SUSTAINABLE PAVEMENT ASSET MANAGEMENT BASED ON LIFE CYCLE MODELS AND OPTIMIZATION METHODS

by

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To my parents,
who gave me a love of life

To my fiancée,
who gave me a life of love

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ABSTRACT

SUSTAINABLE PAVEMENT ASSET MANAGEMENT BASED ON LIFE CYCLE MODELS AND OPTIMIZATION METHODS

Pavement systems provide critical infrastructure services to society but also pose significant impacts related to high material consumption, energy inputs, and capital investment. A new pavement asset management approach, using economic, social, and environmental metrics, is proposed to enhance the sustainability of transportation infrastructure systems.

This dissertation develops methods for evaluating and enhancing the sustainability of pavement infrastructure. Four methods are presented: (1) integrated life cycle assessment and life cycle cost analysis modeling of pavement overlay systems comparing new material Engineered Cementitious Composites (ECC) to conventional materials, (2) project-level pavement asset management system using life cycle optimization, (3) multi-objective and multi-constraint optimization informing policy and enhancing sustainability, and (4) network-level pavement asset management system integrated with geographic information systems.

The integrated life cycle model results indicated that the application of ECC can significantly improve overlay system sustainability. Compared to conventional concrete and hot mixed asphalt (HMA) overlay systems, the ECC overlay system reduces life cycle energy consumption by 15% and 72%, greenhouse gas (GHG) emissions by 32%

and 37%, and costs by 40% and 47%, respectively. Material production, construction related traffic congestion, and pavement surface roughness effects were identified as the greatest contributors to environmental impacts and costs throughout the overlay life cycle.

A project-level pavement asset management system was developed to determine the optimal pavement preservation strategy using life cycle optimization methods. The results of this analysis showed that the optimal preservation strategies reduce the total life cycle energy consumption by 5%-30%, the GHG emissions by 4%-40%, and the costs by 0.4%-12% for the concrete, ECC, and HMA overlay systems, respectively, compared to current MDOT preservation strategies.

Multi-constraint and multi-objective optimization was conducted to study the impact of agency budget constraints on life cycle cost and the relationship between material consumption, traffic congestion, and roughness effects. The influence of fuel prices, fuel taxes and government subsidies on sustainability performance was explored and specific policy recommendations were provided.

The network-level pavement asset management system provides highway agencies the capability to better maintain a well functioning pavement network and to minimize life cycle cost. A case study application showed that the optimal preservation strategy can reduce life cycle cost by 13% compared to current MDOT agency planning methods for the entire pavement network.

CHAPTER 1

INTRODUCTION

1.1 Motivation

Pavement systems are fundamental elements of the automobile and truck transportation systems in the United States. While the transportation of people and goods has expanded significantly in recent decades, pavement systems have serious impacts on the environment and the economy. The U.S. consumes more than 35 million metric tons of asphalt and 48 million metric tons of concrete annually, at a cost of nearly $65 billion, in its transportation infrastructure system alone. Concrete and asphalt are the most common materials used in the construction of pavement systems. The use of both concrete and asphalt poses significant environmental challenges. Additionally, concrete and asphalt each have specific vulnerability limitations, which increase the pavement failure and maintenance frequency. The American Society of Civil Engineers (ASCE) report card assigns US roads a grade of D (poor condition). This poor road condition costs US motorists an estimated $54 billion annually in vehicle repair and operating costs (ASCE, 2006). Shortfalls in budgets and increasing travel demand have placed a significant burden on the pavement system. The Transportation Equity Act for the 21st Century (TEA-21) authorized $173 billion for highway construction and maintenance over 6 years. However, even with TEA-21's commitment, an additional $27 billion is needed to improve conditions and performance of the U.S. highway system, according the Federal Highway Administration (ASCE, 2006).

With increasing expansion of pavement systems globally, the need for more sustainable pavement development becomes even more important. As defined by the Brundtland Commission, sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable pavement system development requires a comprehensive evaluation framework that takes into account environmental, economic, and social indicators. Figure 1.1 illustrates the range of sustainability issues considered in this research. Overall sustainability which is illustrated as the shadow area in the center of Figure 1.1 requires meeting environmental, economic, and social goals simultaneously.

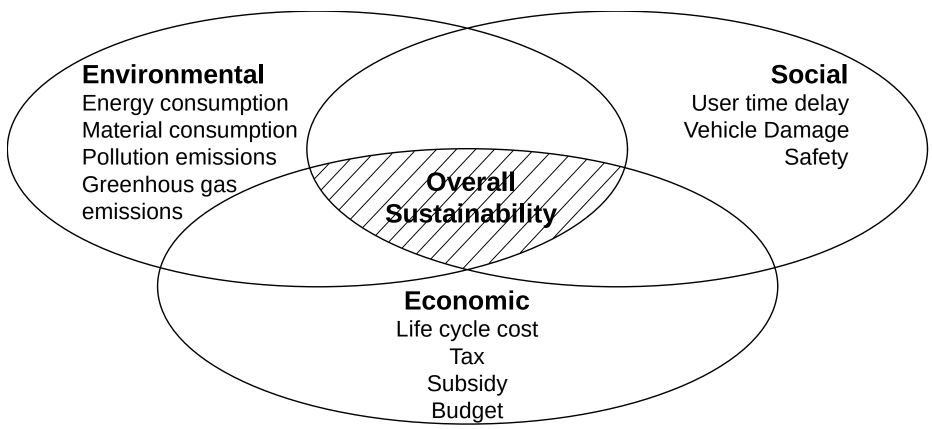

Figure 1.1 Various sustainability issues captured in pavement systems

As a part of National Science Foundation Material Use: Science, Engineering and Society (NSF MUSES) sustainable concrete infrastructure project, a sustainable design framework is developed that encompasses multi-scale boundaries ranging from micro-scale material development to macro-scale system application. Traditionally, material scientists and engineers have focused on a limited set of performance criteria in design activities within the material development process, while industrial ecologists and economists have maintained a macro-level perspective for analyzing the life cycle impacts at the infrastructure systems level. The sustainable design framework helps ensure regular flows of information between these two processes. Alternative materials designed in the material development process are translated into life cycle inventory inputs for life cycle analysis of an infrastructure system. An aggregated set of social, environmental, and economic indicators are derived for the infrastructure system from material resource extraction to end of life management. These sustainability indicators can be used to guide changes in material design in order to optimize system performance. This design, evaluation, and re-design sequence can be repeated until more sustainable solutions are reached.

The multi-scale design process begins with the development of a unique fiber-reinforced material, Engineered Cementitious Composites (ECC) using a microstructural design technique guided by micromechanical principles. Experimental testing of ECC pavement reveals significant improvements in load carrying capacity and system ductility compared to concrete or steel fiber reinforced concrete overlays (Qian, 2007). Thereby, ECC can eliminate common overlay system failures such as reflective cracking (Li, 2003). ECC is a promising candidate material for road repairs, pipeline systems, and bridge deck rehabilitation. A demonstration bridge project was recently constructed in the fall of 2005 to provide performance data on ECC field applications. In this demonstration project, an ECC link slab was applied to substitute for a conventional steel expansion joint between two steel reinforced concrete bridge decks. The project site is Grove Street over Interstate 94 (S02 of 81063) in Ypsilanti, Michigan. A life cycle assessment model for this ECC bridge link slab application has been constructed (Keoleian and Kendall, 2005).

Currently, few sustainability indicators are considered in the evaluation of alternative materials in pavement systems. Traditionally, agency costs are used by highway agencies to compare different designs. Energy consumption, greenhouse gas emissions, user costs, and environmental damage costs are not often considered in the decision making process (Wilde et al., 2001). Additionally, besides the evaluation of pavement construction, many factors during pavement usage are not evaluated by highway agencies, such as traffic congestion caused by construction activities and surface roughness effects caused by pavement deterioration. Thus, a comprehensive framework is necessary to compare ECC to other conventional materials from a long term and preventive perspective rather than a short term and corrective perspective. Life cycle modeling represents a unique analytical technique for assessing sustainability indicators including materials production through end of life management (Keoleian and Spitzley, 2006). In this research, life cycle modeling refers to both life cycle assessment (LCA) and life cycle cost analysis (LCCA). LCA evaluates the potential environmental impacts of a system at each life cycle stage. LCA provides metrics that can be used to measure progress toward environmental sustainability. Life cycle cost analysis is a complementary framework to life cycle assessment. LCCA evaluates the monetary values of the processes and flows associated with a product or system (Keoleian and Spitzley, 2006). Like LCA, LCCA varies in scope and depth, accounting for different kinds of costs. For example, an LCCA model may account only for internal financial costs (agency costs), such as construction costs and maintenance costs; it may also account for social costs, such as user costs which are incurred by motorists who are delayed or detoured by construction related traffic, or environmental costs including environmental damage costs associated with construction events. In this research, LCA and LCCA methods are coupled into an integrated LCA-LCCA model in a single computer-based model to evaluate the life cycle of a pavement system.

While LCA and LCCA methods define and evaluate the sustainability performance, these methods have limited management capabilities to optimize those indicators. A pavement segment or a pavement network can be preserved through a variety of different maintenance and rehabilitation methods and frequencies, which will lead to different long term outcomes for life cycle energy consumption, environmental impacts, and costs. A pavement asset management system (PAMS) is necessary, which allows highway agencies to explore alternative pavement materials, predict pavement deterioration over time, and select optimal preservation strategies based on specific objectives and constraints. There are two major administrative levels of any pavement asset management system: network-level PAMS and project-level PAMS (Mbwana, 2001). Project-level PAMS is intended to predict the pavement deterioration, select the appropriate preservation activity, and develop the optimal preservation schedule for a specific pavement segment. Network-level PAMS determines the pavement segment preservation priority and budget allocation strategy. Network-level PAMS policy will guide project-level PAMS to ensure that each individual pavement segment preservation strategy will result in an overall optimal solution for the entire pavement network.

A number of researchers and practitioners have applied mathematical models to pavement asset management. However, besides the economic costs, those studies do not consider other sustainability indicators (e.g., energy consumption and greenhouse gas emissions) in PAMS. Using dynamic programming, a life cycle optimization model can mathematically determine an optimal preservation strategy to minimize the energy consumption, environmental impacts, and costs associated with all stages of a pavement system life cycle.

The body of literature addressing the relationship between pavement preservation strategy, policy making, and economic factors is very limited. Multi-objective and multi-constraint optimization methods provide a quantitative base for pavement preservation policy making. Using the concept of Pareto efficiency, multi-objective optimization enables highway agencies to develop their preservation strategy based on weighted objectives to achieve maximized benefit. Multi-constraint optimization studies the impact of agency budget constraints on user cost and total life cycle cost. The influence of fuel taxes and government subsidies on financing a pavement system can be evaluated and specific policy recommendations can be informed.

Due to budget constraints, highway agencies cannot preserve their entire pavement network using the optimal preservation strategy identified by a project-level life cycle optimization model. Thus, a priority selection model is necessary to adjust the optimal preservation strategy and allocate the limited budget to the specific pavement segments to achieve the global optimal result. Three priority selection methods are developed based on benefit, benefit cost ratio, and binary integer programming.

Another challenge in developing a pavement asset management system is the ability of managing and analyzing the large pavement condition dataset. A pavement asset management system relies on pavement condition information for identifying pavement construction sections, developing the preservation strategy, and allocating the budget. Geographic information system (GIS), with its spatial analysis capability, allows highway agencies to integrate, manage, query, and visualize pavement conditions. A GIS model integrated with a pavement asset management system provides a unique way to immediately retrieve and visualize important pavement network attributes, such as pavement condition, current pavement preservation activity, and costs, on the graphical map. This new framework is expected to improve the decision making process involved in managing pavement networks.

