Accounting for Rehabilitation Activity Uncertainty in a Pavement Life Cycle Assessment using Probability and Decision Tree Analysis

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Abstract

In any life cycle assessment (LCA) for pavements, the designer must decide on which rehabilitation activities will be used to maintain the pavement over the analysis period. While this sounds simple, the fact is that there are many different rehabilitation scenarios that could be performed when the pavement requires rehabilitation, and which one is used will impact the LCA results. This creates inherent uncertainty and variability in the LCA results solely due to the selection of the rehabilitation scenario used in the analysis.

Currently, most LCA's apply a single standard rehabilitation scenario to all pavements. The problem with this approach is that because each project is unique, the activities may or may not be representative of the actual set of activities done on that particular pavement. The only way to get meaningful indication of a project's pavement environmental impact is to look at the impact of all (or at least most) of the potential rehabilitation activities that could be used to maintain the pavement over the analysis period.

This paper shows how State Highway Agencies (SHAs) can use probability and decision tree analysis to evaluate many rehabilitation scenarios in order to determine a range of LCA results, as well as a probability adjusted, expected value LCA result. This process quantifies the underlying uncertainty that different the rehabilitation selection can have on the LCA results so that a more informed decision can be made when comparing the alternate pavement designs. A case study based on alternative designs and rehabilitation scenarios used by a SHA demonstrates the decision tree analysis process and shows how the risk profiles for the two alternatives considered are not equivalent. For this case, this results in the probability-adjusted LCA results being different than the single standard rehabilitation scenario results.

Introduction

Life cycle assessment (LCA) quantifies the environmental impacts, energy consumption, material use, etc. throughout the life-time of a pavement. It does this by evaluating the material and energy flows for a product from cradle to grave, including raw material extraction, material processing, manufacturing, distribution, use, repair and maintenance, and disposal or recycling. While the mechanics of performing an LCA for a pavement are not terribly difficult, it is extremely data intensive. For this reason, it is essential that a standardized, but comprehensive, pavement LCA framework, such as the one shown in Figure 1 (Santero, Loijos, Akbarian, & Ochsendorf, 2011; Santero, Masanet, & Horvath, 2011), be used to ensure accuracy and consistency of the LCA results. This framework ensures that short term gains do not come at the expense of long-term deficits. Furthermore, while LCAs can be used to evaluate the environmental impact of a single product (e.g., a pavement) in order to determine how to lower impact of that particular product, the fact is that pavement LCAs will be used as a comparison tool between different pavement designs much in the same way that life cycle cost analysis (LCCA) is used to compare costs. Eventually, it is anticipated that LCA will be combined with LCCA to be used in the pavement type selection process to determine which pavement type will be constructed on a particular project.

For the LCA comparisons to be meaningful and reliable, the LCA should reflect the most likely activities for each alternative over the analysis period. As shown in Figure 1, the "Maintenance" of the pavement system is a primary input and it can play a significant role in the LCA results, especially for lower volume applications where the use impacts, such as pavement-vehicle interaction, are not as substantial. While pavement LCAs are not done routinely by state highway agencies (SHAs), most have defined LCCA procedures with maintenance and rehabilitation schedules and it is anticipated that the LCAs will adopt those same maintenance and rehabilitation schedules.

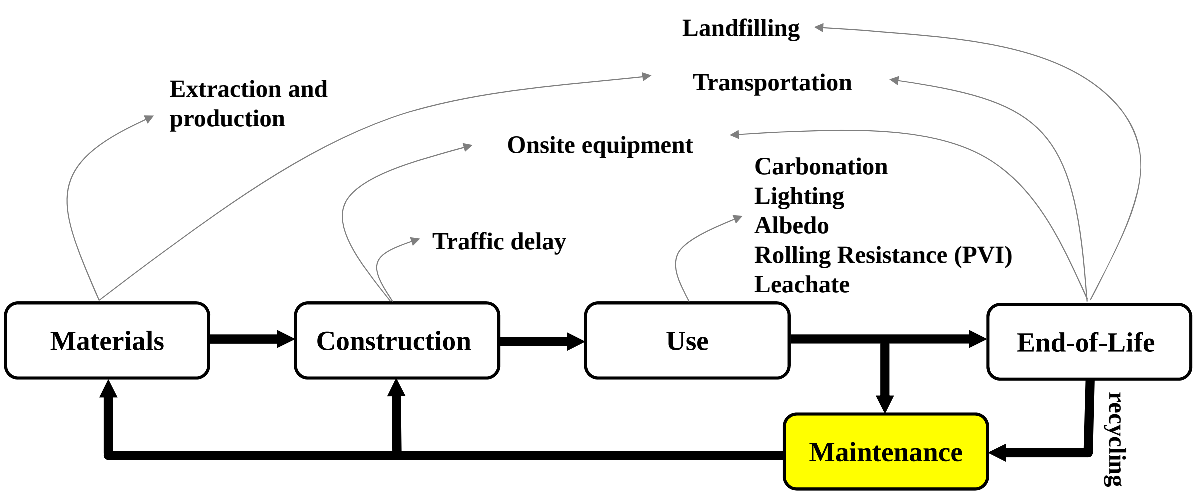


Figure 1. Standardized system boundaries (including life-cycle phases and components) for pavement LCA

