Life-Cycle Civil Engineering – Biondini & Frangopol (eds)
© 2008 Taylor & Francis Group, London, ISBN 978-0-415-46857-2

An integrated life cycle assessment and life cycle analysis model for pavement overlay systems

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ABSTRACT: Pavement systems have significant impacts on the environment and economy due to large material consumption, energy input, and capital investment. To evaluate the sustainability of rigid pavement overlay designs, an integrated life cycle assessment and life cycle cost analysis model was developed to calculate the environmental impacts and costs of overlay systems resulting from material production and distribution, overlay construction and maintenance, construction-related traffic congestion, overlay usage, and end of life management. An unbonded concrete overlay system, a hot mix asphalt overlay system, and an alternative engineered cementitious composite (ECC) overlay system are examined. Model results indicate that the ECC overlay system reduces total life cycle energy by 15% and 72%, greenhouse gas (GHG) emissions by 32% and 37%, and costs by 40% and 58% compared to the concrete overlay system and the HMA overlay system, respectively, over the entire 40 year life cycle. These advantages are derived from the enhanced material properties of ECC which prevent reflective cracking failures (discussed in a complementary paper). Material consumption, traffic congestion caused by construction activities, and roughness effects caused by overlay deterioration are identified as three dominant factors that influence the environmental impacts and costs of overlay systems.

1 INTRODUCTION

Pavement systems are fundamental components of our automobile transportation systems. While the transportation of people and goods is increasing rapidly, pavement systems have serious impacts on the environment and the economy. Yet, the American Society of Civil Engineers (ASCE) report card assigns US roads a grade of D (poor condition). This poor road condition costs US motorists an estimated $54 billion annually in vehicle repair and operating costs (ASCE 2006). Sustainability is increasingly adopted as a framework for designing and constructing pavement systems. Life cycle assessment (LCA) and life cycle cost analysis (LCCA) methodologies provide the means for evaluating the sustainability of pavement systems.

An integrated LCA and LCCA model (LCA-LCCA) was developed to provide sustainability indicators for pavement systems, in this case a pavement overlay system. As pavements age and deteriorate, maintenance and rehabilitation are required to provide a high level of safety and service (Huang 2004). For pavements subjected to heavy traffic, one of the most prevalent rehabilitation strategies is placement of an overlay on top of the existing pavement (DOT 1989). An overlay provides protection to the pavement structure, reduces the rate of pavement deterioration, corrects surface deficiencies, and adds some strength to the existing pavement structure. Depending on local conditions (i.e. traffic volume, truck loads, etc) and existing pavement, two possible designs are generally used: an unbonded concrete overlay or a hot mixed asphalt (HMA) overlay. The use of either concrete or asphalt poses significant environmental challenges. Additionally, concrete and asphalt have some physical limitations that contribute to durability concerns, which increase the likelihood of pavement overlay failure and maintenance frequency. Consequently, alternative materials are being developed to improve overlay performance. Part of the process to introduce new materials into application includes evaluation of the environmental impacts at each stage of the material life cycle from resource extraction through manufacturing, transportation, construction and final disposal.

LCA is an analytical technique for assessing potential environmental burdens and impacts. LCA provides metrics that can be used to measure progress toward environmental sustainability (Keoleian and Spitzley 2006). LCA studies the environmental aspects and potential impacts throughout a product's life from raw material acquisition through production, use and disposal (ISO 1997). An LCA model of a pavement overlay system was developed prior to this study's integration of an LCA and LCCA model. The LCA development is described in Zhang et al (2007).

LCCA model evaluates the monetary values of processes and flows associated with a product or system (Keoleian and Spitzley 2006). Like LCA models, LCCA models vary in scope and depth, accounting for different kinds of costs. For example, LCCA models may account only for internal costs (agency costs), such as construction costs and maintenance costs; it may also account for social costs, such as user costs which are incurred by motorists who are delayed or detoured by construction related traffic, or environmental costs including environmental damage costs associated with construction events.

The life cycle model in this study was applied to compare the environmental impacts for an overlay built using concrete, HMA, and a new material—Engineered Cementitious Composites (ECC), a high performance fiber-reinforced cementitious composite (HPFRCC).