1.2 Research Objectives

The objective of this research is to develop a comprehensive pavement development framework to evaluate the impacts of different construction material applications, manage a pavement network, and allocate limited budget. This framework will be utilized to improve pavement design and preservation to ensure optimal performance. The specific research activities include:

(1) To develop an integrated LCA-LCCA model for unbonded concrete, hot mixed asphalt, and ECC pavement overlay systems to dynamically capture the impacts of users, construction, and overlay deterioration.

(2) To develop a project-level pavement asset management system using life cycle optimization method to determine the optimal preservation strategy for pavement overlay systems.

(3) To investigate highway policy and enhance transportation infrastructure sustainability using multi-objective and multi-constraint optimization methods.

(4) To develop a network-level pavement asset management system including a priority selection model and a GIS model to allocate limited budget efficiently and preserve a healthy pavement network while minimizing sustainability indicators.

Fulfillment of these objectives will provide a comprehensive understanding of the impacts and the relationship of material consumption, traffic congestion, pavement surface deterioration, and preservation strategy in managing pavement systems. In summary, this dissertation provides a framework and the tools that can enhance infrastructure sustainability for pavement material selection, pavement design, and pavement asset management.

1.3 Organization

This dissertation is presented in a multiple manuscript format. Chapter 2, 3, 4, and 5 are written as individual research papers, including the abstract, the main body and the references.

Chapter 2 develops and presents an integrated life cycle assessment and life cycle cost analysis model to evaluate the energy consumption, environmental impacts, and costs of pavement overlay systems resulting from material production and distribution, overlay construction and maintenance, construction-related traffic congestion, overlay usage, and end of life management. A conventional unbonded concrete overlay system, a hot mixed asphalt overlay system, and an alternative Engineered Cementitious Composites (ECC) overlay system are evaluated. Material consumption, traffic congestion caused by construction activities, and roughness effects caused by overlay deterioration are three dominant factors that influence the environmental impacts and costs of overlay systems. A sensitivity analysis is conducted to study the impact of traffic growth and fuel economy improvement (Zhang et al., 2008 and Zhang et al., 2009). The sustainability indicators presented in Chapter 2 provide a quantitative basis for the analysis of following chapters.

Chapter 3 presents the project-level pavement asset management system. A life cycle optimization model is developed to determine the optimal preservation strategy for a single pavement overlay segment which minimizes total life cycle energy consumption, greenhouse gas emissions, and costs within an analysis period. Using dynamic programming optimization techniques, the life cycle optimization model integrates life cycle assessment and life cycle cost analysis models with an autoregressive pavement overlay deterioration model. The project-level pavement asset management system is applied to the conventional unbonded concrete, hot mixed asphalt, and ECC overlay systems. The results of optimal preservation strategies are compared to current Michigan Department of Transportation preservation strategies. The impact of traffic growth to the optimal preservation strategies is discussed (Zhang et al., 2009).

Chapter 4 extends the analysis of a single pavement segment based on the results of Chapter 3. Multi-constraint and multi-objective optimization is conducted to study the impact of agency budget constraints on user costs and total life cycle cost, identify the trade offs between energy consumption and costs, and understand the relationships between material consumption, traffic congestion, and pavement roughness effects. A Pareto optimal solution that minimizes energy and cost objectives is developed to enhance the preservation strategies. The influence of fuel taxes and government subsidies on a pavement system is explored and specific policy recommendations are provided (Zhang et al., 2008).

Chapter 5 develops a network-level pavement asset management system to minimize environmental and economic sustainability indicators for the entire pavement network. Life cycle assessment, life cycle cost analysis, life cycle optimization, and project-level pavement asset management models are incorporated in the network-level pavement asset management system. A priority selection model is implemented to allocate a limited agency budget efficiently. A GIS model is developed to enhance the network-level pavement asset management system by collecting, managing, and visualizing pavement condition data. Query analysis is conducted in the GIS model to identify the specific pavement network in the basic digital map. Linear referencing and dynamic segmentation methods are applied to define the pavement segment and associate pavement information with any pavement portion (Zhang et al., 2009).

Chapter 6 draws the conclusions and summarizes the original contributions of the dissertation. Several topics are also proposed for future research.

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CHAPTER 2

INTEGRATED LIFE CYCLE ASSESSMENT AND LIFE CYCLE COST ANALYSIS MODEL

ABSTRACT

Pavement systems have significant impacts on environment, economy, and society due to large material consumption, energy input, and capital investment. To evaluate the sustainability of pavement systems, an integrated life cycle assessment and life cycle cost analysis model was developed to calculate the energy consumption, environmental impacts and costs of pavement overlay systems resulting from material production and distribution, overlay construction and maintenance, construction-related traffic congestion, overlay usage, and end of life management. An unbonded concrete overlay system, a hot mixed asphalt overlay system, and an alternative engineered cementitious composite (ECC) overlay system are examined. Model results indicate that the ECC overlay system significantly reduces total life cycle energy consumption, greenhouse gas (GHG) emissions, and economic costs compared to conventional overlay systems. These advantages are derived from the enhanced material properties of ECC which prevent reflective cracking failures. Material consumption, traffic congestion, and pavement surface roughness effects are identified as three dominant factors that increase both the environmental impacts and the cost of overlay systems.

2.1 Introduction

Pavement systems are fundamental components of our automobile transportation systems. While the transportation of people and goods is increasing rapidly, pavement systems have serious impacts on the environment and the economy. Yet, the American Society of Civil Engineers (ASCE) report card assigns US roads a grade of D (poor condition). This poor road condition costs US motorists an estimated $54 billion annually in vehicle repair and operating costs (ASCE, 2006).

As the pavements age and deteriorate, preservation (maintenance and rehabilitation) are required to provide a high level of safety and service (Huang, 2004). For pavements subjected to heavy traffic, one of the most prevalent preservation strategies is the placement of an overlay on top of the existing pavement (DOT, 1989). An overlay provides protection to the pavement structure, reduces the rate of pavement deterioration, corrects surface deficiencies, and adds some strength to the existing pavement structure. Depending on the type of overlay and existing pavement, two possible designs are generally used: an unbonded concrete overlay or a hot mixed asphalt (HMA) overlay. An unbonded concrete overlay is typically placed over a pavement which is badly cracked. A separation layer, usually consisting of asphalt less than 50 mm thick, is placed between the new concrete overlay and the cleaned existing pavement to prevent reflective cracking (ACPA, 1990). An HMA overlay usually has several layers with the different mixes of hot mixed asphalt (Huang, 2004). Concrete and asphalt are the most common materials used in the construction of pavement and overlay systems. Nearly 57% of the mileage of interstate highways and other freeways is either concrete surface or concrete base, while other highways, rural roads, or urban streets are asphalt surface (Zapata, 2005). The use of both concrete and asphalt pose significant environmental challenges. The world wide production of cement, a key constituent in concrete, releases more than 1.6 billion metric tons of CO_2 annually, accounting for over 8% of total CO_2 emissions from all human activities (Wilson, 1993), and significant levels of other pollutants, such as particulate matter and sulfur oxides (Estakhri and Saylak, 2005). Asphalt, a petroleum byproduct, is energy intensive and contains 7,354 MJ of feedstock energy per cubic meter (Zapata, 2005). Asphalt is also a large source of volatile organic compounds (VOC) accounting for 200,000 metric ton of VOC emissions each year in the U.S. from asphalt pavement construction (Spivey, 2000). Additionally, concrete and asphalt have some physical limitations that contribute to durability concerns, which increase the likelihood of pavement failure and maintenance frequency. Consequently, alternative materials are being developed to improve road performance. Part of the process to introduce new materials into field application includes evaluation of the environmental impacts at each stage of the material life cycle from resource extraction through manufacturing, transportation, construction and final disposal. Additionally, sustainability is increasingly adopted as a framework for designing and constructing pavement systems. Life cycle assessment (LCA) and life cycle cost analysis (LCCA) methodologies provide the means for evaluating the sustainability of pavement systems.

LCA is an analytical technique for assessing potential environmental burdens and impacts. LCA provides metrics that can be used to measure progress toward environmental sustainability (Keoleian and Spitzley, 2006). LCA studies the environmental aspects and potential impacts throughout a product's life from raw material acquisition through production, use and disposal (ISO, 1997). LCCA evaluates the monetary values of processes and flows associated with a product or system (Keoleian and Spitzley, 2006). Like LCA models, LCCA models vary in scope and depth, accounting for different kinds of costs. For example, LCCA models may account only for internal costs (agency costs), such as construction costs and maintenance costs; it may also account for social costs, such as user costs which are incurred by motorists who are delayed or detoured by construction related traffic, or environmental costs including environmental damage costs associated with construction events.

Two approaches have been used in previous LCA and LCCA studies. One approach uses a process level LCA method to trace the energy consumption and related environmental impact of the system (Zapata, 2005). The other approach is the economic input-output analysis-based life cycle analysis (EIO-LCA) method, developed by Carnegie Mellon University's Green Design Initiative. This method traces the various economic transactions for various sectors and uses an economic input-output matrix of the US economy to evaluate resource requirements and environmental emissions (Horvath and Hendrickson, 1998).

Only a few efforts on pavement life cycle modeling have been made. The Swedish Environmental Research Institute (IVL) conducted a life cycle assessment of concrete and asphalt pavements based on process flows, including pavement construction, maintenance and operation (Stripple, 2001). Additionally, the University of Texas Center for Transportation Research performed a life cycle cost assessment which is an engineering-economic analysis tool used to quantify the differential costs of alternative investment options for a given project, to evaluate concrete pavement (Wilde et al., 2001).

Horvath and Hendrickson used the EIO-LCA model to study the environmental impacts of asphalt and steel-reinforced concrete pavements. However, these studies did not analyze the maintenance procedures and their effects on extending the pavement service life and did not capture the effects of the pavement deterioration on vehicles.

An integrated LCA and LCCA model (LCA-LCCA) was developed and applied to compare the energy consumption, environmental impacts, and costs for an overlay system built using concrete, HMA, or a new material—Engineered Cementitious Composites (ECC), an ultra ductile form of concrete.

ECC is a unique fiber-reinforced composite developed using a microstructural design technique guided by micromechanical principles. ECC is deliberately designed as a fiber reinforced cementitious material with a deformation behavior analogous to that of metals (Li and Fischer, 2002). Experimental testing of ECC overlays reveal significant improvements in load carrying capacity and system ductility compared to concrete or steel fiber reinforced concrete overlays (Qian, 2007). Thereby, ECC can eliminate common overlay system failures such as reflective cracking (Li, 2003). Since the introduction of this material a decade ago, ECC has undergone a major evolution both in the academic and industrial communities (Li, 2002). ECC is a promising candidate material for road repairs, pavement overlays (Li, 2003), and bridge deck rehabilitation (Gilani, 2001). A demonstration bridge project was constructed in the fall of 2005 to provide performance data on ECC field applications. In this demonstration project, an ECC link slab was applied to substitute the conventional steel expansion joint between two steel reinforced concrete bridge decks. The project site is Grove Street over Interstate

94 (S02 of 81063) in Ypsilanti, Michigan. An LCA model for this ECC bridge link slab application has been constructed (Keoleian and Kendall, 2005).

