A Life Cycle Assessment Framework for Pavement Maintenance and Rehabilitation Technologies

or

An Integrated Life Cycle Assessment (LCA) – Life Cycle Cost Analysis (LCCA) Framework for Pavement Maintenance and Rehabilitation

Center for Transportation, Environment, and Community Health
Final Report

by
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16. Abstract

Given a huge amount of annual investment and large inputs of energy and natural resources in pavement maintenance and rehabilitation (M&R) activities, significant environmental improvement and budget saving can be achieved by making eco-friendly and cost-effective decisions in scheduling M&R activities. Traditional scheduling of pavement M&R activities, however, is primarily determined based on cost optimization, using a life cycle cost analysis (LCCA). The environmental impacts of pavement M&R activities are usually ignored. Life cycle assessment (LCA) is an approach for determining the environmental sustainability of a system from cradle to grave. The purpose of this research is to develop an integrated LCA-LCCA framework in assisting decision-making for pavement M&R activities during the entire pavement life cycle. Based on literature review, an integrated LCA-LCCA optimization framework for pavement rehabilitation strategy selection is proposed. In the framework, the LCA model is divided into six modules: material, construction, distribution, congestion, usage, and end-of-life modules. Life cycle energy consumption, greenhouse gas (GHG) emissions, and air pollutants are identified as environmental impact factors. Life cycle agency cost, and user cost are selected as cost factors. Pavement M&R strategies are evaluated as the input variables of the integrated LCA-LCCA model. The LCA-LCCA output variable (e.g., energy consumption, agency cost) may be regarded as an objective function or as a constraint in the mathematical optimization of pavement M&R schedules. In addition, pavement roughness progression model after M&R activities is identified as an essential part of the integrated LCA-LCCA framework. Material, construction-related traffic congestion, and pavement surface roughness effects are three major contributors to energy consumption and GHG emissions for pavement M&R activities.

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SI (MODERN METRIC) CONVERSION FACTORS

Approximate Conversions to SI Units				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		Length		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		Area		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		Volume		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be show n in m^3		
		Mass		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		Temperature (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		Illumination		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		Force and Pressure or Stress		
lbf	poundforce	4.45	new tons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

Approximate Conversions from SI Units				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		Length		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		Area		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		Volume		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		Mass		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		Temperature (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		Illumination		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		Force and Pressure or Stress		
N	new tons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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CHAPTER 1 INTRODUCTION

1.1 Background

Road pavement is a critical component of transportation infrastructure system. Around the world, pavements support more than nine trillion tonne-kilometers of freight and transport passengers more than fifteen trillion kilometers each year (BTS, 2010; IRF, 2010). After the construction of a pavement system, pavement condition will deteriorate with time due to a number of factors, including material aging, traffic loading, and environmental impacts. As pavement condition deteriorates, vehicle operating cost and its corresponding environmental impacts (e.g., emission of greenhouse gases, criteria air pollutants) would increase.

To restore pavement performance and reduce the negative effects on users, maintenance and rehabilitation (M&R) activities need to be carefully planned and implemented. If pavement M&R activities are performed too frequently, material consumption and traffic congestion due to such activities may significantly increase costs and environmental impacts. Conversely, if such activities are performed too scarcely, high pavement roughness would lead to poor vehicular fuel economy as well as high emissions (Zhang, 2009; Wang et al., 2014).

Given a huge amount of global annual investment and large inputs of energy and natural resources in pavement M&R activities, significant environmental improvement and budget saving can be achieved by making eco-friendly and cost-effective decisions in scheduling of M&R activities during the entire pavement life cycle. However, traditional scheduling of pavement M&R activities (Li & Madanat, 2002; Abaza and Abu-Eisheh, 2003) is primarily based on minimization of life cycle cost (LCC) incurred by highway agencies and users. The environmental impacts of pavement M&R activities are usually ignored. Life cycle assessment (LCA) is an approach for determining the environmental sustainability of a system by calculating the resource energy flows consumed and the consequent environmental effects from cradle to grave (Harvey et al., 2015). When the LCA is combined with a life cycle cost analysis (LCCA), the integrated LCA-LCCA approach may be used to identify the cost-effective and eco-friendly pavement M&R strategy.

1.2 Objective

The purpose of this research is to develop an integrated LCA-LCCA framework in assisting decision-making for pavement M&R activities during the entire pavement life cycle. The pavement M&R decisions focus on selection of appropriate M&R activities and determination of the optimal schedule for a specific pavement segment. The decision-making process relies on the whole life-cycle environmental assessment, cost analysis, and future pavement performance. To achieve the above objective, three essential questions need to be addressed:

- How to evaluate the effect of M&R treatments on environmental impacts during pavement life cycle?
- How to optimize pavement M&R treatments from both environmental and economic views?
- How to evaluate the effect of M&R treatments on pavement roughness progression?

1.3 Organization of Report

The effect of pavement M&R activities on life cycle environmental impacts is illustrated in Chapter 2. To identify cost-effective and eco-friendly pavement M&R treatments, an integrated LCA-LCCA optimization model is proposed in Chapter 3. As a key component bridging the pavement M&R decisions with life cycle environmental and economic performance, pavement roughness progression model in current LCA studies is reviewed in Chapter 4. Finally, the conclusions and future work are summarized in Chapter 5.

CHAPTER 2 PAVEMENT M&R ACTIVITIES AND LIFE CYCLE ASSESSMENT

2.1 Pavement Life Cycle Phases

The key step to make eco-friendly pavement M&R decisions is to understand where environmental impacts are created in the pavement life cycle, as well as how, and to what extent various M&R activities actually affect those environmental impacts. In the LCA process, pavement life cycle phases are typically classified into material production phase, construction, maintenance and rehabilitation phase, use phase, and end-of-life (EOL) phase (Harvey et al., 2015). To evaluate the effect of M&R on environmental impacts during pavement life cycle, pavement M&R is evaluated as an input variable instead of a component in LCA. The relationship between the input variable and environmental impacts over pavement LCA phases is illustrated as follows.

2.1.1 Material Production Phase

The material production phase of a pavement LCA includes raw material acquisition and material processing in the process of pavement M&R activities. To be specific, the material production phase includes: (1) the process of raw material acquisition; (2) mining and crushing of aggregates; (3) production of asphalt, cement, and other binders; (4) manufacture of other materials, such as additives; (5) transport to, from, and within the manufacturing sites; and (6) mixing processes, such as hot mix asphalt (HMA) and portland cement concrete (PCC).

Different pavement M&R activities may change the type and the amount of materials consumed in construction. Because feedstock energy (the energy stored in a material) can be harvested later during the recycling process, it is ignored in the LCA process for different pavement M&R activities.

