Network-Level Pavement Asset Management System Integrated with Life-Cycle Analysis and Life-Cycle Optimization

Han Zhang[1]; Gregory A. Keoleian[2]; and Michael D. Lepech[3]

Abstract: The authors have developed a new network-level pavement asset management system (PAMS) utilizing life-cycle analysis and optimization methods. Integrated life-cycle assessment and cost analysis expand the scope of the conventional network-level PAMS from raw material extraction to end-of-life management. To aid the decision-making process, the authors applied a life-cycle optimization model to determine the near-optimal preservation strategy for a pavement network. The authors utilized a geographic information system (GIS) model to enhance the network-level PAMS by collecting, managing, and visualizing pavement information data. The network-level pavement asset management system proposed in this paper allows decision makers to preserve a healthy pavement network and minimize life-cycle energy consumption, greenhouse gas (GHG) emissions, or cost as a single objective, and also meet budget constraints and other agency constraints within an analysis period. A case study of a pavement network in Michigan compares the near-optimal preservation strategy to the Michigan DOT's current preservation practice. Compared with the current preservation plan, the optimal preservation strategy reduces life-cycle energy consumption, GHG emissions, and cost by 20, 24, and 10%, respectively. The authors also analyzed the impact of annual preservation budget cuts on total life-cycle cost. A US$3 million annual preservation budget reduction (75% reduction of current annual budget) will significantly increase user cost (caused by congestion and pavement surface deterioration) by US$450 million for a 40-year analysis period. **DOI: 10.1061/(ASCE)IS.1943-555X.0000093.**

CE Database subject headings: Pavements; Assets; Life cycles; Costs; Optimization.

Author keywords: Pavement asset management; Life-cycle assessment; Life-cycle cost analysis; Optimization.

Introduction

Highway agencies are facing the challenges of aging highways, deteriorating networks, and inadequate pavement preservation budgets. Passed in 2005, the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) federal transportation legislation provided a guaranteed funding of US$244.1 billion to promote more efficient and effective federal surface transportation programs by focusing on highways, highway safety, and the environment. This program gave state and local transportation decision makers more flexibility for solving transportation problems, such as reducing traffic congestion, improving efficiency in freight movement, protection of the environment, and improving safety (SAFETEA-LU 2005). However, DOT decision makers need a network-level pavement asset management system (PAMS) to allocate increasingly limited budgets efficiently.

There are two major administrative levels of any pavement asset management system, project- and network-level PAMS (Mbwana 2001). Project-level PAMS are intended to predict pavement deterioration, select the appropriate preservation activity, and develop the optimal preservation schedule for a specific pavement segment. Network-level PAMS incorporate a pavement segment preservation prioritization scheme that accounts for a budget allocation strategy. Network-level PAMS polices build on the optimal polices for the project-level PAMS recommendations to ensure that each individual pavement segment preservation strategy will result in an overall optimal solution for the entire pavement network (Sathaye and Madanat 2011).

Network-level PAMS have become an important tool for state highway agencies to determine maintenance and rehabilitation schedules and allocate limited resources. In 1982, Arizona developed a pavement management system to optimize maintenance policies for its highway network (Golabi et al. 1982). This system was based on linear programming and focused on minimizing cost. In 1989 the Federal Highway Administration (FHwA) issued a policy that requires each state highway agency to have a PAMS (FHwA 1989). Currently, the Michigan DOT (MDOT) relies on the Michigan Road Quality Forecasting System (RQFS) to develop preservation strategies for regional DOT management districts. This software uses current pavement condition data from their pavement management system to predict future network conditions. However, a mix of fixes approach, based on pavement remaining service life, decides the future preservation strategy. The lack of knowledge on optimization and sustainability consideration prevents the MDOT from identifying the most efficient and

[1]Research Assistant, Center for Sustainable Systems, School of Natural Resources and Environment, Univ. of Michigan, 440 Church St., Dana Building, Ann Arbor, MI 48109. E-mail: hanzhang@umich.edu

[2]Co-Director, Center for Sustainable Systems; Professor, School of Natural Resources and Environment; Professor, Civil and Environmental Engineering, Univ. of Michigan, 440 Church St., Dana Building, Ann Arbor, MI 48109 (corresponding author). E-mail: gregak@umich.edu

[3]Assistant Professor, Dept. of Civil and Environmental Engineering, Stanford Univ., 285B 473 Via Ortega, Stanford, CA 94305. E-mail: mlepech@stanford.edu

Note. This manuscript was submitted on June 4, 2011; approved on January 12, 2012; published online on January 14, 2012. Discussion period open until August 1, 2013; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Infrastructure Systems***, Vol. 19, No. 1, March 1, 2013. © ASCE, ISSN 1076-0342/2013/1-99-107/$25.00.

effective preservation strategy to improve the environmental performance of a pavement network.

To improve sustainability, pavement asset management systems should have the ability to account for sustainability indicators, such as user time delay caused by preservation activities, additional fuel consumption caused by pavement surface deterioration, and other environmental impacts. Life-cycle assessment (LCA) and life-cycle cost analysis (LCCA) have been identified as the most comprehensive tools to evaluate sustainability performance (Keoleian and Spitzley 2006; Zhang et al. 2008, 2010b). Recent literature suggests that LCA and LCCA have been applied to evaluate environmental and economic impacts of transportation infrastructure (Horvath and Hendrickson 1998; Zapata and Gambatese 2005; Keoleian et al. 2005; Bilec et al. 2006; Santero and Horvath 2009; Bilec et al. 2010; Sathaye and Madanat 2011). Several researchers have further demonstrated the integration of optimization methods with LCA or LCCA to improve design and management (Fwa et al. 1996; Azapagic and Clift 1999; Kim et al. 2003; Furuta and Frangopol 2008; Zhang et al. 2010a). Previous studies have only included a limited number of applicable life cycle components and sustainability indicators in their analysis, thus generating an incomplete picture of the pavement sustainability and an ineffective pavement preservation strategy. User time delay caused by pavement preservation activities and pavement surface deterioration were identified as key factors in determination of the environmental impacts of a pavement system (Santero and Horvath 2009; Zhang et al. 2010b). Given that a pavement segment can be preserved through a variety of different rehabilitation methods and frequencies, which will lead to differences in life cycle energy consumption, environmental impacts, and costs, a life-cycle optimization (LCO) model that integrates with LCA and LCCA concepts is necessary to effectively improve pavement management and performance.

