PAVEMENT LCA 2014

INTERNATIONAL SYMPOSIUM ON
Pavement Life Cycle Assessment

October 14-16, 2014

Davis, California, USA

Editors: John Harvey and Agnès Jullien

Co Editor: David Jones

Papers from the International Symposium on Pavement Life Cycle Assessment 2014, Davis, CA, USA
14 to 16 October, 2014

Papers from the International Symposium on Pavement Life Cycle Assessment 2014

Editors

John Harvey

University of California Pavement Research Center, UC Davis, USA

Agnès Jullien

LUNAM Université, IFSTTAR, France

Co-editor

David Jones

University of California Pavement Research Center, UC Davis, USA

Reference: Papers from the International Symposium on Pavement Life Cycle Assessment 2014 – Harvey, Jullien and Jones (Eds).
ISBN 978-0-692-29357-7.

Published by: University of California, Davis Repro Graphics
3820 Chiles Road, Davis, CA, 95618
reprographics@ucdavis.edu

Table of Contents

Part 4: Pavement Life Cycle Assessment Tools

Preface

Life Cycle Assessment (LCA) is a systems approach developed to provide decision support for questions regarding the environmental impact of industrial processes and products. The application of LCA to pavement management, design and construction helps to avoid the paradox of decisions that improve one aspect of sustainability of a pavement system, while unintentionally causing greater harm elsewhere. LCA is a field with ongoing developments and improvements. As applied to pavement, interest in the application of LCA to pavement is relatively new, except for some early pioneering works. Research, development, and implementation of LCA to pavement are increasing rapidly. These include moves towards more widespread standardization of practice, better alignment with international norms in other fields, resolution of gaps in data and technical approaches, and greater understanding of LCA on the part of pavement researchers, practitioners and decision-makers, including both its power to assist decision-making and its pitfalls. However, as a field, the application of LCA to pavement is still only just leaving its childhood.

The International Symposium on Pavement LCA 2014 was held on October 14-16, 2014 in Davis, California. The symposium website with information regarding all activities over the three days is www.ucprc.ucdavis.edu/LCA2014/. This symposium is the third in a series that began with a Pavement Life Cycle Assessment Workshop held in Davis, California in May, 2010 (www.ucprc.ucdavis.edu/p-lca/), and was followed by the International Symposium on Life Cycle Assessment and Construction, Civil Engineering and Buildings held in Nantes, France in July, 2012 (lca-construction2012.ifsttar.fr/).

The intent of each of these symposia has been to bring together practitioners, researchers and users with experience in pavements and/or LCA from academia, government and industry in an environment of open and honest discussion. The goals are to discuss current issues, resolve them where possible and identify differences requiring further work, and overall to improve the science and practice of LCA as applied to pavement. A further goal is to expand communication of the results of pavement LCA to policy-makers outside the world of pavement.

The organization of this third symposium included invited presentations on current topics in pavement LCA, including:

- Towards the big picture – the path from one-dimensional footprints to complete environmental sustainability assessments
- Urban metabolism
- Application of pavement LCA in Northern Europe
- Current status and future of Product Category Rules/Environmental Product Declaration) in US
- Approaches for developing regional Life Cycle Inventory datasets
- Integration of LCA into traditional/existing pavement management systems and decision-making
- Integration of LCA into new design method, and consideration of pavement vehicle interaction, freight damage and logistics

- Pavement vehicle interaction and fuel consumption, initial results of Caltrans model comparison project (panel discussion)
- End-of-life allocation issues as LCA methodology
- Policy, implication and application: unintended consequences
- Environmental policy for transportation infrastructure, how should industry, academia and government be communicating?
- Use of LCA in different infrastructure delivery methods: Legislation and polices
- Implementation of LCA by different organizations (panel discussion)
    - Government perspectives
    - Industry perspectives

The invited sessions were followed by breakout sessions in which symposium participants discussed issues and questions posed by the invited presentations, the results of which were then summarized to produce a document identifying areas of consensus and areas requiring further work.