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

2.2 Methodology

2.2.1 System Definition

The overlay designs analyzed in this study are constructed upon an existing reinforced concrete pavement originally built by the Michigan Department of Transportation (MDOT). The three overlay systems are modeled as 10 km long and four lanes wide (two lanes in each direction). Figure 2.1 illustrates the structures of the different types of the overlay systems in one direction including the thickness of different layers. The thickness of the overlay depends on the material and construction methods. These pavement overlay designs are based on the results from an experimental study conducted by University of Michigan's Department of Civil and Environmental Engineering and typical pavement overlay designs (Huang, 2004). In the integrated LCA-LCCA model, the unbonded concrete overlay and HMA overlay is designed for a 20 year service life by MDOT (MDOT, 2005). The service life of the ECC overlay is expected to be twice that of the concrete overlay. This design is based on experimental and analytical modeling of ECC pavement overlays (Qian, 2007).

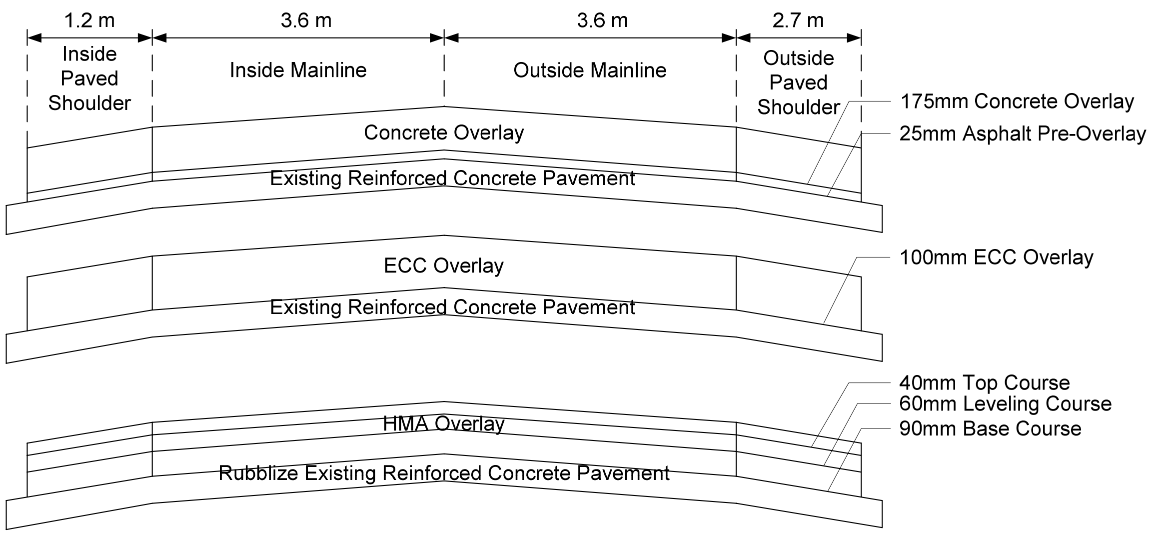

Figure 2.1 Overlay structure and thickness in one direction

The construction and preservation schedule for the concrete overlay and HMA overlay systems are based on the historical maintenance and pavement management records (MDOT, 2005). The ECC overlay is expected to extend service life by preventing commonly observed overlay failure modes, such as reflective cracking (Li, 2003). This failure results from overlay cracks forming directly above existing cracks in the substrate concrete or "reflecting" through the overlay. When ECC is applied as overlay material, reflective cracks are suppressed by becoming trapped inside the ECC overlay through a unique "kinking and traping" 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). Thus, ECC overlays can achieve a longer life with a much thinner thickness compared with concrete. In addition, maintenance frequency and maintenance material consumption are minimized. Figure 2.2 shows the construction and maintenance schedule for the three overlay systems. The life cycles for each of the three systems begin with overlay construction. The concrete overlay is reconstructed in its 21st year, with major maintenance events at year 11 and year 31. The HMA overlay is reconstructed in its 20th year, with major maintenance events in year 8 and year 28, and minor maintenance events in year 6, 12, 26, and 30. The ECC overlay is expected to last the entire 40 years service life with a single major maintenance event and no reconstruction.

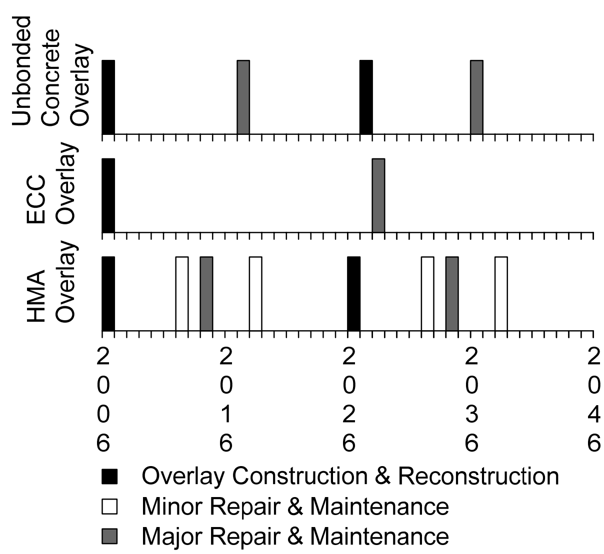

Figure 2.2 Timeline and maintenance schedule for construction activities

The total material consumption over the entire life cycle for the three systems is provided in Table 2.1, along with the energy intensity of each material and the source of life cycle inventory data for each material.

Table 2.1 Total material consumption in each overlay system and associated data sources

Material	Concrete overlay (Mt)	ECC overlay (Mt)	HMA overlay (Mt)	Energy intensity (MJ/kg)	Sources
Portland cement	26,789	15,749	0	4.5-6.6	Portland Cement Association (PCA 2002), Athena Sustainable Material Institute, and SimaPro 6.0
Gravel	88,605	0	0	0.11	SimaPro 6.0
Sand	66,861	12,616	39,292	0.11	SimaPro 6.0
Fly ash	4,042	19,299	0	0	Fly ash is a byproduct of power plant, so no energy intensity is allocated in this study
PVA fiber	0	702	0	101	Life cycle Modeling of Concrete Bridge Design (Keoleian and Kendall 2005)
Super plasticizer	0	473	0	35.2	Life cycle Modeling of Concrete Bridge Design (Keoleian and Kendall 2005)
Asphalt	900	0	15,112	14.5	SimaPro 6.0, Athena Sustainable Material Institute, and IVL Swedish Environmental Research Institute
Crushed aggregate	9,986	0	167,630	0.21	SimaPro 6.0, Athena Sustainable Material Institute, and IVL Swedish Environmental Research Institute
Limestone	623	0	10,462	0.08	SimaPro 6.0 and IVL Swedish Environmental Research Institute

2.2.2 Integrate LCA-LCCA Model

The methodology for the life cycle model used in this study followed the international standard, ISO 14040, ISO 14041, and ISO 14042 methods (ISO, 1997; ISO, 1998; ISO, 2000). The complete integrated LCA-LCCA model framework, including modules which make up the model, is shown in Figure 2.3.

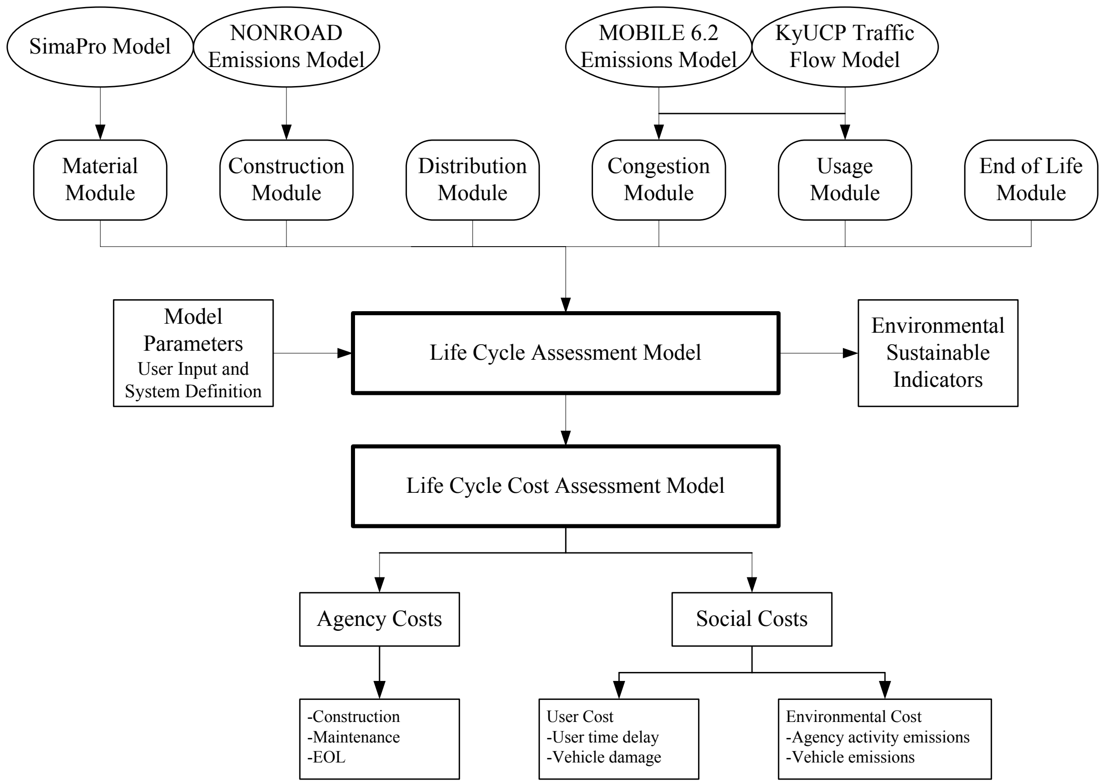

Figure 2.3 Integrated LCA-LCCA model framework

2.2.2.1 Life Cycle Assessment Model

The LCA model quantifies the environmental and social performance of an overlay system throughout its life cycle, from raw material acquisition to final disposal or recycling. The LCA model is divided into six modules: material production, consisting of the acquisition and processing of raw materials; construction, including all construction processes, maintenance activities, and related construction machine usage; distribution, accounting for transport of materials and equipment to and from the construction site; traffic congestion, which models all construction and maintenance related traffic congestion; usage, including overlay roughness effects on vehicular travel and fuel consumption during normal traffic flow; and end of life, which models demolition of the overlay and processing of the materials.

The material production module is modeled using data sets from various sources, including the Portland Cement Association, the Athena Sustainable Materials Institute, and the SimaPro 6.0 life cycle data base. The modeled material compositions of concrete, HMA, and ECC are shown in Figure 2.4.

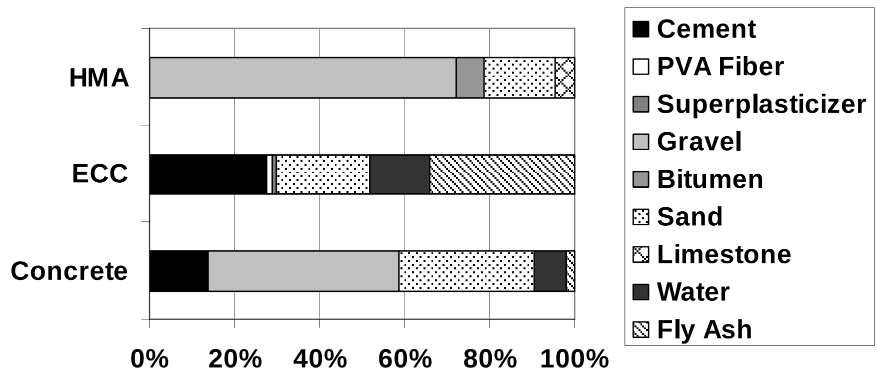

Figure 2.4 Material composition of concrete, HMA, and ECC materials

The total primary energy contribution per volume for each material constituent is shown in Figure 2.5. The unit volume primary energy consumption for concrete, ECC, and HMA is 2,212, 7,103, and 9,142 MJ/m^3, respectively. In the case of HMA, although the asphalt is only 6.5% of HMA by volume, the feedstock energy (7,353 MJ/m^3 HMA) contained in the asphalt binder accounts for 80% of the total energy consumed in HMA production. In comparing ECC and concrete, ECC contains a large amount of fly ash (33.9% of ECC by volume compared to 2.1% of concrete), which is a byproduct of coal consumption. Consequently, there is no environmental burden or energy consumption allocated to this substitute. However, the particular ECC mix used in this study contains twice as much cement per volume compared to concrete (27.7% compared to 13.7%), which accounts for the higher energy intensity for ECC. Additionally, poly-vinyl-alcohol (PVA) fiber (1.2% of ECC by volume) also contributes to a major portion of energy in the production of ECC (36% of total energy consumption).