ECC is a unique fiber-reinforced composite developed using a microstructural design technique driven by micromechanical principles. ECC is deliberately designed as a fiber reinforced cementitious material with a deformation behavior analogous to that of metals (Li 2003). Experimental testing of ECC overlays reveals significant improvements in load carrying capacity and system ductility over concrete or steel fiber reinforced concrete overlays (Qian 2007). Thereby, ECC can eliminate common overlay system failures such as reflective cracking (Li 2003). ECC is a promising candidate material for road repairs, pavement overlays, and bridge deck rehabilitation (Li 2003).

The objective of this research is to create a model that can analytically measure the sustainability indicators of pavement overlay systems. In addition, pavement construction and maintenance, roadway deterioration, and the impacts of traffic are dynamically captured. This integrated model is unique in its ability to capture pavement overlay life cycle energy consumption, environmental impacts, and costs including the upstream burdens of materials and fuel production. In the following section, the system boundary is defined and the integrated LCA-LCCA models are described. Subsequently, the life cycle model is applied to compare the environmental impacts and the costs of three pavement overlay systems. Finally, sensitivity analysis is performed for different traffic growth rates and fuel economy improvement scenarios.

2 METHODOLOGY

2.1 *System definition*

The overlay designs analyzed in this study are constructed upon an existing reinforced concrete pavement. The annual average daily traffic (AADT) is approximately 70,000 vehicles with 8% heavy duty trucks (MDOT 1997). In the baseline scenario, the annual traffic growth rate is 0%. The three overlay systems are modeled as 10 km long freeway sections in two directions. Each direction has two 3.6 m wide lanes, a 1.2 m wide inside shoulder, and a 2.7 m wide outside shoulder. The thickness of the overlay depends on the material (concrete, HMA, or ECC) and construction methods. The concrete overly is 175 mm thick and unbonded from the existing pavement by a 25 mm asphalt separating layer. The ECC overlay is 100 mm thick and constructed directly on the existing pavement. The HMA overlay is 190 mm thick. These pavement overlay designs are based on the results from experimental studies conducted at the University of Michigan and typical pavement overlay designs (Qian 2007 and Huang 2004). In the LCA model, the concrete and HMA overlays are designed for a 20 year service life by the Michigan Department of Transportation (MDOT 2005). The service life of ECC overlay is expected to be twice that of the concrete overlay by preventing commonly observed overlay failure modes, such as reflective cracking (Li 2003).

2.2 *Integrated LCA-LCCA model*

Figure 1 shows the integrated LCA-LCCA model framework. The LCA model is divided into six modules: material production, consisting of the acquisition and processing of raw materials; construction, including all construction processes, maintenance activities, and related construction machine usage; distribution, accounting for transport of materials and equipment to and from the construction site; traffic congestion, which models all construction and maintenance related traffic congestion; usage, including overlay roughness effects on vehicular travel and fuel consumption during normal traffic flow; and end of life, which models demolition of the overlay and processing of the materials. Details of each module are described in Zhang et al (2007). Input and output data from each module are evaluated to capture the material consumption, energy

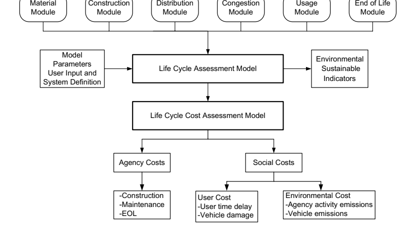

Figure 1. Integrated LCA-LCCA model framework.

consumption, and environmental impacts of the overlay system throughout its service life. Several datasets are required to provide the life cycle information for input materials or processes. For example, the dataset for ECC production provides the raw material consumption, total primary energy consumption, pollutant emissions, and wastes associated with producing a unit volume of ECC. Raw material consumption quantifies the non-fuel material inputs, such as the mass of cement required. Total primary energy consumption includes the energy required for extraction, refining, transportation, and processing the material. The air and water pollutant emissions and solid wastes are also modeled for each life cycle stage. These datasets and sources can be found in Keoleian et al and Zhang et al (Keoleian et al 2005; Zhang et al 2007).

The LCA model is linked to four external models: (1) a material environmental impact model, SimaPro 7.0 developed by PRe Consultants (Pre 2007); (2) a vehicle emissions model, MOBILE 6.2 developed by U.S. Environmental Protection Agency (EPA) (US EPA, 2002), and four localized MOBILE 6.2 data inputs for the winter and summer seasons which include annual temperature range, Reid vapor pressure, age distribution of the vehicle fleet, and average vehicle miles traveled data (SEMCOG 2006); (3) a construction equipment model, NONROAD, also developed by the EPA (US EPA, 2005); (4) and a traffic flow model developed at the University of Kentucky (KTC 2002).