In setting up the maintenance and rehabilitation schedules, most agencies apply a single, standard, policy set rehabilitation scenario to all pavements based on historical performance. The primary drawback with this is that it assumes that the historical performance used in the analysis will be representative of the performance of the specific design being evaluated. This is probably not true. Historical data is often based on old pavement designs, designs with different features, or is from non-like roadways (e.g. using high volume road data for low volume road applications).

As an example of how historical data can be misleading, below is a summary of Georgia Department of Transportation (DOT) study that looked at the historical concrete pavement performance in their state. (Tsai, Wu, & Wang, 2012). Over the last 50 years, GDOT has had 4 basic concrete pavement designs. The first era of pavements, built in the 1960's, consisted of non-doweled Jointed Plain Concrete Pavements (JPCP) with joint spacings of 20 feet (6.0 m) or greater on soil / soil cement stabilized subgrades. The average time to first rehabilitation for these pavements was 17 years, though the actual time varied from as little as 10 years to as high as 29 years. The next era consisted of non-doweled JPCP's with joint spacings of 20 feet (6.0 m) or greater on graded aggregate bases (GAB). The average age at first rehabilitation for these pavements was 21 years, and ranged from 14 years to 29 years. In the mid 1970's, GDOT started using dowels and reduced the joint spacing down to 20 feet (6.0 m). These pavements were used until the 1990. At the time of the study, the average age of these pavements was 29 years, but none had received a major rehabilitation. The last era of pavements, which are still being used today, consists of doweled JPCP with 15-foot (4.5 m) joint spacing, 13 foot (3.9 m) widened lanes on a 3" (75 mm) HMA base over GAB (note these pavements were not reviewed in the study because the oldest pavements are only 22 years old, and there was limited distress on which to make a conclusions).

As such, while using policy-set rehabilitation schedules is easy and simplifies the LCCA/LCA calculation, the set of activities used in the analysis are most likely not what

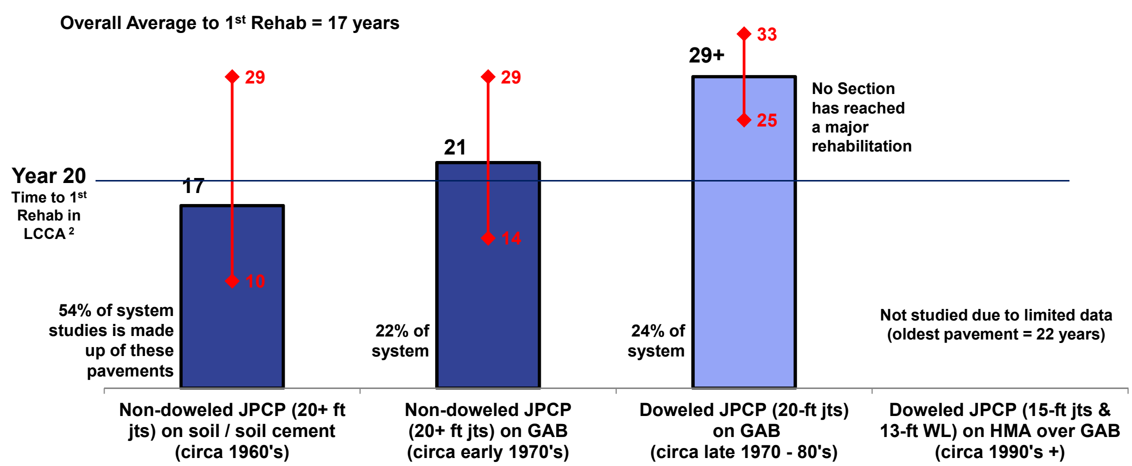


Figure 2. Average time (years) to first major rehabilitation of concrete pavement in Georgia.

will be done, which means the results will not be representative for the pavements being compared. That is, unless the pavements behave exactly as anticipated, and are rehabilitated using the exact same activities, the LCA results will not represent the environmental impact of the pavements. Furthermore, as there is often considerable disagreement over which activities should or will be used, there is a lack of confidence in the results due to disagreements about the correctness of the rehabilitation activities. Therefore, in order to increase the level of confidence in a comparative LCA, the LCA process should use risk analysis to account for inherent variation and uncertainty of the rehabilitation activities in order to give the decision-maker greater confidence on the full range of potential results.