The papers included in this volume cover a wide range of subjects regarding pavement LCA, and were reviewed by experts in both pavements and LCA. Each of these papers was also presented at poster sessions to further stimulate discussion among symposium attendees.

We would like to sincerely thank all of the authors for sharing their work. We would also like to thank the Pavement LCA 2014 scientific and organizing committees for their work, including the members of the Transportation Research Board Sustainable Pavements Subcommittee, AFD00(1); the Federal Highway Administration Sustainable Pavements Technical Working Group (SP TWG); the organizers of the RILEM/IFSTTAR/CSTB sponsored second symposium in Nantes; the International Society for Concrete Pavements; the International Society for Asphalt Pavements; the California Department of Transportation; the National Center for Sustainable Transportation at UC Davis; and the Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux (IFSTTAR).

John Harvey and Agnès Jullien, Editors
David Jones, co-Editor

Davis, California, 2014

Conference Organization

Chairpersons

John Harvey	University of California, Davis, Pavement Research Center
Agnès Jullien	Nantes - IFSTTAR, Environment, Planning, Safety and Eco-design Laboratory

Symposium Committee

Imad Al-Qadi	University of Illinois, Center for Transportation
Gerardo Flintsch	Virginia Tech, Civil & Environmental Engineering
Arpad Horvath	University of California, Berkeley, Civil & Environmental Engineering
Alissa Kendall	University of California, Davis, Civil & Environmental Engineering
Joep Meijer	The Rightenvironment, Inc.
Tony Parry	University of Nottingham, Engineering
Wynand Steyn	University of Pretoria, Civil Engineering

On-Site Organizing Committee

David Jones	University of California, Davis, Pavement Research Center
Hui Li	University of California, Davis, Pavement Research Center
Ting Wang	University of California, Davis, Pavement Research Center
Laura Melendy	University of California, Berkeley, ITS Technology Transfer Program
Samer Madanat	University of California, Berkeley, Institute of Transportation Studies
Joe Holland	California Department of Transportation (Caltrans)
Deepak Maskey	California Department of Transportation (Caltrans)
Nicholas Santero	PE International, Inc.
Tom Van Dam	Nichols Consulting Engineers

Scientific Review Committee

Gina Ahlstrom, USA
Enrico Benetto, Luxembourg
Neeraj Buch, USA
Heather Dylla, USA
Jon Epps, USA
Adélaïde Feraille, France
John Harvey, USA
Joe Holland, USA
Arpad Horvath, USA
David Jones, USA
Agnès Jullien, France
Amnon Katz, Israel
Alissa Kendall, USA
Harn Wei Kua, Singapore
Nina Stirmer, Croatia
Gabriele Tebaldi, Italy
Tom Van Dam, USA
Anne Ventura, France
Hui Li, USA
James Mack, USA
Samer Madanat, USA
Caroline Mauduit, France
Joep Meijer, USA/Netherlands
Hasan Ozer, USA
Tony Parry, UK
Manfred Partl, Switzerland
Cheryl Richter, USA
Arash Saboori, USA
Nicholas Santero, USA
Mark Snyder, USA
Mike Southern, UK
Wynand Steyn, South Africa
Ting Wang, USA
Leif Wathne, USA
Matthew Wayman, UK
James Willis, USA

Part 1: Development of practice for pavement life cycle assessment

DEVELOPING ROBUST REHABILITATION SCENARIO PROFILES FOR LIFE CYCLE ASSESSMENT USING DECISION TREE ANALYSIS

James W. Mack[1]*, Xin Xu[2], Jeremy Gregory[2], and Randolph E Kirchain[2]

[1] CEMEX, 929 Gessner Road, Suite 1900, Houston, TX 77024
[2] Dept. of Civil and Environmental Engineering, Engineering Systems Division, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139-4307

