Life-Cycle Optimization of Pavement Overlay Systems

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Abstract: Preservation (maintenance and rehabilitation) strategy is the critical factor controlling pavement performance. A life-cycle optimization (LCO) model was developed to determine an optimal preservation strategy for a pavement overlay system and to minimize the total life-cycle energy consumption, greenhouse gas (GHG) emissions, and costs within an analysis period. Using dynamic programming optimization techniques, the LCO model integrates dynamic life-cycle assessment and life-cycle cost analysis models with an autoregressive pavement overlay deterioration model. To improve sustainability in pavement design, a promising alternative material for pavement overlays, engineered cementitious composites (ECCs), was studied. The LCO model was applied to an ECC overlay system, a concrete overlay system, and a hot mixed asphalt (HMA) overlay system. The LCO results show that the optimal preservation strategies will reduce the total life-cycle energy consumption by 5–30%, GHG emissions by 4–40%, and costs by 0.4–12% for the concrete, ECC, and HMA overlay systems compared to the current Michigan Department of Transportation preservation strategies, respectively. The impact of traffic growth on the optimal preservation strategies was also explored.

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Introduction

Pavement structures and systems are fundamental elements of the automobile transportation system in the United States. Shortfalls in budgets and increasing travel demand have placed a significant burden on the transportation system. In 2005, the ASCE infrastructure report card assigned U.S. roads a grade of D (poor condition) (ASCE 2005). The Transportation Equity Act for the 21st Century (TEA-21) provided $173 billion for highway construction and maintenance over six years. However, even with TEA-21's commitment, another $27 billion is needed to improve conditions and performance of the highway system, according to the Federal Highway Administration (FHWA) (ASCE 2006). The budgetary pressure on highway agencies will result in the delay of many pavement projects and, as a consequence, decrease pavement performance. Thus, an effective pavement management optimization approach, which allows highway agencies to explore alternative pavement materials, predict pavement deterioration over time, assess effectiveness of preservation strategies, and select optimal solution and design parameters, becomes crucial. To address these needs, life-cycle optimization (LCO) with integrated life-cycle assessment and life-cycle cost analysis (LCA-LCCA) methodologies has been applied to pavement overlay systems to improve the allocation of resources and pavement performance.

Pavement overlays are the most prevalent rehabilitation method which can provide protection to the pavement structure, reduce the rate of pavement deterioration, and extend pavement service life. Two common designs of overlays are unbonded concrete overlay and hot mixed asphalt (HMA) overlay (Huang 2004). However, concrete and asphalt, which are commonly used in overlay construction, pose significant environmental challenges. Additionally, the physical limitations of concrete and asphalt, which are factors in pavement overlay failure and higher maintenance frequency, have driven the research of alternative materials. Previously, an LCA model of overlay systems was constructed (Zhang et al. 2008, 2010). This model was used to compare the life-cycle environmental impacts of both a concrete and an HMA overlay system with a novel overlay system using engineered cementitious composites (ECCs) and a high performance fiber reinforced cementitious composite (Li 2003). A broad range of sustainability indicators including total primary energy consumption, greenhouse gas (GHG) emissions, criteria air pollutants, and waterborne emissions, resulting from overlay material production and distribution, construction and preservation, construction-related traffic congestion, overlay deterioration and surface roughness increase, and end of life management, was evaluated in a companion paper (Zhang et al. 2010). Additionally, the LCA model provides the necessary input information to an LCCA model. The LCCA model evaluates the monetary values of processes and flows associated with a product or system, which is more informative and useful to the decision makers (Keoleian and Spitzley 2006). Horvath and Hendrickson developed a model using an economic input-output matrix of the U.S. economy to evaluate resource requirements and environmental emissions of

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asphalt and steel-reinforced concrete pavements (Horvath and Hendrickson 1998). Other models have also been developed for LCCA of pavements, such as RealCost, developed by the FHWA Office of Asset Management (FHWA 2004), and PaLATE, developed by Horvath et al. (2004).

A pavement overlay can be preserved through a variety of different rehabilitation methods and frequencies. This leads to a series of different life-cycle energy consumptions, environmental impacts, and costs and results in a set of optimal solutions. Several pavement management optimization methods have been developed. In 1982, the state of 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. Since then, many state-of-the-art optimization methods, including those using Markov decision processes for decision making, have been developed (Camahan et al. 1987; Feighan et al. 1988; Golabi and Separd 1997; Guignier and Madanat 1999). Fwa et al. (1996) applied genetic algorithm programming to develop the road maintenance and rehabilitation strategy based on different agency costs. Mamlouk et al. (2000) developed a project-level optimization approach to minimize the life-cycle costs of a flexible pavement. Madanat et al. (2006) developed an adaptive infrastructure maintenance, repair, and reconstruction optimization methodology using an open-loop feedback control approach to minimize agency-related costs and user costs. Their results showed that the adaptive infrastructure management system provided outcomes sufficiently close to optimal strategies. Furuta and Frangopol applied life-cycle cost optimization based on genetic algorithm with emphasis on bridges (Furuta and Frangopol 2008). While life-cycle cost, safety level, and service life were considered as bridge performance indicators, energy consumption and environmental impacts were not studied.

There is also existing software for applying optimization methods to pavement asset management. The Washington State Department of Transportation has developed its Washington State Pavement Management System to manage the State's pavements. The portion of pavement in good condition increased from 50% in 1970 to 93.5% in 2005 (FHWA 2008). Currently, the Michigan Department of Transportation (MDOT) relies on the Michigan Road Quality Forecasting System to develop preservation strategies for regional DOT management districts. This software uses current pavement condition data from the pavement management system to predict future network conditions at different levels of investment. Other models have also been developed for assisting pavement asset management, such as the Highway Design and Maintenance model (HDM-4), developed by the World Road Association (PIARC 2002). This program predicts the consequences of different maintenance options and corresponding user benefits over time.

However, besides the economic costs, these studies do not consider other sustainability indicators (e.g., energy and GHG emissions) in the optimization model as objective functions. Incorporating LCA and LCCA methods into an optimization framework can enable highway agencies to develop rehabilitation strategies that can improve pavement management and performance from both environmental and economic sustainability perspectives.

Accordingly, the objective of this research is to develop an LCO model with an integrated LCA-LCCA model to optimize pavement overlay preservation strategies based on minimization of total life-cycle energy consumption, environmental impacts, or costs for pavement overlay systems. Overlay deterioration, roughness effects, traffic congestion, traffic growth, and maintenance activities can be dynamically captured by the model. In addition, the LCO model developed here can enable decision makers to select the optimal overlay preservation strategy in an efficient and accurate way.

In this paper, three models including an integrated LCA-LCCA model, a pavement deterioration model, and an LCO model are described and used to analyze the following three pavement overlay systems: concrete, ECC, and HMA overlay systems. Subsequently, the optimal overlay preservation strategies found to minimize the life-cycle energy consumption, GHG emissions, and costs of the concrete, ECC, and HMA overlay systems are evaluated and discussed.