A network-level PAMS also must have the ability to manage and analyze the large pavement condition dataset. A network-level PAMS relies on pavement condition information for identifying pavement construction sections, developing preservation strategies, and allocating budgets. Geographic information systems (GIS), with their unique spatial analysis capability, allow highway agencies to integrate, manage, query, and visualize pavement conditions. A number of researchers and highway agencies have applied GIS platforms for enhancing pavement asset management. Medina et al. (1999) developed a prototype low-volume roads pavement management system using a GIS tool for Fountain Hills, AZ. The Illinois DOT developed a GIS-based pavement information and management system using a weighted benefit ranking procedure (Bham et al. 2001). These systems are anticipated to considerably improve the communication between PAMS and the decision maker.

The objective of this paper is to develop a network-level pavement asset management system that incorporates integrated LCA-LCCA and LCO models. The integrated LCA-LCCA model evaluates sustainability, including energy consumption, greenhouse gas (GHG) emissions, and economic costs of a pavement network. Subsequently, the LCO model develops the near optimal pavement network preservation strategy to minimize sustainability metrics, and also meet budget constraints and other agency constraints within an analysis period. Additionally, the authors developed a GIS model to enhance the network-level PAMS by collecting, managing, and visualizing pavement information data. The authors applied the network-level pavement asset management system to a case study of a pavement network in Michigan to compare the near optimal preservation strategy with the Michigan DOT's current preservation practice.

Methodology

Fig. 1 shows the framework of the network-level PAMS. The integrated LCA-LCCA model evaluates the life-cycle costs for a pavement network. User time delays caused by preservation activities, pavement surface roughness effects, and environmental damage costs are also captured by the integrated LCA-LCCA model. Details of this model are described in Zhang et al. (2008, 2010b). The GIS model provides the pavement information (e.g., pavement condition, age, and type) to the integrated LCA-LCCA model and LCO model. The LCO model develops the optimal pavement network preservation strategy to minimize one or multiple sustainability metrics (e.g., costs and energy consumption) based on current pavement network condition and budget constraint. The integrated LCA-LCCA model calculates the life cycle results based on the optimal preservation strategy. The GIS model stores these results for efficient retrieval and viewing.

Integrated Life-Cycle Assessment and Life-Cycle Cost Analysis Model

The authors carried out an integrated LCA-LCCA study of pavement systems by following ISO standards (2006a, b) to capture the life cycle energy consumption, environmental impacts, and economic costs. Details of LCA modeling were described in Zhang et al. (2010b). Fig. 2 shows the life cycle phases of a pavement system. The authors further divided the life cycle of a pavement system into six modules, as follows:

- 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 equipments from the nearest supplier locations by a combination of roadway, railway, and waterway,
- Traffic congestion, which models all construction and maintenance related traffic congestion,
- Usage, including pavement roughness effects on vehicular travel and fuel consumption during normal traffic flow, and
- End of life, which modeled preservation and reconstruction process of a pavement at the end of its designed service life.

The authors used LCA software, SimaPro (PRe 2012), to calculate material and energy balances and to quantify the burdens and

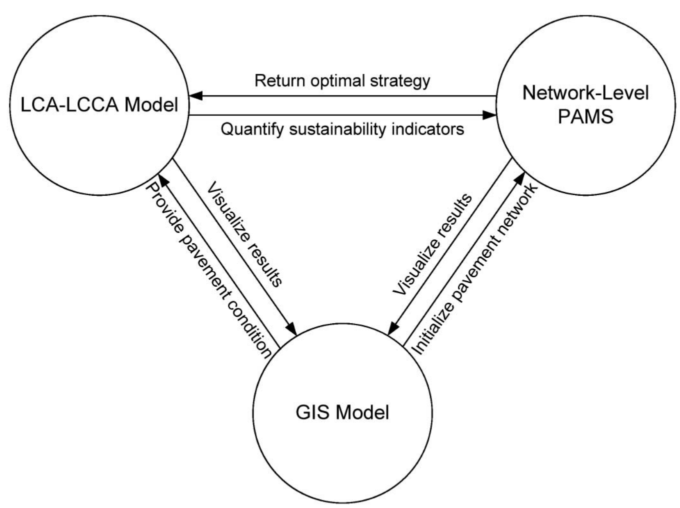

Fig. 1. Integrated framework of the network-level PAMS

J. Infrastruct. Syst. 2013.19:99-107.

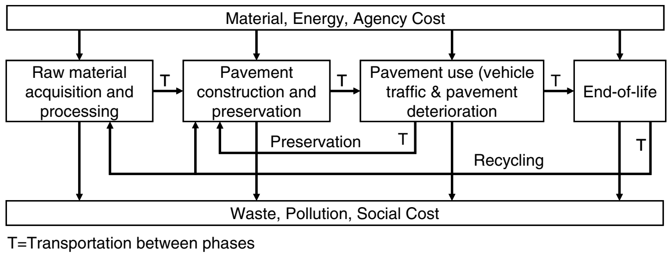

Fig. 2. Life cycle phases of a pavement system

impacts of each module. Additionally, the authors used three external models, as follows:

- The authors used *MOBILE 6.2* developed by the U.S. EPA to model on-road vehicle emissions based on 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 [Southeast Michigan Council of Governments (SEMCOG) 2006] to model on-road vehicle emissions,
- The uthors used *NONROAD*, also developed by the U.S. EPA, to calculate non-road emissions from construction equipment, and
- The authors used KyUCP, a traffic flow model developed at the University of Kentucky (Kentucky Transportation Center 2002), to simulate the traffic congestion caused by construction events.

The LCCA model incorporates the results of life cycle assessment modeling to calculate agency and social costs. Agency costs include all costs incurred directly by the highway agency over the lifetime of a pavement system. Social costs are not often addressed in the construction and maintenance activities of the transportation agency. Generally, social costs include user and environmental damage costs. Pavement construction and preservation activities, along with the condition of the pavement itself, affect traffic flow. These impacts are termed user costs, which are incurred by highway users traveling on the pavement system. In Michigan, a distress index (DI) quantifies the pavement surface condition. The DI value starts at 0, which indicates perfect pavement conditions. Although there is no upper limit for the DI value, the MDOT uses a threshold DI of 50 to indicate the need for pavement rehabilitation or reconstruction (Ahmed et al. 2006). The authors used DI to determine the surface roughness of a pavement to calculate direct impact on vehicle energy consumption and environmental impacts (Lee et al. 2002). In the case of comparative models, user costs are limited to the differential costs incurred while driving in normal operations versus driving in work zone operations or on poorly maintained pavement. User costs are an aggregation of user delay costs (Walls and Smith 1998; Zhang 2008, 2010b), vehicle operating costs (Wilde et al. 2001; Davis and Diegel 2004), and risk of traffic accidents (MDOT 2002; Chandler 2004). Environmental damage costs measure the pollution damage costs over the entire life cycle of a pavement system. These costs are related to both direct and indirect impacts to human health from air pollution, such as the inhalation of air pollutants detrimental to human health and GHG emissions that contribute to global warming. The unit damage cost of each pollutant can be found in Kendall et al. (2008). In the LCCA model, the authors applied a fixed discount rate of 4%, recommended by the U.S. Office of Management and Budget (OMB), to agency and user costs (USOMB 2010). Because of significant uncertainty in environmental impacts and their damage costs, the authors used a series of sliding-scale discount rates, ranging from 2–4%, to calculate the future environmental damage costs (Zhang et al. 2010a).