* Corresponding author: jamesw.mack@cemex.com

ABSTRACT

A primary input into any life cycle assessment (LCA) for pavements is the set of rehabilitation activities that are used to maintain the system over the analysis period. For the LCA to be meaningful and reliable, the analysis must reflect the most likely activities for each alternative over that analysis period. Currently, most state highway agencies (SHA) apply a single standard rehabilitation scenario to all pavements, which may or may not be representative of the actual set of activities that will be done. The fact is that there are many different rehabilitation scenarios that could be performed when the pavement requires rehabilitation, and which one is selected will impact the results. This creates inherent uncertainty and variability in the LCA results solely due to the selection of which standard rehabilitation scenario is used in the analysis. This paper shows how SHAs can use probability and decision tree analysis to evaluate different rehabilitation scenarios in order to determine the range of LCA results as well as an expected value LCA result. This information helps quantify the underlying risk assumptions that the rehabilitation selection has on the LCA results so that a more informed decision can be made when comparing the LCA results of pavement designs. A case study based on alternative designs and rehabilitation scenarios used by a SHA demonstrates the extent to which the decision tree analysis could affect the outcome of an LCA. In this case, the risk profiles for the two alternatives considered are not equivalent and therefore, the probability-adjusted LCA results are different than the results based on a single maintenance schedule.

INTRODUCTION

Life cycle assessment (LCA) is a method to assess 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 *(1,2)*, be used to ensure accuracy and consistency of the LCA approach. This life cycle 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 produce a version of that particular product with lower impact, 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.

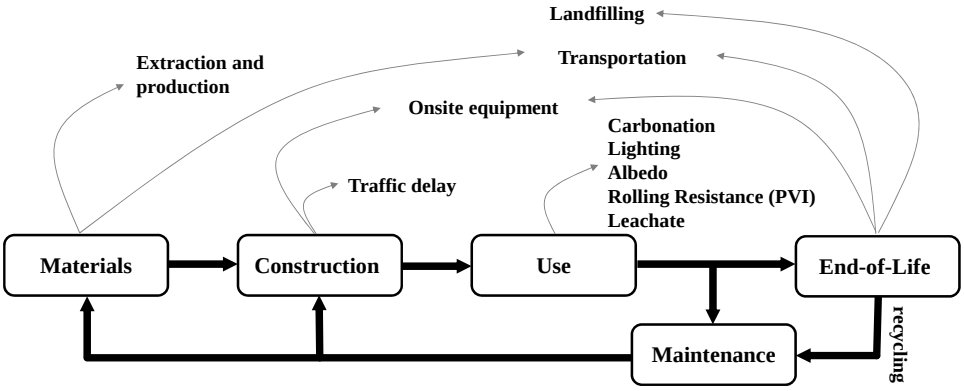


Figure 1: Standardized system boundaries (including life-cycle phases and components) for pavement LCA *(1,2)*

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.

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 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 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 use the exact same rehabilitation activities, the LCA results will not be representative of 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 trust 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 incorporate a risk analysis process 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 *(3,4)*. 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 factors that will impact the final LCA results considerably. Some of these other factors 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 *(5)*. For concrete pavements, ODOT gives the following list of activities as potential options for the first and second of rehabilitation for use in their LCCAs:

- First rehabilitation (Year 18 – 25): 2% - 10% full-depth rigid repairs, 1% - 5% partial depth bonded repairs, diamond grinding, 3" - 6" (~75 - 150 mm) asphalt overlay, sawing and sealing.
- Second rehabilitation (Year 28 – 32): 1% - 3% full- and/or partial-depth repairs, 1.25" - 2" (~32 - 50 mm) second asphalt overlay with or without milling, 3" - 4" (~75 - 100 mm) 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, 1.25" - 3" (~32 - 75 mm), with or without milling.
- Second rehabilitation: Year 18 - 25: thick asphalt overlay, 3" - 7" (~75 - 175 mm), with milling, possibly pavement repairs.
- Third rehabilitation: Year 28 - 32: thin asphalt overlay or micro-surfacing or crack sealing.