Methodology

System Definition

The overlay designs analyzed in this study are constructed upon an existing reinforced concrete pavement which was originally built by the MDOT. The annual average daily traffic 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 a 10-km-long freeway 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 and construction methods. The concrete overlay 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; Huang 2004). In the LCA model, the concrete overlay and HMA overlay are designed for a 20-year service life by MDOT (2005). The service life of the ECC overlay is expected to be at least twice that of the concrete overlay by preventing commonly observed overlay failure modes, such as reflective cracking (Li 2003). When ECC is applied as an overlay material, reflective cracks are suppressed by becoming trapped inside the ECC overlay through a unique "kinking and trapping" phenomenon (Lim and Li 1997). This kink-trap phenomenon is repeated a number of times, resulting in a pattern of closely spaced microcracks, effectively eliminating reflective cracking and surface failure modes (Li 2003). The reflective cracking resistance mechanism of ECC overlay has been experimentally confirmed and is reported by Qian (2007). Under fatigue loading test, ECC shows great enhancement in fatigue stress–fatigue life relation when compared with concrete currently used by MDOT. Under the same fatigue stress level, the fatigue life of ECC is at least nine orders of magnitude higher when compared with concrete. This test indicated that the introduction of ECC will greatly enhance the service life with a much thinner overlay thickness compared to concrete material. More details on the design of ECC overlay can be found from Qian (2007). A demonstration bridge deck link slab in Michigan and a completely jointless ECC/steel composite bridge deck in Japan also support this mechanism (Lepech 2006).

Integrated LCA-LCCA Model

Fig. 1 shows the integrated LCA-LCCA model framework. The LCA model is divided into six modules: material production, con-

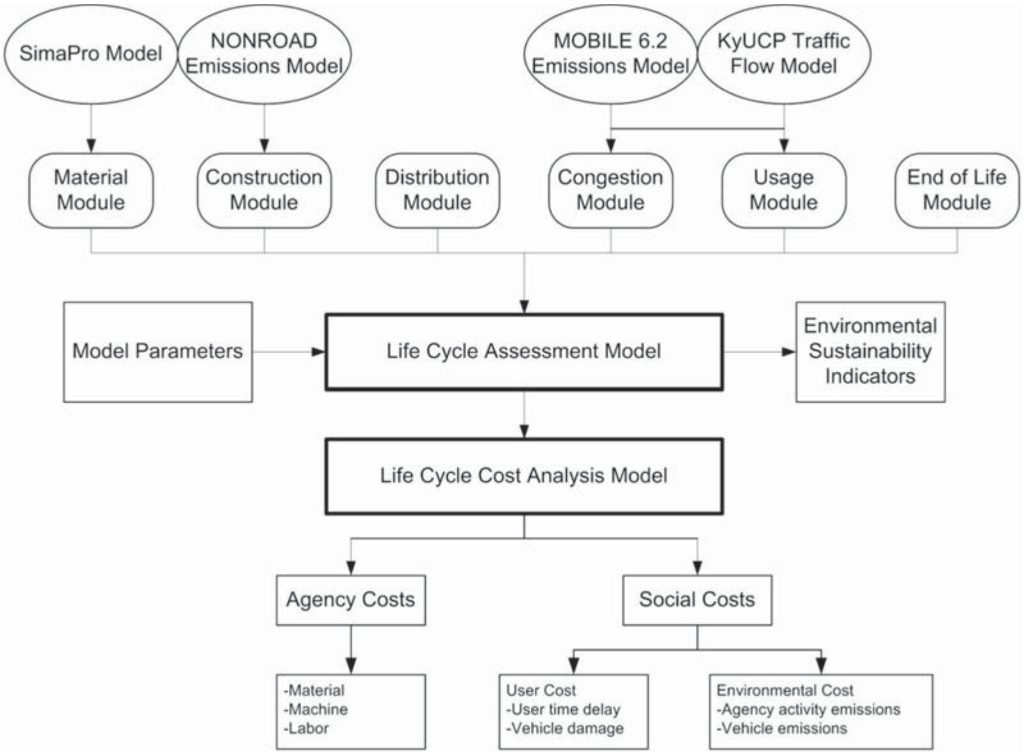

Fig. 1. Integrated LCA-LCCA model framework

sisting 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 congestions; usage, including overlay roughness effects on vehicular travel during normal traffic flow; and end of life, which models demolition of the overlay and processing the materials. Details of each module are described by Zhang et al. (2010). Input and output data of each module are evaluated to capture the material consumption, energy consumption, and environmental impacts of the overlay system over its service life. Several data sets, including the Portland Cement Association, the Athena Institute, and the SimaPro 6.0 life-cycle database (Franklin U.S. LCI Database), are required to provide the life-cycle inventory data for an input material or process. The detailed documentation of data sets and sources can be found from Keoleian et al. (2005) and Zhang et al. (2010). These data sets provide the raw material consumption, total primary energy consumption, pollutant emissions, and wastes to produce a unit volume of concrete, ECC, and HMA. Raw material consumption quantifies the nonfuel 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.

The LCA model is linked to four external models: (1) a material environmental impact model, SimaPro 7.0, developed by PRe Consultants [SimaPro 7.0, Product Ecology Consultant (Pre), The Netherlands, 2007]; (2) a vehicle emissions model, MOBILE 6.2, developed by U.S. Environmental Protection Agency (EPA) [MOBILE 6.2, United States Environmental Protection Agency (USEPA), Ann Arbor, Mich., 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 [Southeast Michigan Council of Governments (SEMCOG) 2006]; (3) a construction equipment model, NONROAD, also developed by the EPA (NONROAD, USEPA, Ann Arbor, Mich., 2000); and (4) a traffic flow model developed at the University of Kentucky [Kentucky Transportation Center (KTC) 2002].

The LCCA model uses the results of the LCA model to calculate life-cycle costs, which is the sum of agency and social costs. The framework of the LCCA model was first developed by Kendall et al. (2008).

Agency cost includes costs incurred directly by the 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 collected from MDOT construction contracts. Table 1 shows the agency costs breakdown for the construction activities modeled.

Social costs are not commonly addressed in the construction and maintenance activities of many transportation agencies. Generally, social costs include user cost and environmental cost. While about 40% of states incorporate user cost associated with maintenance activities such as user time delay at work zones, environmental cost is not explicitly considered by most states in life-cycle cost analyses (Chan et al. 2008). The literature is limited in examining how social costs are actually applied by state DOTs.