The LCCA model incorporates the results of life cycle assessment modeling to calculate agency and social costs. The framework of the LCCA model was first developed by Kendall et al (2006).

Agency costs include all costs incurred directly by the Michigan Department of Transportation over the lifetime of the overlay system. These are typically construction and maintenance costs including material costs, equipment rental and operating costs, and labor costs. The actual agency costs were obtained directly from MDOT construction contracts.

Social costs are often not directly considered in the evaluation of DOT construction and maintenance activities. Generally, social costs include user costs and environmental costs. User costs are more likely to be considered in more densely populated states or urban areas, while environmental costs are not considered by any transportation agency in the US (Chan 2006). Even so, the literature is limited in examining how social costs are actually applied by state DOTs.

As mentioned in description of the LCA model, overlay construction and maintenance activities, and overlay deterioration will affect traffic flow. These traffic impacts result in user costs, since they are incurred by highway users traveling on the system. User costs are the differential costs incurred while driving between normal operations and work zone operations or poor pavement conditions. User costs are an aggregation of user delay costs, vehicle operating costs (including fuel costs), and risk of traffic accidents (Wilde et al 2001).

User delay costs normally dominate user costs. The total cost of travelers sitting in traffic is determined by multiplying the value of driver time with the additional number of hours spent in work zone congestion or on detours as compared to the number of hours spent traveling the equivalent distance in normal traffic flow conditions. The value of time (delay costs rate) for passenger vehicles, single unit trucks, and combination trucks is \$11.58/veh-hr (vehicle hour), \$18.54/veh-hr, and \$22.31/veh-hr respectively, estimated by the Federal Highway Administration (Wall and Smith 1998). Costs are in 1996 dollars and updated to 2006 dollars in the LCCA model using the Consumer Price Index.

Vehicle operating costs account for higher fuel consumption and thus higher fuel costs when driving through a work zone or on a deteriorated overlay as compared to normal conditions. If drivers choose to detour to avoid congestion, they will travel a greater distance which also increases fuel consumption. Due to surface deterioration, the overlay surface roughness increases continuously over time. Roughness is often measured using the International Roughness Index (IRI), which was developed by the World Bank in 1986 (Sayers and Gillespie 1986). Increased road roughness is estimated to reduce onroad fuel economy. The effect of roughness on fuel consumption is shown in Equation 1 (WesTrack 1999), where FCF is the fuel consumption factor (greater than 1.0).

$$FCF = 0.0667IRI + 0.8667 \quad (1)$$

User costs are also based on increased risk of traffic accidents. Both traveling through construction work zones and traveling additional distances when detours are chosen contribute to increased costs of traffic accidents. In the state of Michigan, an additional \$0.13/VMT traveled in the construction zone and a \$0.09/VMT traveled in a detour are used to estimate the increased risk costs (MDOT 2003).

User costs should be considered when deciding the proper long term design of an overlay system, since user costs associated with overlay construction and maintenance usually exceed agency costs significantly (Zhang et al 2007 and Wilde et al 2001). Minimizing the interruption of traffic flow during construction and maintenance activities over the total life cycle of an overlay is important for highway designers.

Environmental costs include the pollution damage costs over the entire life cycle of an overlay system. These costs are related to both direct and indirect impacts to human health from air pollution; the inhaling of air pollutants detrimental to human health, and

Table 1. Air pollution damage costs by impacted region (Kendall et al 2006).

	Average cost (2006 US $/t)			
Pollutants	Urban	Urban fringe	Rural	Global
SO_x	$6,732	$3,013	$877	
NO_x	$171	$71	$21	
CO	$186	$96	$23	
$PM_{2.5}$	$2	$1	$0	
Pb	$4,333	$2,256	$526	
VOC	$2,147	$2,147	$2,147	
CO_2				$23
CH_4				$7,792
N_2O				$421

greenhouse gases that result in global warming. Six criteria pollutants specified by the US EPA which have direct impact to human health are considered, including sulfur dioxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), particular matter ($PM_{2.5}$), lead (Pb), and volatile organic compounds (VOC). Three major greenhouse gases that are inventoried include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The marginal costs of those pollutants are shown in Table 1 (Kendall et al 2006). Since the criteria pollutants are sensitive to geographic region, values for urban, urban fringe and rural areas are calculated separately. GHG emissions have global consequences, therefore global costs are used.