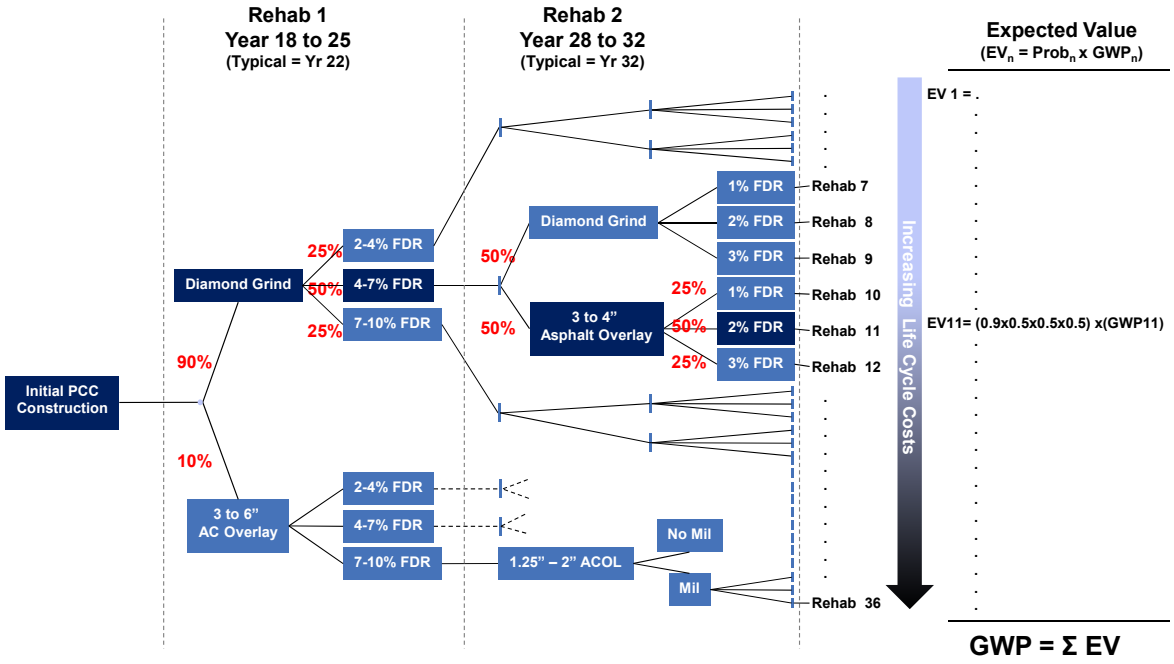
As one might imagine, the specific activities selected for both the concrete and asphalt alternatives will impact which pavement is selected in the pavement type selection process. In addition, the selection of activities can influence the *risk profile* between the two alternates. That is, if the rehabilitation for one pavement is selected based on very conservative rehabilitation activities and timing, and the other uses very liberal or generous rehabilitation activities, 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