SimaPro software (https://simapro.com/) can be applied to estimate the energy consumption and greenhouse gas (GHG) emissions in the material production phase. Table 2-1 provides a list of materials and their associated environmental impacts. The overall environmental impacts in material production phase can be evaluated for different pavement M&R treatments.

Table 2-1 Impact Inputs of Materials in Pavement M&R Process

Production	Units	Value	Source
Asphalt Concrete	MJ/ton	641	SimaPro
Asphalt Concrete	kg CO_2 eq/ton	84.7	SimaPro
Gravel	MJ/ton	265	SimaPro
Gravel	kg CO_2 eq/ton	14.10	SimaPro
Sand	MJ/ton	61.8	SimaPro
Sand	kg CO_2 eq/ton	4.25	SimaPro

2.1.2 Construction Phase

Construction phase includes the transport and placement of pavement materials, and equipment use and work zone effects in the construction process of pavement M&R activities. To be specific, it includes: (1) transport of equipment to and from site; (2) equipment use at the construction site; (3) transport of materials from and to the site; (4) energy used on site, such as lighting if construction work is implemented at night; and (5) changes to roadway traffic flow, such as work zone speed changes and traffic delay (Harvey et al., 2010).

Different pavement M&R activities may change the type and usage of equipment, the type and magnitude of material transported at a construction site, duration of construction, temporary traffic control, and other construction operations (e.g., traffic delay). PaLATE (http://rmrc.wisc.edu/palate/) is an Excel-based tool which can be used to estimate constructional impacts based upon user inputs of detailed overlay design, material type, and machinery information. In addition, NONROAD2008 (https://www.epa.gov/moves/nonroad-model-nonroad-engines-equipment-and-vehicles) model can be used to calculate emissions based on provided emission factors for different types of construction equipment. A list of construction operations and their associated environmental impacts is provided in Table 2-2.

Table 2-2 Impact Inputs of Required Construction Items in Pavement M&R Process

Construction	Units	Value	Source
Asphalt Milling	MJ/yd^3	6.23	SimaPro
Asphalt Milling	kg CO_2 eq/yd^3	0.409	SimaPro
Asphalt Paving	ton/hr	10	PaLATE
Asphalt Rolling	ton/hr	395	PaLATE
Construction Machine Operation	MJ/hr	10816	SimaPro
Construction Machine Operation	kg CO_2 eq/hr	72	SimaPro
Dump Truck Transportation	MJ/(ton*mile)	5.134	SimaPro
Dump Truck Transportation	kg CO_2 eq/(ton*mile)	0.321	SimaPro

In the construction phase, traffic delay incurred by M&R activities has a significant influence on energy consumption and pollutant emissions compared with those under normal vehicular operation conditions, especially for heavy-traffic highways (Santero and Horvath, 2009; Yu and Lu, 2012; Trupia et al, 2017). The QuickZone (https://ops.fhwa.dot.gov/wz/traffic_analysis/quickzone/) software can be used to estimate the traffic flow, traffic delay, and queue length in the work zone. Then, vehicle delay information (e.g., detour rate, queue length, and speed reduction) can be coupled with fuel consumptions and vehicle emissions to evaluate the environmental impacts. Vehicle fuel economy can be obtained from the U.S. Environmental Protection Agency (EPA) fuel economy guide (EPA, 2006). GHGs can be calculated with the fuel consumption effects (Coe, 2005), based on the assumption that all passenger cars burn gasoline and trucks combust diesel. Other vehicle emissions are calculated at different traffic speeds using U.S. EPA's MOVES (Motor Vehicle Emission Simulator) 2014a software (https://www.epa.gov/moves). The outputs of the fuel consumptions and environmental burdens are calculated as the differences between those of work zone and those of normal operations, which are given by Equation (2-1).

$$Y_{total} = VMT_{queue} \times Y_{queue} + VMT_{workzone} \times Y_{workzone} + VMT_{detour} \times Y_{detour} - VMT_{normal} \times Y_{normal} \quad (2\text{-}1)$$

where Y_i is the value of different environmental indicators, such as, fuel usage (L/km) or emission value (g/km); VMT_i is the total miles traveled by vehicles (km), i is a scenario index, representing total, waiting in queue, passing through the work zone, taking detour, or operating under normal conditions.

2.1.3 Use Phase
The pavement use phase can be classified into two key processes: (1) the travel of vehicles on the pavement; and (2) the interaction of the pavement with the climate and surrounding environment (e.g., albedo effect, carbonation, leachate) (Yu and Lu, 2014; Harvey et al., 2015).

Pavement M&R activities mainly affect the use phase environmental impacts of the first process by changing pavement rolling resistance (i.e., roughness, structural effect, and macrotexture). Pavement roughness have been validated to affect vehicle fuel economy (Zaabar and Chatti, 2010; Chatti and Zaabar, 2012). Pavement roughness progression model is needed to predict the international roughness index (IRI) after the implementation of M&R activities.

The Highway Development and Management software (HDM-4) can be used to evaluate the effects of pavement properties (e.g., IRI, mean texture depth, and deflection) on the rolling resistance. Then, by updating the rolling resistance coefficient, the environmental impacts of use phase can be calculated with the EPA MOVES 2014a software. Table 2-3 provides a list of materials and their associated environmental impacts in the use phase.

Table 2-3 Impact Inputs of Gasoline and Diesel in Use Phase

Use	Units	Value	Source
Gasoline	MJ/gal	130	EPA
Gasoline	lb CO_2 eq/gal	19.64	EPA
Diesel	MJ/gal	137	EPA
Diesel	lb CO_2 eq/gal	22.38	EPA

2.1.4 End-of-Life (EOL) Phase
The activities at the end of pavement service life can be classified into three types: (1) removal of materials and disposal in landfills; (2) pavement in-place reuse (in-place use); (3) pavement material recycling. Because the pavement sections are most likely to remain in place at the end of analysis period, a “cut-off” allocation method can be adopted by assigning no environmental impacts to the EOL phase for all M&R scenarios in comparison (Santos et al., 2015).

2.2 Pavement LCA and M&R Activities
Pavement LCA may be conducted by one of two broadly accepted methods: a process-based approach and an economic input-output approach. Most of pavement studies employed the process-based LCA approach (Santero et al., 2010). The process-based LCA model is typically developed with a four-step procedure, which consists of goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. To evaluate the effects of pavement M&R activities on environmental impacts, the four-step LCA process is illustrated as follows.

2.2.1 Goal and Scope Definitions

The goal and scope definitions are conducted to establish the system to be evaluated and the boundaries of the study (Harvey et al., 2015). In this step, the study objective, functional unit, analysis period, life cycle phases, pavement structure, M&R techniques, traffic and weather characteristics, and current pavement performance need to be clearly identified. The following is an example of such definitions.