Using Decision Tree Analysis to Account for Which Activities May Occur

While a few SHA LCCA guidelines (and therefore presumably LCA guidelines) recognize that pavements can be rehabilitated using several different activities, most, if not all, SHA guidelines provide a single, or standard, set of activities that is used in the calculations. There may be different set of standards for different classification of roadways (e.g., urban interstates vs rural farm to market roadways), but a single standard is used. The fact is that for any pavement design, there are many different rehabilitation scenarios that could be performed when the pavement requires rehabilitation and what activities are selected will have a large impact on the results.

Decision tree analysis (DTA), also known as Decision Theory, is a numerical analysis procedure that accounts for all, or most, of the possible alternatives and results of a future course of action that requires various other decisions. DTA is commonly used in operations research, decision analysis and other research areas to help identify the optimal strategy for an investment, or to reach a goal. It has recently been applied to pavement engineering as a way to look at all the alternatives in the rehabilitation range of activities, from minor repairs to extreme interventions (Pour & Jeong, 2012) (Pour & Jeong, 2013). This allows the analyst to determine the possible consequences of different actions and take into account the inherent uncertainty in rehabilitation selection.

As an example, rehabilitation activities for concrete pavements typically consist of either concrete pavement preservation (CPP) or an asphalt overlay. However, for each of these, there are a number of other options that will impact what the final rehabilitation scenario activity is. Some of these include:

- How much patching will be done on a CPP project? Is it 1%, 5%, 10%?
- How thick will the AC overlay be? Is it 2-inches or 6-inches? Will there be pre-overlay repairs? If so how much?
- What are my options for second rehabilitation activities? Will CPP be applied again or will an overlay be used? How much patching will be done or how thick will the AC overlay be?

Depending on how each of these decisions is made in developing the rehabilitation strategy, the LCA results can change significantly.

The Ohio DOT Rehabilitation Strategy

The Ohio Department of Transportation (ODOT) is one of the state DOTs that recognizes that both concrete and asphalt can be rehabilitated with many different activities (ODOT, 1999). For concrete pavements, ODOT gives the following list of activities as potential first and second of rehabilitation options for use in their LCCAs:

- First rehabilitation (Year 18 – 25): 2% - 10% full-depth rigid repairs, 1% - 5% partial depth bonded repairs, diamond grinding, 75 - 150 mm (3" - 6") asphalt overlay, sawing and sealing.
- Second rehabilitation (Year 28 – 32): 1% - 3% full- and/or partial-depth repairs, 32 - 50 mm (1.25" - 2") second asphalt overlay with or without milling, 75 - 100 mm (3" - 4") first asphalt overlay, sawing and sealing, micro-surfacing, crack sealing, diamond grinding.

For asphalt pavements, the list of activities that can be done are:

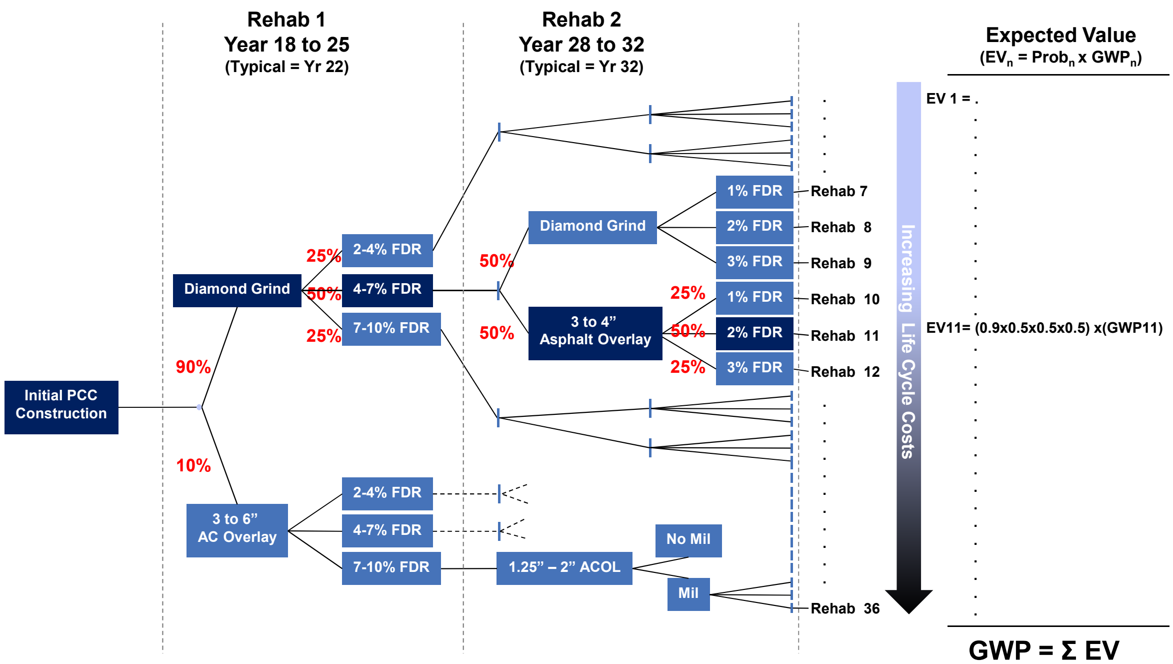
- First rehabilitation: Year 10 - 15: thin asphalt overlay, 32 - 75 mm (1.25" - 3"), with or without milling.
- Second rehabilitation: Year 18 - 25: thick asphalt overlay, 75 - 175 mm (3" - 7"), with milling, possibly pavement repairs.
- Third rehabilitation: Year 28 - 32: thin asphalt overlay or micro-surfacing or crack sealing.