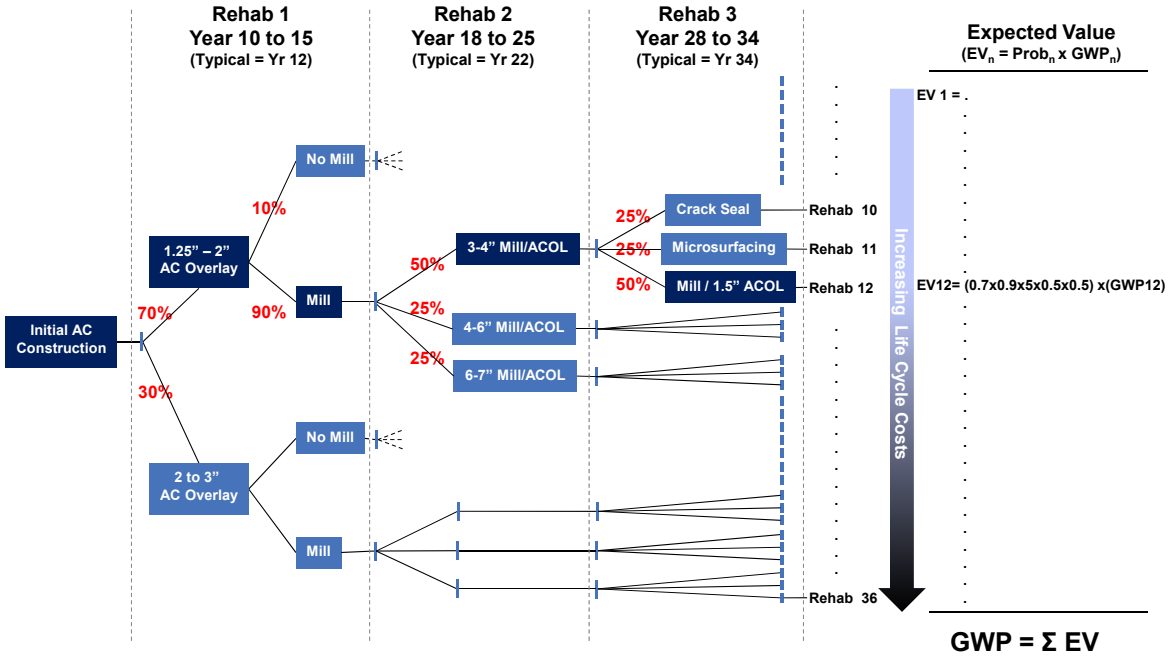
Decision trees are simply a flowchart-like structure that shows the relationships among many courses of action and realizations of the future. Typically, a decision tree is made up of two kinds of nodes: decision nodes – where an option is to be selected and chance nodes – where various future realizations 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 2(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 made more compact by combining the decision and chance nodes and only showing a part of the decision tree so that the concept can be understood). At the first node a decision has to be made on what type of activity will be done – CPP or asphalt overlay. If CPP is chosen (top node), a second decision has to be made on how much full depth repair (FDR) should 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. At the second rehabilitation, a decision again has to be made on what type of activity will be done - CPP or asphalt overlay – and the process repeats itself until all alternatives are defined and the end of the analysis period is reached. For this example, there are 36 different sets of rehabilitation activities (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 2(b) is a graphical representation of a potential decision tree for ODOT's asphalt pavement rehabilitation strategies. In both Figure 2(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 in order to keep the example simple. However, the asphalt overlay thickness can be anywhere from 3 to 6 in., with the thickness used impacting the LCA results. A more thorough analysis may have actually broken the first decision down into 3 choices: CPP, 3 to 4-inch asphalt overlay, or 5 to 6-inch asphalt overlay.



a) Concrete pavement activities



b) Asphalt pavement activities

Figure 2: Decision tree of ODOT's pavement rehabilitation activities.

Once the decision tree is complete, the analyst assigns a chance to each node that shows the probability, or likelihood, that a 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.*" As such, the likelihood of doing a diamond grinding as the first

rehabilitation is high, so 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 potential set of rehabilitation activities (branch) can be calculated. That is, currently agencies 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 to calculate GWP for a pavement, the GWP for each branch is calculated, and the GWP, or the expected value of 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 value for a branch is calculated, the final EV_{GWP} of the concrete or asphalt alternative is the summation of the Expected Values (Eq. 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 this process 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 Reference *(3)*, 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 (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

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 3 shows actual pavement designs used in an LCCA for a project in Ohio *(6)* and which serve as the designs considered in 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.