The study objective is to evaluate the life cycle environmental impacts (i.e., energy consumption, GHG emissions, and criteria air pollutants) for different overlay designs; pavement M&R treatments include thin asphalt overlay (e.g., 0.5, 1.0, and 1.5 inches) and structural asphalt overlay (e.g., 2.0 and 5.0 inches); the functional unit is one lane-mile of a flexible pavement with three lanes in each traffic direction; a typical mainline lane of 12 ft. is assumed in the study and only construction and materials related to layers above the subgrade are included; the current pavement condition is at the end of service life (e.g., present serviceability index [PSI] is 2.5); the analysis period is selected as 40 years; life cycle phases include material production, construction, and use phase; the traffic conditions comprise an annual average daily traffic (AADT) of 80,000, with 14% of truck, at a compound annual growth rate of 2%; the average annual temperature is 30°C and the average annual rainfall is 59 inches; the pavement structure includes 10-in lime-rock base course, 6-in structural course, and ¾-inch friction course (FC-5).

2.2.2 Life Cycle Inventory (LCI)

The LCI includes quantification and documentation of the inputs and outputs in each phase of pavement life cycle. An LCI analysis would provide a list containing the quantities of GHG emissions and air pollutants released to the environment and the amount of energy and material consumed. For material production phase and construction phase, data can be collected from different sources, such as public agencies, material suppliers, equipment manufacturers, contractors, and software package. For use phase, the inputs and outputs should be determined using different estimation methods (Inyim et al., 2016). Because quantification of inputs and outputs during the use phase is influenced by pavement condition, traffic information, vehicle emissions, and pavement-vehicle interaction, a pavement roughness progression model has to be developed. A comprehensive LCI database over material production phase, construction phase, and use phase needs to be developed for different M&R activities.

2.2.3 Life Cycle Impact Assessment (LCIA)

Life cycle impact assessment translates the effects of the input and output flows tracked in the LCI into environmental impact indicators. The environmental impact indicators evaluated for different M&R activities are energy consumption, GHG emissions (e.g., carbon dioxide [CO_2], methane [CH_4], nitrous oxide [N_2O]), and criteria air pollutants (e.g., nitrogen dioxide [NO_2], carbon monoxide [CO], sulfur dioxide [SO_2], and particulate matter [PM]).An LCIA can be used to establish a linkage between the phase and its potential environmental impacts, which provides a basis to make comparisons.

2.2.4 Interpretation

The interpretation step for LCA is conducted to evaluate the results of the LCI and LCIA to select the preferred M&R activities with a clear understanding of the uncertainty and the assumptions used to generate the results. To address the uncertainty issue in the LCA process, sensitivity analysis or risk analysis may be conducted.

2.3 Pavement LCA Studies on M&R Activities

In recent years, several researchers have developed life cycle assessment (LCA) models to evaluate the effects of pavement M&R activities on environmental impacts. The LCA models developed for pavement M&R activities may serve as a foundation of an integrated LCA-LCCA optimization approach to enhance pavement sustainability. LCA studies on pavement M&R activities are reviewed and illustrated as follows.

In 2009, Zhang et al. estimated the environmental impacts for three pavement overlay systems (concrete overlay, asphalt overlay, and engineered cementitious composites [ECC] overlay) by using a pavement LCA model. The LCA model was divided into six modules: material production, construction, distribution, traffic congestion, usage, and EOL. Material, construction-related traffic congestion, and pavement surface roughness effects were found to be the greatest contributors to environmental impacts throughout an overlay system life cycle. From that case study, compared to a conventional concrete overlay system, the ECC overlay system may reduce the life-cycle energy consumption and GHG emissions by 15% and 32%, respectively (Zhang et al., 2009).

In 2010, Weiland and Muench compared three rehabilitation treatments (PCC overlay, HMA overlay, and crack, seat and HMA overlay) for an aging portland cement concrete (PCC) pavement with the use of a process-based LCA approach. They found that the materials production (e.g., cement, asphalt, PCC, and HMA) dominates the energy use, emissions for all three rehabilitation options when only material production and construction activities are considered (Weiland and Muench, 2010). However, environmental impacts incurred by traffic delay and pavement usage were not considered in the study.

In 2012, Yu and Lu developed a comprehensive pavement LCA model by combining material, distribution, construction, congestion, usage, and end-of-life modules. A case study of three overlay systems (PCC overlay, HMA overlay, and crack, seat and HMA overlay) was conducted with the proposed LCA approach. For that case, PCC overlay was found to have less environmental burdens than HMA overlay. In addition, material production, traffic delay, and pavement usage were identified as the three major sources of energy consumptions and air pollutant emissions (Yu and Lu, 2012).

In 2012, Wang et al. evaluated energy use and GHG emissions from pavement rehabilitation strategies by proposing a pavement LCA model. Case studies of pavement rehabilitation for both asphalt and concrete pavements with different rolling resistances and traffic levels were performed with the proposed LCA model. They found that the energy and GHG savings accrued during the use phase due to reduced rolling resistance can be significantly larger than the energy use and GHG emissions from material production and construction for high-traffic-volume highways. On low-traffic-volume highways, construction quality and material selection play a significant role in determining whether there is a net positive or negative effect of pavement rehabilitation on energy use and GHG emissions (Wang et al., 2012).

In 2014, Wang and Gangaram quantified the impact of different pavement preservation treatments (HMA thin overlay, crack seal, slurry seal, and chip seal) on energy consumption and GHG emissions by developing a LCA model. Among the preservation treatments, the thin overlay was found to have the greatest energy and GHG savings at usage stage and the highest energy consumption and GHG emissions at material production stage and construction stage. In addition, they found that the reductions of GHG emissions at usage stage are much greater than the GHG emissions produced at construction stage for all preservation treatments (Wang and Gangaram, 2014).

In 2015, Santos et al. conducted a comprehensive LCA of three M&R strategies (recycling-based M&R strategy, traditional reconstruction, and corrective M&R strategy) for a pavement segment and compared the relative environmental impacts of each strategy. For that case study, the recycling-based M&R strategy reduces the overall life cycle environmental impacts and energy consumption by as much as 30% compared to the corrective M&R strategy. In addition, they found that the reconstruction strategy has the worst environmental performance with respect to the materials and construction stages (Santos et al., 2015).

2.4 Summary

Pavement M&R activities have a significant impact on life-cycle environmental impacts, especially in material production, construction, and use phases. The essential relationship between M&R activities and pavement LCA is summarized in Table 2-4. Specially, pavement roughness progression models for different M&R activities are very important for evaluating environmental impacts in the use phase.