As one might imagine, the specific activities selected for both the concrete and asphalt alternatives will impact the LCCA / LCA results and which pavement will be selected in the pavement type selection process. Furthermore, the selection of activities will influence the *risk profile* differences between the two alternates. That is, if one pavement's rehabilitation activities and timing are selected very conservatively and the other uses very liberal rehabilitation activities and timing, the two pavements will not have similar risk profiles and this will affect the results. This will be demonstrated later in this paper.

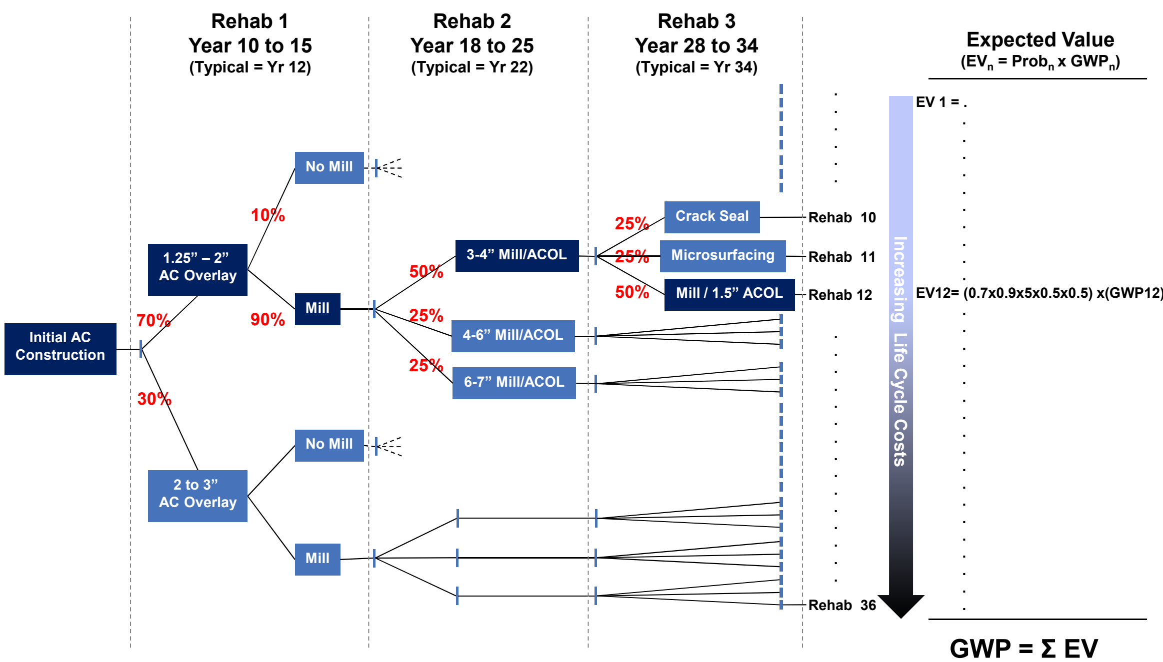
Developing a Decision Tree

Decision trees are flowchart-like structures that show relationships among many courses of action and realizations of the future. Typically, a decision tree is made up of two kinds of nodes: decision nodes – where an option is to be selected and chance nodes – where various future realizations along with some probability of occurrence are represented. The combination of decision and chance represents the outcome of the decision. As additional decisions about subsequent activities are made, the branches expand until the end of the analysis period is reached. By systematically working through all potential options for each rehabilitation cycle (i.e., each branch is expanded), all feasible rehabilitation activity paths can be mapped out.