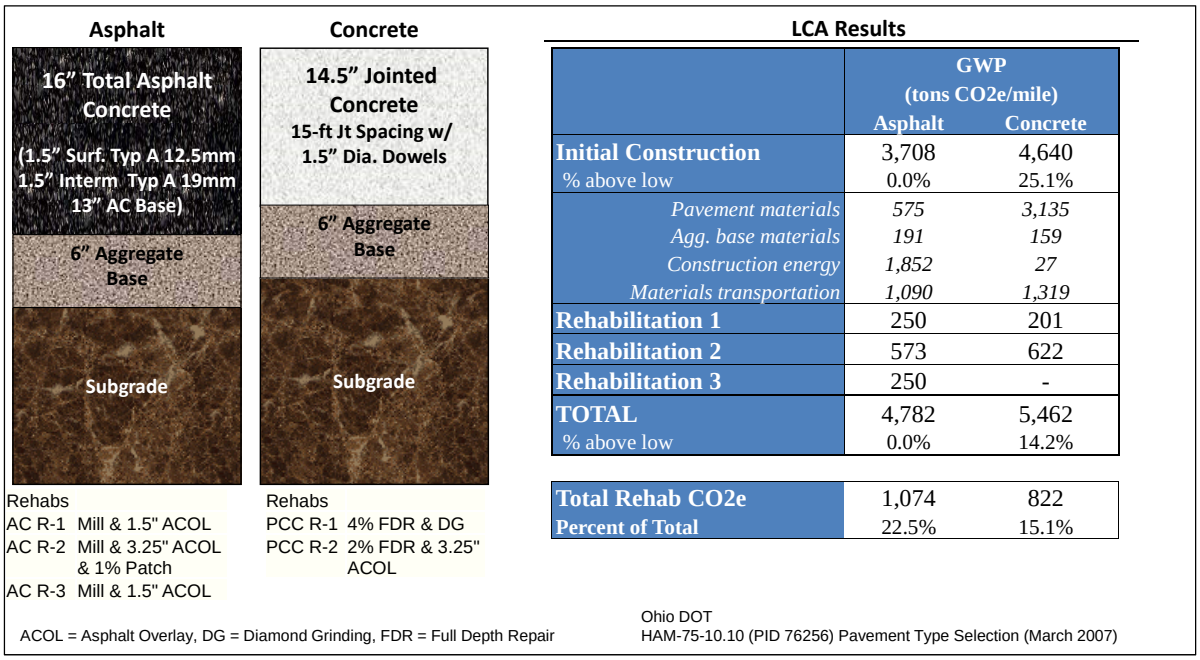


Figure 3: LCA results using ODOT's standard rehabilitation schedule as defined below the pavement designs. Results for "materials" categories include upstream impacts of materials extraction and production. Rehabilitation results include both impacts of materials and construction.

The two pavement designs being compared are a 16-inch asphalt pavement over a 6-inch aggregate base and a 14.5-inch concrete pavement, with 15-foot joint spacing also over a 6-inch aggregate base. The initial pavement designs, design lives and the standard rehabilitation schedules (the dark blue boxes in Figure 2) are from ODOT's Pavement Design and Rehabilitation Manual *(7)*. 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 and highlight the impact that rehabilitation scenarios can have on the results. 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 (CO_2e), is used as the metric for environmental impact.

The results in Figure 3 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 CO_2e 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 2, there are

at 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.

Table 1: LCA Data Sources and Assumptions

Life cycle Phase	Quantity Data Source	Impact Data Source	Key Assumptions
Materials			
Steel reinforcement	Ohio DOT *(6)*	Worldsteel (2011) *(15)*	70% recycled content; 70% recycled at EOL
Concrete			Mix design from Ohio DOT
Cement Materials	PCA Environmental Surveys *(10,11)*	USLCI / *Ecoinvent (12,13)*	
Cement	Ohio DOT *(6)*	USLCI / *Ecoinvent (12,13)*	
Water		*Ecoinvent (13)*	
Aggregate			
Concrete Mixing	Zapata & Gambatese (2005) *(9)*	*Ecoinvent (13)*	Diesel
Asphalt Concrete			
Bitumen	Ohio DOT *(6)*	*Ecoinvent (13)*	Bitumen, at refinery/RER
Aggregate			
Stabilized Subgrade /Soil	Ohio DOT *(6)*	n/a	
Aggregate / Aggregate Base	Ohio DOT *(6)*	*Ecoinvent (13)*	
Construction			
Concrete Paving	Chappat & Bilal (2003)/IVL *(16)*	*Ecoinvent (13)*	Diesel
Asphalt Paving			
Placement-other layers			
Maintenance			
Onsite activities: diamond grinding, joint sawing, milling, overlay placement	International Grooving & Grinding Assn (IGGA) *(17)*	*Ecoinvent (13)*	Diesel
Traffic Delay			
Fuel loss	Santero (2009) *(14)*	n/a	
User cost	*RealCost (18)*	n/a	
Work Zone Speed		n/a	
Gas	(calculated using above inputs)	*Ecoinvent*: (divided by amount of fuel used) *(13)*	Gas: 6.073 lb/gal (Operation, passenger car, petrol, fleet average 2010/RER U)
Diesel			Diesel: 6.943 lb/gal (Operation, truck >16t, fleet average/RER U)
Landfilling		*Ecoinvent (13)*	Half of all recovered waste is landfilled
Crushing/recycling conc.	Stripple (2001) *(8)*		Energy required to crush aggregate
Excavation	Stripple(2001) *(8)*		