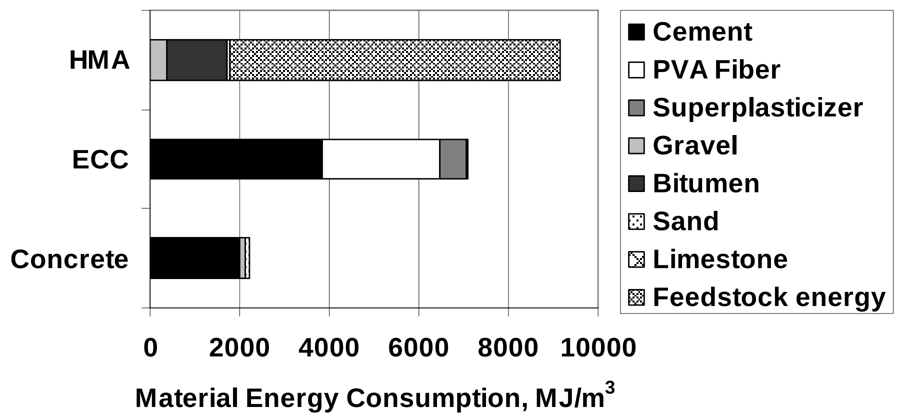

Figure 2.5 Primary energy consumption per volume of each material

The distribution module is closely linked to the material and EOL modules. All the materials, equipment and wastes are transported by a combination of roadway, railway, and waterway. The distribution distance was modeled using the nearest material supplier locations relative to the construction site. The environmental impacts for distribution include both fuel production for transportation vehicles and their emissions.

In the construction module, the operating time of the equipment during construction events is estimated by using previous construction project documents from MDOT and the production rate of each machine. The fuel-related emissions from this equipment are assessed using the United States Environmental Protection Agency (EPA) NONROAD2005 model of diesel engine emissions for Michigan. The equipment used in this study is presented in Table 2.2. Fuel usage is obtained from the NONROAD2005 model and the upstream process impacts for this fuel are calculated by using SimaPro 6.0 fuel production data.

Table 2.2 Total equipment usage during construction activities in hours

Equipment	Power, kw	Concrete system	ECC system	HMA system
Crawler-mounted hydraulic excavator	320	256	128	256
Air compressor	260	128	64	128
Dumper	17	336	192	288
Hydraulic hammer	75	160	64	128
Motor grader	123	32	32	32
Water truck	335	64	64	64
Vacuum truck	132	64	64	64
Wheeled front end loader	175	416	192	384
Signal boards	4	65,338	35,404	79,401
Concrete paver	186	662	435	0
Concrete truck	223	662	435	0
Resonant breaker	447	0	0	200
Asphalt paver	150	56	0	902
Asphalt roller	93	16	0	310
Asphalt truck	223	56	0	843

The traffic congestion considered in this study is caused only by the construction activities. The changes in traffic flow and congestion are estimated using the KyUCP model (KTC, 2002). The delays are calculated using model input parameters such as annual average daily traffic (AADT), work zone speed limits, lane capacity, detour distance, and the number of lane closures during construction. The AADT is approximately 70,000 vehicles with 8% heavy duty trucks (MDOT, 1997). In the baseline scenario, the annual traffic growth rate is 0%. To facilitate partial-width construction, only one lane in each direction will be closed during all construction events. Speed limit is reduced from 105 km/h to a work zone speed of 65 km/h. In this scenario, 12% of drivers are assumed to self-detour 2.5 km on nonhighway roads, thus resulting in slower travel speeds (65 km/h) and longer travel distances (Keoleian and Kendall, 2005).

Once vehicle delay and congestion due to construction and preservation events are calculated, these results are coupled with fuel consumption and vehicle emissions to measure environmental impacts. Fuel consumption is determined using fuel economy estimated by city and highway drive cycles. The city drive cycle is used to estimate the fuel consumption during congestion and detour modes. Likewise, the highway drive cycle is used to model the normal traffic flow during free flowing traffic periods. Fuel consumption for passenger cars, light duty vehicles and heavy duty vehicles is taken from the Vision Model, developed by US Department of Energy (DOE) Center for Transportation Research at Argonne National Laboratory (DOE, 2004). Carbon dioxide (CO_2) emissions are derived using fuel consumption, carbon content, and engine efficiency. Other vehicle emissions are calculated using USEPA's MOBILE 6.2 software at varying traffic speeds. MOBILE 6.2 is used to predict the tailpipe emissions and evaporative emissions on a per year basis through 2050. Four localized MOBILE 6.2 data inputs for the winter and summer seasons used in this study include annually temperature range, Reid vapor pressure, age distribution of the vehicle fleet, and average vehicle miles traveled data (SEMCOG, 2006). The output results of fuel consumption and vehicle emissions in the LCA model are calculated using Equation 2.1 based on the difference between traffic flow during construction periods and traffic flow during normal conditions. VMT_x represents the total vehicle miles traveled under normal, highway, work zone, detour, and queue conditions. Y_x represents the marginal change for different environmental indicators, such as emission values (g/km) and fuel usage (L/km).

$$Y_{Total} = VMT_{Highway} * Y_{Highway} + VMT_{Queue} * Y_{Queue} + VMT_{Work\ zone} * Y_{Workzone} + VMT_{Detour} * Y_{Detour} - VMT_{Normal} * Y_{Normal} \quad (2.1)$$

For pavement infrastructure with a long service life cycle, the output results are highly dependent on future changes in fuel economy and annual traffic growth rate. This effect will be discussed in the scenario analysis section.

The traffic congestion module predicts how construction activities affect traffic flow and emissions. The usage module describes the effects on traffic during normal operation of the overlay section, and this module is significantly more complex than the other modules. There are two primary factors which affect fuel consumption and vehicle emissions: fuel economy changes and pavement roughness changes over time.

In this model, the fuel economy of a heavy duty truck combining cost-effective conventional improvements with hybridization is predicted to save 32% of total energy consumption over a 20 year period (Langer, 2004). This is described by Equation 2.2.

$$FE_n = FE_{base} * (1 + r)^n \qquad (2.2)$$

FE_n is the heavy duty truck fuel economy factor for nth year and FE_{base} is the 2003 baseline heavy duty truck fuel economy factor which is presented in the Vision model. The value r is the annual fuel economy improvement, estimated at 1.5% fuel consumption savings per year due to increased boosting, improved combustion control and other design changes.

For passenger cars and other light duty vehicles, there are two methods to estimate future fuel economy trends. The first method is also described by Equation 2.2. In this case, FE_{base} is the 2003 baseline car and light duty vehicle fuel economy factor based on the data from the Transportation Energy Data Book developed by the DOE Center for Transportation Analysis (Davis and Diegel, 2002). The value r is estimated at 1% fuel consumption savings per year (Davis and Diegel, 2002), based on fuel economy trends from 1995-2005. The second method is based on a model of future performance of the internal combustion engine (ICE) over a 30 year time horizon (Heywood et al., 2004) shown as Equation 2.3. The time period is extrapolated to 40 years to match the service life of the three overlay system. In this equation, n_0 and n are the initial year and the nth year of this project, respectively.

$$FE_n = -4.96\times10^{-4}\times(n-n_0)^3 + 4.08\times10^{-2}\times(n-n_0)^2 - 2.28\times10^{-1}\times(n-n_0) + 1.88\times10^{-1} + FE_{base} \quad (2.3)$$

Due to surface deterioration, the overlay surface roughness increases continuously over time. Roughness is generally defined as an expression of road surface irregularity which affects the operation of a vehicle, including speed of travel, fuel economy, emissions and safety. Hence, it also impacts vehicle operation costs and maintenance costs. Roughness is often measured using the international roughness index (IRI), which was developed by the World Bank in the 1980s (Sayers et al., 1986). The IRI is a ratio of a standard vehicle's accumulated suspension motion (in mm, inches, etc.) divided by vehicle distance traveled during the measurement (km, mi, etc.). The commonly recommended unit of IRI is meters per kilometer (m/km) (Sayers and Karamihas, 1995). The IRI describes a linear scale of roughness beginning with 0 m/km for a perfectly flat surface and no theoretical upper limit, although IRI values above 8 m/km means driving uncomfortably and reducing the speed. (Archondo-Callao, 1999).

The pavement performance of the concrete and HMA overlays was predicted by MDOT based on empirical data (MDOT, 2005). By suppressing reflective cracking, the pavement performance of the ECC overlay is much better than the concrete overlay (Qian, 2007). To gauge pavement conditions in Michigan, a Distress Index (DI) is used which represents a holistic measure of pavement condition including surface roughness and deterioration. A set of plots showing the evolution of DI for each overlay over time is shown in Figure 2.6. As can be seen, the distress of overlay decreases from individual preservation activities (Figure 2.2). The DI and time relationship for each overlay can be described by several polynomial equations.

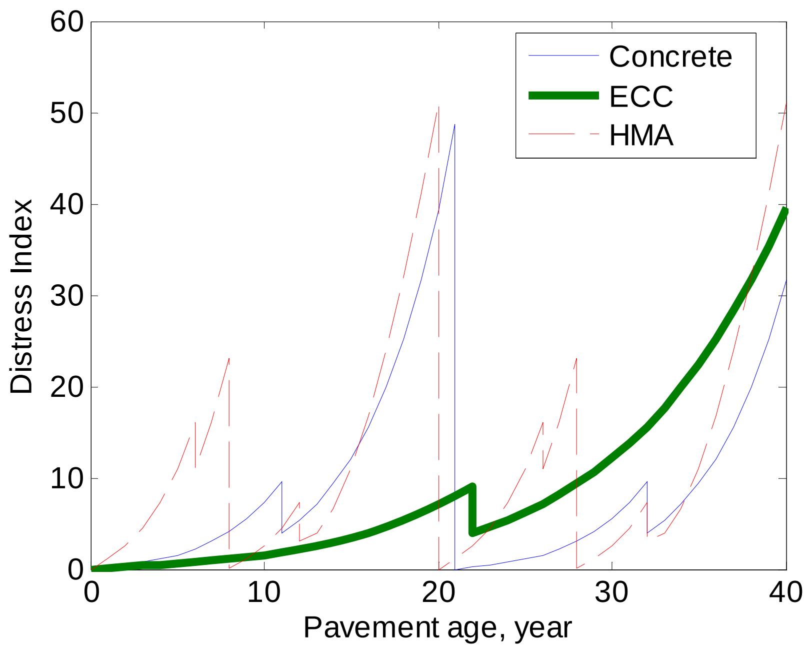

Figure 2.6 Distress index of each pavement

DI and IRI have been related for the concrete and HMA overlays through Equation 2.4 and Equation 2.5, respectively (Lee et al., 2002). For the ECC overlay, the same equation was used as the concrete overlay.

$$IRI = \left(\frac{16.44DI}{35-DI}\right)^{0.30} \tag{2.4}$$

$$IRI = \left(\frac{26.84DI}{35-DI}\right)^{0.308} \tag{2.5}$$

Increased road roughness is estimated to reduce onroad fuel economy by 4.2% relative to the government listed fuel economy (EPA, 2006). WesTrack has related roadway roughness effects to the fuel consumption of heavy duty trucks at a constant speed (WesTrack, 1999), shown in Equation 2.6.

$$FCF = 0.0667 IRI + 0.8667 \quad (2.6)$$

where FCF is the fuel consumption factor (greater than 1.0).