Figure 3(a) shows a graphical representation of a potential decision tree for ODOT's concrete pavement rehabilitation strategies (note: in the interest of brevity, clarity and space limitations, the tree has been compacted by combining the decision and chance nodes to illustrate the concept). At the first node a decision has to be made on what type of rehabilitation will be used – CPP or asphalt overlay. If CPP is chosen (top node), a second decision has to be made on how much full depth repair (FDR) will be done (i.e., 2 to 4%, 4 to 7%, or 7 to 10%). If an asphalt overlay is chosen (bottom node), again a second decision needs to be made on how much full depth patching should be done. Once these decisions are made, the analysis is through the first rehabilitation cycle.



a) Concrete pavement activities



b) Asphalt pavement activities

Figure 3. Decision tree of ODOT's pavement rehabilitation activities.

At the second rehabilitation, a decision again has to be made on what type of activity will be used – CPP or asphalt overlay – and the process repeats itself until the end of the analysis period is reached and all scenarios are defined. For this example, there are 36 different sets of rehabilitation scenarios (branches) that could be applied to the pavement over its life, with the lowest life cycle impact options being at the top and the highest option at the bottom.

Figure 3(b) is a graphical representation of a potential decision tree for ODOT's asphalt pavement rehabilitation strategies. In both Figure 3(a) and (b), the dark blue boxes represent ODOT's standard set of rehabilitation activities used in most of their LCCAs. It is important to note that at each node, there are different degrees of detail that can go into each decision. For example, for the concrete option, the first decision was simply a choice between two options: CPP or asphalt overlay. This was done to keep the example simple. However, the asphalt overlay thickness can be anywhere from 75 - 150 mm (3 - 6 inches), and which thickness is used will impact the LCA results. A more thorough analysis could have broken the first decision down into 3 choices: CPP, 75 - 100 mm (3 - 4 inches) asphalt overlay, or 125 - 150 mm (5 - 6 inches) asphalt overlay.

Once the decision tree is complete, the analyst assigns a probability to each node that shows likelihood that the specific activity will occur at that node. For example, ODOT's LCCA manual states: "*Best practice dictates the use of diamond grinding for the first treatment. Placing an asphalt overlay on a concrete pavement brings on a new set of problems and is discouraged as the first predicted maintenance action*." Since the likelihood of doing a diamond grinding as the first rehabilitation is high, it was assigned a chance or probability of 90% in this analysis, while the asphalt overlay was assigned a probability of 10%. At the second node (amount of FDR to be done), ODOT's standard process of using 4-7% FDR was given a probability of 50% and the other two options were given a 25% chance each. This process is continued until all branches have their probability defined.

The reason that probabilities are assigned to each branch is so that the expected value (EV) for each branch (potential rehabilitation scenario) can be calculated. That is, current practice is to define one set of activities to use in an LCA and calculate the environmental impacts (e.g., global warming potential (GWP), ozone depletion potential, photochemical ozone creation potential, etc.) based on that set of activities. However, when using DTA, the GWP for each branch is calculated, and the expected GWP value for that branch is calculated by multiplying the GWP for that set of activities by the probability of those activities being done (eqn. 1). Once the expected values for all branches are calculated, the final EV_{GWP} of the concrete or asphalt alternative is the summation of the Expected Values (eqn 2).

$$EV_i = (\sum Prob_i \ x \ GWP_i) \quad (1)$$

$$EV_{GWP} = \sum EV_i \quad (2)$$

where:

EV_i = global warming potential expected value for rehabilitation activity set *i*

$Prob_i$ = probability that a given rehabilitation activity along rehabilitation activity set *i (*i.e., branch *i*) is done

GWP_i = global warming potential of rehabilitation activity set *i*

EV_{GWP} = Overall global warming potential expected value for either the concrete or asphalt alternative

One of the issues with DTA is determining the probabilities to use at each node, which admittedly can be subjective. Currently, the authors see three ways, either used separately or in combination, to develop the probabilities. The first is to use engineering judgment based on experience. The second is to use pavement performance models, such as the AASHTO Pavement-ME Design Program, to define pavement condition and then apply probabilities based on the projected condition of the pavement. The final process, and the procedure adopted by Pour and Jeong (2012), is to use historical patterns based on review of actual activities used by the agency. While each process has its pros and cons, the key point to understand is that by defining many different rehabilitation possibilities, a range of LCA results is determined that covers the extreme, as well as more likely scenarios. The item that changes, based on the probabilities chosen at each node, is where the expected value GWP (EV_{GWP}) falls within the range of all potential GWP values. This information is helpful in determining the relative risk profile of each alternative, which will be further explained in the example below.

