LIFE CYCLE COST MODEL FOR EVALUATING THE SUSTAINABILITY OF BRIDGE DECKS

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ABSTRACT

Concrete infrastructure systems require large capital investments and resource flows to construct and maintain. An integrated life cycle assessment and cost model was developed to evaluate infrastructure sustainability, and compare alternative materials and designs using environmental, economic and social indicators. The model is applied to two alternative concrete bridge deck designs: one a conventional steel reinforced concrete (SRC) deck with mechanical steel expansion joints, and the other an SRC deck with engineered cementitious composite (ECC) link slabs. Life cycle energy, greenhouse gas emissions, agency costs for construction and rehabilitation, and social costs including construction-related user delay costs and environmental pollutant damage costs are quantified for each system over a 60-year bridge service life. Results show that the ECC link slab system has a 37% cost advantage over the conventional system, consumes 40% less total primary energy, and produces 39% less carbon dioxide.

1. INTRODUCTION

Environmental, economic, and social performance indicators demonstrate significant impacts of current concrete infrastructure systems (ASCE 2001, TRIP 2002). Concrete's brittleness and limited durability lead to significant infrastructure failure and repair. An estimated one-third of US roadways are in poor condition (ASCE 2001), burdening society with large capital investments and construction-related impacts such as congestion (TRIP 2001b). New infrastructure and maintenance of existing infrastructure has led to a global output of construction-related concrete that exceeds 12 billion tons per year (van Oss and Padovani 2002b). This enormous volume represents huge flows of material between natural and human systems, which is expected to increase significantly as world population urbanizes (UNFPA 2001). Cement production accounts for 5% of all global anthropogenic carbon dioxide (CO_2) emissions

(Hendricks et al. 1998, Worrell 2001) and significant levels of SO2, NOx, particulate matter and other airborne pollutants (WBCSD 2002, US EPA 1999, US EPA 2000).

Currently, only functional performance and conventional financial costing guide the design of new infrastructure materials. A new life cycle framework to integrate broader social, environmental and economic issues into the R&D and application of new materials is critical for achieving sustainable infrastructure. This framework is being developed and applied by the University of Michigan (UM) through a five-year National Science Foundation Materials Use: Science, Engineering, and Society (MUSES) Biocomplexity Program grant. This research draws upon the diverse expertise and resources of a core network of seven UM faculty. Participating units include the Advanced Civil Engineering Material Research Lab, the Center for Sustainable Systems, College of Engineering, School of Public Health, School of Natural Resources and Environment, and the Department of Geological Sciences.

This paper addresses our macroscale research effort and presents life cycle based environmental, economic and social indicators for assessing the sustainability of a bridge deck. This study compared two bridge deck systems: one with conventional concrete (CC) joints, the other with engineered cementitious composite (ECC) link slabs. ECC is a unique fiber-reinforced material with a microstructure design driven by micromechanical principles (Kanda and Li 1998b, Li 1998). Unlike other concrete materials, ECC strain-hardens after first cracking, similar to a ductile metal, and demonstrates a strain capacity 500-600 times greater than normal concrete (Li 2003). ECC contains ingredients similar to those in fiber-reinforced concrete (e.g., water, cement, sand, fiber and chemical additives); coarse aggregates are notably absent in ECC. The amount of fiber (e.g., polyvinyl alcohol and polyethylene) in ECC is generally 2% or less by volume.

2. INTEGRATED LIFE CYCLE ASSESSMENT AND COST MODEL

The life cycle model used to evaluate infrastructure sustainability indicators consists of two integrated elements: 1) a life cycle inventory analysis/impact assessment model of material production, construction, use, repair, and demolition stages; and 2) a life cycle cost model of agency and social costs. This integration is shown (Fig. 2) along with other model components that characterize the infrastructure system, vehicle emissions, and traffic flows. Environmental impact categories evaluated include energy and material resource consumption, air and water pollutant emissions, and solid waste generation. Agency costs consisted of material, construction, and end-of-life costs, while social costs were comprised of pollution damage costs from agency activities, and vehicle congestion, user delay, vehicle crash, and vehicle operating costs. These indicators are evaluated for the total 60-year service life of a bridge with a traffic flow rate of 35,000 cars per day in each direction.