In mathematical terms, the life cycle energy consumption, environmental impacts, and costs can be determined as follows:

$$\begin{aligned}\mathrm{LCI}_b &= B_b[i,j,DI(i)]\\ &= \sum_i \{M[i,j,DI(i)] + CS[i,j,DI(i)] + D[i,j,DI(i)]\\ &\quad + CG[i,j,DI(i)] + U[i,j,DI(i)] + E[i,j,DI(i)]\}\omega_b\end{aligned} \tag{1}$$

where LCI = life cycle inventory of b; b = energy consumption (MJ), GHG emissions (kg), or costs (US$); i = index of year; j = maintenance alternative decisions (0, 1, and 2 indicate no action, minor maintenance, and major maintenance, respectively); $[DI(i)]$ = distress value at year i; ω_b = life cycle energy consumption, GHG emissions, or costs associated with one unit of raw material, utility, or process; $B_b[i,j,DI(i)]$ = burden (life cycle energy consumption, GHG emissions, or costs) at year i with decision j for one DI value; $[M(i,j)]$ = material consumption at year i with decision j; $CS(i,j)$ = construction equipment usage at year i with decision j; $D(i,j)$ = transportation of materials and equipment at year i with decision j; $CJ[i,j,DI(i)]$ = construction-related traffic congestion at year I with decision j; $U[i,j,DI(i)]$ = pavement surface roughness impact at year i with decision j for one DI value; and $E[i,j,DI(i)]$ = end of life management of pavement system at year i with decision j for one DI value.

Life-Cycle Optimization Model

A pavement segment in the pavement network can be managed through a variety of different preservation methods and frequencies, which lead to a variety of different life cycle energy requirements, environmental impacts, and economic costs (Zhang et al. 2010b). The authors developed a life-cycle optimization model to provide a unique, optimal pavement preservation strategy based on a specific objective(s) and constraint(s). The authors assume in this study that all construction and preservation events are conducted during the daytime. A possible method to decrease the impact of construction and maintenance activities is to apply nighttime construction and maintenance methods. Because of lower traffic volumes at night, the user time delay cost will decrease. However, there is a potential increase in labor cost and accident-related cost.

Given that most factors in a pavement asset management system are nonlinear, an efficient nonlinear programming algorithm such as those used in knapsack or resource allocation problems should be applied (Sathaye and Madanat 2011). In this application, dynamic programming methods have been selected to solve the nonlinear and discrete time multistage decision making problem, because it is more efficient to solve problems exhibiting the properties of overlapping sub-problems and easy to formulate. Dynamic programming has been widely used in pavement management optimization (Feighan et al. 1988; Madanat and Ben-Akiva 1994; Ravirala and Grivas 1995; Durango and Madanat 2002; Durango 2004; Ouyang 2007). Dynamic programming takes advantage of avoiding full enumeration, thus reducing the number of computations. The pavement life is broken into several stage and state variables. The stage variable represents each year in the analysis period. The state variable is the pavement condition. At each stage and each possible state, a set of preservation decisions can be made for each pavement segment.

The authors developed a backward dynamic programming procedure to select the optimal preservation strategy from all candidate decisions. The computation starts at year N (stage variable), the final year of the analysis period. At the year N, the DI value (state variable) of 0 is first examined. The LCO model calculates the energy consumption, GHG emissions, and costs of each possible decision to remember the minimum result. Next, the DI value increases discretely by 0.5 from 0–50 and the LCO model repeats the process. At year $N-1$, started again from a DI value of 0, the highway agency has the opportunity to perform a major maintenance activity, a minor maintenance activity, or do nothing. Each decision has its impact on the DI value of year N. If the decision at year $N-1$ is "do nothing," the DI value at year N will increase and can be calculated by using the auto-regression model equation. The development of the auto-regression model has been discussed in Zhang et al. (2010a). If the decision at year $N-1$ is "do a major maintenance," the DI value at year N will decrease. The authors estimate the magnitude of the DI reduction based on the level of the current DI value. For example, if the current DI value of a concrete overlay is 10, after the major maintenance, the next year's DI value is 3.

The LCO model calculates the intermediate result $f_b[i, DI(i)]$, which is the sum of the following: (1) the annual burden, $B_b[i, j, DI(i)]$, and (2) the expected intermediate result $f_b[i+1, DI(i+1)]$ of the future stage resulting from the applied decision. The detailed equation for $f_b[i, DI(i)]$ is given by Eq. (2), as follows:

$$f_b[i, DI(i)] = \begin{cases} \min\limits_{j=0,1,2} \{B_b[i, j, DI(i)] + f_b[i+1, DI(i+1)]\} & \forall\ i = n, \ldots, N \\ 0 & \forall\ i > N \end{cases} \tag{2}$$

Each solution, therefore, is a series of preservation decisions of the form "perform a major maintenance at year 8 and minor maintenance activity at year 12," for example. To solve each of these dynamic programs, a computer program using Visual Basic Application (VBA) and run within Microsoft Excel software was coded to implement the LCO model and connect with the integrated LCA-LCCA model.

If the highway agency has an unrestricted budget, all segments in the pavement network should follow the optimal preservation strategy developed by the life-cycle optimization model to achieve the optimal results (minimizing life cycle energy consumption, GHG emissions, or economic costs). However, if the total budget of the highway agency is not sufficient to maintain an optimal pavement condition throughout the entire pavement network, the network-level PAMS is necessary to adjust the optimal preservation strategy developed from the life-cycle optimization model and to allocate the limited budget to specific pavement segments based on a priority selection process. Thus, a priority selection model is a key part within the network-level PAMS. Yeo et al. (2010) developed a two stage bottom-up approach, which used project-level optimal solution and evolutionary algorithms to identify the near optimal solution for a pavement network. Their study demonstrated the feasibility of combining project- and network-level optimization to effectively solve the budget allocation of multiple facilities. However, environmental impacts such as GHGs and primary energy consumption are not considered as objectives in the decision making process.