Table 2-4 Effects of Pavement M&R Activity on LCA

Phase	Module	Software	M&R Effect on LCA
Material	Material	SimaPro	• Type and amount of materials consumed • Transport of materials within manufacturing site
Construction	Construction	PaLATE; NONROAD	• Equipment use within construction site
	Distribution	GREET	• Transport of materials to/from construction site • Transport of equipment to/from construction site
	Congestion	QuickZone;MOVES	• Construction duration • Temporary traffic control
Use	Usage	HDM-4; MOVES	• Pavement rolling resistance • Pavement roughness progression

Based on the literature, material, construction-related traffic congestion, and pavement surface roughness effects are identified as three major contributors to energy consumption and GHG emissions for pavement M&R activities. For high-traffic-volume highways, energy and GHG savings accrued during the use phase due to reduced rolling resistance can be significantly larger than the energy use and GHG emissions from material production and construction in pavement M&R activities.

CHAPTER 3 A LCA-LCCA MODEL FOR PAVEMENT M&R TREATMENTS

3.1 Introduction

As pavement condition deteriorates, users would experience a significant increase in both vehicle operating cost and the corresponding environmental impacts (GHG emissions, air pollutant). Pavement condition can be improved through M&R activities to reduce the negative effects on the public, but these activities also have significant cost and environmental impacts. To make eco-friendly and cost-effective pavement M&R decisions, both environmental impacts and cost should be evaluated simultaneously with an integrated LCA-LCCA model. Then, the environment- and cost-effective M&R treatment may be identified with mathematical optimization techniques.

3.2 Pavement LCCA and M&R Treatments

The calculation and comparison of the costs and benefits of different pavement M&R alternatives over the analysis period is a life-cycle cost analysis (LCCA) (Hall et al., 2001). The LCCA procedure consists of selecting an analysis period, selecting a discount rate, selecting a measure of economic worth, and determining monetary agency costs (materials and construction) and user costs (traffic delay costs, crash costs, and vehicle operating costs). To be specific, vehicle operating costs include fuel consumption, vehicle repair and maintenance, and tire wear. It is worth mentioning that pavement roughness progression after M&R activities is very important for the estimation of vehicle operating cost.

Federal Highway Administration (FHWA) RealCost software (https://www.fhwa.dot.gov/infrastructure/asstmgmt/lccasoft.cfm) or APA LCCA software (http://www.asphaltroads.org/why-asphalt/economics/life-cycle-cost/) can be used to conduct the LCCA for various pavement M&R treatments. More detailed information about the LCCA has been summarized in a review paper (Babashamsi et al., 2016).

3.3 Review of Integrated LCA-LCCA Studies on Pavement M&R Treatments

To propose a comprehensive LCA-LCCA framework for pavement M&R strategy selection, current research studies about pavement LCA-LCCA model have been reviewed as follows.

In 2009, Zhang developed an integrated LCA-LCCA model framework for evaluating pavement life cycle environmental impacts and cost. As shown in Figure 3-1, the LCA model was divided into six modules: material module, consisting of the acquisition and processing of raw materials; construction module, including all construction processes, maintenance activities, and related construction machine usage; distribution module, accounting for transport of materials and equipment to and from the construction site; congestion module, accounting for construction and maintenance related traffic delay; usage module, including overlay roughness effects on vehicular travel during normal traffic flow; and end-of-life module, modeling the demolition of an existing pavement and processing of the removed materials. Then, the LCA model was integrated with the LCCA model by the principle that environmental impacts were converted to monetary values (Zhang, 2009). However, given the uncertainties inherent in the environmental damage cost estimation, the robustness and reliability of the integrated LCA-LCCA model would be significantly affected.

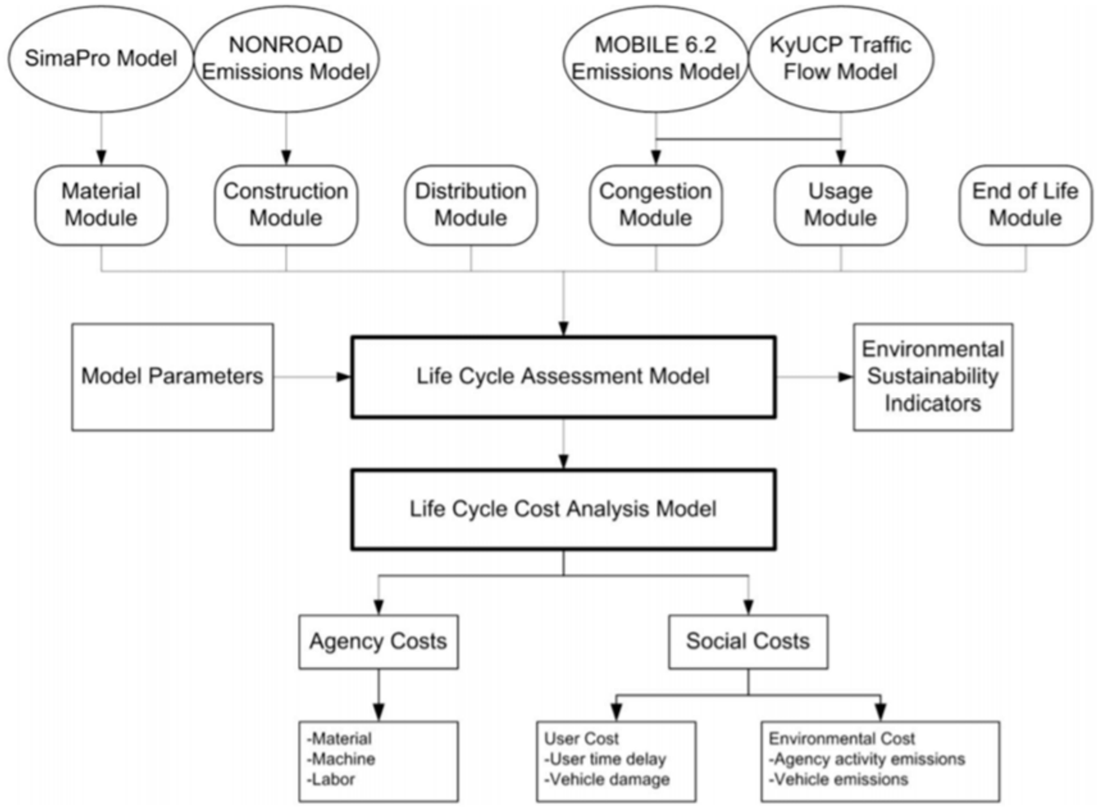

Figure 3-1 Integrated LCA-LCCA Model Framework (Zhang, 2009)