2.1 Bridge System

The life cycle assessment (LCA) focuses on material production, construction, use, and end-of-life management stages related to bridge deck repair (Fig. 3). Consequently, the initial bridge construction, which is common to both conventional and ECC systems, is excluded from this study. For application in this LCA model, the bridge deck service life is assumed to be 30 years

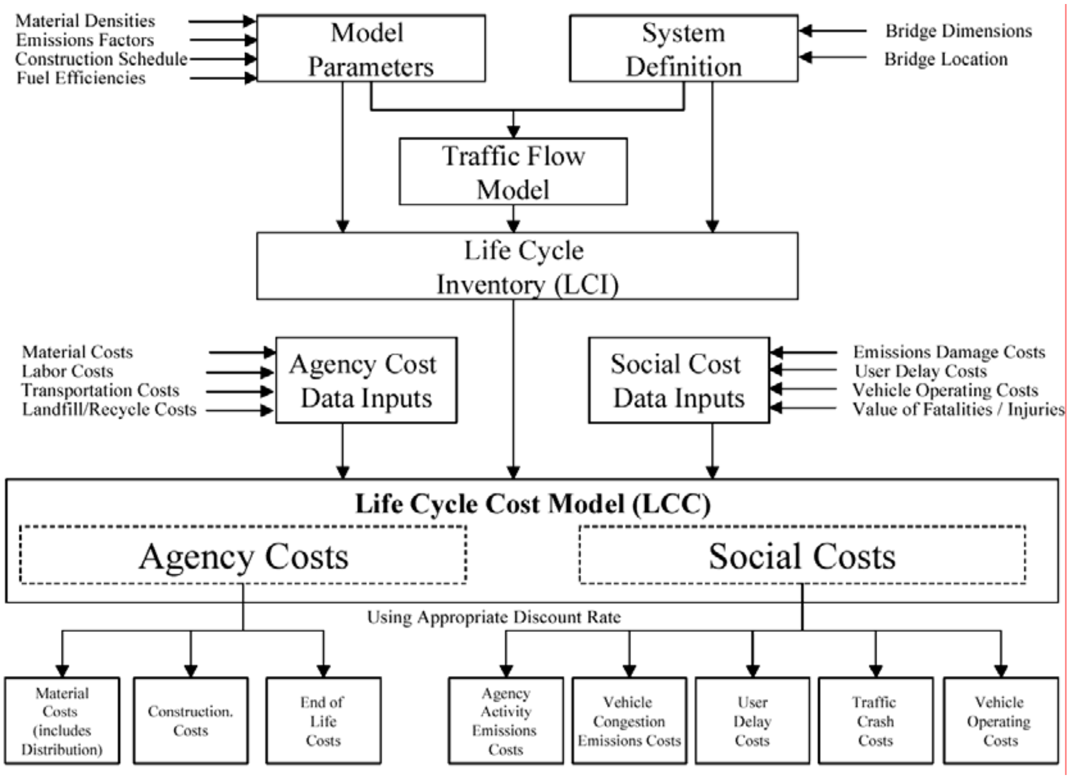

Figure 2. Integration of Traffic Flow, Life Cycle Inventory, and Life Cycle Cost Models

for the conventional steel-reinforced concrete system, and 60 years for the ECC system. The doubling of service life for the ECC system has yet to be validated with additional field and laboratory testing. These properties and design specifications are based on estimates provided by a professional construction agency and results from a pilot study sponsored by the Michigan Department of Transportation (Li et al. 2003).

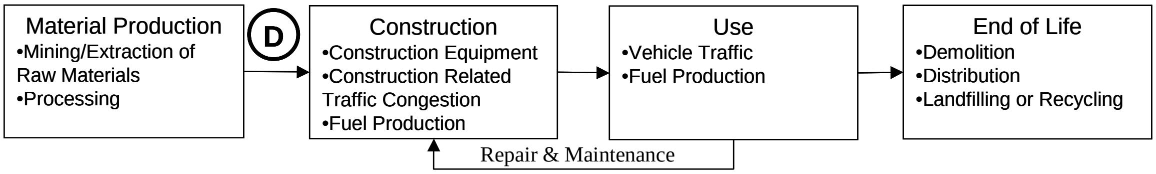

Figure 3: Bridge Deck Life Cycle Phases (D = distribution)

The ECC link slab is three meters long and is poured in direct contact with the adjoining concrete (Fig. 4). The conventional joint consists of two steel expansion devices, with a rubber seal between them. There are three main re-construction options for a bridge: bridge deck replacement, deck resurfacing, and repair and maintenance.