Overlay construction and maintenance activities and overlay deterioration will affect traffic flow. These impacts are termed user cost since they are incurred by highway users traveling on the system. User cost is the differential cost incurred while driving between normal operations and work zone operations or on

Table 1. Agency Cost Breakdown for Overlay Construction Activities

Construction activity	Overlay type	Process	Cost, 2006 U.S.$/lane mile
Overlay initial construction	Concrete	Overlay placement	$170,500
	ECC	Overlay placement	$210,800
	HMA	Rubblize and overlay placement	$171,000
Overlay minor maintenance	Concrete	Replace 10% seals, crack seal any cracked slab (est 8%)	$8,000
	ECC	N/A	N/A
	HMA	Crack seal	$6,400
Overlay major maintenance	Concrete	Replace 30% seals, replace 15% joints, crack seal any cracked slab (est 15%)	$46,000
	ECC	Replace 30% seals, replace 15% joints, crack seal any cracked slab (est 15%)	$68,000
	HMA	Crack seal, patch	$58,000
Overlay reconstruction	Concrete	Overlay placement	$154,000
	ECC	N/A	N/A
	HMA	Overlay placement	$154,500

poor pavement conditions. User cost is an aggregation of user delay cost, vehicle operating cost, and risk of traffic accident (Wilde et al. 2001).

User delay cost normally dominates user cost. The total cost of travelers sitting in traffic is determined by multiplying the value of time and the additional number of hours spent in work zone congestion or on detours compared to the number of hours spent traveling the equivalent distance in normal traffic flow conditions. The values of time (delay cost rate) for passenger vehicles, single unit trucks, and combination trucks are $11.58, $18.54, and $22.31/vehicle h, respectively, estimated by the FHWA (Walls and Smith 1998). Costs are in 1996 dollars and updated to 2006 dollars in the LCCA model using Consumer Price Index (CPI) (2006).

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 a detour to avoid congestion, they will travel a greater distance and consume more fuel. 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 WesTrack project Epps et al. (1999) has tested the impact of roadway roughness on the fuel consumption of heavy duty trucks at a constant speed. The result showed that the fuel economy decreased from 4.4 to 4.2 mpg, while the IRI increased from 1.2 to 2.4 m/km. Based on this result, a linear equation [Eq. (1)] is developed to represent the relationship between fuel consumption and road surface roughness, where FCF is the fuel consumption factor (greater than 1.0). Fuel costs are based on a 2006 average of retail fuel costs in Michigan. Fuel price changes have little impact on total user cost since fuel accounts for less than 3% of total user cost as compared to 85% for user delay costs

$$\mathrm{FCF} = 0.0397\mathrm{IRI} + 0.9524 \tag{1}$$

The last element of user cost is based on increased risk of traffic accidents. Both traveling through construction work zones and traveling additional distance when detours are chosen to avoid work zone congestion 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 costs due to a higher risk of fatality and injury compared to roadway use when no construction zone is in place (MDOT 2002). These estimations are based on the data for construction zone accidents in the state of Michigan (Michigan Department of State Police 1994–2001).

User cost 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 by a significant amount (Wilde et al. 2001; Zhang et al. 2010). Minimizing the interruption of traffic flow during construction and maintenance activities over the total life cycle of an overlay is important for highway design.

Environmental cost estimates are applied to estimate 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 either due to the inhalation of air pollutants detrimental to human health or GHGs that result in global warming. Six criteria pollutants specified by the EPA which have direct impact on human health are considered, including sulfur oxides (SO_x), nitrogen oxides (NO_x), carbon monoxide (CO), particular matter ($PM_{2.5}$), lead (Pb), and volatile organic compounds (VOCs). Three major GHGs that are inventoried include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The criteria pollutants directly affect human health when inhaled, and it is in this capacity that damage costs are estimated based on human morbidity and mortality effects (Banzhaf et al. 1996; Matthews and Lave 2000).

Tol (1999) estimated the cost of GHG emissions by simulating a broad array of climate change effects on humans and our economic systems. GHG emissions, instead of having direct impact on human health, cause climate change. Climate change in turn affects the livelihoods and health of individuals as well as regional and global economic systems and activity.

Previous studies show that pollution damage costs are difficult to calculate and carry significant uncertainty. For example, damage cost estimates of SO_x range from $21 to $119,102/t (Banzhaf et al. 1996; Delucchi 1998; ExternE 2001). To address the uncertainty in pollution damage costs, a Monte Carlo simulation is conducted in a later section.

The baseline unit pollution damage costs used in this research are shown in Table 2 as summarized by Kendall et al. (2008). 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. While these are the key pollutants in the pavement system, there are several other environmental costs, such as other pollutant emissions, land use impacts, water con-

Table 2. Air Pollution Damage Costs by Impacted Region (Data from Kendall et al. 2008)

Pollutant name	Average cost (2006 U.S.$/mt)			
	Urban	Urban fringe	Rural	Global
SO_x	$170	$88	$21	
NO_x	$156	$65	$19	
CO	$2	$1	$0	
$PM_{2.5}$	$6,144	$2,750	$800	
Pb	$3,955	$2,059	$480	
VOC	$1,960	$1,960	$1,960	
CO_2				$21
CH_4				$384
N_2O				$7,112

Table 3. Autoregression Model Equations for Different Pavement Overlays

Pavement overlay type	Autoregression model equation
Concrete	$DI(t)=1.11\times DI(t-1)+0.15\times age(t-1)+0.09$
ECC	$DI(t)=1.06\times DI(t-1)+0.03\times age(t-1)+0.04$
HMA	$DI(t)=1.37\times DI(t-1)+0.01\times age(t-1)+1.1$

sumption, and noise which are caused by the system but not considered in this analysis. The environmental damage cost is calculated using environmental pollution emissions multiplied by the environmental damage costs shown in Table 2.

The discount rate is a central element to economic analysis and can significantly influence LCCA results. In the LCCA model, a real discount rate is used which reflects 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 U.S. Office of Management and Budget (OMB) (2005).

Environmental cost is discounted differently than agency cost and user cost due to 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 for environmental cost was divided into the following scale: for the immediate future (Years 1–5), a 4% environmental cost discount rate is used; for the near future (Years 6–25), a 3% environmental cost discount rate is used; for the medium future (Years 26–75), a 2% environmental cost discount rate is used (Weitzman 2001).

Pavement Overlay Deterioration Model

In Michigan, a distress index (DI), which represents a holistic measure of pavement condition including both surface roughness and deterioration, is used rather than IRI to gauge pavement conditions (MDOT 2005). However, the DI and the 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. Many statistical models have been developed to predict overlay deterioration, such as the S-shaped curve model, the Markov chain model, and neural network models (Shahin 1994; Ferregut and Abdullah 1998; de Melo e Silva et al. 2000; Ahmed et al. 2006). The selection of a particular model is based on local conditions and deterioration rates of pavements. Previous research showed that an autoregression model produced the best prediction results based on Michigan pavement DI data (Ahmed et al. 2006). Autoregression uses the estimation of a stochastic process that can be described by a weighted sum of its previous values (Kennedy 1998). The autoregression model used in this study is described in Table 3, where DI(t) is the DI value at age t (Kennedy 1998). Pavement age is defined as the absolute number of years of a pavement from the last reconstruction. Thus, pavement age is the time from the last reconstruction and independent of previous rehabilitation activities. Currently, MDOT uses a threshold DI of 50 to indicate the need for overlay reconstruction.