In 2011, Zhang et al. conducted a case-study about identifying the optimal rehabilitation strategy for a pavement overlay system to minimize the total life cycle energy consumption, GHG emissions, and costs within an analysis period. Based on the proposed LCA-LCCA framework in the previous work (Zhang, 2009), life-cycle burden (agency costs, user costs, and environmental costs) was identified as the single objective function in the life cycle optimization (LCO) model. Then, discrete-state dynamic programming optimization technique and autoregressive pavement overlay deterioration model were applied to minimize the life-cycle burden (Zhang et al., 2011). However, the effects of traffic volume and environmental characteristics on the pavement deterioration are ignored in pavement deterioration model. In addition, instead of IRI, the distress index (DI) is used as pavement performance indicator. The transformation of DI trend to IRI progression will add model uncertainty. By following the similar procedure, Yu et al. conducted a case study to optimize the maintenance plans for the three overlay designs (HMA overlay, PCC overlay, and Crack, seat and overlay) with a LCA-LCCA optimization model. In their study, pavement overlay deterioration models for three overlay designs were estimated with the MEPDG (Mechanistic-Empirical Design Guide) software (Yu et al., 2013). However, due to a series of assumed inputs, the predicted roughness trends from MEPDG software may not reflect the actual pavement deterioration process after rehabilitation.

In 2013, Lidicker et al. conducted a multi-criteria optimization for single-facility, continuous-state, continuous-time pavement resurfacing problem with the two objectives of minimizing costs and GHG emissions. Instead of conducting pavement LCA study, the researchers evaluated the life cycle environmental impacts by using agency and user emissions. Agency emissions were assumed to be a function of overlay thickness. User emissions were assumed to be a function of pavement roughness change. They found that minimum achievable roughness, deterioration rates, vehicle fuel economy and overlay emissions all affect life-cycle costs and GHG emissions (Lidicker et al., 2013). However, the assumption of agency and user emissions may not reflect the actual environmental impact process in the pavement resurfacing process. In addition, the energy consumption and air pollutants were not considered in the study.

In 2015, Yu et al. conducted a multi-objective optimization for asphalt pavement maintenance plans at project level by integrating pavement performance, environmental impacts, and cost. In the study, pavement LCA and LCCA were combined to evaluate the life cycle environmental impacts and cost. Pavement performance element was decided as the multiplier of PSI and traffic volume (Yu et al., 2015). However, traffic delay costs and vehicle crash costs were ignored in the LCA-LCCA framework. In addition, instead of using pavement roughness progression model, AASHTO 1993 PSI deterioration model was indirectly used to estimate the vehicle operating cost and emissions. The transformation from PSI to IRI throughout pavement life cycle may introduce a great level of uncertainty.

In 2017, Santos et al. integrated a LCA-LCCA model into the multi-objective optimization framework for identifying the optimal M&R strategy. The life cycle agency costs, life cycle user costs, and life cycle GHG emissions were selected as the objective functions (Santos et al., 2017) However, energy consumption and air pollutants were ignored in pavement LCA. The effects of pavement structure, traffic characteristics and weather information on pavement deterioration were not considered in the pavement deterioration model. In addition, the pavement roughness progression model should not assume to be the same over different M&R activities.

In 2017, Chong et al. conducted a multi-objective optimization for asphalt pavement maintenance decisions based on sustainability principles and mechanistic-empirical pavement analysis. In their study, pavement life cycle simulations (i.e., different traffic volumes, base layer thicknesses, and roughness trigger value) based on the MEPDG were used to predict pavement performance. The predicted pavement performance and timing for reconstruction and rehabilitation was used as the input to conduct the integrated LCA-LCCA. Then, regression analysis was conducted to develop the relationship between the outputs (life cycle cost, energy consumption, and GHG emissions) of LCA-LCCA and decision variables (pavement thickness and roughness trigger value). The regression models were subsequently used as the objective functions in the multi-objective optimization process. They found that the optimum IRI trigger value for rehabilitation does not vary greatly with traffic levels. Cost savings favor the use of a thinner pavement and a higher IRI trigger value, while the reductions in GHG emissions and energy consumption favor the use of a thicker pavement and a lower IRI trigger value (Chong et al., 2017). However, pavement roughness model developed from simulated data and MEPDG model may not reflect the actual pavement deterioration process. For example, in practice pavements are more likely to be designed with thicker layers under heavy traffic. In addition, air pollutants were not considered in the pavement LCA.

Based on the literature review above, most of the integrated LCA-LCCA frameworks only considered energy consumption and GHG emissions as environmental impact factors. However, the air pollutants with great health effects were not considered in the LCA. In addition, for

LCCA, traffic delay cost and vehicle crash cost were also ignored in the previous studies. Most importantly, the best way to estimate the vehicle operating costs and environmental impacts in pavement usage stage is to directly combine pavement roughness progression model with roughness impact model (HDM-4). However, most of studies used the other pavement performance indicators, such as present serviceability index (PSI), distress index (DI), and critical condition index (CCI).

3.4 An Integrated LCA-LCCA Framework

Based on the identified shortcomings in the current LCA-LCCA models, an improved integrated LCA-LCCA framework is proposed and shown in Figure 3-2. Instead of regarding pavement M&R as one of pavement life cycle phases, pavement M&R strategy alternatives are evaluated as the input variable for both LCA and LCCA.