The computational difficulty tends to increase dramatically when applying dynamic programming to large pavement networks. Thus, to decide the priority of each pavement segment, the authors propose an approximation method using binary integer programming to identify the near optimal solutions based on the limited agency budget. The objective function is defined as the following:

$$\text{Minimize } F_1X_1^T + F_2X_2^T + \cdots + F_nX_n^T \tag{3}$$

where F_k = burden vector of pavement segment k, from the current analysis period to the last analysis period; and X_k = preservation activity vector of pavement segment k, as follows:

$$F_k = [f_{k1}, f_{k2}, \ldots, f_{km}], \qquad X_k = [x_{k1}, x_{k2}, \ldots, x_{km}]$$

f_{kj} = burden of performing preservation activity j of pavement segment k, from the current analysis period to the last analysis period; and x_{kj} = preservation activity j of pavement segment k.

Subject to the following:

$$C_1X_1^T + C_2X_2^T + \cdots + C_nX_n^T \le C \tag{4}$$

where C_k = agency cost vector of pavement segment k; and C = total annual budget.

$$C_k = [c_{k1}, c_{k2}, \ldots, c_{km}]$$

c_{kj} = agency cost of preservation activity j of pavement segment k.

The other constraints include the following:

$$DI \le \text{Max}\, DI(50); \quad \text{if } DI > 50, \text{ perform reconstruction} \tag{5}$$

$$x_{kj} \in \{0, 1\}, \quad k = 1, 2, \ldots, n; \; j = 1, 2, \ldots, m \tag{6}$$

$$\sum_{j=1}^{m} x_{kj} = 1, \quad k = 1, 2, \ldots, n; \; j = 1, 2, \ldots, m \tag{7}$$

GIS Model

To integrate GIS with the network-level pavement asset management system, several GIS base map layers are created, each of which contains various sets of attributes, such as pavement management control section (CS), pavement type (concrete or asphalt), pavement remaining service life (RSL), annual average daily traffic (AADT), commercial average daily traffic (CADT), and pavement condition (distress index). The linear referencing method has been applied to associate these attributes to portions of the pavement (ESRI 2004). To generate the final pavement segments and visualize them on map, the authors use a dynamic segmentation method (ESRI 2004). The authors used the commercial GIS software *ArcGIS 9.2* to create the digital pavement network map and conduct the linear referencing and dynamic segmentation process.

J. Infrastruct. Syst. 2013.19:99-107.

Case Study: Washtenaw County Pavement Network

Pavement Network Initialization

The authors selected Washtenaw County, Michigan, as a case study. Washtenaw County covers 1,871 km^2 and has almost 350,000 residents (U.S. Census Bureau 2012). Several major highways cross Washtenaw County, including I-94 (Interstate), US-23 (United States highway), and M-14 (Michigan State Trunkline). These pavements in Washtenaw County are owned by the MDOT. The DOT also collects and maintains static, annual, and semi-annual pavement information data for this network. These data provide the length, width, location, pavement type, pavement distress index, and traffic flow of each pavement. To construct the case study pavement network a query analysis was conducted in the GIS model for identification of the pavement sections that satisfy the following predefined intervention criteria:

1. All pavement sections are freeways,
2. AADT ≥ 30,000, and
3. CADT ≥ 4,000.

The authors applied linear referencing and dynamic segmentation methods to the initial dataset. A total number of 29 pavement segments (total 120 km long) are generated. The description of each pavement segment is listed in Table 1.

Network-Level Pavement Asset Management Results

The network-level PAMS was applied to the previously discussed pavement network to develop the optimal preservation strategy for a 40-year analysis period. The annual budget for the entire pavement network was derived from the Michigan Five-Year Transportation Program (FYTP); see MDOT (2007). In the 2007–2011 FYTP, Washtenaw County and other nine nearby counties expect to receive approximately US$368 million for 2,150 lane-km of road preservation. Therefore, the annual budget allocated to the pavement network in this research was estimated to be US$4 million/year based on roadway length within the case study.

Alternative preservation methods used in this research are defined in the Michigan Pavement Design and Selection Manual (MDOT 2005). The unit costs are shown in Table 2.

Using the network-level PAMS, an optimal preservation strategy was developed. Another case based on the MDOT preservation plan was also generated to compare with the optimal preservation strategy. Fig. 3 shows the pavement surface condition, which is represented by the distress index in the 40-year analysis period using different preservation strategies. Because of more efficient allocation of resources, the pavement surface condition using the network-level PAMS method is generally better than the conditions using the current MDOT strategy.

The improved pavement surface condition decreases the fuel consumption for highway drivers and associated GHG emissions. The network-level PAMS also optimizes the preservation method selection and preservation frequency. It decreases traffic congestion caused by the interruption of normal traffic flow and decreases user time delay. User time delay has been identified as accounting for more than 80% of total life cycle cost for a high traffic volume freeway system in a 40-year analysis period (Zhang et al. 2008, 2010b). Thus, decreasing user time delay costs will further decrease the total life cycle cost. Fig. 4 shows the comparison of life cycle energy consumption, GHG emissions, and cost of the MDOT preservation strategy and network-level PAMS optimal strategy.