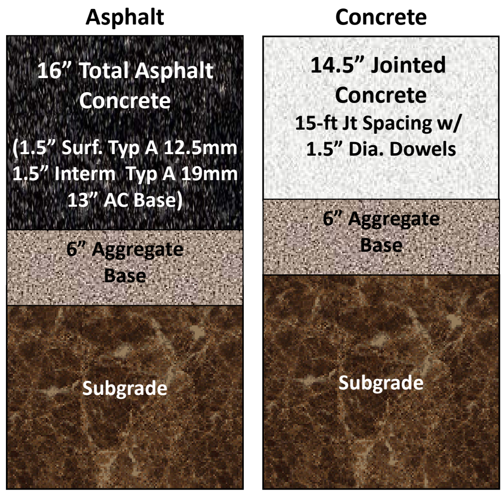
Interpreting the Results of a Decision Tree Analysis

As discussed, the primary advantage of using a DTA is that instead of getting a single LCA value for GWP, the result is a range of potential GWP values as well as a probability adjusted, EV_{GWP}. This additional information provides several insights, which will be demonstrated using a case study. Figure 4 shows actual pavement designs used in an LCCA for a project in Ohio (ODOT, 2007) and which serves as the designs for this case study. Note that ODOT does not do comparative LCAs for pavements, but since they have alternate rehabilitation activities for LCCAs, they are being used only as a demonstration to show how selection of pavement rehabilitation strategies can impact the results of a LCA and how using a DTA can be used to address the shortcomings of using a single pavement rehabilitation strategy in the LCA.

The two pavement designs being compared are a 400-mm (16-inch) asphalt pavement over a 150-mm (6-inch) aggregate base and a 363-mm (14.5-inch) concrete pavement, with 4.5-m (15-foot) joint spacing also over a 150-mm (6-inch) aggregate base. The initial pavement designs, design lives and the standard rehabilitation schedules (the dark blue boxes in Figure 3) are from ODOT's Pavement Design and Rehabilitation Manual (ODOT, 1999). For this analysis, the functional unit is defined as one mile of pavement from the top of the surface to the subgrade soil, extending from the outside shoulder to the outside edge of the opposite shoulder. The pavement design is 20 years and the analysis period is 50 years. Table 1 provides the information on the LCA data sources and assumptions under which the LCA was conducted.

The elements included in the LCA are materials extraction and production; construction; transportation of materials; and rehabilitation. The use phase and end-of-life components are excluded to simplify the analysis so that impact that differing rehabilitation scenarios can have on the results can be highlighted. A more comprehensive LCA would include elements such as pavement-vehicle interaction, carbonation, albedo, and lighting. Global warming potential, denoted by the units of carbon dioxide equivalents (CO2e), is used as the metric for environmental impact.

The results in Figure 4 show that, for these particular designs and the standard ODOT rehabilitation schedule, the concrete section has a higher initial GWP and life cycle GWP. This is mainly the result of the thick concrete pavement section and the amount of CO2e produced in the cement production. However, it is important to note that the rehabilitation activities make up 22.5% and 15.1 % of the total LCA GWP for the asphalt and concrete sections, respectively. However, as shown in Figure 3, there are at



Rehabs
AC-1 Mill & 1.5" ACOL
AC-2 Mill & 3.25" ACOL & 1% Patch
AC-3 Mill & 1.5" ACOL

Rehabs
PCC-1 4% FDR & DG
PCC-2 2% FDR & 3.25" ACOL

LCA Results

	GWP (tons CO2e/mile)	
	Asphalt	**Concrete**
Initial Construction	**3,708**	**4,640**
% above low	0.0%	25.1%
Pavement materials	*575*	*3,135*
Agg. base materials	*191*	*159*
Construction energy	*1,852*	*27*
Materials transportation	*1,090*	*1,319*
Rehabilitation 1	250	201
Rehabilitation 2	573	622
Rehabilitation 3	250	-
TOTAL	**4,782**	**5,462**
% above low	0.0%	14.2%
Total Rehab CO2e	**1,074**	**822**
Percent of Total	22.5%	15.1%

ACOL = Asphalt Overlay, DG = Diamond Grinding, FDR = Full Depth Repair

Ohio DOT
HAM-75-10.10 (PID 76256) Pavement Type Selection (March 2007)

Figure 4 – LCA results using ODOT's standard rehabitlation schedule. Results for "materials" categories include upstream impacts of materials extraction and production. Rehabilitation results include both impacts of materials and construction.

least 36 different rehabilitation scenarios that could be used on the asphalt and concrete pavements respectively and which scenario is used will impact the results.