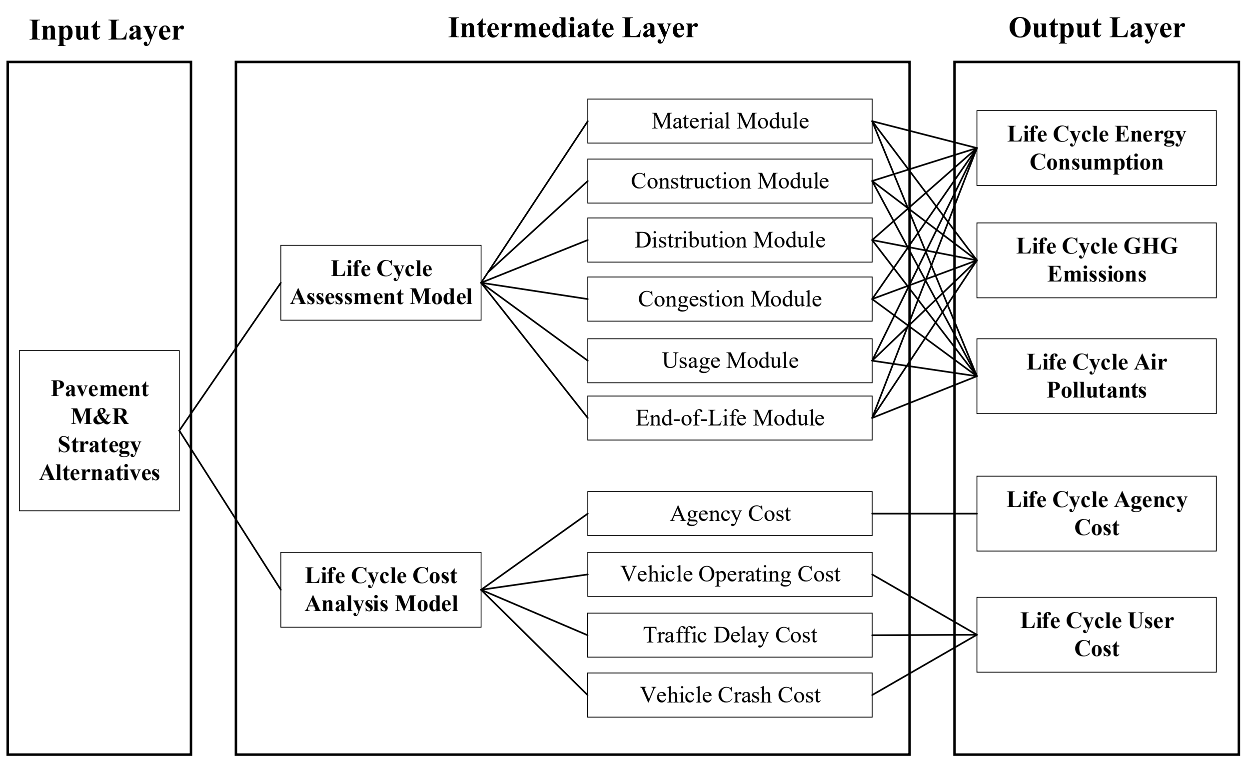

Figure 3-2 Integrated LCA-LCCA Framework for Pavement M&R Strategy Selection

As shown in Figure 3-2, the LCA model is divided into six modules: material module, construction module, distribution module, congestion module, usage module, and end-of-life module. To be specific, the material module includes the process of raw material acquisition; mining and crushing of aggregates; production of asphalt, cement, and other binders; manufacture of other materials, such as additives; transport to, from, and within the manufacturing sites; and mixing processes. The construction module accounts for equipment use and energy use at the construction site. The distribution module accounts for transport of materials and equipment to and from the construction site. The congestion module accounts for construction related traffic delay. The usage module accounts for the travel of vehicles on the pavement during normal traffic flow. The end-of-life module is user-defined for modeling either one of three types of activities at the end of pavement service life.

Life cycle energy consumption, GHG emissions, and air pollutants are identified as environmental impact factors. Life cycle agency cost and user costs (vehicle operating cost, traffic delay cost, and vehicle crash cost) are selected as economic factors. The LCA-LCCA output variable can be regarded as an objective function or as a constraint in the mathematical optimization analysis for pavement M&R strategy selection. If there is only one objective function, the pavement M&R strategy selection will become a single objective optimization problem. The optimal pavement M&R strategy would be unique. If two or more objective functions exist, the pavement M&R strategy selection will become a multi-objective optimization problem. Because these objectives, such as minimizing the life cycle cost and minimizing the life cycle energy consumption, are generally conflicting and competing with each other, it is impossible to find a solution that is optimal for all objectives at the same time. Then, highway agencies can choose different Pareto optimal solutions based on a specific objective function. For example, Pareto optimal solution for a two-objective optimization situation is illustrated in Figure 3-3. Points A, B, and C represent feasible solutions for two objectives, f_1 and f_2. Smaller values are preferred to larger ones for each objective. Given a set of feasible solutions, any movement from one solution to another that can improve at least one objective without making any other worse off is termed a Pareto improvement (e.g., moving from solution C to Solution A or B). If no further Pareto improvement can be made (e.g., moving from solution A to solution B along an indifference curve), Pareto efficiency has been reached. The Pareto frontier is the set of solutions that are Pareto optimal.

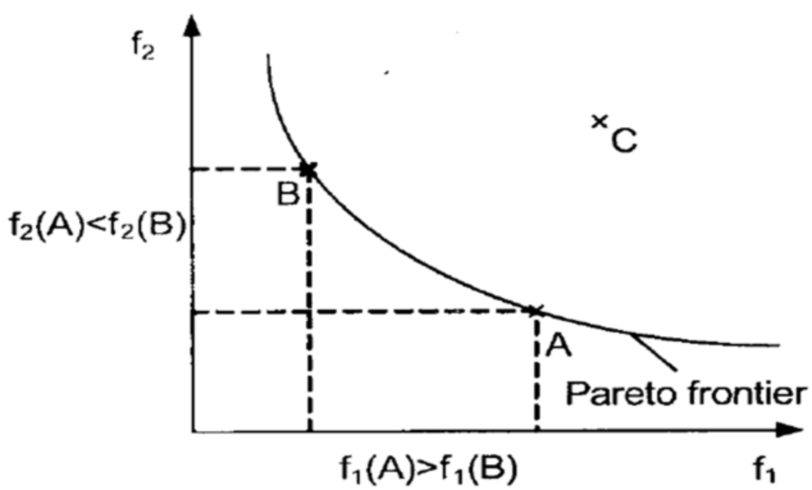

Figure 3-3 Multi-objective Optimization and Pareto Frontier (Zhang, 2009)

CHAPTER 4 PAVEMENT M&R EFFECT ON ROUGHNESS PROGRESSION

4.1 Introduction

A pavement roughness progression model is defined as the pavement roughness trend over the analysis period of time, which models the relationship between the IRI and a set of causal variables. Pavement roughness progression model is a key component that bridges the decision variables (M&R treatments) with the economic and environmental performance in an integrated LCA-LCCA optimization framework (Chong et al., 2017). Rough pavements have been validated to have a significant effect on vehicle operating costs in terms of extra fuel consumption, vehicle repair and maintenance, and tire wear (Watanatada et al., 1987; Zabbar and Chatti, 2010; Chatti and Zabbar, 2012; Wang et al., 2012). Pavement surface roughness effect was also identified as an important contributor to extra vehicle fuel consumption and emissions during pavement usage stage in LCA. In addition, pavement roughness trigger value can be used to determine the timing of M&R treatment in an integrated LCA-LCCA optimization framework.

4.2 Pavement M&R Treatment Effect on Roughness Progression in LCA Studies

To estimate the life cycle environmental impacts and costs of pavement M&R treatments during the pavement usage phase, pavement roughness models for different M&R treatments have to be developed. The effect of pavement M&R treatments on pavement roughness progression in current LCA or LCA-LCCA studies are reviewed and summarized as follows.

