model. As for the chip seal, the aggregate spreader, binder distributor, roller and sweeper constitute the treatment construction checklist (FHWA 2013). The mill-and-fill operation consisted of milling part of or all of the existing HMA layer, replacing it with HMA laid down using a paver and compacted with a roller. The construction-equipment inventory was used to calculate the energy use during the construction practices of the two pavement designs.

5 RESULTS AND DISCUSSION

5.1 *Environmental Impact Assessment*

The environmental impact results for CIR and its equivalent conventional paving alternative with various hauling distances (i.e., 30 and 160 km) in this study are shown in Figure 2, separated by activity type, as well as material production (including mixing and raw material transportation), equipment operation, and materials hauling to site.

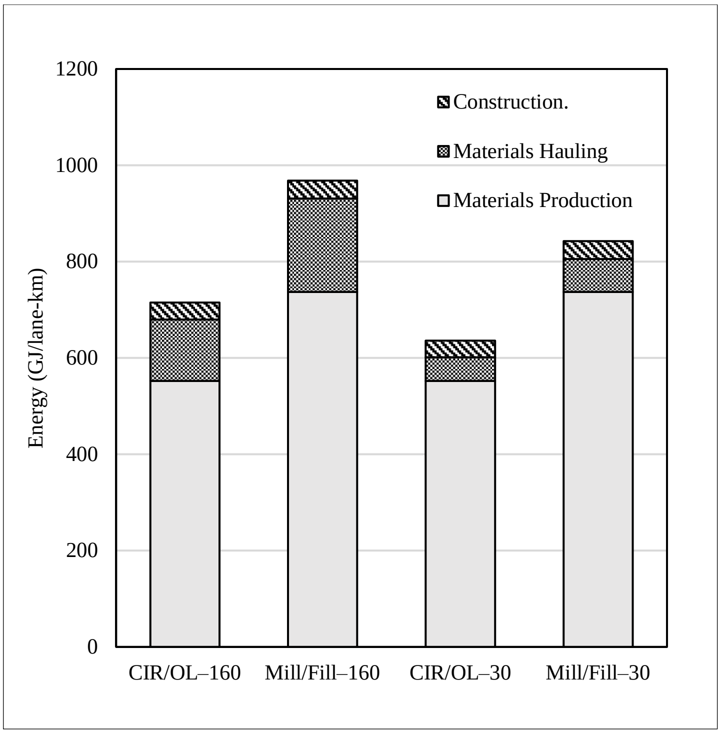

Figure 2. Energy from CIR versus conventional paving by hauling distances.

The results of the energy assessment of the case study (Figure 2) show that energy consumption associated with material production is 889 GJ for CIR/OL and 1186 GJ for mill-and-fill. CIR and mill-and-fill consume approximately the same amount of energy during the construction stage, with an average of 58 GJ, which makes the construction-stage contribution to the total energy savings very low, up to 0.95%. The construction stage for the two treatments are very similar because a similar set of equipment is used, with only a few exceptions. For the hauling stage, as the HMA hauling distance increases, the hauling energy increases from 56 GJ to 206 GJ for CIR/OL, and from 110 GJ to 312 GJ for mill-and-fill. Overall, the energy consumed during CIR/OL life stages showed a savings of 24% when the hauling distance is 30 km and a savings of 26% when the hauling distance is 160 km. The materials production stage contributes the most to energy consumption with 77%–87% to CIR/OL processes, while it contributes 76%–87% to mill-and-fill processes.

5.2 *Performance assessment and sustainability interpretation*

The decision-making process relies on the whole life-cycle environmental assessment, cost analysis, and future-performance prediction. As for the environmental assessment, while the previous analysis may favor using CIR over conventional paving processes, a life-cycle approach requires that future performance, use, and end-of-life of the pavement be considered. As a full LCA is out of scope, a scenario analysis based on expected treatment life was used. The expected treatment life of a thin, dense-graded asphalt concrete overlay is typically 7–15 years, while that of CIR with asphalt concrete overlay is 7–20 years (ARRA 2015). Annualizing energy consumption over a range of expected treatment lives for both processes produces the relationships presented in Figure 3. It is important to note that the excess fuel consumption due to roughness and texture is not considered at this stage. However, the same concept of equivalency analysis will still be utilized with part of the use stage impact categories.