Table 1: LCA Data Sources and Assumptions *(continued)*

Life cycle Phase	Quantity Data Source		Impact Data Source	Key Assumptions
Transportation				
Concrete	Truck (40.2 km)	U.S. Commodity Flow Survey (2007) *(19)*	*Ecoinvent (13)*	Concrete truck (tank)
Steel	Truck (684 km)	BTS (2007) – Articles of Base Metal *(19)*		
	Rail (1,624 km)			
Cement	Truck (201 km)	PCA Environmental Surveys *(10,11)*		
	Rail (430 km)			
	Water (644 km)			
Aggregates	Truck (88.5 km)	BTS (2007) – Gravel and crushed stone *(19)*		
	Rail (684 km)			
	Water (620 km)			
Bitumen	Truck (158 km)	BTS (2007) – Coal and petroleum products *(19)*		
	Rail (1,893 km)			
	Water (1,207 km)			
Waste	Truck (50 km)	Assumption		

Figure 4 shows the range of all possible LCA results based on the rehabilitation scenarios in Figure 2. The light blue columns show the results using the standard ODOT LCCA rehabilitation schedule as developed in Figure 3. 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.

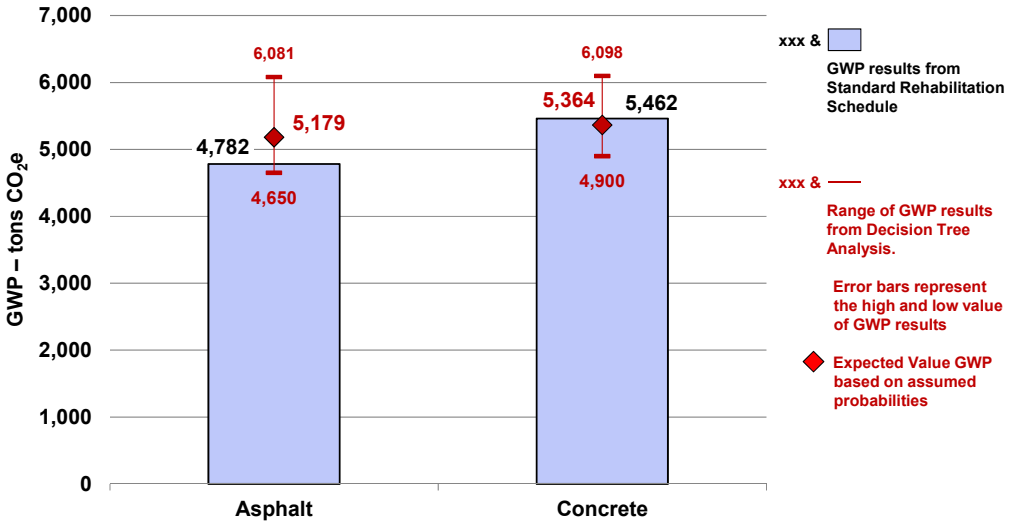


Figure 4: LCA results from both the standard rehabilitation schedule and the decision tree analysis

That is, the standard rehabilitation scenario LCA results (light 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 of the potential rehabilitation activities for the asphalt

design is higher than the GWP for 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 thus 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.

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 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 band of potential $EV's_{GWP}$, 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 over a defined analysis period to determine which has the lowest impact over the analysis period. For this comparison to be meaningful and reliable, the analysis should reflect the range of different rehabilitation activities for each pavement alternative that could occur over the analysis period. Currently, most agencies apply a single, standard, policy-set rehabilitation scenario to all pavements based on historical performance. The drawback with this approach 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 unlikely to be true.