The discount rate is a central element to economic analysis which can significantly influence LCCA results. Historical trends over last several years indicate that the real time value of money ranges approximately between 3% to 5% (Wilde et al 2001). In the LCCA model, a real discount rate is used. Real discount rates reflect the true time value of money with no inflation premium. The real discount rate of 4% for agency and user costs was estimated based on values recommended by the U.S. Office of Management and Budget (OMB) (Office of Management and Budget 2005).

Environmental costs are not discounted traditionally, due to the significant uncertainty in environmental impacts and their associated costs. A series of sliding-scale discount rates was developed by Weitzman using a gamma discounting approach. The discount rate was divided into following scale: for the immediate future (years 1–5), a 4% discount rate is used; for the near future (years 6–25), a 3% discount rate is used; for the medium future (years 26–75), a 2% discount rate is used (Weitzam 2001).

2.3 *Pavement overlay deterioration model*

Pavement overlay deterioration modeling is important to connect pavement maintenance strategies to impacts on users. In Michigan, a Distress Index (DI), which represents a holistic measure of pavement condition (including surface roughness and deterioration), is used rather than IRI to gauge pavement conditions (MDOT 2005). However, DI and IRI are correlated. No mechanics based theoretical model for DI exists as it depends on many factors such as temperature, traffic flow and load, types of pavements, and age of pavement. Currently, MDOT uses a threshold of DI of 50 to indicate the need for overlay reconstruction.

The construction and maintenance strategies for the concrete and HMA overlay systems are based on historical maintenance and pavement management records (MDOT 2005). The life cycles for each of the three systems begin with overlay construction. The concrete overlay is reconstructed in its 21st year, with major maintenance events at year 11 and year 31. The HMA overlay is reconstructed in its 20th year, with major maintenance events in year 8 and year 28, and minor maintenance events in year 6, 12, 26, and 32. The ECC overlay lasts for a 40 year service life with a single maintenance event and no reconstruction. Based on these construction and maintenance strategies, Figure 2 shows the DI increasing trends over time.

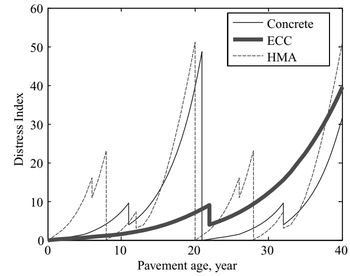

Figure 2. Distress index of each pavement.

3 RESULTS

3.1 *Life cycle assessment result*

Total life cycle results represent the environmental impacts from the material module, construction module, distribution module, traffic congestion module, usage module (roughness effect on vehicle fuel economy) and end of life (EOL) module over a 40 year timeline. The environmental indicators in this study include energy consumption and greenhouse gas emissions.

The primary energy consumptions for 10 kilometers of the concrete, ECC and HMA overlays are 6.8×10^5 GJ, 5.8×10^5 GJ and 2.1×10^6 GJ, respectively. As shown in Figure 3, the life cycle energy consumption for the three overlay systems is dominated by material

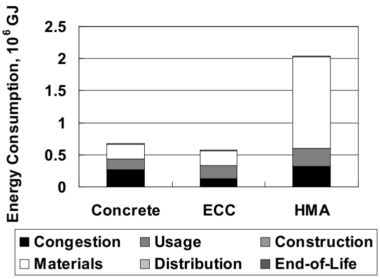

Figure 3. Primary energy consumption by life cycle phase.

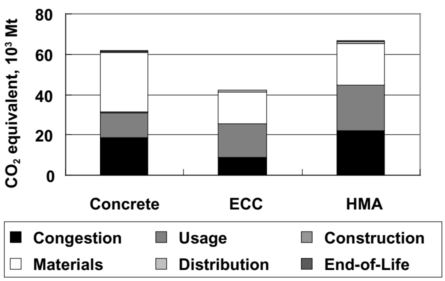

Figure 4. Greenhouse gas emissions by life cycle phase.

production energy, traffic congestion related energy, and roughness related energy. Roughness related fuel consumption has not been previously studied using LCA methods. Without considering surface roughness effects, the life cycle energy consumptions of three overlay systems decreases by 23%, 36%, and 14%, respectively.