Table 1. Pavement Segments Information List

ID	Name	CS	BMP	EMP	Type	AADT	CADT	RSL	DI
1	I-94	81,041	0	3,790.8	Concrete	85,233	9,200	10	17.4
2	I-94	81,062	0	4,828.0	Asphalt	55,900	7,900	12	15.5
3	I-94	81,062	4,828.0	11,265.4	Asphalt	70,650	7,900	12	11.6
4	I-94	81,062	11,265.4	14,661.0	Asphalt	85,433	8,633	9	3.9
5	I-94	81,063	0	3,128.7	Asphalt	106,900	11,600	9	2.0
6	I-94	81,063	3,128.7	4,828.0	Asphalt	103,500	11,600	3	2.0
7	I-94	81,063	4,828.0	5,809.6	Asphalt	103,500	11,600	7	6.4
8	US-23	81,074	0	6,437.4	Concrete	73,850	6,950	6	9.3
9	US-23	81,074	6,437.4	12,028.0	Concrete	70,500	6,900	6	4.1
10	M-14	81,075	0	1,810.0	Concrete	56,100	5,500	11	25.3
11	US-23	81,075	0	4,828.0	Asphalt	64,300	6,000	11	21.1
12	US-23	81,075	4,828.0	11,748.2	Asphalt	65,820	6,000	11	20.0
13	US-23	81,075	0	1,209.8	Asphalt	63,100	7,900	11	24.5
14	US-23	81,076	0	1,609.3	Concrete	36,900	6,300	12	9.4
15	US-23	81,076	1,609.3	11,265.4	Asphalt	41,817	6,300	7	13.2
16	US-23	81,076	11,265.4	15,922.9	Asphalt	57,233	6,833	8	16.8
17	M-14	81,103	0	1,609.3	Asphalt	70,100	6,900	13	5.8
18	M-14	81,103	1,609.3	4,828.0	Asphalt	63,600	5,500	7	13.9
19	M-14	81,103	4,828.0	6,437.4	Asphalt	63,600	5,500	16	4.1
20	M-14	81,103	6,437.4	8,046.7	Asphalt	62,200	5,500	9	8.3
21	M-14	81,103	8,046.7	9,656.1	Asphalt	62,200	5,500	1	9.8
22	M-14	81,103	9,656.1	11,265.4	Asphalt	62,200	5,500	4	8.6
23	M-14	81,103	11,265.4	12,874.8	Asphalt	62,200	5,500	6	5.6
24	M-14	81,103	12,874.8	13,850.0	Asphalt	61,700	5,500	8	5.2
25	I-94	81,104	0	9,656.1	Asphalt	49,067	8,600	7	6.1
26	I-94	81,104	9,656.1	19,312.1	Asphalt	55,500	9,200	3	21.1
27	I-94	81,104	19,312.1	28,968.2	Asphalt	61,050	8,983	7	9.3
28	I-94	81,104	28,968.2	29,396.3	Asphalt	46,600	7,900	12	5.7
29	M-14	81,105	0	5,886.9	Concrete	32,750	4,400	3	1.7

Note: CS = control section; BMP = beginning meter point; EMP = ending meter point; AADT = annual average daily traffic; CADT = commercial average daily traffic; RSL = remaining service life; and DI = distress index.

J. Infrastruct. Syst. 2013.19:99-107.

Table 2. Alternative Preservation Methods and Unit Costs

Construction activity	Surface type	Process	Unit cost (2006 US$lane-mile)
Initial construction	Concrete	Concrete pavement construction	170,500
	HMA	HMA pavement construction	171,000
Minor maintenance	Concrete	Replace 10% seals, crack seal any cracked slab (estimated as 8%)	8,000
	HMA	Crack seal	6,400
Major maintenance	Concrete	Replace 30% seals, replace 15% joints, crack seal any cracked slab (estimated as 15%)	46,000
	HMA	Crack seal, patch	58,000
Overlay construction	Concrete	Overlay placement	154,000
	HMA	Overlay placement	154,500

Note: Data from MDOT (2005). HMA = hot-mix asphalt.

The results are presented in relative scale ranging from 0–100% (normalized to the current MDOT preservation strategy). The network-level PAMS optimal strategy decreases life cycle energy consumption, GHG emissions, and cost by 20, 24, and 10%, respectively.

Optimality Evaluation

Given that the authors applied the binary integer programming method to identify the near optimal solutions, an optimality evaluation has been conducted to determine the accuracy of the approximation. The authors evaluated 1,000 random cases for a three-segment pavement network for a 20-year analysis period. To simplify the calculation, the authors assumed each segment to have the same length. In each case, segments were randomly generated with initial pavement condition, pavement age, and pavement type (concrete or asphalt). The network-level pavement asset management model described in previous sections was applied to calculate the near optimal costs of each case. For comparison, true optimal costs for each case were calculated by exhaustive search. The result shows that in 96% of 1,000 cases near optimal costs are within a 2% difference of true optimal costs.

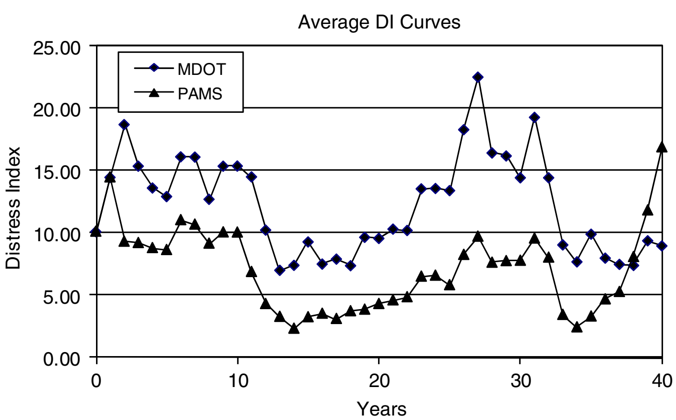

Fig. 3. Average DI curves based on different preservation strategies

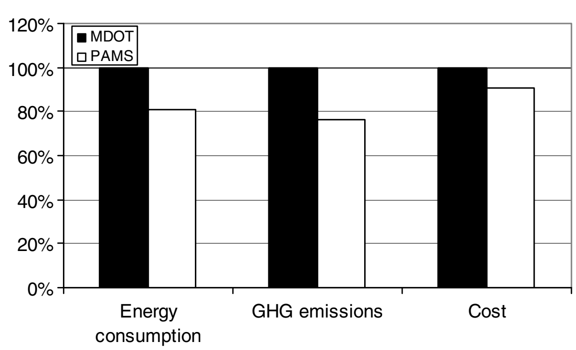

Fig. 4. Comparison of life-cycle energy consumption, GHG emissions, and cost of MDOT preservation strategy and network-level PAMS optimal strategy

Impact of Annual Preservation Budget

The annual preservation budget is an important factor that determines the total resources the highway agency can use for pavement preservation. To identify the impact of annual preservation budget on total life cycle cost, a sensitivity analysis was conducted. Fig. 5 shows the results. As the annual budget decreases from US$4–US$1 million, the total life cycle cost increases from US$1,310–US$1,690 million. As expected, agency costs decrease as the budget constraint tightens. However, user congestion costs and user roughness costs, which combined are approximately eight times higher than agency costs over the 40-year lifetime of a pavement system, increase as the annual preservation budget decreases, thus shifting costs from the DOT to the motoring public. The model also indicates that a budget of less than US$1 million/year is not enough to preserve the entire pavement network without failure (DI > 50).