The initial construction and preservation strategies for the concrete overlay and HMA overlay systems are based on historical maintenance and pavement management records (MDOT 2005). The ECC overlay system is expected to extend the service life and minimize the preservation frequency by preventing reflective cracking (Qian 2007). The life cycle for each of the three systems begins with overlay construction. The concrete overlay is reconstructed in its 21st year, with major maintenance events at Years 11 and 31. The HMA overlay is reconstructed in its 20th year, with major maintenance events in Years 8 and 28 and minor maintenance events in Years 6, 12, 26, and 32. The ECC overlay service life is 40 years, with a single maintenance event and no reconstruction. Based on these construction and maintenance strategies, the DI of three overlay systems can be predicted by the autoregression model. Fig. 2 shows the DI prediction results.

LCO

LCO is a promising optimization method which evaluates the energy consumption, environmental impacts, and costs associated with all stages of a product or system's life cycle in an effort to identify approaches for minimizing these burdens. Azapagic and Clift (1999) developed an LCO model using a linear programming method for identifying and evaluating the best possible option for environmental management of a product system. However, pavement overlay preservation is a discrete time multistage decision making process. Dynamic programming is a nonlinear optimization technique that is particularly applicable to problems requiring a sequence of interrelated decisions (Dreyfus and Law 1977). Each decision transforms the current situation into a new situation. A sequence of decisions, which in turn yields a new sequence of situations, is sought that minimizes (or maximizes) an objective function. The value of the objective function

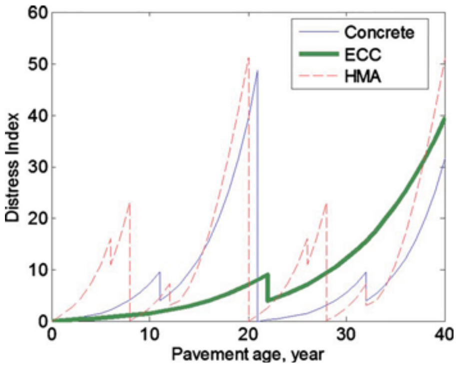

Fig. 2. Distress index of each pavement

for a sequence of decisions is generally equal to the sum of the value of the individual decisions and therefore the sum of situations in the sequence.

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-Cohen 2004; Robelin and Madanat 2007). To formulate the problem, stage and state variables are defined. In a system, the stage is considered the monotonic variable that will increase or decrease by 1 after each decision. State variables describe the current situation at the given stage variable. The stage and state variables constitute a description of the situation adequate to allow for a dynamic programming solution (Dreyfus and Law 1977). Additionally, at each stage and every possible state, a set of decisions is made. A transition matrix is generated using the autoregression model for each overlay system to represent the pavement condition from one stage to the next after each potential action or rehabilitation event. The pavement deterioration is described by the matrix values. At each stage and state, the dynamic program calculates the particular return of burdens for each particular decision. Burdens refer to the energy consumption, GHG emissions, and costs. For example, when burden refers to costs, it is the summation of agency cost, user cost, and environmental cost. Each cost component is calculated using different modules. The material module, construction module, distribution module, and end of life module provide raw material consumption, construction equipment use, labor use, etc. These parameters are further converted to agency cost. Traffic congestion module and roughness module provide the construction-related user time delay and additional fuel consumption. Then, they are converted to user cost. Environmental cost is calculated by multiplying total environmental pollution emissions by unit environmental damage costs which is presented in Table 2.

For this study, dynamic programming parameters are summarized as follows:

Objective function: Minimize life-cycle burdens (energy consumption, environmental impacts, or cost)

Constraint: Keep all overlay systems within a defined performance standard (DI$<$50)

Analysis period: 40 years

State: DI values

Stage: Index of year in the analysis period

Decision variables: No maintenance, minor maintenance, and major maintenance

Transition matrix: Autoregression DI prediction model

Return: Expected cumulative burdens at each stage and state

For each objective (minimizing energy consumption, GHG emissions, and costs), a backward dynamic program is constructed to optimize over a finite horizon of predicted data. Fig. 3 shows the dynamic programming procedure.

The computation starts at year N (stage variable), the final year of the analysis period. At the year N, 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. Then, the DI value increases discretely by 0.5 from 0 to 50 and the LCO model repeats the process. In mathematical terms, the life-cycle energy consumption, environmental impacts, and costs for each DI value at year i with decision j can be determined as follows:

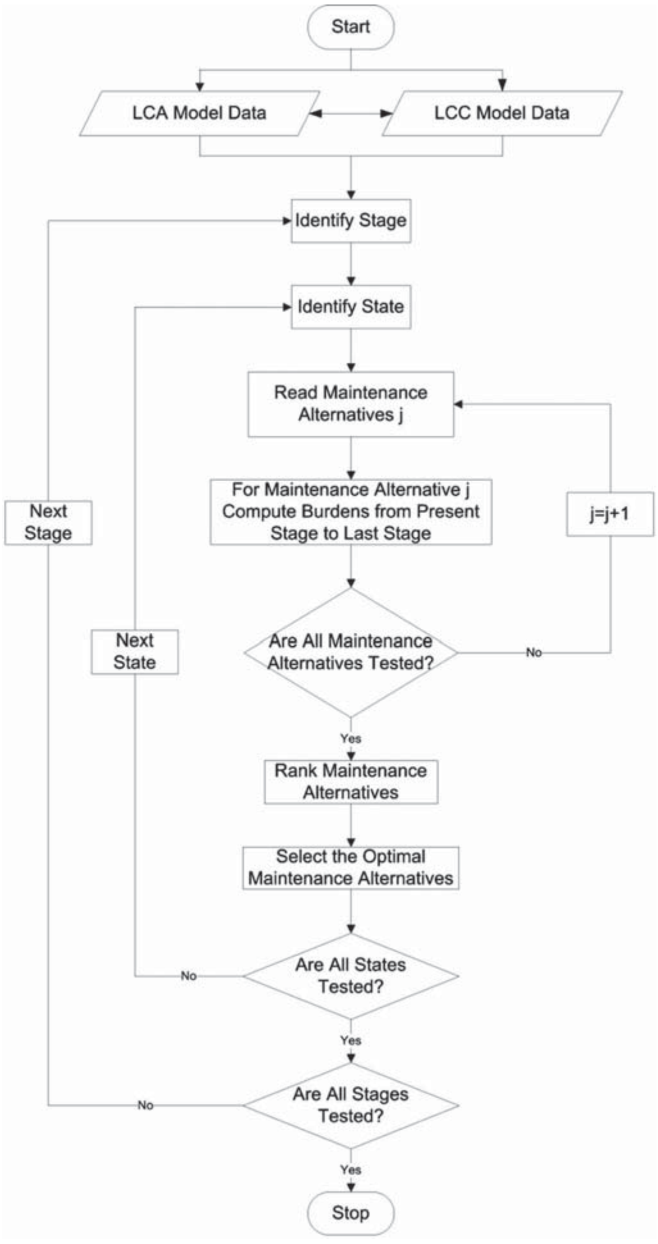

Fig. 3. LCO model operation flowchart using dynamic programming

$$B_b[i,j,\mathrm{DI}(i)] = \begin{cases} 0 & \text{if } i=0 \\ \mathit{Material}[i,j,\mathrm{DI}(i)]\omega_b^{material} + \mathit{Construction}[i,j,\mathrm{DI}(i)]\omega_b^{construction} & \\ \quad + \mathit{Distribution}[i,j,\mathrm{DI}(i)]\omega_b^{distribution} + \mathit{Congestion}[i,j,\mathrm{DI}(i)]\omega_b^{congestion} & \text{if } i>0 \\ \quad + \mathit{Usage}[i,j,\mathrm{DI}(i)]\omega_b^{usage} + \mathrm{EOL}[i,j,\mathrm{DI}(i)]\omega_b^{EOL} & \end{cases} \tag{2}$$