Using this fuel consumption factor, the total fuel consumption can be assessed by multiplying the ideal fuel consumption on a perfectly smooth overlay by the FCF. The final result is expressed as the difference between fuel consumed during vehicle operation on a rough overlay and on a ideally smooth overlay.

To estimate the effect of roughness on emissions, both driving behavior and engine load are considered. Most drivers slow down when driving on a rough road. The World Bank classifies “comfortable riding conditions” as up to 80-95 km/h when the IRI is 3.5-4.5 m/km (Archondo-Callao, 1999). The speed adjustment factor S , based on average running speed and IRI, is described by Equation 2.7 (Wilde et al., 2001).

$$S = 4.3065 e^{(0.52 - 0.26 IRI)^{0.0928}} \quad (2.7)$$

Roughness changes affect highway capacity due to speed reduction. Highway capacity decreases approximately 150 passenger car units per hour per lane as IRI increases by 1 m/km (Chandra, 2004). This lane capacity change directly determines queue formation and detour selection, assessed through the KyUCP model.

Operating emissions for a vehicle traveling on a rough overlay versus on an ideally smooth overlay are calculated using the speed adjustment factor and the lane capacity change factor.

Another source of increased vehicle emissions is engine load changes owing to increased friction and vertical acceleration of the vehicle body caused by additional roughness. To estimate emissions produced by engine load change a typical torque curve for an engine (Tunnell, 2005) was used. Within the region of maximum torque, there is an area designated the Not-To-Exceed (NTE) zone. The EPA defines the NTE zone to control heavy-duty engine emissions over the full range of speed and load combinations commonly experienced during vehicle operation. Inside this zone, under the maximum torque curve of an engine the emissions must not exceed a specified value for any of the regulated pollutants.

Because of the constraints imposed by NTE limits, a constant emission rate (in grams of emission per liter of fuel burned) is assumed for a typical speed of operation (90 km/h to 105 km/h) of a truck (Tunnell, 2005). Any additional emissions produced as a result of engine load increasing can be estimated as proportional to the fuel consumption increase calculated by Equation 2.6.

In the end of life module, all material is assumed deposited in a landfill in the baseline scenario. The disposal materials transported from the construction site to landfill are modeled in the same method as the distribution module.

By quantifying environmental and social impacts, the LCA model can also provide the input data for a life cycle cost model.

2.2.2.2 Life Cycle Cost Analysis Model

The LCCA model calculates the agency, user, and environmental costs. The framework of the LCCA model was first developed by Kendall et al (Kendall et al., 2006).

Agency costs include all costs incurred directly by the highway agencies over the lifetime of the overlay system. These are typically construction and preservation costs including material costs, equipment rental and operating costs, and labor costs. The actual agency costs were collected from MDOT construction contracts. Table 2.3 shows the agency costs breakdown for the construction activities modeled.

Table 2.3 Agency costs breakdown for overlay construction activities

Construction activity	Overlay type	Process	Total 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
Overly 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

Social costs are not directly addressed in the construction and preservation activities of a transportation agency. Generally, social costs include user costs and environmental costs. User costs are more likely to be considered in more densely populated states or urban areas, while environmental costs are not considered by any state (Chan et al., 2006). The literature is limited in examining how social costs are actually applied by state DOTs.

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

User time delay costs normally dominate user costs. The total costs of travelers sitting in traffic are 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 value of time (delay costs rate) for passenger vehicles, single unit trucks, and combination trucks is $11.58/Veh-hr (vehicle hour), $18.54/Veh-hr, and $22.31/Veh-hr respectively, estimated by the Federal Highway Administration (Wall and Smith, 1998). Costs are in 1996 dollars and updated to 2006 dollars in the LCCA model using the Consumer Price Index.

Vehicle operating costs account for higher fuel consumption and thus higher fuel costs when driving through a work zone or on a deteriorated overlay, as compared to normal conditions. If drivers choose 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. Fuel costs are based on a 2006 average of retail fuel costs in Michigan. Fuel price changes have little impact on total user costs, since fuel accounts for less than 3% of total user costs as compared to 85% for user delay costs.

The last element of user costs 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 risk costs (MDOT, 2002).

User costs should be considered when deciding the proper long term design of an overlay system, since user costs associated with overlay construction and maintenance usually exceed agency costs by a significant amount (Zhang et al., 2009; Wilde et al., 2001). Minimizing the interruption of traffic flow during construction and preservation activities over the total life cycle of an overlay is important for highway design.

Environmental costs measure the pollution damage costs over the entire life cycle of an overlay system. These costs are related to both direct and indirect impacts to human health from air pollution; the inhaling of air pollutants detrimental to human health, and greenhouse gases 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 (VOC). Three major greenhouse gases that are inventoried include carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). The marginal costs of these pollutants are shown in Table 2.4 (Kendall et al., 2006). Since the criteria pollutants are sensitive to geographic region, values for urban, urban fringe and rural areas are calculated separately. GHG emissions have global consequences, therefore global costs are used.

Table 2.4 Air pollution damage costs by impacted region (Kendall et al., 2006)

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

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

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

2.3 Results and Discussions

2.3.1 Life Cycle Assessment Results

Total life cycle assessment results represent the environmental impacts from the material module, construction module, distribution module, traffic congestion module, usage module and EOL module over the 40 year life cycle. The environmental indicators in this study include energy consumption, greenhouse gas emissions, air pollutant emissions, and water pollutant emissions.

2.3.1.1 Energy consumption

Life cycle energy consumptions for 10 kilometers of the concrete overlay, ECC overlay and HMA overlay are 6.8×10^5 GJ, 5.8×10^5 GJ, and 2.1×10^6 GJ, respectively. The life cycle energy consumption by stage is shown in Figure 2.7. The life cycle energy consumption for three systems is dominated by material production energy, traffic congestion related energy and roughness related energy. Roughness related energy has not been previously studied using LCA. Without considering the roughness effect, the life cycle energy consumptions of concrete, ECC, and HMA overlay systems will decrease 23%, 36%, and 14%, respectively.

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

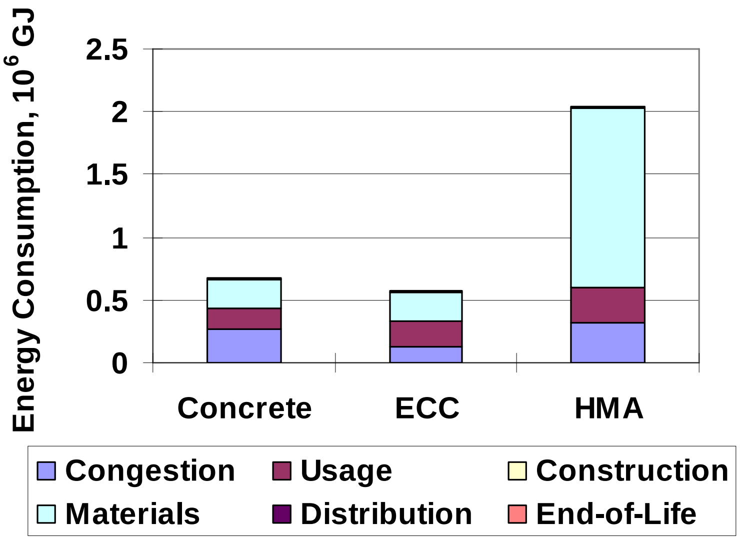

Figure 2.7 Life cycle energy consumption by life cycle phase

2.3.1.2 Greenhouse Gas Emissions

Greenhouse gas (GHG) emissions inventoried in this study include CO_2, methane, and nitrous oxide. The global warming impact is characterized by GHG emissions in metric tons of CO_2 equivalent. This is calculated by multiplying the mass of each GHG emission by its global warming potential (GWP), where GWP is 1 for CO_2, 23 for methane, and 296 for nitrous oxide (Houghton, 2001). Figure 2.8 shows the global warming impact of each overlay system in CO_2 equivalent, 10^3 Mt.

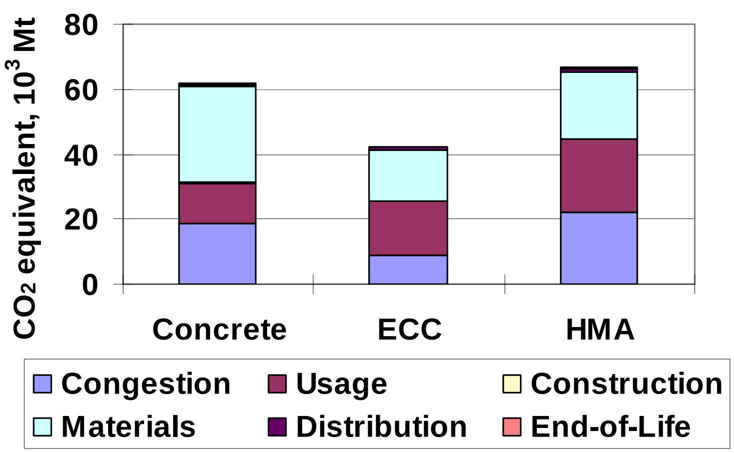

Figure 2.8 Greenhouse gas emissions by life cycle phase

CO_2 emissions significantly dominate the contribution to global warming impact. In the concrete overlay system CO_2 represents 99.2% of total life cycle GWP, in the ECC system CO_2 represents 99.4% of total life cycle GWP, and in the HMA system CO_2 represents 94.4% of total life cycle GWP. The ECC system reduces GHG emissions by 32% and 37% compared to the concrete overlay system and HMA overlay system, respectively. Generally, CO_2 emission reflects energy consumption; however, cement production releases CO_2 during calcination of limestone. Additionally, a large amount of primary energy consumption in the HMA overlay system is the feedstock energy. Carbon embodied in the material is fixed and does not generate CO_2 unless it is burned. This relationship is evident in the comparison of Figure 2.7 and Figure 2.8 wherein the CO_2 emissions of the HMA overlay system are not significantly higher than the other two systems.

2.3.1.3 Air Pollutant emissions

Other air pollutant emissions in addition to the GHG emissions in this analysis include nitrogen oxides (NO_x), sulfur oxides (SO_x), nonmethane hydrocarbons (NMHC), particulate matter ($PM_{2.5}$), carbon monoxide (CO), and volatile organic compounds (VOC). Figure 2.9 presents these air pollutant emissions by life cycle stage.