The results obtained through the network-level pavement asset management system were then imported to the GIS model and visualized on the previously created digital map. As shown in Fig. 6(a), most pavement segments are predicted to be in good condition in the year 2010. Fig. 6(b) shows the cumulative life cycle cost from

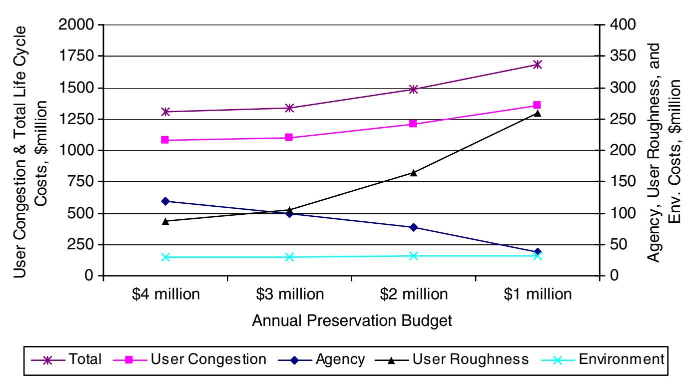

Fig. 5. Total life-cycle cost based on different annual budget

J. Infrastruct. Syst. 2013.19:99-107.

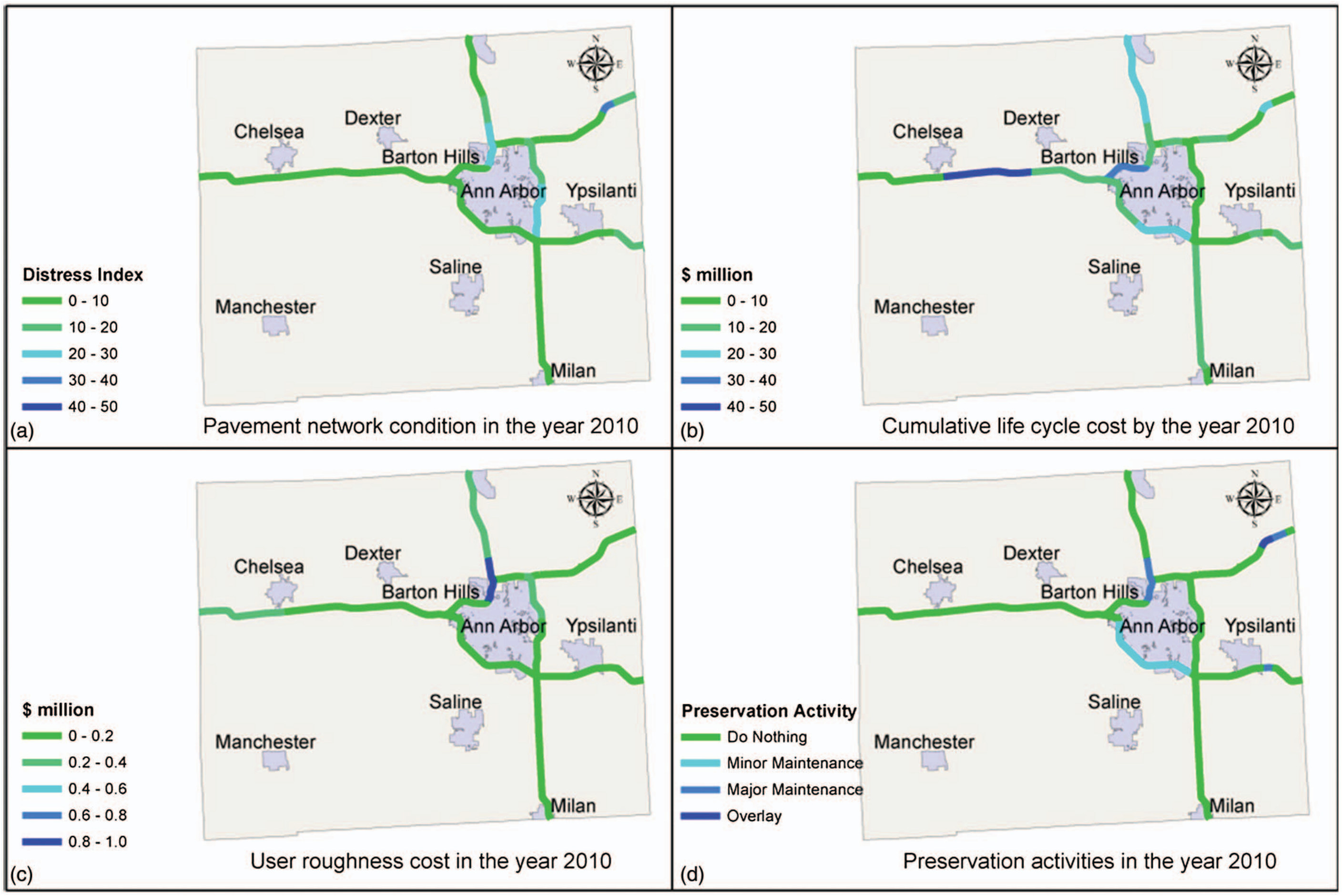

Fig. 6. (Color) Visualization of different attributes in GIS map

the year 2006 to the year 2010. The pavement segment between Chelsea and Dexter (segment 26) will have the highest cumulative life cycle cost. The reasons for this are the relatively high commercial traffic flow (CADT) and poor initial pavement condition on this section. The highway agency should consider using a more durable material and design for this specific pavement segment. This would decrease the maintenance and repair frequency, and decrease the traffic congestion caused by construction events, which would lower the cumulative life cycle cost. Fig. 6(c) illustrates the user roughness cost in the year 2010. Fig. 6(d) shows the planed preservation activities in the year 2010. The locations and methods of these preservation activities are determined by the PAMS model to minimize total life cycle cost and meet the pavement condition constraint. In conjunction with this PAMS model, more detailed transportation planning, not considered in this paper, should be used to avoid closing adjacent segments and to preserve connectivity in the pavement network during preservation activities. All other attributes associated with any pavement section can be selected and visualized on the graphical map.

Sensitivity Analysis

The objective of this network-level PAMS is to derive the pavement preservation strategies aimed at minimizing sustainability metrics, including life cycle energy consumption, GHG emissions, and costs. Thus, the authors conducted a sensitivity analysis based on the parameter that is likely to impact these indicators (Sathaye et al. 2010). Previous studies show that traffic volume has a significant impact on the life cycle footprint of a pavement (Santero and Horvath 2009; Zhang et al. 2010b). The case study presented in a previous section is based on a high traffic volume pavement network. Lower traffic volume reduces pavement deterioration, which ultimately affects traffic congestion, roughness effects, and preservation strategies. Two lower volume traffic scenarios were developed to demonstrate the effect of traffic volume. The total life cycle costs decrease by 40 and 57% if the AADT is reduced to 50 and 15% of the traffic volume, respectively, in the Washtenaw County case study. Based on current traffic volume in the Washtenaw County, user congestion costs and roughness costs dominate the total life cycle costs. With 50% of current AADT, material consumption and construction have a comparable impact on the total life cycle costs with that of traffic congestion and roughness. With 15% of current AADT, agency costs become the only dominant factor, which account for 87% of the total life cycle costs. This result indicates the sensitivity of the optimal pavement preservation strategy to changes in traffic volume. For the high traffic volume pavement network, the highway agency should focus on minimizing the traffic congestion and improving pavement surface conditions. If the traffic volume is low, the PAMS should adjust its strategy to minimize pavement material consumption.