This paper described how decision tree and probability analysis can be used to characterize a range of possible future rehabilitation activities for a life cycle assessment. DTA evaluates the range of rehabilitation options and calculates an expected range of environmental impacts (e.g., GWP) and a probability adjusted (i.e., expected value) environmental impact, thereby taking into account the associated risk profile of each alterative in the analysis. By systematically adopting and using the methodology laid out in this paper, transportation agencies can develop more robust LCAs that address the lack of trust in the LCA results that sometimes occur due to disagreements about the representativeness of the rehabilitation schedules. This type of risk-based approach can facilitate discussion in comparative LCAs about the impact on uncertainty in future rehabilitation schedules on the outcomes of such analyses.

REFERENCES

1. Santero, N., A. Loijos, M. Akbarian and J. Ochsendorf, *Methods, Impacts, and Opportunities in the Concrete Pavement Life Cycle*, Concrete Sustainability Hub, Massachusetts Institute of Technology, Cambridge MA, 2011.
2. Santero, N., E. Masanet and A. Horvath, Life-cycle assessment of pavements. Part I: Critical review. *Resources, Conservation, and Recycling*. 55(9–10): 801–809.," 2011.

3. Pour, S.A. and D. Jeong, Realistic Life-Cycle Cost Analysis Using Typical Sequential Patterns of Pavement Treatments via Association Analysis, *Transportation Research Board (TRB Paper 12-3390)*, Stillwater, Oklahoma, 2012.
4. Pour, S.A. and D. Jeong, Factors Influencing the Life cycle Performance of Pavement Utilizing Decision Tree Analysis, *Transportation Research Board (TRB Paper 13-4983)*, Stillwater, Oklahoma, 2013.
5. ODOT, *Ohio Department of Transportation Pavement Design Manual (PDM)*, Section 700 - Life-Cycle Cost Analysis, 1999.
6. ODOT, *HAM-75-10.10 (PID 76256) Pavement Type Selection*, Ohio Department of Transportation, 2007.
7. ODOT, *Pavement Design and Rehabilitation Manual*, Ohio Department of Transportation, 1999.
8. Stripple, H. *Life Cycle Inventory of Asphalt Pavements*. IVL Swedish Environmental Research Institute Ltd., 2000.
9. Zapata, P. and J. Gambatese, *Energy Consumption of Asphalt and Reinforced Concrete Pavement Materials and Construction*. 2005.
10. Nisbet, M. and M. Marceau, *Environmental Life Cycle Inventory of Asphalt Concrete*, Portland Cement Association. PCA R&D Serial No. 2487, 2001.
11. Nisbet, M., M. Marceau, M. Van Geem and J. Gajda, "Environmental Life Cycle Inventory of Portland Cement Concrete and Asphalt Concrete Pavements," Portland Cement Association. PCA R&D Serial No. 2489, 2001.
12. USLCI, *U.S. Greenhouse Gas Inventory Report.*, Environmental Protection Agency, EPA, 2009 . Online. Available: http://www.epa.gov/climatechange/emissions/downloads09/GHG2007entire_report-508.pdf.
13. *SimaPro Ecoinvent Database.*
14. Santero, N. *Pavements and the Environment: A Life-Cycle Assessment Approach, Doctoral Dissertation in Civil and Environmental Engineering,* University of California, Berkeley, 2009.
15. Worldsteel, *Life Cycle Assessment Methodology Report: Life cycle inventory study for steel products*, World Steel Association, Brussels, Belgium, 2011.
16. Chappat, M. and J. Bilal, *La route écologique du futur. Consommation d'énergie et émissionde gaz à effet de serre*, COLAS, Paris, 2003.
17. IGGA, *Technical Information*, International Grooving & Grinding Association (IGGA), Online. Available: http://www.igga.net/technical-information/technical-information.cfm. Accessed 2014.
18. Caltrans, *Life-Cycle Cost Analysis Procedures Manual*, State of California Department of Transportation, 2007.
19. "*United States: 2007 Commodity Flow Survey*," Bureau of Transportation Statistic (BTS), Online. Available: http://www.rita.dot.gov/bts/sites/rita.dot.gov.bts/files/publications/commodity_flow_survey/index.html. Accessed 2014.