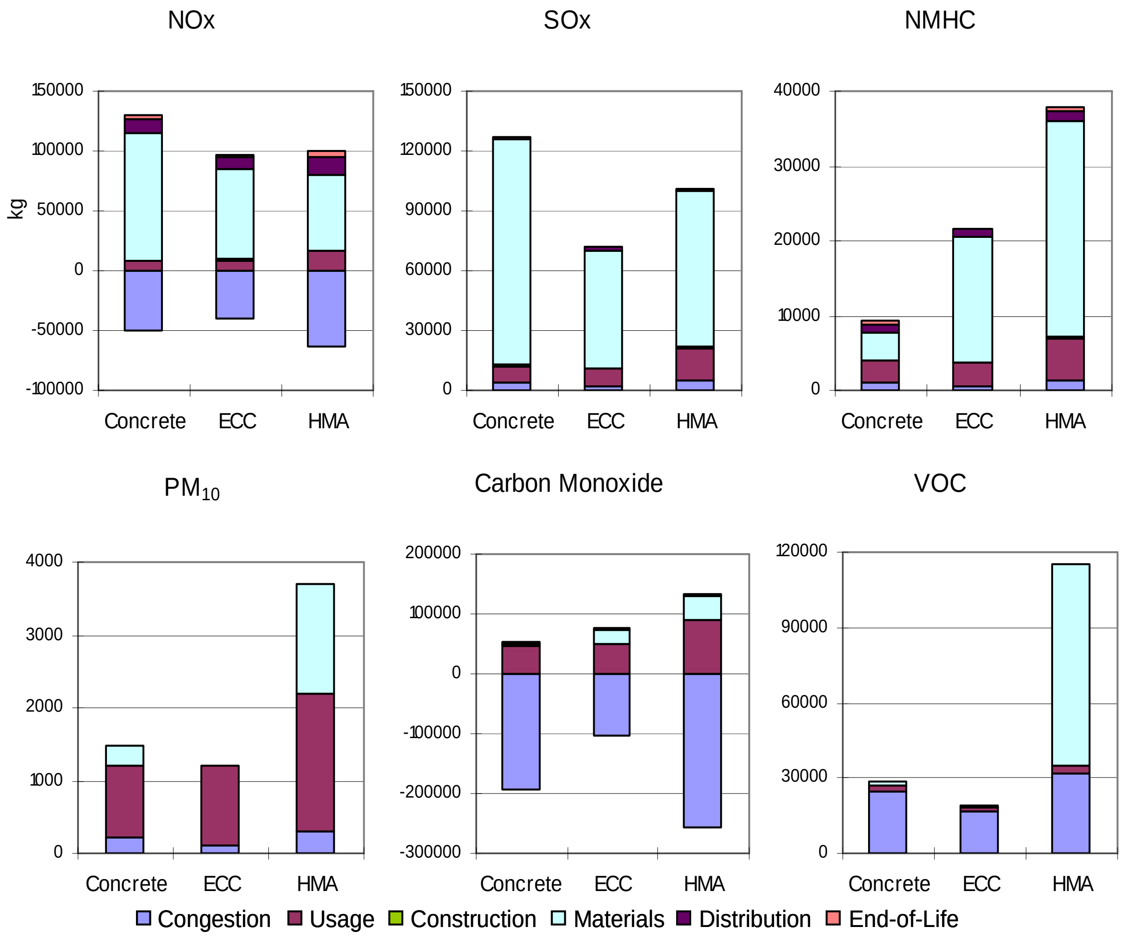

Figure 2.9 Air emissions by life cycle phase

In most cases, material phase related emissions dominate total pollutant emissions. The emissions of NO_x and CO show negative values for the traffic congestion module and usage module for all systems resulting from NO_x and CO production being greater at high speeds than at low speeds. While most pollutants increase with congestion and overlay deterioration, NO_x and CO emissions decrease (Sher, 1998). The large VOC emissions associated with the HMA overlay system result from the evaporation of petroleum distillate solvent, or diluent, used to liquify the asphalt cement during maintenance. VOC emissions occur at both the construction site and the mixing plant. The road surface emissions at the construction site are the largest source of emissions and an emission which can last for 4 months (EPA, 2006). In this study, these emissions are assumed as an instantaneous emission which is grouped within liquefied asphalt emissions.

2.3.1.4 Water Pollutant Emissions

Water pollutant emissions including biological oxygen demand (BOD), ammonia, phosphate emissions, and dissolved matter as a function of life cycle are shown in Figure 2.10.

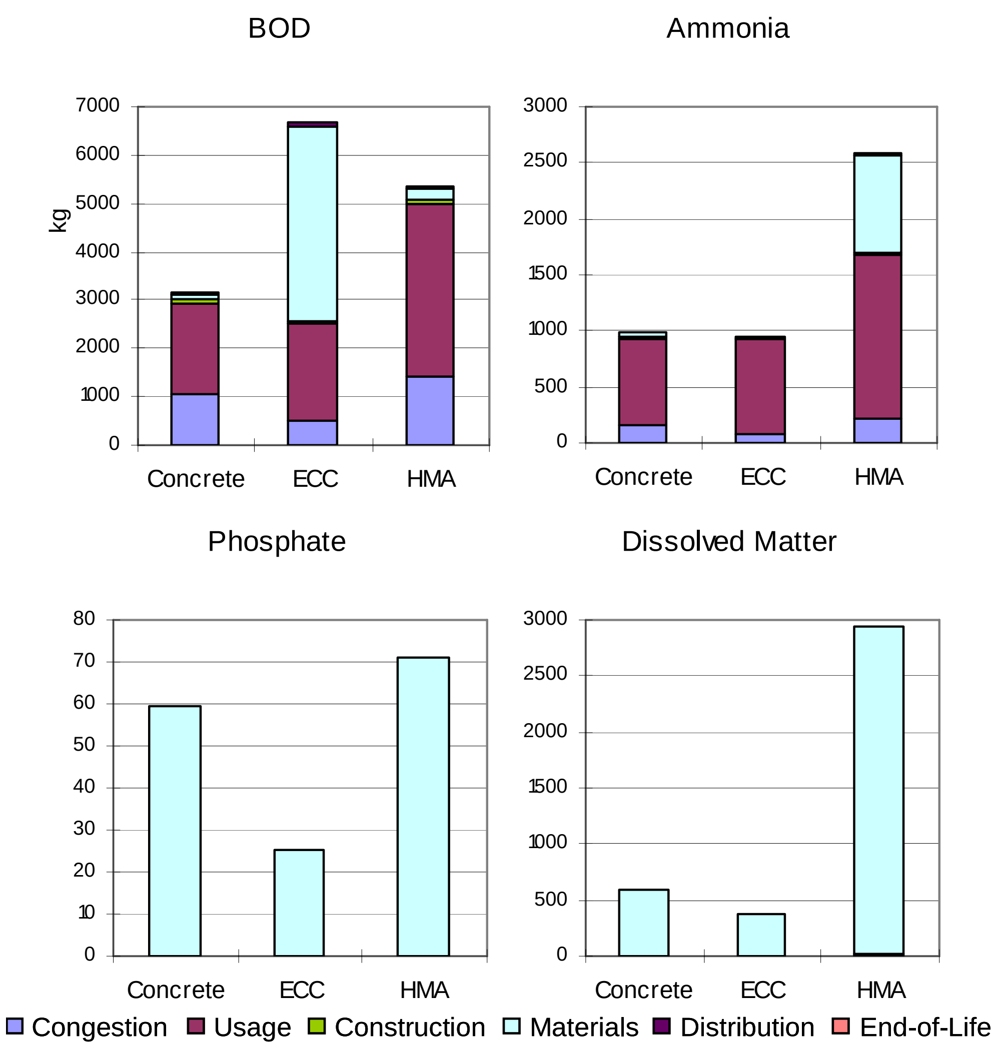

Figure 2.10 Water pollutant emissions by life cycle phase

For both BOD and ammonia emissions, the use phase has a significant effect on total emissions. However, the PVA fiber used in ECC overlay system and asphalt used in the HMA overlay system are also responsible for large BOD emissions and ammonia emissions, respectively. For phosphate and dissolved matter emissions, the material phase overwhelmingly dominates the total emissions.

Table 2.5 summarizes the life cycle impact results. The environmental impacts of the ECC overlay system are listed in the table along with percentage changes relative to concrete overlay and HMA overlay systems. As seen, ECC shows significant advantages in many environmental impact categories.

Table 2.5 Summary of life cycle impact results

Item	ECC	vs. Concrete	vs. HMA
Total primary energy consumption, GJ	5.8×10^5	-15%	-72%
GHG, mt	4.2×10^4	-32%	-37%
Carbon Monoxide, kg	4.2×10^4	+19%	+30%
VOC, kg	2.2×10^4	-34%	-81%
NMHC, kg	2.2×10^4	+137%	-41%
$PM_{2.5}$, kg	1.3×10^3	-11%	-63%
NO_x, kg	7.3×10^4	-26%	+6%
SO_x, kg	7.3×10^4	-42%	-27%
Ammonia, kg	1.0×10^3	+5%	-58%
BOD, kg	7.0×10^3	+102%	+36%
Dissolved matter, kg	3.8×10^2	-36%	-87%
Phosphates, kg	25.5	-57%	-64%

2.3.2 Life Cycle Cost Analysis Results

Table 2.6 shows the results for life cycle costs. The ECC overlay system demonstrates a cost advantage over the other two overlay systems in all cost categories assessed.

Table 2.6 Life cycle costs for overlay systems

	Concrete	ECC	HMA	ECC cost advantage
Agency cost	$11.6m	$7.4m	$13.8m	36%
User cost	$67.5m	$40.8m	$77.6m	40%
Environmental cost	$0.9m	$0.6m	$1.1m	33%
Total cost	$80.0m	$48.8m	$92.5m	39%

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

A possible way to decrease the impact of construction and maintenance activities is to apply night time construction and maintenance methods. Due to lower traffic volume at night, the user time delay cost will be minimized. However, there is a potential increase in labor cost and accidental cost.

Despite higher initial construction costs for the ECC overlay system, the lower preservation frequency due to improved ECC material properties, it is estimated that accumulated agency cost savings for ECC will result compared to the concrete and HMA overlay systems. Figure 2.11 shows the cumulative life cycle costs for each overlay system.

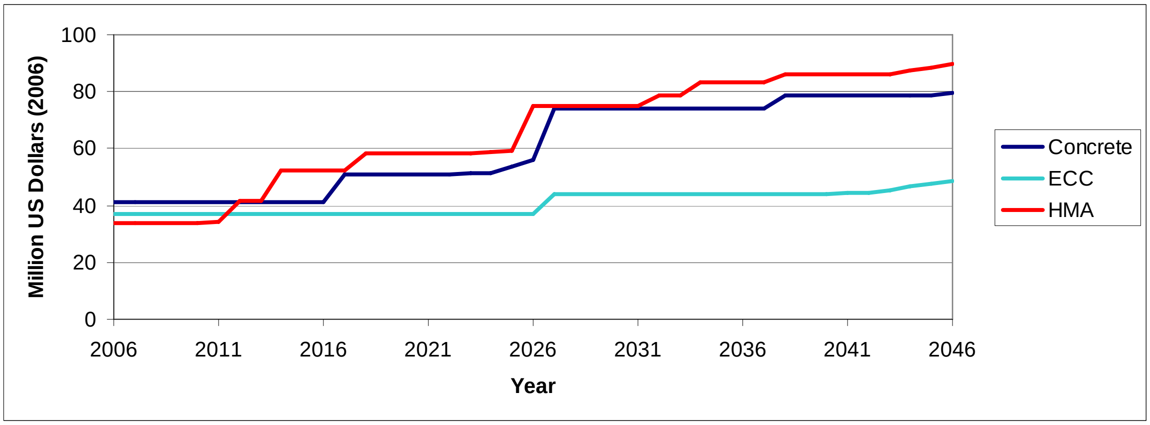

Figure 2.11 Cumulative life cycle costs for overlay systems

2.3.3 Sensitivity Analysis

The results discussed above assume a baseline scenario which has no traffic flow growth or fuel economy improvements over time. Traffic flow growth will affect traffic related energy consumption and costs by increasing total vehicle miles traveled and congestion. Figure 2.12 shows the energy consumption and life cycle costs at different traffic growth rate of 0%, 1%, and 2%, annually. In the baseline scenario, the ECC overlay system uses 15% less total energy and 40% less life cycle costs than the concrete overlay system. If traffic flow increases over time, the ECC overlay system will save even more energy and costs than the concrete overlay system. The low traffic volume scenarios are discussed in Appendix A.