Conclusions

This paper describes the development of a new network-level pavement asset management system (PAMS) that integrates life-cycle analysis, optimization, and GIS. Life-cycle optimization was applied to determine the optimal preservation strategy for a pavement network and to minimize sustainability metrics within an analysis period. The authors developed a priority selection method using binary integer programming methods to efficiently allocate the limited agency budget. The PAMS model captures life cycle energy consumption, GHG emissions, user congestion cost, user roughness cost, and environmental damage costs caused by air pollutants, in addition to agency costs. Previous PAMS research has not thoroughly evaluated many of these components within their assessment approaches, thus underestimating opportunities to improve the sustainability of a pavement network. Whereas the impact of each component depends on its contextual details such as pavement materials, traffic levels, and deterioration rates, the authors expect the framework and methods developed in this study to be applicable to other pavement systems.

A GIS model and user interface was developed to enhance the network-level pavement asset management system by collecting, managing, and visualizing pavement condition data. Linear referencing and dynamic segmentation methods were applied to define the pavement segment and associated pavement information with a pavement portion. A GIS model integrated with the network-level PAMS provides a unique way to immediately retrieve and visualize on a map all pavement network attributes, such as pavement condition, current pavement preservation activity, and economic costs. This unique function enables more effective communication between highway agency decision makers and preservation strategy developers.

A case study of the pavement network in Washtenaw County, MI, demonstrated the capability of the PAMS to improve preservation performance. Compared with the preservation practice currently used by the MDOT, the network-level PAMS optimal strategy can reduce total life cycle energy consumption, GHG emissions, and cost by 20, 24, and 10%, respectively. The results are not intended to be precise quantifications, but rather to demonstrate the large impact of pavement preservation strategy on sustainability.

Annual preservation budgets have a significant impact on total life cycle cost, along with the distribution of these costs between transportation agencies and network users. A preservation budget reduction from US$4 million/year to US$1 million/year (US$120 million for 40 years) increases the total life cycle cost from US$1.3 billion to US$1.7 billion. In the present application of the PAMS model, the annual budget was fixed, but the model could also be implemented with variable budget constraints for a given analysis period. Furthermore, with the flexibility of life-cycle analysis and life-cycle optimization, the pavement asset management system developed in this research can be scaled up to larger pavement networks.

Pavement deterioration is a key factor to determine future pavement preservation strategies and is very difficult to predict accurately. This study used an auto-regression model based on Michigan pavement empirical data to predict future pavement deterioration. The authors will conduct more sensitivity analyses to address uncertainty and understand the hotspot in pavement preservation. This study evaluated the impact of low traffic volume on life cycle costs and preservation strategy. However, other parameters, such as emissions factors, material recycle rate, and nighttime construction may affect pavement preservation strategies. These parameters should be further studied.

This paper explores optimal PAMS with respect to individual objectives (energy consumptions, GHG emissions, and costs). Multi-objective and multi-criteria optimization techniques based on these life cycle metrics can also be applied to facilitate decision making for pavement asset management system. In the future, more research is needed to understand the trade-off between different sustainability indicators and their impact on pavement preservation strategies.

Acknowledgments

This research was funded through an NSF Materials Use: Science, Engineering, and Society (MUSES) Biocomplexity Program Grant (CMS-0223971 and CMS-0329416). MUSES supports projects that study the reduction of adverse human impacts on the total interactive system of resource use, the design and synthesis of new materials with environmentally benign impacts on biocomplex systems, and the maximization of efficient use of materials throughout their life cycles. The authors also thank the support of the Terman Faculty Fellowship at Stanford University.

References

Ahmed, K., Abu-Lebdeh, G., and Lyles, R. W. (2006). "Prediction of pavement distress index with limited data on causal factors: An auto-regression approach." *Int. J. Pavement Eng.*, 7(1), 23–35.

Azapagic, A., and Clift, R. (1999). "The application of life cycle assessment to process optimisation." *Comput. Chem. Eng.*, 23(10), 1509–1526.

Bham, G. H., Gharaibeh, N. G., and Darter, M. I. (2001). "Development of GIS-based Illinois highway pavement management system." *Proc., ESRI User Conf.*, ESRI, Redlands, CA.

Bilec, M., Ries, R., and Matthews, H. S. (2010). "Hybrid life cycle assessment model for construction processes: Methodology, model, results, and comparisons." *J. Infrastruct. Syst.*, 16(3), 199–205.

Bilec, M., Ries, R., Matthews, H. S., and Sharrard, A. L. (2006). "Example of a hybrid life cycle assessment of construction processes." *J. Infrastruct. Syst.*, 12(4), 207–215.

Chandler, R. F. (2004). "Life-cycle cost model for evaluating the sustainability of bridge decks: A comparison of conventional concrete joints and engineered cementitious composite link slabs." M.S. thesis, Univ. of Michigan, Ann Arbor, MI.

Davis, S. C., and Diegel, S. W. (2004). *Transportation energy databook*, Center for Transportation Analysis, Oak Ridge National Laboratory, Oak Ridge, TN.

Durango, P. (2004). "Maintenance and repair decision making for infrastructure facilities without a deterioration model." *J. Infrastruct. Syst.*, 10(1), 1–8.

Durango, P., and Madanat, S. (2002). "Optimal maintenance and repair policies in infrastructure management under uncertain facility deterioration rates: An adaptive control approach." *Transport. Res. A*, 36A(6), 768–769.

ESRI. (2004). *Linear referencing in ArcGIS*, Redlands, CA.

Federal Highway Administration (FHwA). (1989). "Pavement policy for highways." *Fed. Regist.*, 54(8), 1353–1358.

Feighan, K. J., Shahlin, M. Y., Sinha, K. C., and White, T. D. (1988). "Application of dynamic programming and other mathematical techniques to pavement management systems." *Transportation Research Record 1200*, Transportation Research Board, Washington, DC, 90–98.

Furuta, H., and Frangopol, D. M. (2008). "Life-cycle cost of civil infrastructure with emphasis on bridges." *First Int. Symp. on Life-Cycle Civil Engineering*, Taylor & Francis, London, 47–58.

Fwa, T. F., Chan, W. T., and Tan, C. T. (1996). "Genetic-algorithm programming of road maintenance and rehabilitation." *J. Transport. Eng.*, 122(3), 246–253.