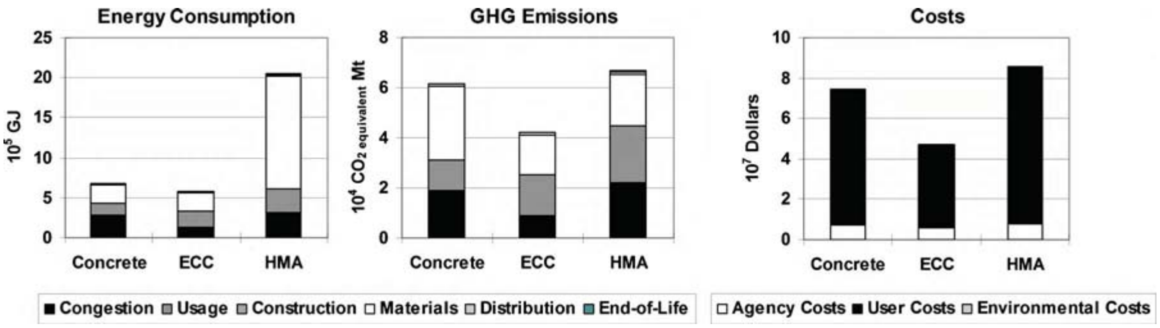

Fig. 4. Integrated LCA-LCCA results based on the previous strategies

where b=life cycle energy consumption, GHG emissions, or costs; i=index of year; j=maintenance alternative decisions; 0 means no action, 1 means minor maintenance, and 2 means major maintenance; $\mathrm{DI}(i)$=distress index value at year i; ω_b=life cycle energy consumption, GHG emissions, or costs associated with one unit of raw material, utility, or process; $B_b[i,j,\mathrm{DI}(i)]$ =burden (life-cycle energy consumption, GHG emissions, or costs) at year j with decision j for one DI value; $\mathit{material}[i,j,\mathrm{DI}(i)]$=material consumption at year i with decision j for one DI value; $\mathit{construction}[i,j,\mathrm{DI}(i)]$=construction equipment usage at year i with decision j for one DI value; $\mathit{distribution}[i,j,\mathrm{DI}(i)]$=transportation of materials and equipment at year i with decision j for one DI value; $\mathit{congestion}[i,j,\mathrm{DI}(i)]$=construction related traffic congestion at year i with decision j for one DI value; $\mathit{usage}[i,j,\mathrm{DI}(i)]$ =pavement surface roughness impact at year i with decision j for one DI value; and $\mathrm{EOL}[i,j,\mathrm{DI}(i)]$=end of life management of pavement system at year i with decision j for one DI value.

At year $N-1$, started from 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 autoregression model equation. If the decision at year $N-1$ is "do a major maintenance," the DI value at year N will decrease. The magnitude of DI reduction is estimated based on the level of 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. This estimation is based on the empirical pavement maintenance data (MDOT 2005). Undoubtedly, the DI transition of pavement maintenance is associated with uncertainty. Previous research shows that this transition can be modeled as a stochastic process (Jiang et al. 1989; Madanat et al. 1995, 1997). A number of research papers describe how transition probabilities can be derived from empirical condition data (Ravirala and Grivas 1995; Guignier and Madanat 1999; Mishalani and Madanat 2002). Exploring these transition probabilities will be an important topic of future work.

The LCO model calculates the intermediate result $f_b[i,\mathrm{DI}(i)]$, which is the sum of the following: (a) the annual burden $B_b[i,j,\mathrm{DI}(i)]$ and (b) the expected intermediate result $f_b[i+1,\mathrm{DI}(i+1)]$ of the future stage resulting from the applied decision. The detailed equation for $f_b[i,\mathrm{DI}(i)]$ are given in Eq. (3)

$$f_b(i,\mathrm{DI}(i)) = \begin{cases} \min\limits_{j=0,1,2} \{B_b[i,j,\mathrm{DI}(i)] + f_b[i+1,\mathrm{DI}(i+1)]\} & \forall\ i = n, \ldots, N \\ 0 & \forall\ i > N \end{cases} \tag{3}$$

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," etc. To solve each of these dynamic programs, a computer program using Visual Basic application and running within Microsoft Excel software was coded to implement the LCO model and connect with the integrated LCA-LCCA model.

Results

Integrated LCA-LCCA Results without Optimization

Before optimization, the overlay preservation strategies are entered into the integrated LCA-LCCA model. As indicated in the overlay deterioration model description, the original preservation strategies of the concrete and HMA overlay systems were based on MDOT empirical data and the current preservation strategy. For ECC overlay, the original preservation schedule assumes a single repair event in the middle of its service life. This result is based on the experimental test that ECC prevents commonly observed overlay failure modes, such as reflective cracking (Li 2003). The reflective cracking resistance mechanism of ECC overlay has been experimentally confirmed and is reported by Li et al. (2008). Results from a demonstration bridge deck link slab in Michigan and a completely jointless ECC/steel composite bridge deck in Japan also provide supporting evidence for this mechanism (Lepech 2006; Li 2005). More details on the development of the preservation schedule for ECC overlay can be found from Qian (2007). Based on these preservation strategies, the energy consumption, GHG emission, and costs of each overlay system are shown in Fig. 4. The LCA results consist of six life-cycle phases: material production, construction, distribution, traffic congestion, usage (roughness effect on vehicle fuel economy), and end of life. The LCCA results are represented as agency cost, user cost, and environmental cost. Due to the superior material properties of ECC compared to the other overlay materials, an ECC overlay system reduces the life-cycle energy consumption, GHG emissions, and costs compared to concrete and HMA overlay systems.