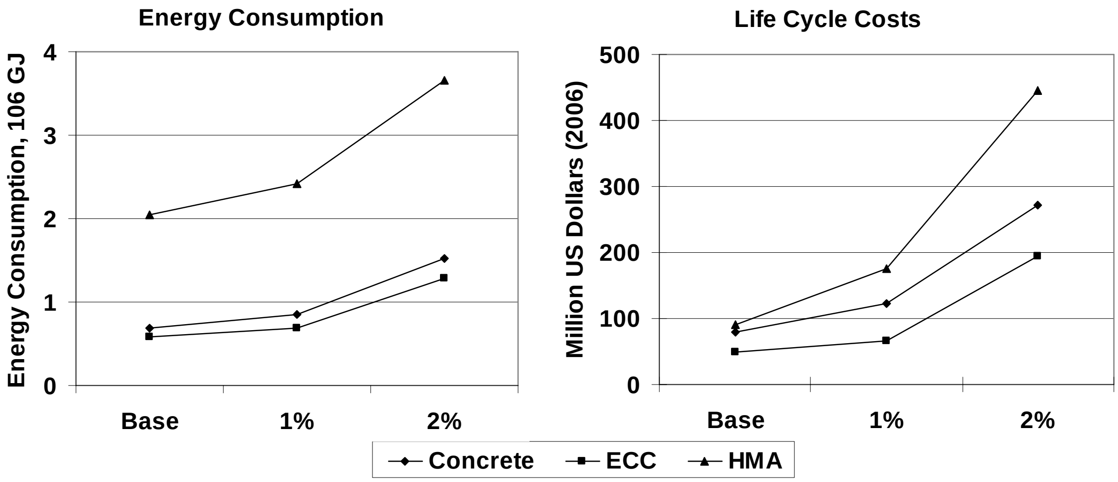

Figure 2.12 Energy consumption and life cycle costs at different traffic growth rate

Fuel economy improvements will decrease traffic related energy consumption. The impact of hybrid vehicle technology diffusion forecasted by Heywood was also studied (Heywood et al., 2004). Figure 2.13 shows the energy consumption based on different fuel economy improvement scenarios. For sensitivity analysis, a constant growth rate was also studied where fuel economy improvements increased 1% and 2% per year. Fuel economy improvements also allow the ECC overlay system to save more energy than the concrete overlay system because the roughness impact on the ECC overlay system occurs at the end of life. This phenomenon can be explained by Figure 2.6. Due to improved durability, the roughness impact on the ECC overlay system is postponed relative to the concrete and HMA overlay systems. Consequently, the cumulative benefit from fuel economy improvement for the ECC overlay system is larger than expected compared to the other two systems. Since fuel economy improvements can not decrease construction related traffic congestion which is the dominant part of the life cycle costs, fuel economy improvements have less impact on the life cycle costs.

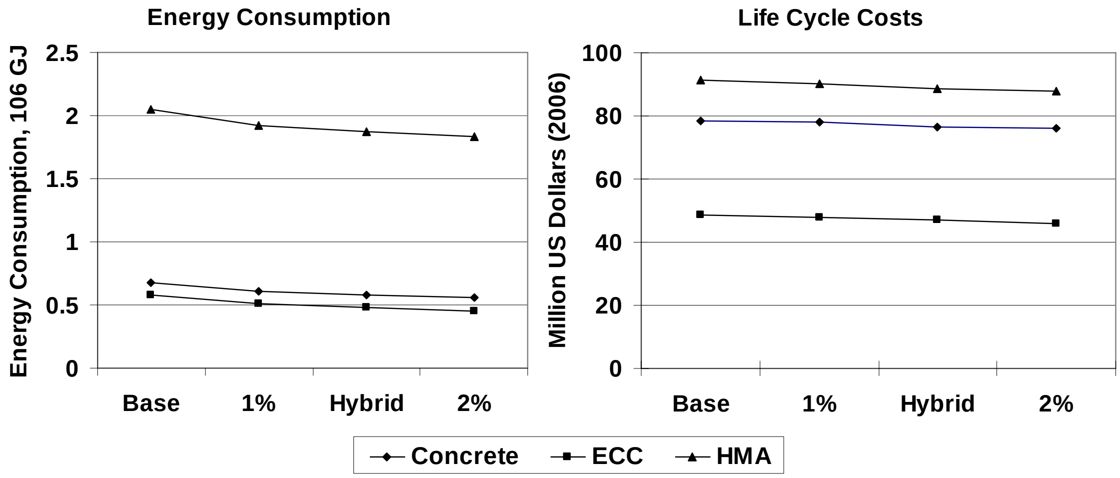

Figure 2.13 Energy consumption and life cycle costs at different fuel economy improvements rate

Considering that the average traffic growth rate in the United States has been estimated at 2.4% since 1994 (Davis and Diegel, 2002) and assuming continual fuel economy improvements through technology innovations such as fuel cell vehicles, the ECC overlay system can achieve greater energy and costs savings over the concrete and HMA overlay systems. Comparing the fuel economy improvements and the traffic growth scenarios, traffic growth rate has a much greater effect on total primary energy consumption and costs than improving the fuel economy of vehicles on the road.

2.4 Conclusions

This study indicated that the ECC overlay system had lower energy consumption, environmental impacts, and life cycle costs over a 40 year service life compared to concrete and HMA overlay systems. By extending the service life and minimizing preservation frequency, the ECC overlay system reduces total life cycle energy by 15%, GHG emissions by 32%, and life cycle costs by 40%. Material, traffic, and roughness effects were identified as the greatest contributors to environmental impacts throughout the overlay system life cycle. User costs significantly dominate total life cycle costs. The analysis also showed the potential of environmentally preferable mixtures which use industrial byproducts to substitute for energy intensive or environmentally harmful materials, such as waste fly ash for Portland cement in the ECC overlay system (as noted previously, this assumes no allocation of power plant environmental impacts to the waste fly ash). This substitution results in significantly reduced raw material and energy consumption, and decreased environmental burdens while maintaining or improving overlay system performance.

Both the service life and preservation strategy are the key factors determining overlay system performance. Alternative overlay design strategies, such as varying overlay thickness and different maintenance schedules, can be implemented based on local traffic loads and pavement requirements. Using this approach, the decision maker is able to select an optimal overlay design for alternative materials.

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

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CHAPTER 3

PROJECT-LEVEL PAVEMENT ASSET MANAGEMENT SYSTEM USING LIFE CYCLE OPTIMIZATION

ABSTRACT

Preservation strategy is the critical factor controlling pavement performance. A project-level pavement asset management system (PAMS) was developed to determine an optimal preservation strategy for a pavement overlay system. A life cycle optimization (LCO) model was incorporated into the project-level pavement asset management system to minimize life cycle energy consumption, 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 deterioration model. The project-level pavement asset management system was applied to an ECC overlay system, a concrete overlay system, and a hot mixed asphalt (HMA) overlay system. The 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 overlay system, the ECC overlay system, and the HMA overlay system compared to the current Michigan Department of Transportation preservation strategies, respectively. The impact of traffic growth on the optimal preservation strategies is presented.

3.1 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. The Transportation Equity Act for the 21st Century (TEA-21) provided $173 billion for highway construction and maintenance over 6 years. However, even with TEA-21's commitment, another $27 billion is needed to improve conditions and performance of the highway system, according the Federal Highway Administration (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 asset 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, a project-level pavement asset management system integrated with life cycle optimization, life cycle assessment, and life cycle cost analysis methodologies has been applied to pavement overlay systems to more efficiently allocate resources and improve pavement performance.

Pavement overlay preservation strategies identified in Chapter 2 are key factors in the determination of overlay system energy consumption, environmental impacts, and costs (Zhang et al., 2009). Since a pavement overlay can be preserved through a variety of different maintenance and rehabilitation methods and frequencies, which leads to a set of different life cycle energy consumption, environmental impacts, and costs, an analysis resulting in a series of optimal solutions is necessary. Incorporating modern optimization methods with LCA and LCCA concepts, pavement asset management system can effectively improve pavement performance.

There are two major administrative levels of any pavement asset management system: network-level PAMS and project-level PAMS (Mbwana, 2001). At the network-level, the main objectives of PAMS are the establishment of a pavement segment preservation priority selection scheme and a budget allocation strategy for the entire pavement network. Working at a smaller scale, project-level PAMS determines the optimal preservation strategy for a specified pavement segment by assessing pavement deterioration, comparing and selecting alternative maintenance and rehabilitation techniques and schedules, and evaluating design parameters such as pavement materials and structures. Chapter 3 focuses on developing and analyzing a project-level PAMS which provides detailed information for network-level PAMS.

Several project-level pavement asset management optimization methods have been developed. Mamlouk developed a project-level optimization approach to minimize the total costs of a flexible pavement (Mamlouk et al., 2000). This research demonstrated the feasibility of combining modern optimization methods with empirical and mechanistic prediction methods to identify cost-effective ways to manage pavement systems. Mamlouk classified the total pavement costs as the agency costs and user costs. While Mamlouk noted the increasing importance of social costs, the environmental impacts and overlay roughness effects were not considered by his analysis.

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 and rehabilitation options and corresponding user benefits over time. The major weakness is that it requires exogenously specified maintenance and rehabilitation options for comparison. Accordingly, it is difficult to reach a global optimal result.

The objective of this chapter is to develop a project-level pavement asset management system integrated with a life cycle optimization model to identify more optimal pavement overlay preservation strategies based on the minimization of total life cycle energy consumption, greenhouse gas emissions, or costs for pavement overlay systems. Overlay deterioration, roughness effects, traffic congestion, traffic growth, and preservation activities can be dynamically considered by this model. In addition, the LCO model developed in this chapter enables decision makers to select an optimal overlay preservation strategy more efficiently and accurately.

In this chapter, a pavement deterioration model and an LCO model will be described and used to analyze the following three pavement overlay systems: concrete, ECC, and HMA overlay systems. Subsequently, the optimal overlay maintenance and rehabilitation strategies are identified to minimize the life cycle energy consumption, environmental impacts, and economic costs of the concrete, ECC, and HMA overlay systems.

3.2 Methodology

3.2.1 System Definition

The overlay designs analyzed in this study are the same designs presented in Chapter 2. The overlays are constructed upon an existing reinforced concrete pavement which was originally built by the Michigan Department of Transportation (MDOT). The annual average daily traffic (AADT) is approximately 70,000 vehicles with 8% heavy duty trucks (MDOT, 1997). In the baseline scenario, the annual traffic growth rate is 0%. The three overlay systems are modeled as a 10 km long freeway in two directions. Based on the results from experimental studies conducted at the University of Michigan and typical pavement overlay designs (Qian, 2007; Huang, 2004), the concrete overlay and HMA overlay are designed for a 20 year service life by MDOT (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).

3.2.2 Pavement Overlay Deterioration Model

In Michigan, a Distress Index (DI), representing a holistic measure of pavement condition including both surface roughness and deterioration, is used rather than International Roughness Index (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 regression models (Ahmed et al., 2006). The selection of a particular model is based on local conditions and deterioration rates of the pavement. Ahmed et al. found that an auto-regression model produced the best prediction results for Michigan pavement DI data (2006). Auto-regression uses the estimation of a stochastic process that can be described by a weighted sum of its previous values along with a white noise error term (Kennedy, 1998). The auto-regression model in this study is represented in Equation 3.1.

$$DI(t+1) = f[DI(t), Age(t)] + \varepsilon_t \tag{3.1}$$

where $DI(t)$ is the DI value at age t, ε_t is the white noise error term. Currently, MDOT uses a threshold of DI of 50 to indicate the need for overlay reconstruction. The historical distress index data analyzed in this research are provided by the Michigan Department of Transportation, including 27 unbonded concrete overlay projects and 67 hot mixed asphalt overlay projects from 1991-2005.