Golabi, K., Kulkarni, R. B., and Way, G. B. (1982). "A statewide pavement management system." *Interfaces*, 12(6), 5–21.

Horvath, A., and Hendrickson, C. (1998). "Comparison of environmental implications of asphalt and steel-reinforced pavements." *Transportation Research Record 1626*, Transportation Research Board, Washington, DC, 105–113.

International Organization for Standardization (ISO). (2006a). "Environmental management–Life cycle assessment—Principles and framework." ISO 14040, Geneva, Switzerland.

International Organization for Standardization (ISO). (2006b). "Environmental management—Life cycle assessment—Requirements and guidelines." ISO 14044, Geneva, Switzerland.

Kendall, A., Keoleian, G. A., and Helfand, G. (2008). "An integrated life cycle assessment and life cycle cost analysis model for concrete bridge deck applications." *J. Infrastruct. Syst.*, 14(3), 214–222.

Kentucky Transportation Center (KTC). (2002). "The costs of construction delays and traffic control for life-cycle cost analysis of pavements." *Rep. KTC-02-07/SPR197-99&SPR218-00-1F*, Lexington, KY.

Keoleian, G. A., et al. (2005). "Life cycle modeling of concrete bridge design: Comparison of engineered cementitious composite link slabs and conventional steel expansion joints." *J. Infrastruct. Syst.*, 11(1), 51–60.

Keoleian, G. A., and Spitzley, D. V. (2006). "Life cycle based sustainability metrics." *Sustainability science and engineering: Defining principles*, M. A. Abraham, ed., Vol. 1, Elsevier, Amsterdam, The Netherlands, 127–159.

Kim, H. C., Keoleian, G. A., Grande, D. E., and Bean, J. C. (2003). "Life cycle optimization of automobile replacement: Model and application." *Environ. Sci. Technol.*, 37(23), 5407–5413.

Lee, D., Chatti, K., and Baladi, G. Y. (2002). "Use of distress and ride quality data to determine roughness thresholds for smoothing pavements as a preventive maintenance action." *Transp. Res. Rec.*, 1816.

Madanat, S., and Ben-Akiva, M. (1994). "Optimal inspection and repair policies for infrastructure facilities." *Transport. Sci.*, 28(1), 55–62.

Mbwana, J. R. (2001). "A framework for developing stochastic multiobjective pavement management system." *Technology transfer in road transportation in Africa*, Arusha, Tanzania, 350–363.

Medina, A., Flintsch, G. W., and Zaniewski, J. P. (1999). "Geographic information systems-based pavement management system." *Transportation Research Record 1652*, Transportation Research Board, Washington, DC, 151–157.

Michigan Dept. of Transportation (MDOT). (2002). *Michigan transportation facts & figures 2001*, Lansing, MI.

Michigan Dept. of Transportation (MDOT). (2005). *Pavement design and selection manual*, Lansing, MI.

Michigan Dept. of Transportation (MDOT). (2007). *Five-year transportation program*, Lansing, MI.

MOBILE 6.2 [Computer software]. U.S. Environmental Protection Agency, Ann Arbor, MI.

NONROAD [Computer software]. U.S. Environmental Protection Agency, Ann Arbor, MI.

Ouyang, Y. (2007). "Pavement resurfacing planning on highway networks: A parametric policy iteration approach." *J. Infrastruct. Syst.*, 13(1), 65–71.

PRe Consultants. (2012). "SimaPro 7: Introduction into LCA." ⟨http://www.pre.nl⟩ (Dec. 9, 2012).

Ravirala, V., and Grivas, D. A. (1995). "State increment method of life-cycle cost analysis for highway management." *J. Infrastruct. Syst.*, 1(3), 151–159.

Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). (2005). *A summary of highway provisions in SAFETA-LU*, Washington, DC.

Santero, N., and Horvath, A. (2009). "Global warming potential of pavements." *Environ. Res. Lett.*, 4(3), 034011.

Sathaye, N., Horvath, A., and Madanat, S. (2010). "Unintended impacts of increased truck loads on pavement supply-chain emission." *Transport. Res. Part A*, 44(1), 1–15.

Sathaye, N., and Madanat, S. (2011). "A bottom-up solution for the multifacility optimal pavement resurfacing problem." *Transport. Res. Part B*, 45(7), 1004–1017.

Southeast Michigan Council of Governments (SEMCOG). (2006). *Ozone and carbon monoxide conformity analysis for the proposed amendment of the 2030 regional transportation plan for southeast Michigan*, Detroit, MI.

U.S. Census Bureau. (2012). ⟨http://quickfacts.census.gov/qfd/states/26/26161.html⟩ (Dec. 9, 2012).

U.S. Office of Management and Budget (USOMB). (2010). *Discount rates for cost-effectiveness, lease, purchase and related analyses. Appendix C to guidelines and discount rates for benefit-cost analysis of federal programs*, Washington DC.

Walls, J., and Smith, M. R. (1998). "Life-cycle cost analysis in pavement design—Interim technical bulletin." *Rep. FHwA-SA-98-079*, U.S. Dept. of Transportation, Washington, DC.

Wilde, W. J., Waalkes, S., and Harrison, R. (2001). *Life cycle cost analysis of portland cement concrete pavement*, Univ. of Texas at Austin, Austin, TX.

Yeo, H., Yoon, Y., and Madanat, S. (2010). "Maintenance optimization for heterogeneous infrastructure systems: Evolutionary algorithms for bottom-up methods." *Sustainable and resilient critical infrastructure systems: Simulation, modeling, and intelligent engineering*, K. Gopalakrishnan and S. Peeta, eds., Springer, New York, 185–199.

Zapata, P., and Gambatese, J. A. (2005). "Energy consumption of asphalt and reinforced concrete pavement materials and construction." *J. Infrastruct. Syst.*, 11(1), 9–20.

Zhang, H., Keoleian, G. A., and Lepech, M. D. (2008). "An integrated life cycle assessment and life cycle analysis model for pavement overlay systems." *First Int. Symp. on Life-Cycle Civil Engineering*, Taylor & Francis, London, 907–915.

Zhang, H., Keoleian, G. A., Lepech, M. D., and Kendall, A. (2010a). "Life-cycle optimization of pavement overlay systems." *J. Infrastruct. Syst.*, 16(4), 310–322.

Zhang, H., Lepech, M. D., Keoleian, G. A., Qian, S., and Li, C. V. (2010b). "Dynamic life-cycle modeling of pavement overlay systems: Capturing the impacts of users, construction, and roadway deterioration." *J. Infrastruct. Syst.*, 16(4), 299–309.