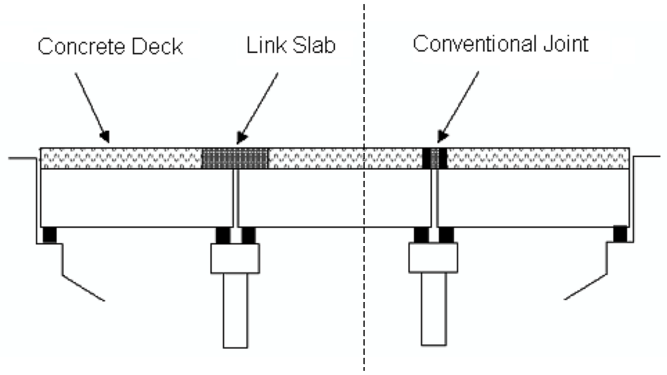

Figure 4. Bridge deck with ECC link slab and conventional mechanical steel expansion joint

2.2 Life cycle assessment model

Life cycle assessment is an analytical technique for evaluating the full environmental burdens and impacts associated with a product system (ISO 1997). Modeling the complete life cycle of a bridge system is complex and data intensive. Data sets necessary for modeling the material production phase were obtained from various sources including the Portland Cement Association (2000 cement data for four kiln types and wide range of efficiencies), DEAMTM (Ecobilan's Database for Environmental Analysis and Management), and the International Iron and Steel Institute (2000 steel data). For the construction stage of the life cycle, estimates of each machine's operating times during the construction process were made, and fuel-related emissions were estimated using the US EPA NONROAD model of diesel engine emissions (USEPA 2000a). The model allows specification of construction equipment based on 26 machinery types, and 15 horsepower classes.

Traffic congestion related to construction activities is included in the scope of this analysis. Traffic delays are estimated using the KyUCP model developed by the Kentucky Transportation Center (KTC 2002), which is based on methodology from the Federal Highway Administration. Construction related delays are calculated using model input parameters such as traffic flow rate, road capacity, work zone speed limits, lane width, and lane closure. The impacts of construction events on fuel consumption for highway vehicles were estimated using fuel economy data from US EPA and US DOE. A city drive cycle is the closest estimate of fuel economy available for modeling stop-and-go movement typical of congestion. Likewise, a highway drive cycle for normal traffic flow is used to model flow during non-construction and non-congestion periods.
Energy use, fuel consumption, and emissions for the traffic stage is always calculated based on the difference between traffic flow during construction periods and the baseline scenario under normal highway flow conditions. Automotive emissions are based on US EPA MOBILE6.2 data. The construction timeline and other details of the life cycle assessment model are described elsewhere (Kendall 2004, Keoleian et al. 2005).

2.3 Life cycle cost model

The term life cycle cost (LCC) is not used consistently. The more traditional view of LCC evaluates costs incurred by government agencies all through the value chain (from raw material acquisition to end of life). Such costs are termed "agency costs." Recently, efforts have been made to broaden this definition to be more inclusive of other costs associated with construction projects. In particular, several studies, using a more holistic LCC approach, have been conducted with the goal of determining agency costs as well as user costs, which are expenses incurred by those using the system in question. For instance, Ravirala and Grivas looked at determining life cycle costs for highway management and included traditional agency costs, such as construction and traffic control, as well as user delay costs – costs incurred by those waiting in construction traffic (Ravirala and Grivas 1995). Ehlen has conducted several studies that look to expand the definition of life-cycle costing even further by recognizing costs due to environmental effects and those inflicted upon businesses affected by construction (Ehlen 1997, Ehlen 1999). While Ehlen's studies note the importance of such externality costs, his studies do not account for them in calculating life-cycle costs.

For agency costs in this analysis, a Michigan construction company provided information about the bridge deck and construction process. This included material, labor, and equipment cost data; construction activity schedules, and construction equipment used throughout the life cycle of the bridge deck. Fuel cost data for industrial consumers in the State of Michigan as of November 2003 were provided by the Department of Energy (USDOE 2004).

A 4% discount rate was used for all construction activities. In addition, all non-emissions social costs will also use a 4% discount rate, reflecting the opportunity cost of the agencies that bear these costs. The social costs from air pollutant emissions for each stage of the life cycle were estimated using environmental loadings from the life cycle assessment model and unit damage costs taken from several sources. The traffic congestion created by construction events leads not only to additional emissions, but also to lost time for the drivers of the vehicles. Sitting in construction related traffic reduces the productivity of the drivers (e.g., individuals headed to work or freight trucks hauling finished goods). The value of a driver's time was estimated using data from the Federal Highway Administration (FHWA) (USDOT 1998). Determining the number of work-zone-related traffic crashes, injuries, and fatalities for the bridge was a more difficult task, which is described in detail elsewhere (Chandler 2004).

8. RESULTS

The results of the life cycle cost analysis are presented in Table 1. The total life cycle cost of the conventional system was $35.7 million compared to $22.6 million for the ECC system. The ECC system has an approximate cost advantage of 37% over the conventional system. While ECC is more costly on a per volume basis, the total agency costs for the ECC system were considerably less than the conventional system over the 60 year service life of the bridge.