Figure 5 shows the range of all possible LCA results based on the rehabilitation scenarios in Figure 3. The columns show the results using the standard ODOT LCCA rehabilitation schedule as developed in Figure 4. The darker blue (bottom) portion is the GWP due to the initial construction and the lighter blue (top) portion is the GWP due to rehabilitation. The data in red is the results from the DTA analysis. The red lines represent the range of potential GWP results from the 36 rehabilitation scenarios and the red diamond is the EV_{GWP}. It is evident that there is a large increase for the asphalt EV_{GWP} and a slight decrease of the concrete EV_{GWP}. The reason for the differences between the standard and DTA LCA results is that the implied risk profiles used in the ODOT standard LCCA/LCA analysis are not the same for the two pavement designs.

That is, the standard rehabilitation scenario LCA results (blue columns) for the asphalt design is on the low end of the range of all potential EV_{GWP} results (red lines), while the concrete design standard rehabilitation LCA result is slightly higher than the middle of the range of EV_{GWP} results. This indicates that there is a high upside risk that the GWP for the asphalt design will be higher than predicted by the standard rehabilitation scenario. By comparison, the GWP of the concrete standard rehabilitation scenario is in the middle of the range of EV_{GWP} results and has about an equal exposure for upside and downside risk. The key take-away is that the concrete and asphalt GWP results using these standard rehabilitation scenarios do not fall within same area of their respective bands (i.e. bottom, middle or top) and thus, there is a difference in the risk profiles of the assumed LCA results that should be acknowledged by decision-makers when comparing LCA results.

Table 1. LCA Data Sources and Assumptions

Lifecycle Phase	Quantity Data Source	Impact Data Source	Key Assumptions
Materials			
Steel reinforcement	Ohio DOT (2007)	Worldsteel (2011)	70% recycled content; 70% recycled at EOL
Concrete			Mix design from Ohio DOT
Cement Materials	PCA Environmental Surveys (Nisbet & Marceau, 2001) (Nisbet M. , Marceau, VanGeem, & Gajda, 2001)	USLCI (2009) / Ecoinvent (Weidema, et al., 2013)	
Cement	Ohio DOT (2007)	USLCI (2009) / Ecoinvent (Weidema, et al., 2013)	
Water		Ecoinvent (Weidema, et al., 2013)	
Aggregate			
Concrete Mixing	Zapata & Gambatese (2005)	Ecoinvent (Weidema, et al., 2013)	Diesel
Asphalt Concrete			
Bitumen	Ohio DOT (2007)	Ecoinvent (Weidema, et al., 2013)	Bitumen, at refinery/RER
Aggregate			
Stabil. Subgrade /Soil	Ohio DOT (2007)	n/a	
Aggregate / Agg Bas	Ohio DOT (2007)	Ecoinvent (Weidema, et al., 2013)	
Construction			
Concrete Paving	Chappat & Bilal (2003) /IVL	Ecoinvent (Weidema, et al., 2013)	Diesel
Asphalt Paving			
Placement-other layers			
Maintenance			
Onsite activities: diamond grinding, joint sawing, milling, overlay placement	International Grooving & Grinding Assn (IGGA) (2014)	Ecoinvent (Weidema, et al., 2013)	Diesel
Traffic Delay			
Fuel loss	Santero (2009)	n/a	
User cost	RealCost (CALTRANS, 2007)	n/a	
Work Zone Speed		n/a	
Gas	(calculated using above inputs)	Ecoinvent (Weidema, et al., 2013) divided by amount of fuel used	Gas: 0.728 kg/L (6.073 lb/gal) (Operation, passenger car, petrol, fleet average 2010/RER U)
Diesel			Diesel: 0.832 kg/L (6.943 lb/gal) (Operation, lorry >16t, fleet average/RER U)
Landfilling		Ecoinvent (Weidema, et al., 2013)	Half of all recovered waste is landfilled
Crushing/recycling conc.	Stripple (2000)		Energy required to crush aggregate
Excavation	Stripple (2000)		

Table 1. LCA Data Sources and Assumptions (cont.)