Due to the superior material properties of ECC, which can double overlay service life compared to the other materials, the ECC overlay uses about 15% and 72% less energy than the concrete overlay and the HMA overlay, respectively. The high energy consumption for an HMA overlay is caused by the high feedstock energy contained in asphalt which accounts for 30% of the total life cycle primary energy consumption for HMA system.

Greenhouse gas (GHG) emissions inventoried in this study include CO_2, methane, and nitrous oxide. The global warming impact is characterized by GHG emissions in metric tons of CO_2 equivalent. This is calculated by multiplying the mass of each GHG emission by its global warming potential (GWP), where GWP for CO_2 is 1, for methane is 23, and for nitrous oxide is 296. Figure 4 shows the global warming impact of each overlay system.

CO_2 emissions significantly dominate the contribution to global warming impact. In the concrete overlay system CO_2 represents 99.2% of total life cycle GWP, in the ECC system CO_2 represents 99.4% of total life cycle GWP, and in the HMA system CO_2 represents 94.4% of total life cycle GWP. The ECC system reduces GHG emissions by 32% and 37% compared to the concrete overlay system and HMA overlay system, respectively. Generally, CO_2 emissions correlate with energy consumption; however, cement production releases CO_2 during calcination of limestone, which results in twice the CO_2 that would be produced from energy consumption alone (Keoleian et al 2005). Additionally, a large amount of primary energy consumption in the HMA overlay system is the feedstock energy. Carbon embodied in the material is fixed and does not generate CO_2 unless it is burned. This relationship is evident in the comparison of Figure 3 and Figure 4 wherein the CO_2 emission of the HMA overlay system is not significantly higher than the other two systems.

Table 2. Life cycle costs for overlay systems.

	Concrete	ECC	HMA
Agency cost	$10.1 m	$6.2 m	$14.8 m
User cost	$61.9 m	$37.4 m	$84.2 m
Environmental cost	$0.9 m	$0.7 m	$1.1 m
Total cost	$72.9 m	$44.3 m	$100 m

3.2 *Life cycle cost analysis result*

Table 2 shows the results for life cycle costs. The ECC overlay system demonstrates a cost advantage over the other two overlay systems in all cost categories assessed.

Despite higher initial construction costs for the ECC overlay system, the lower maintenance frequency due to improved ECC material properties results in an accumulated agency cost savings for ECC compared to the concrete and HMA overlay systems.

User costs account for more than 80% of total life cycle costs in each overlay system. Environmental costs are small compared to agency and user costs. Essentially, the cost distribution is driven by traffic parameters. Since this research deals with a high traffic volume freeway, congestion-related user time delays are significant. Thus, user costs overwhelmingly dominate total life cycle costs. If assumed traffic volume is lower, the likely impact of user costs in total life cycle costs will decrease and the impact of agency costs and environmental costs will rise.

4 CONCLUSION

The results of this study show that an ECC overlay system had lower environmental burdens and life cycle costs over a 40 year service life compared to concrete and HMA overlay systems. By extending the service life and minimizing maintenance frequency, the ECC overlay system reduces total life cycle energy by 14%, GHG emissions by 32%, and costs by 40%, compared to the concrete overlay system. Material, traffic, and roughness effects were identified as the greatest contributors to environmental impacts throughout the overlay system life cycle. User costs significantly dominate total life cycle costs. Both the service life and maintenance schedule are key factors which determine the overlay system performance. Alternative overlay design strategies, such as varying overlay thickness and different maintenance schedules, can be implemented based on local traffic conditions and pavement requirements. Using this approach, the decision maker is able to design a more optimal overlay system among a number of alternative materials.

The integrated LCA-LCCA model outlined in this paper dynamically captures cumulative traffic flows, overlay deterioration over time, and maintenance activities to evaluate life cycle environmental burdens and costs. The incorporation of pavement overlay roughness effects on fuel consumption and related life cycle environmental burdens represents a significant extension of existing models. The resulting life cycle model enables decision makers to evaluate pavement infrastructure projects from a more holistic, long term perspective while providing criteria for more sustainable infrastructure material selection.

ACKNOWLEDGEMENTS

The authors would like to graciously thank the US National Science Foundation MUSESE Grant (CMS-0223971 and CMS-0329416) for funding this research.

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