The three dominant phases that influence the life-cycle energy consumption and GHG emissions for the three overlay systems are material production, traffic congestion, and usage phases, while the life-cycle costs are dominated by user cost. The identification of those four dominant factors is unexpected in that they are directly related to one another. Due to surface deterioration, overlay surface roughness increases continuously over time. Increased surface roughness reduces onroad fuel economy and increases tailpipe emissions. These roughness effects can be

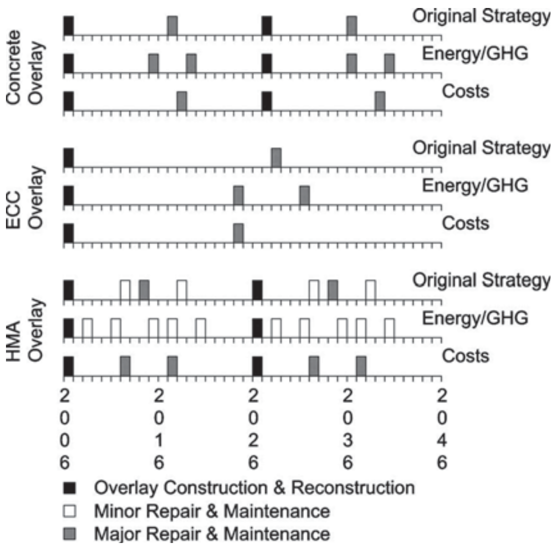

Fig. 5. Optimal preservation strategies for three overlay systems

rehabilitated by proper maintenance activities, although they increase material consumption and generate traffic congestion which increases user time delay costs.

LCO Results

The LCO model is used to determine optimal preservation strategies based on the integrated LCA-LCCA results. Optimizations are conducted to minimize life-cycle energy consumption, GHG emissions, and cost, with results that also show the impacts of optimal maintenance planning on criteria pollutant emissions. The optimal preservation strategies and the original preservation strategies (MDOT strategies for the concrete and HMA overlay systems, experimental planning for the ECC overlay system) for the three overlay systems are shown in Fig. 5. The optimal preservation strategy to minimize energy consumption and GHG emissions for the concrete overlay system involves constructing an initial overlay in Year 2006 (the first year), applying four major maintenance activities in Years 2015, 2019, 2036, and 2040, and reconstructing in Year 2027. The optimal preservation strategies to minimize energy consumption and GHG emissions are identical and driven by reductions in fossil fuel combustion, which contribute predominately to both energy consumption and GHG emissions for each overlay system. As can be seen in Fig. 5, the preservation schedule for energy/GHG objectives has more frequent maintenance activities than the preservation schedule for cost minimization objectives. This phenomenon can be attributed to the dominance of user time delay cost as a part of user cost. User time delay costs are related to the traffic congestion caused by maintenance activities. Therefore, minimizing preservation frequency or substituting several minor maintenance activities with one major maintenance activity can efficiently decrease the life-cycle costs of an overlay system.

Table 4 gives the optimization results and associated criteria pollutant emissions for the three overlay systems. The negative value of CO emissions results from greater CO tailpipe emissions at high speeds as compared to low speeds. Therefore, congestion delays effectively decrease CO emissions (Sher 1998; MOBILE 6.2, USEPA, Ann Arbor, Mich., 2002). Compared to the original preservation strategies (MDOT strategies for the concrete and HMA overlay systems, experimental planning for the ECC overlay system), energy/GHG optimal strategies save 6, 23, and 30% of life-cycle energy consumption and 4, 25, and 40% of GHG emissions for the concrete overlay system, ECC overlay system, and HMA overlay system, respectively. Since LCCA has been required by MDOT in the design of all projects with paving costs greater than $1 million since 1998, cost optimal strategies only save 0.4, 0.5, and 8% of costs for the concrete overlay system, ECC overlay system, and HMA overlay system, respectively.

As shown in Fig. 6, the trade-offs between material consumption, traffic congestion, and roughness effects (captured in the usage phase) play an important role in identification of optimal preservation strategies. For energy objectives, reducing roughness effects that impact vehicle fuel economy is an effective way to decrease the overall energy consumption, even though energy consumption increases during maintenance events due to traffic congestion. For cost objectives, the optimization strategy is opposite to that of energy. User time delay costs caused by traffic congestion dominate total life-cycle costs. An effective way to decrease the total life-cycle costs is to decrease the preservation frequency and thereby user time delay costs. Moving from a cost objective to energy objective increases economic costs from 11 to 22%. However, the relative magnitude of the decrease in energy consumption ranges from 12 to 36%.

Sensitivity and Uncertainty Analysis

Traffic Growth Scenario

The optimal preservation strategies discussed above are designed with no assumed traffic flow growth over time. However, traffic growth will affect user cost, traffic related energy consumption, and pollutant emissions by increasing total vehicle miles traveled and overall system congestion. These factors will change the op-

Table 4. Life-Cycle Burdens of Optimal Preservation Strategies for Each Overlay System

Optimization objectives		Life-cycle burdens Energy (10^5 GJ)	GHG (10^4 mt CO_2 equivalent)	SO_x (10^5 kg)	NO_x (10^5 kg)	$PM_{2.5}$ (10^2 kg)	Pb (kg)	VOC (10^4 kg)	CO (10^4 kg)	Cost (10^7 \$)
Concrete	Energy/GHG	6.40	5.96	1.33	1.02	16.3	6.19	3.83	−7.36	8.99
	Costs	7.30	6.58	1.29	1.02	24.4	5.67	3.44	1.0	7.80
ECC	Energy/GHG	4.44	3.14	0.70	0.72	6.81	2.33	2.33	−1.06	5.36
	Costs	5.20	3.76	0.71	0.70	12.8	2.13	2.19	2.85	4.85
HMA	Energy/GHG	14.3	3.98	0.74	0.53	23.0	3.41	4.41	−5.63	10.3
	Costs	22.3	5.69	1.08	0.61	25.6	5.17	1.88	1.63	8.43

Note: Possible rounding error may occur.