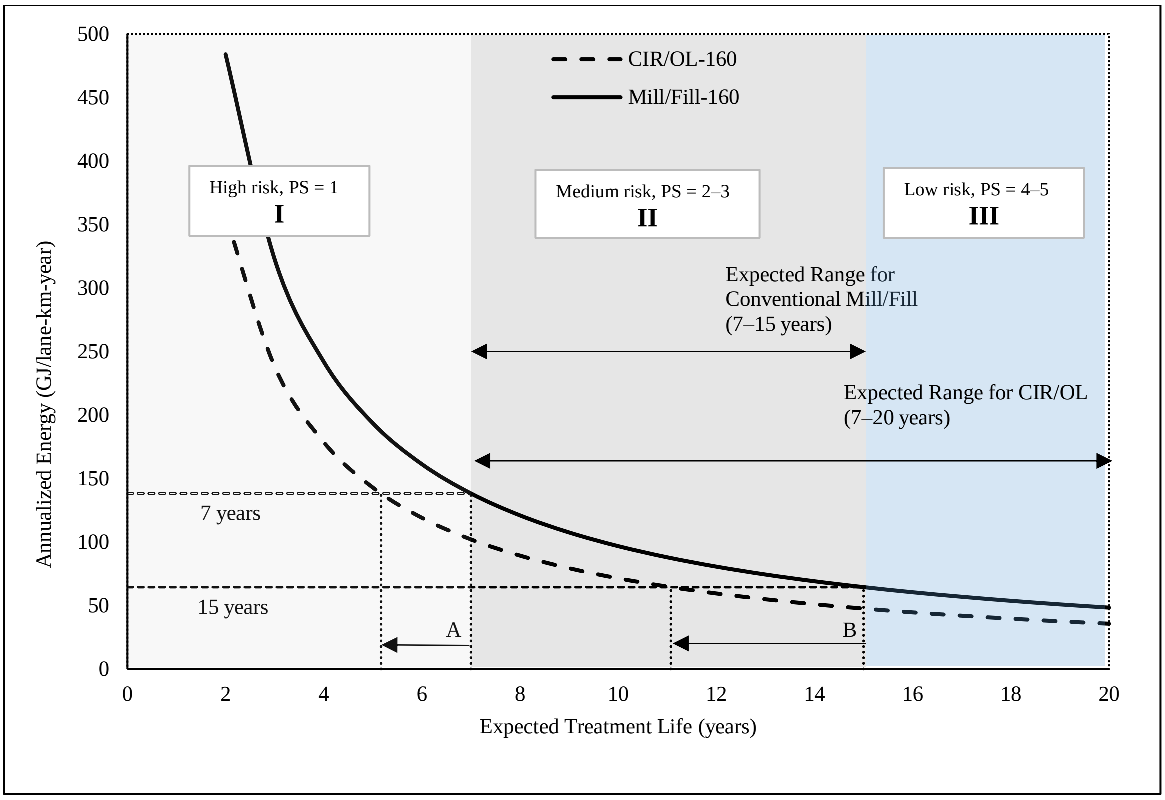

Figure 3. Scenario analysis for different expected treatment lives for each process using annualized energy.

In Figure 3, the energy is annualized by expected treatment life for the 160 km hauling case. Arrow A shows that CIR/OL–160 can have a reduced treatment life as low as 5.8 years and still have the same annualized energy consumption as a poor-performing Mill/Fill-160 with a life of 7 years. By contrast, Arrow B shows that an CIR/OL–160 would need a minimum treatment life of 12.4 years to match a well-performing Mill/Fill-160 of 15 years for the same annualized energy consumption; the CIR/OL would need to perform beyond what is typically expected, indicating that it may be more effective to use Mill/Fill when the pavement is expected to perform very well. The areas I, II, and III represent the risk in performance level zones, based on the multi-criteria performance estimation approach. The annualized energy decreases with the decrease of risk on performance level. The risk level depends on the project conditions where the treatment is applied. CIR is effective when applied in a local, low-traffic road having a good soil support (Caltrans 2008).

6 CONCLUSIONS

This study presents the functions of a new LCA tool being developed for FHWA. A case study was investigated using the tool, to perform a comparative study of two equivalent in-place recycling and conventional methods to demonstrate the capacity of the tool to perform LCA.

Deterministic performance models are viewed as the best approach to predict pavement performance. However, such models may not always exist, especially for the types of treatments this study focuses on. Therefore, an alternative multi-criteria performance estimation approach is proposed, to be implemented when such deterministic models are not available. The approach can be applied to a potential treatment by collecting on-site conditions consistent with the design variables.

This tool allows to systematically develop a broad baseline assessment of the preservation and rehabilitation treatments. Contractors and state and local agencies will be able to utilize this baseline to conduct their own environmental assessments.

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