Transportation			**Impact Data Source**	**Key Assumptions**
Concrete (km)	Truck (40.2 km)	U.S. 2007 Commodity Flow Survey (BTS, 2007)	Ecoinvent Database (Weidema, et al., 2013)	Concrete truck (tank)
Steel (km)	Truck (684 km)	Articles of Base Metal (BTS, 2007)		
	Rail (1624 km)			
Cement (km)	Truck (201 km)	PCA Environmental Surveys (Nisbet & Marceau, 2001) (Nisbet M. , Marceau, VanGeem, & Gajda, 2001)		
	Rail (430 km)			
	Water (644 km)			
Aggregates	Truck (88.5 km)	Gravel and crushed stone (BTS, 2007)		
	Rail (684 km)			
	Water (620 km)			
Bitumen	Truck (158 km)	Coal and petroleum products (BTS, 2007)		
	Rail (1893 km)			
	Water (1207 km)			
Waste	Truck (50 km)	Assumption		

In contrast, the decision tree analysis adjusts the EV_{GWP} based on the probabilities assigned to the different activities at each decision node to create a probability-adjusted GWP. For this case, the probability adjustment raises the asphalt expected GWP closer

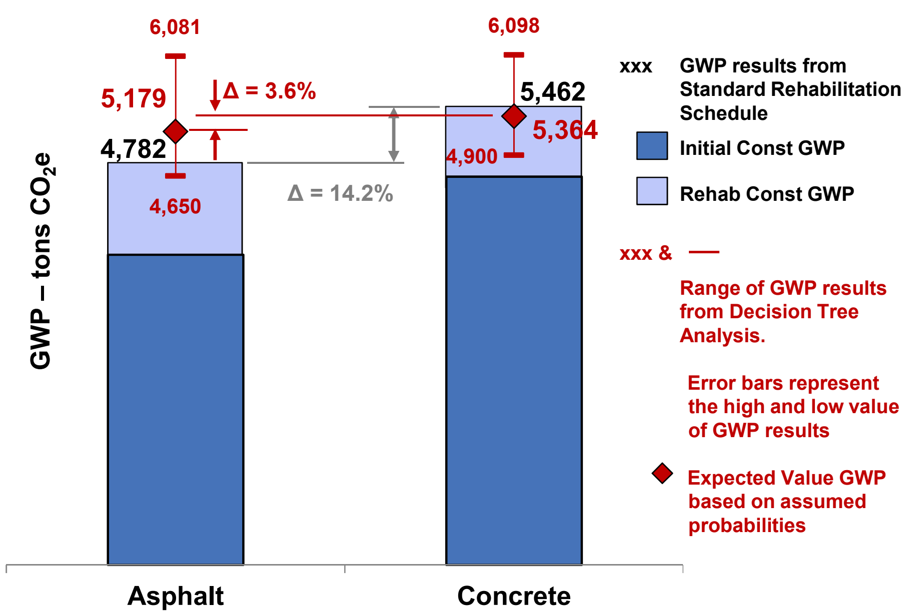


Figure 5. LCA results from both the standard rehabilitation schedule and the decsion tree analysis.

to the middle of the range so that the risk profiles reflect the range of likely GWP based on the potential rehabilitation activities. As discussed earlier the location of the EV_{GWP} within the range of all potential EV_{GWP} values is based on the probabilities chosen at each node, which as discussed earlier is somewhat subjective. However, the EV_{GWP} will always fall within the range of potential GWP's, thus giving an indication of the uncertainty of the results. That is, the first node on the asphalt decision tree (overlay thickness) had a 70%/30% split. If the split were increased to 90%/10% the EV_{GWP} for the asphalt would drop, and if the split were decreased to a 50/50% it would rise. However the result would always lie somewhere on the red line.

Summary

Life cycle assessment is a methodology that can be used to compare the environmental impacts of alternative pavement designs to determine which has the lowest impact over the analysis period. A primary input in the LCA is the rehabilitation activities that will be used to maintain the pavement over the analysis period. Currently, most LCAs use a single, standard, policy-set rehabilitation scenario based on expected or historical performance. The drawback with this approach is that it assumes that the rehabilitation scenario used in the analysis will be representative of the rehabilitation activities used on the pavement. This is unlikely to be true. The fact is that there are many different rehabilitation scenarios that could be performed when the pavement requires rehabilitation, and which one is used will impact the LCA results, createing inherent uncertainty and variability.

This paper described how probability and decision tree analysis can be used to evaluate many different rehabilitation scenarios to determine a range of LCA results as well as a probability adjusted (i.e., expected value) LCA result. By adopting and using the methodology laid out in this paper, transportation agencies can address the underlying uncertainty that can lead to a lack of trust in the LCA results that sometimes occurs due to disagreements about the representativeness of the rehabilitation schedules.

This process also takes into account the associated risk profile of each alterative in the analysis and facilitates discussion in comparative LCAs about the impact on uncertainty in future rehabilitation schedules. The end result is a more meaningful, reliable and robust life cycle assessment.

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