In Zhang's pavement LCA studies (Zhang, 2009; Zhang et al., 2010, 2011), the autoregressive overlay pavement deterioration model was firstly estimated with the historical distress index (DI) data of 27 unbounded concrete overlay projects and 67 hot mix asphalt (HMA) overlay projects from 1991 to 2005 in Michigan. A DI is typically used to gauge pavement conditions including surface roughness and deterioration in Michigan. Then, pavement overlay distress index models were transformed into pavement overlay roughness model by considering the relationship between DI and IRI. The specific overlay deterioration (DI) model and the relationship between DI and IRI for concrete overlay and HMA overlay are shown in Equations (4-1) through (4-4).

Concrete overlay: $$DI_t = 1.11DI_{t-1} + 0.15Age_{t-1} + 0.09 \quad (4\text{-}1)$$

HMA overlay: $$DI_t = 1.37DI_{t-1} + 0.01Age_{t-1} + 1.10 \quad (4\text{-}2)$$

Concrete overlay: $$IRI = \left(\frac{16.44DI}{35-DI}\right)^{0.300} \quad (4\text{-}3)$$

HMA overlay: $$IRI = \left(\frac{26.84DI}{35-DI}\right)^{0.308} \quad (4\text{-}4)$$

where pavement age is defined as the absolute number of years of a pavement from the last reconstruction. The DI value starts at 0 which indicates perfect pavement condition. A threshold of DI of 50 is used to indicate the need for overlay reconstruction (Ahmed et al., 2006).

In Yu's pavement LCA studies (Yu and Lu, 2011; Yu et al., 2012, 2013), the overlay roughness progression models for three overlay options (PCC overlay, HMA overlay, and CSOL overlay) were estimated by using the mechanistic empirical pavement design guide (MEPDG) models. And, it was assumed that IRI would be restored to its initial values when rehabilitation is performed every 16 years. The development trends of IRI for the three pavement overlay options are shown in Figure 4-1.

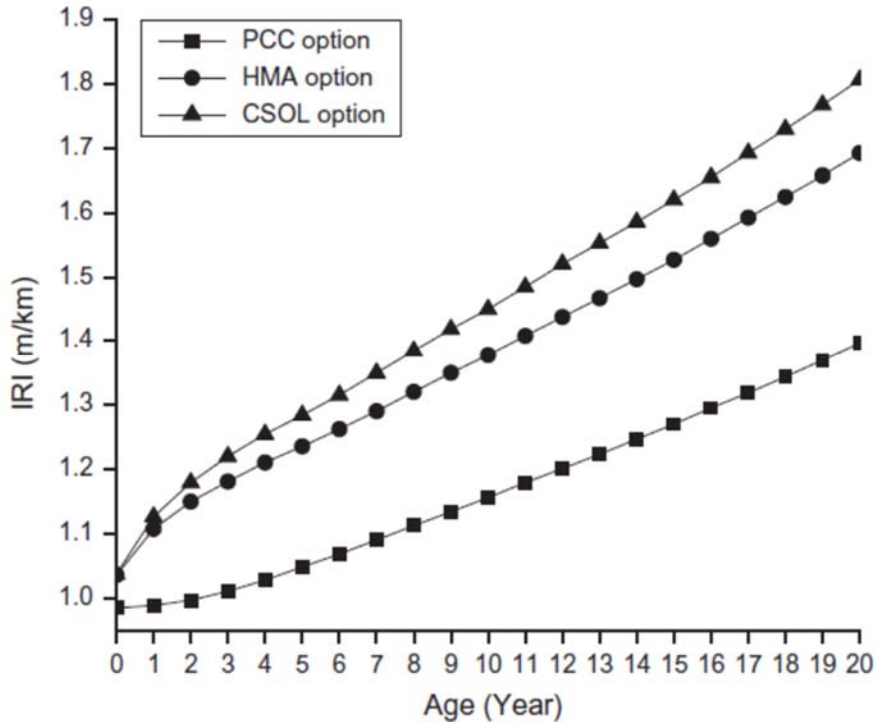

Figure 4-1 Pavement Overlay Roughness Progression Trends with MEPDG

In Wang's pavement LCA study (Wang et al., 2012), the pavement roughness progression after HMA overlay was obtained directly from California Department of Transportation (Caltrans) pavement condition survey (PCS) database at those locations in the case study. To evaluate the effect of concrete diamond grinding, linear regression models for both IRI drop and IRI progression after grinding were estimated with a sample of Caltrans grinding projects. The IRI drop and IRI progression for concrete diamond grinding are shown in Equations (4-5) and (4-6).

$$IRI_{drop} = -0.6839 + 0.6197 IRI_{before\ grinding} \quad (4\text{-}5)$$

$$IRI_{progression} = \left[-0.174 + 9.66 \times 10^{-5} \times \sqrt{CumESAL} + 1.15 \times \sqrt{Initial\ IRI}\right]^2 \quad (4\text{-}6)$$

where the unit for IRI_{drop}, $IRI_{before\ grinding}$, and $IRI_{progression}$ is m/km; $CumESAL$ is the cumulative equivalent single axle load (ESAL) that a lane has received after the grinding; $Initial\ IRI$ is the IRI value right after the grinding project. However, these samples may not be representative of all the grinding projects across the state.

In Wang and Gangaram's pavement LCA study (Wang and Wangaram, 2014), the effects of pavement preservation treatments on pavement roughness progression were represented by directly using the 10-year field roughness data at the typical site in the long-term pavement performance program (LTPP) specific pavement studies (SPS-3).

In Santos's LCA study (Santos et al., 2015), the pavement roughness progression for three different M&R strategies were estimated with historical IRI data. The pavement roughness progression models for the recycling-based M&R strategy, corrective M&R strategy, and reconstruction are shown in Equations (4-7) through (4-9).

$$\text{Recycling based M\&R:} \quad IRI_t = 0.002t^2 + 0.017t + 0.868 \tag{4-7}$$

$$\text{Corrective M\&R:} \quad IRI_t = 0.015t^2 + 0.050t + 0.868 \tag{4-8}$$

$$\text{Reconstruction:} \quad IRI_t = 0.002t^2 + 0.017t + 0.868 \tag{4-9}$$

where IRI_t is roughness at time t (m/km), t is number of years since the last M&R activity.

In Lidicker's integrated LCA-LCCA study (Lidicker et al., 2013), pavement overlay roughness progression model was developed as a function of both the roughness at the time of overlay application and the thickness of the overlay. The pavement overlay roughness improvement (Li and Madanat, 2002) is shown in Equation (4-10).

$$\Delta IRI = 5\sqrt{w} + 0.78IRI_{prior} - 66 \tag{4-10}$$

where IRI_{prior} is roughness value at the time immediately prior to overlay application (quarter-car index [QI], counts per kilometer, where the metric IRI = QI/13 for IRI < 17 m/km [Paterson, 1986]); w is overlay thickness (mm); ΔIRI is the reduction in roughness resulting from the application of an overlay (QI, counts per kilometer). Then, the pavement overlay roughness progression model (Paterson, 1987) was shown in Equation (4-11).

$$IRI_t = [IRI_0 + 725(1+N)^{-4.99} l_t] exp(0.0153t) \tag{4-11}$$

where IRI_t is roughness at time t (m/km); IRI_0 is the roughness immediately after the overlay (m/km), N is the structural design number of the pavement segment, t is number of years since the last overlay; and l_t is the cumulative ESALs until time t in units of million ESALs/lane.