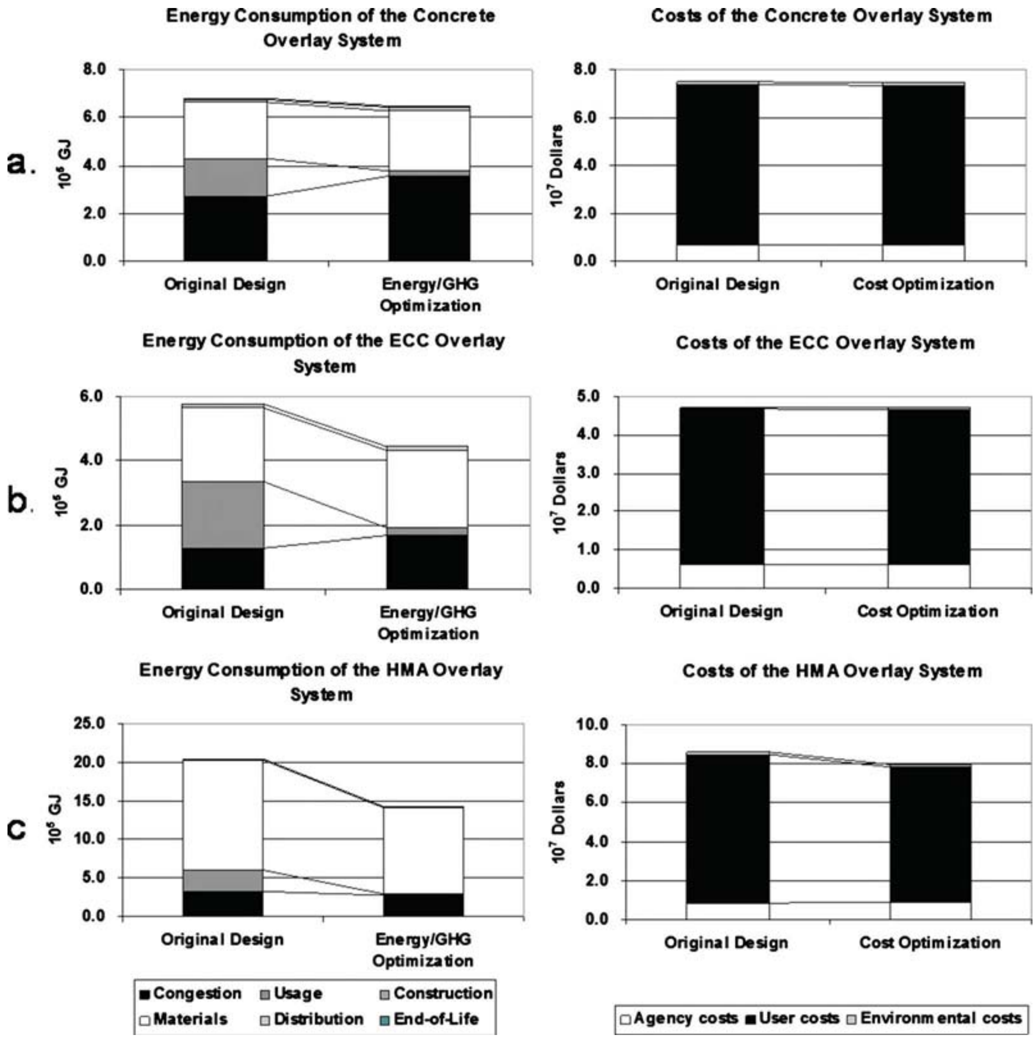

Fig. 6. Comparison of energy and costs for MDOT preservation strategies and optimal strategies for the following: (a) concrete; (b) ECC; and (c) HMA overlay systems

timal preservation strategy for each overlay system. Fig. 7 shows the optimal preservation strategies under an assumed 2% annual traffic growth rate. The preservation frequency decreases and preservation activities occur earlier, thus avoiding higher costs from future high traffic volumes.

Fig. 8 shows the total life-cycle results with annual traffic growth rates increasing from 0 to 2%. As can be seen, with 2% annual traffic growth, the original preservation strategies (MDOT strategies for the concrete and HMA overlay systems, experimental planning for the ECC overlay system) which neglect traffic growth, are inefficient. Energy consumption, GHG emissions, and costs increase dramatically. Compared to the original preservation strategies (MDOT strategies for the concrete and HMA overlay systems, experimental planning for the ECC overlay system), energy/GHG optimal strategies save 4, 18, and 14% of energy consumption and 4, 18, and 8% of GHG emissions for the concrete overlay system, ECC overlay system, and HMA overlay system, respectively. Cost optimized preservation planning saves 3, 36, and 14% of total life-cycle costs for the concrete overlay system, ECC overlay system, and HMA overlay system, respectively. When traffic growth is incorporated into the model, use of the ECC overlay system results in the greatest energy, GHG, and cost savings.

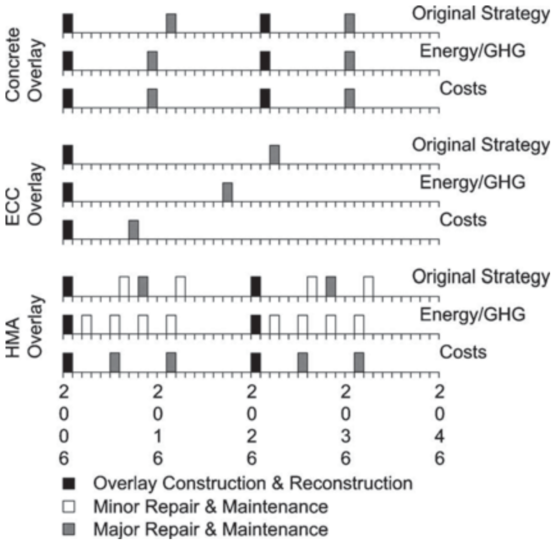

Fig. 7. Optimal preservation strategies for three overlay systems with 2% annual traffic growth rate

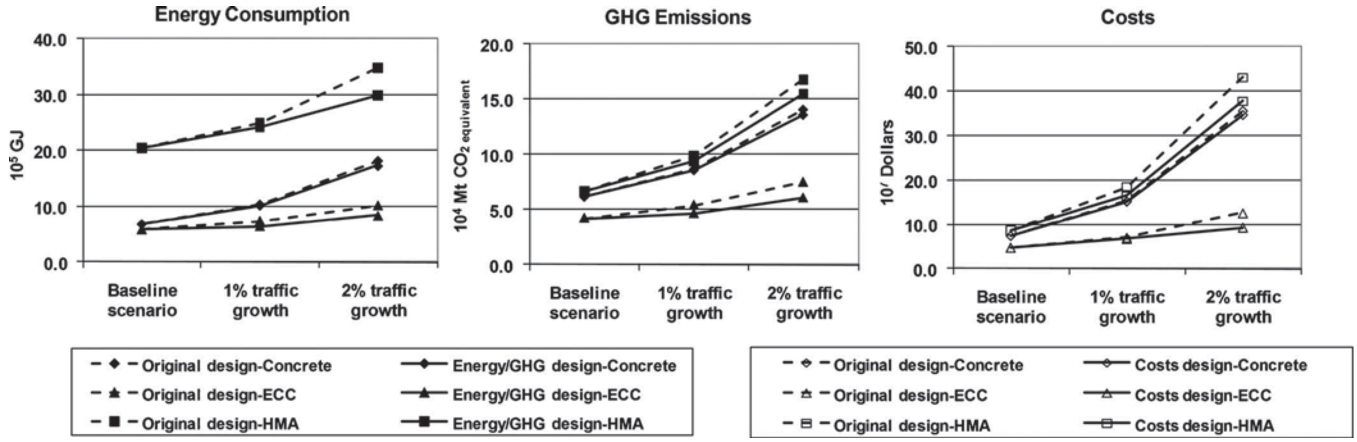

Fig. 8. Life-cycle results with different annual traffic growth rates

Monte Carlo Simulation Applied to Environmental Cost

While environmental cost in this model is relatively small compared to agency cost and user cost, the uncertainty of environmental cost is high. This is primarily a result of the complexity of the science and economics behind pollution damage. To address the uncertainty in environmental cost, Kendall et al. (2008) used the Monte Carlo simulation to develop a range of costs for pollution damage over the service life of a bridge system. Table 5 shows the probability distributions developed by Kendall et al. and used in this research. The probability distribution for the marginal environmental damage cost of GHG gas emissions is based on a metaanalysis performed by Tol (2005). Tol created a probability density function (PDF) of marginal costs using 103 previous studies. Kendall et al. developed a best-fit curve for Tol's PDF that resulted in the lognormal distribution described in Table 5.