Table 1. Life Cycle Cost Results

	CC	**ECC**
Total Agency Cost	$751,058	$488,888
User Cost (time, fuel, crash)	$34,908,776	$22,074,667
Environmental Costs	$43,105	$23,399
Total Life Cycle Costs	$35,702,939	$22,586,954

The agency costs for construction and rehabilitation activities are dwarfed by the social costs. As with the LCA model, the LCC model shows that user-related costs such as time lost to motorists and commercial trucks due to construction related congestion dominate the total life cycle costs calculated in the model. In fact user costs, led primarily by the costs of delays from construction-related traffic congestion, account for 98% of costs in the ECC and conventional systems. The user and environmental costs were substantially lower for the ECC system. Fewer days of construction for the ECC system resulted in lower user costs than the CC system. User delay, vehicle operating and traffic crash costs were all lower for the ECC system. Environmental costs from pollution had a small impact on the total life cycle costs, representing only 0.1% the total.

In addition to the cost reductions of the ECC system over the conventional, the ECC system results in a net savings of both energy and material mineral resources. The total life cycle energy consumption over the 60 year time horizon was 75,000 GJ for the conventional system compared to 45,000GJ for the ECC system, which represents a 40% reduction. Total energy consumption for both systems modeled is dominated by traffic-related energy consumption as is evident in Fig. 5. The distribution of greenhouse gas (GHG) emissions is similar to those for energy consumption as shown in Fig. 6. Traffic related carbon dioxide (CO_2) dominates total GHG production for both the ECC and conventional bridge systems. Material production is the only other significant contributor. Typically, CO_2 emissions mirror energy consumption; however, the production of cement involves the release of additional CO_2 during pyroprocessing (conversion of calcium carbonate to calcium oxide), which results in twice the CO_2 that would be produced from energy consumption alone (CEMBUREAU 1998).

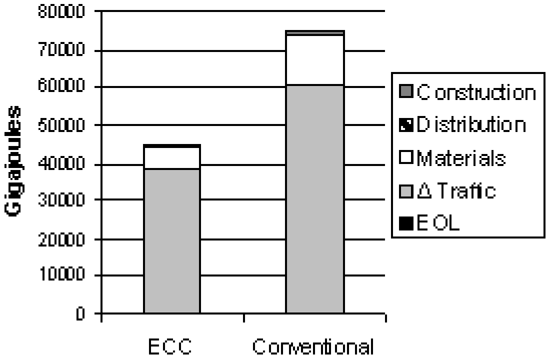

Figure 5: Total Primary Energy Consumption by Life Cycle Stage

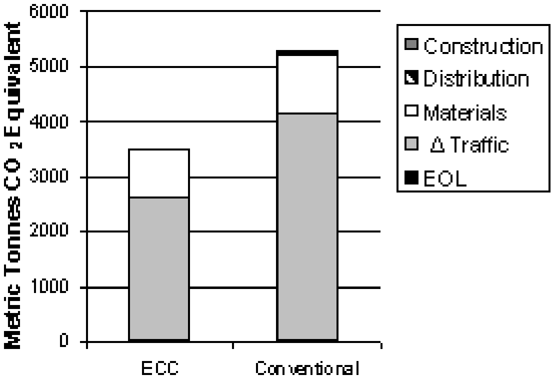

Figure 6: Total Global Warming Potential by Life Cycle Phase

Life cycle solid waste generation totaled 3970 metric tonnes for the conventional system, and 2000 metric tonnes for the ECC system, approximately half the solid waste generation of the conventional system. In both systems, bridge materials constitute the majority of solid waste, accounting for 87% in the ECC system and 90% in the conventional system.

CONCLUSIONS

This paper demonstrates a model and indicators for evaluating the sustainability of an infrastructure system. By integrating life cycle assessment and life cycle cost analysis, environmental indicators and agency and social costs can be evaluated. The application of this integrated model to bridge deck joint design highlighted the critical importance of using the life cycle modeling in order to enhance the sustainability of infrastructure systems. This study showed that the ECC link slab bridge deck design resulted in significantly lower environmental impacts and costs over a 60 year bridge deck service life compared to the conventional steel expansion joint system. A key finding from life cycle modeling was the dominance of construction related traffic on the social cost results and environmental performance of both deck systems. Consequently, predicting maintenance and repair schedules for each system is critical in evaluating alternative materials from life cycle cost and environmental performance perspectives.

A primary goal of the MUSES project is to link the macroscale life cycle modeling presented herein with ECC microstructure tailoring research to improve the material design process. New formulations of ECC are currently being tested and evaluated. The environmental, social and economic performance indicators can be used to guide changes in material design in order to optimize sustainability of the system. The integrated life cycle approach is also transferable to other emergent materials and infrastructure systems that are characterized by large societal investments.

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