In Yu's integrated LCA-LCCA study (Yu et al., 2015), the post-treatment pavement deterioration model for different preventive strategies referred to the research report (Huang and Dong, 2009). As shown in Equation (4-12), the post-treatment pavement performance model in terms of PSI was estimated with 36 typical maintenance projects. Then, as shown in Equation (4-13), post-treatment pavement roughness progression can be achieved by considering the relationship between PSI and IRI (Gulen et al., 1994).

$$PSI = \begin{cases} 3.454 - 0.0397t & for\ micro-surfacing \\ 3.977 - 0.0643t & for\ slurry\ seal \\ 3.560 - 0.0468t & for\ HMA\ overlay \\ 3.655 - 0.0401t & for\ Mill\ and\ fill \end{cases} \tag{4-12}$$

$$PSI = 7.21exp(-0.47IRI) \quad (R^2 = 0.84) \tag{4-13}$$

where IRI is in inches per mile, t is number of years since the last maintenance treatment.

In Santos's integrated LCA-LCCA study (Santos et al., 2017), pavement post-treatment deterioration models in terms of CCI (critical condition index) for corrective maintenance (CM), restorative maintenance (RM), and reconstruction (RC) were shown in Equations (4-14) through (4-16).

$$\text{CM: } CCI_t = CCI_0 - exp\left(9.176 + 9.18 \times 1.27295^{ln\left(\frac{1}{t}\right)}\right) \tag{4-14}$$

$$\text{RM: } CCI_t = CCI_0 - exp\left(9.176 + 9.18 \times 1.25062^{ln\left(\frac{1}{t}\right)}\right) \tag{4-15}$$

$$\text{RC: } CCI_t = CCI_0 - exp\left(9.176 + 9.18 \times 1.22777^{ln\left(\frac{1}{t}\right)}\right) \tag{4-16}$$

where CCI_t is the critical condition index in year t since the last M&R activity, i.e. CM, RM, or RC; CCI_0 is the critical condition index immediately after treatment. In Virginia, CCI is an aggregated indicator ranging from 0 (complete failure) to 100 (perfect condition) that represents the worst of either load-related or non-load-related distresses. In the study, the pavement condition immediately after three M&R treatments was assumed to be perfect ($CCI_0 = 100$). In addition, as shown in Equation (4-17), pavement roughness progression model for different M&R strategies was estimated with a linear regression model.

$$IRI_t = IRI_0 + 0.08t \tag{4-17}$$

where IRI_t is roughness at time t (m/km); IRI_0 is the roughness immediately after the overlay (m/km); t is number of years since the last maintenance treatment.

Based on the above literature review, pavement roughness progression model in most of current LCA studies (Zhang et al., 2010, 2011; Yu et al., 2015; Santos et al., 2017) only has pavement age as the predictor. The effects of traffic volume, pavement structure, and environmental characteristics on pavement deterioration are not considered. In addition, instead of using IRI, some researchers (Zhang, 2009; Zhang et al., 2010, 2011; Santos et al., 2017) developed pavement deterioration models in terms of regional performance indicators (e.g., DI, CCI). The transformation from regional performance indicators to IRI would add more uncertainty to the pavement roughness progression model. What’s more, instead of using the pavement roughness progression model, some researchers (Wang and Wangaram, 2014) directly used observed roughness trend after M&R activities. However, the results from that case study may not provide much reference to the engineering practice. In addition, the pavement roughness progression model estimated with MEPDG models and assumed inputs (e.g., site factor) may not reflect the actual pavement deterioration process. In a word, pavement roughness progression models for different M&R activities need to be further studied with in-service pavement performance data.

4.3 Post-Rehabilitation Pavement Roughness Progression Model

A sound pavement performance model should incorporate: (1) relevant variables that affect deterioration process; (2) physical principles that reflect deterioration mechanisms; and (3) rigorous statistical approaches for estimating the model (Hong and Prozzi, 2004).

In Empirical-Mechanistic pavement roughness progression models, to simulate the actual pavement deterioration process, function form and specification (choice of predictors) are based on physical considerations (mechanistic principles) and the model parameters are estimated with empirical data and statistical techniques (Madanat et al., 2005). Unlike Mechanistic-Empirical models (e.g., MEPDG), due to the absence of pavement response models, Empirical-Mechanistic models require a relative small set of variables. This modeling approach is also feasible for developing IRI progression models because the exact physical process of pavement surface roughness deterioration is too complex to be fully understood.

To estimate the effect of pavement M&R on pavement roughness progression, endogeneity bias problem will occur when observation data are used. Because pavements are typically designed with higher standards when the roads are expected to carry higher levels of traffic during the design life, maintenance activities are more likely to be implemented for those pavements with higher traffic volumes. Therefore, experimental data is best suitable for developing post-rehabilitation pavement roughness progression models.

CHAPTER 5 CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

The purpose of this research is to develop an integrated LCA-LCCA framework to assist in making the environmental and cost-effective pavement M&R decisions. A comprehensive literature review focusing on previous pavement LCA and integrated LCA-LCCA studies was conducted. Based on the literature review, the major conclusions are summarized as follows.

- Pavement M&R activities have a significant impact on life cycle environmental impacts, especially in material production phase, construction phase, and use phase.
- Material, construction-related traffic congestion, and pavement surface roughness effects are three major contributors to energy consumption and GHG emissions for pavement M&R activities.
- Most of integrated LCA-LCCA frameworks only consider energy consumption, GHG emissions, agency cost, and vehicle operating cost as life cycle performance indicators. The air pollutants, traffic delay cost, and vehicle crash cost are typically ignored.
- Pavement roughness progression models after M&R activities are identified to be an essential part of the integrated LCA-LCCA framework.
- Pavement roughness progression models in most of current LCA studies only have pavement age as the predictor. The effects of traffic volume, pavement structure, and environmental characteristics on pavement deterioration are not considered.
- Further study is needed to develop an Empirical-Mechanistic pavement roughness progression model for different M&R activities with a large sample of in-service pavement performance data.

5.2 Future Work

To bridge the research gaps existing in the current pavement LCA-LCCA studies, a research study focusing on post-rehabilitation pavement roughness progression model will be conducted with the Long Term Pavement Performance (LTPP) database in the next phase.

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