Due to the lack of a PDF describing the underlying distributions for criteria pollutant estimates, uniform distributions were applied to their marginal environmental damage costs. Damage cost estimates for criteria pollutants were available as ranges with maximum and minimum values. Applying uniform distributions results in the most conservative outcome for a Monte Carlo simulation because each point within the upper and lower bounds of a uniform distribution is equally likely. Thus, when a Monte Carlo simulation is applied, the outcome distribution will reflect this uncertainty of which value within the upper and lower bounds for the criteria pollutants is most correct. If criteria pollution damage costs significantly influence the simulation outcome, then using uniform distributions will both widen most confidence intervals and "flatten" the distribution leading to points toward the tails of the distribution to be weighted more heavily.

Table 5. Probability Distribution Functions for Pollution Damage Costs [Data from Tol (1999) and Kendall et al. (2008)]

Air pollutant	Probability distribution function ($/t)
CO_2	Lognormal: mean=26, SD=76
CH_4	Lognormal: mean=600, SD=1,700
N_2O	Lognormal: mean=7,900, SD=22,000
CO	Uniform: range=0.09–1.51
Pb	Uniform: range=1,865–2,253
NO_x	Uniform: range=38–91
PM (<10 μ)	Uniform: range=2,243–3,258
SO_x	Uniform: range=519–125
VOC	Uniform: range=210–5,767

To conduct the Monte Carlo simulation, Crystal Ball, a spreadsheet-based software developed by Oracle, was used. The number of trials to run the Monte Carlo simulation is 2,000 and a 90% confidence level is reported. The environmental costs from the simulation for each overlay system are shown in Table 6.

The result shows that even when considering the uncertainty environmental cost is relatively small compared to user cost. However, within the 90% confidence interval, the range of potential environmental cost is significantly large. At the upper limit of the 90% certainty interval environmental cost is even larger than user cost. This result highlights the importance of incorporating environmental cost into pavement design. The potential large environmental cost would have significant impact on the development of optimal preservation strategies.

Impact of Pavement Condition Constraints

Currently, MDOT uses a threshold DI of 50 to indicate the need for overlay reconstruction. However, different highway agencies may use different thresholds of DI to trigger the reconstruction. Fig. 9 shows the optimal preservation strategies for an HMA overlay system based on different pavement condition constraints. With stricter pavement condition constraints, the preservation frequency increases and the life-cycle costs increase. The life-cycle costs are $\$8.43 \times 10^7$, $\$9.23 \times 10^7$, and $\$1.08 \times 10^8$ for DI<50, DI<30, and DI<20 constraints, respectively.

Conclusion

This paper describes the development of a new LCO model and its application to a pavement overlay system. Three potential

Table 6. Monte Carlo Simulation Applied to Environmental Costs

Overlay type	Mean ($)	Median ($)	90% certainty ($)
Concrete	1.68×10^6	6.53×10^5	$4.80 \times 10^4 – 6.93 \times 10^7$
ECC	1.19×10^6	4.47×10^5	$2.94 \times 10^4 – 5.63 \times 10^7$
HMA	2.08×10^6	1.05×10^6	$1.08 \times 10^5 – 7.04 \times 10^7$

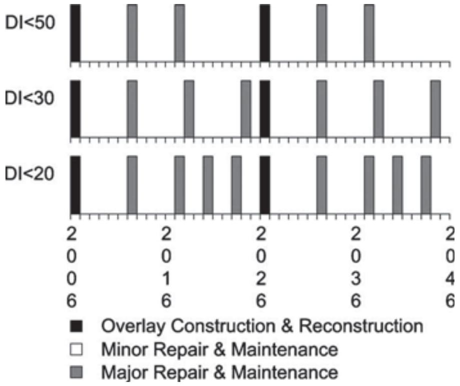

Fig. 9. Optimal preservation strategies for an HMA overlay system based on different pavement condition constraints

overlay systems were evaluated: a concrete overlay system, an ECC overlay system, and an HMA overlay system. Construction events, traffic congestion, and roughness effects are dynamically captured by the LCO model. Model results show that the optimal preservation strategies will reduce total life-cycle energy consumption by 5–30%, GHG emissions by 4–40%, and cost by 0.4–12% for concrete overlay system, ECC overlay system, and HMA overlay system, respectively, when no traffic growth is considered. Since MDOT has already incorporated LCCA into pavement design, total life-cycle costs have been controlled nearly to the optimal results.

The importance of optimizing maintenance and rehabilitation strategy in future years proved to be even more critical when the uncertainty of future traffic condition was considered. MDOT's pavement preservation strategies cannot model traffic flow changes. Results show that the preservation strategy is highly sensitive to traffic flow. With a 2% annual traffic growth rate, the optimal preservation strategies show greater advantages when compared to MDOT preservation strategies. Due to improved material properties and extended service life, under any traffic growth scenario, the ECC overlay system is superior in terms of reducing energy consumption, GHG emissions, and cost compared to the concrete overlay system and HMA overlay system. While the assumption of longer service life of the ECC overlay system is supported by results of experimental tests and bridge deck applications, it is necessary to verify the result with a field application of ECC material in an overlay system and observe its performance over time.

The application of dynamic programming as an optimization tool in LCO of pavement overlay systems has great potential for obtaining outputs considerably faster and more accurately compared to conventional methods. The combination of modern optimization techniques and life-cycle analysis methods improves the management capability of transportation agencies as compared to current pavement management practice.

Because of significant uncertainty in model parameters, uncertainty analysis was performed on environmental damage cost and the pavement condition constraints. Using the Monte Carlo simulation, a range of costs for pollution damage over the service life was developed. The result shows that at the upper limit of the 90% certainty interval environmental cost increases significantly. This result highlights the importance of incorporating environmental cost into pavement design. The pavement condition constraint determines when the pavement requires an overlay reconstruction activity. Different thresholds of pavement condition were investigated. With stricter pavement condition constraints, the preservation frequency increases and the life-cycle costs increase.

This study highlights the trade-offs between material consumption, traffic congestion, and pavement surface roughness effects. Energy/GHG optimization leads to a more frequent preservation strategy, while cost optimization favors a less frequent preservation strategy. These results also demonstrate the importance of including user cost and roughness effects in pavement management and accounting. The methodology developed during this study should lead to a more cost effective and environmentally sensitive pavement management system.

The LCO model can be applied to other States' pavement systems by substituting the life-cycle inventory data, traffic parameters, and pavement condition constraint with local data. Additionally, other sustainability indicators can be incorporated into the model, such as water usage and human exposure to environmental pollution. The future model will be enhanced by incorporating more uncertainty analysis, such as the robustness of preservation strategy, traffic congestion, and life-cycle inventory data quality.

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