The initial construction and preservation strategies for the concrete overlay and HMA overlay systems are based on historical preservation and pavement management records (MDOT 2005). The preservation strategy for the ECC overlay system is developed based on fatigue testing (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 year 11 and 31. The HMA overlay is reconstructed in its 20th year, with major maintenance events in year 8 and 28, and minor maintenance events in years 6, 12, 26, and 32. The ECC overlay lasts for a 40 year service life with a single maintenance event and no reconstruction. Based on these construction and preservation strategies, the DI of three overlay systems can be predicted by the auto-regression model.

3.2.3 Life Cycle Optimization

Life cycle optimization (LCO) is a promising optimization method which evaluates the energy consumption, environmental impacts, and economic costs associated with all stages of a product or system's life cycle in an effort to identify approaches for minimizing these burdens. Current optimization techniques provide a scientific basis for life cycle optimization. Based on different systems and problems, several optimization techniques have been developed such as linear programming, integer programming, and dynamic programming. Linear programming is a simple optimization technique and is widely used in industry. However, most factors in this study, such as the overlay deterioration, are not linear. This life cycle optimization 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 for a sequence of decisions is generally equal to the sum of the value of the individual decisions and situations in the sequence.

A recent LCO model developed for the optimization of generic vehicle replacement provides a useful method for determining optimal lifetimes of products (Kim et al., 2003). In this study, the dynamic programming technique was used to evaluate optimal vehicle replacement strategies from energy, emissions, and cost perspectives.

Dynamic programming is computationally less intensive to solve multistage decision making problems than enumeration methods which search for all possible results. Dynamic programming takes advantage of avoiding full enumeration by eliminating early partial decision solutions that cannot lead to the final optimal solution. It reduces a single n-dimensional problem into n one-dimensional problems. Ideally, dynamic programming seeks to translate one single complicated problem into several simple solvable problems.

In the case of overlays, a project lasts n years and each year has m possible decision variables, for a total of m^n possible outcomes. Using the dynamic programming technique, the optimal result of the same problem could be selected among $n \times m$ outcomes. Moreover, within the framework of life cycle modeling, dynamic programming identifies a globally optimal solution.

Dynamic programming does not have a particular algorithm or a set of rules for finding the optimal solution. 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 one 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 function is necessary to move from one stage to the next with a given state and decision. At each stage and state, the dynamic program calculates the particular return for each particular decision.

For this study, dynamic programming parameters are summarized as:

(1) Objective function: Minimize life cycle burdens (energy consumption, environmental impacts or costs).

(2) Constraint: Keep all overlay systems within a defined performance standard (DI<50). The impacts of different pavement condition constraints are discussed in Appendix B.

(3) Analysis period: 40 years. The impacts of different analysis period are discussed in Appendix C.

(4) State: DI values.

(5) Stage: Each year in the analysis period.

(6) Decision variables: No maintenance, minor maintenance, and major maintenance.

(7) Transition function: Auto-regression DI prediction model.

(8) Return: Expected cumulative burdens at each stage and state.

3.2.4 Life Cycle Optimization Model Operation

The life cycle optimization process uses a backward dynamic programming procedure starting the computation at year N, the final year of the analysis period. The mathematical model for dynamic programming is constructed by first calculating the current overlay system burdens, as described by Equation 3.2.

$$U(i,j)=\begin{cases} B_M(i,j)+B_C(i,j)+B_D(i,j)+B_{CG}(i,j)+B_E(i,j)+B_U(i,DI(i)) & if\ i>0 \\ 0 & if\ i=0 \end{cases} \quad (3.2)$$

where i is the current stage, j is the maintenance alternative, $B_M(i,j)$ is the burden associated with the material module at year i with decision j. Similarly, $B_C(i,j)$, $B_D(i,j)$, $B_{CG}(i,j)$, and $B_E(i,j)$ are the burdens of construction, distribution, traffic congestion, and end of life modules, respectively, at year i with decision j. $B_U(i,DI(i))$ is the burden of overlay usage which is caused by overlay roughness effects at year i with a particular distress index.

Equation 3.3 is used to calculate the total burdens from year N to year n.

$$f(i)=\begin{cases} \min\limits_{j=0,1,2}\{U(i,j)+f(i+1)\} & \forall i=n,\dots,N \\ 0 & \forall i>N \end{cases} \quad (3.3)$$

where $f(i)$ is the minimum possible burden accumulated from year n to the end of year N given a particular maintenance alternative.

A computer program using Visual Basic (VBA) and running within Microsoft Excel software was coded to implement the LCO model and link it to the integrated LCA-LCCA model. A flowchart of the LCO model operation is shown in Figure 3.1.

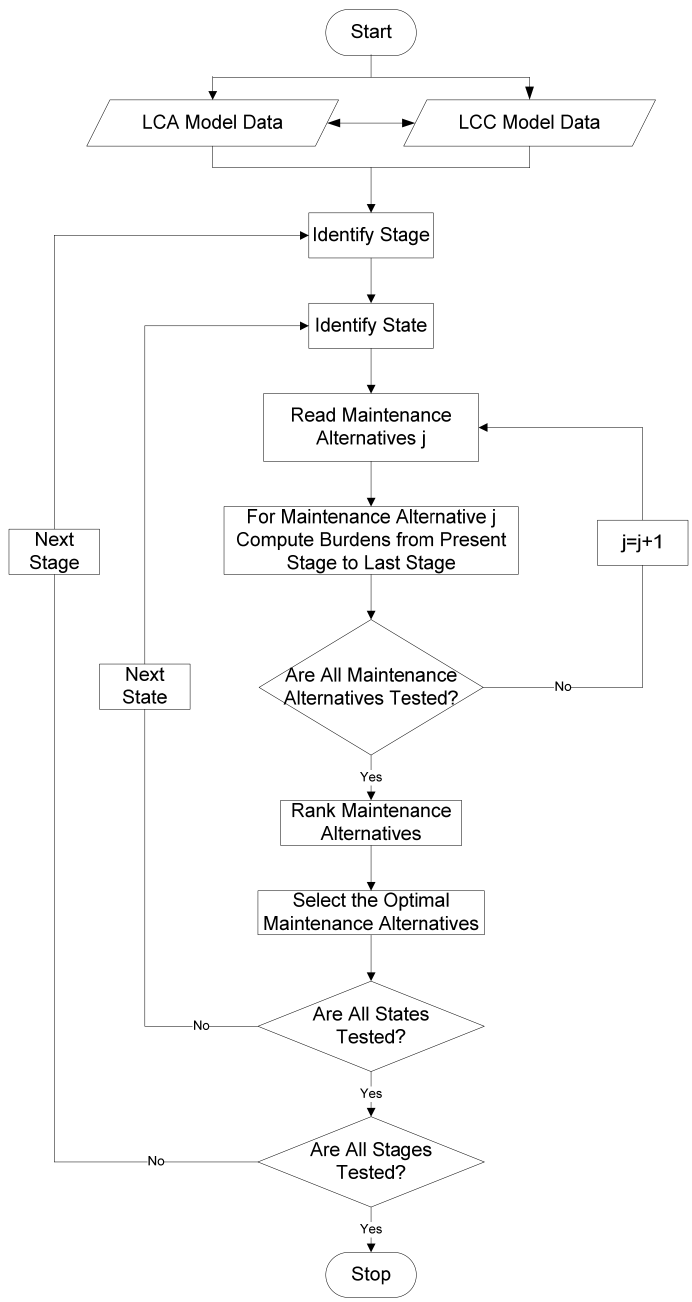

Figure 3.1 LCO model operation flowchart using dynamic programming

3.3 Results and Discussions

3.3.1 Life Cycle Optimization 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 total costs. The results also show the impacts of optimal preservation strategy 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 Figure 3.2. 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), performing four major maintenance activities in year 2015, 2019, 2036, 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. Figure 3.2 presents the maintenance and rehabilitation schedule for energy/GHG objectives. It demonstrates more frequent preservation activities than the maintenance and rehabilitation schedule for cost minimization objectives. This phenomenon can be attributed to the dominance of user time delay costs as a part of user costs. User time delay costs are related to the traffic congestion caused by preservation activities. Therefore, minimizing maintenance and rehabilitation frequency or substituting several minor maintenance activities with one major maintenance activity can efficiently decrease the life cycle costs of an overlay system.

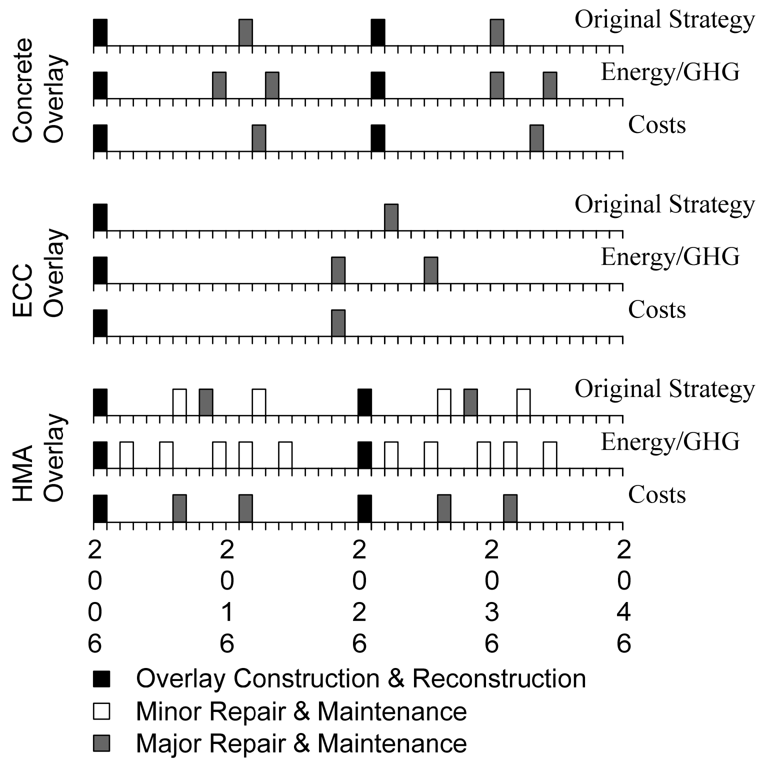

Figure 3.2 Optimal preservation strategies for three overlay systems

Table 3.1 gives the optimization results and associated criteria pollutant emissions for the three overlay systems.

Table 3.1 Life cycle burdens of optimal preservation strategies for each overlay system

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

(note: values shown in table should not imply three significant figures; they are provided to avoid potential rounding errors)

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; US EPA, 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 save 0.4%, 0.5%, and 8% of costs for concrete overlay system, ECC overlay system, and HMA overlay system, respectively.

As shown in Figure 3.3, 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/GHG objectives, reducing roughness effects that impact vehicle fuel economy is an effective way to decrease the overall energy consumption and GHG emissions, even though energy consumption and GHG emissions increase during maintenance and rehabilitation events due to traffic congestion. For cost objectives, the optimal strategy is opposite to that of energy/GHG objectives. User time delay costs caused by traffic congestion dominate total life cycle costs. An effective way to decrease the total life cycle cost is to decrease the maintenance and rehabilitation frequency and thereby user time delay costs. Moving from a cost objective to energy/GHG objectives increases economic costs from 11% to 22%.

However, the relative magnitude of the decrease in energy consumption ranges from 12% to 36% and the decrease in GHG emission ranges from 10% to 30%.

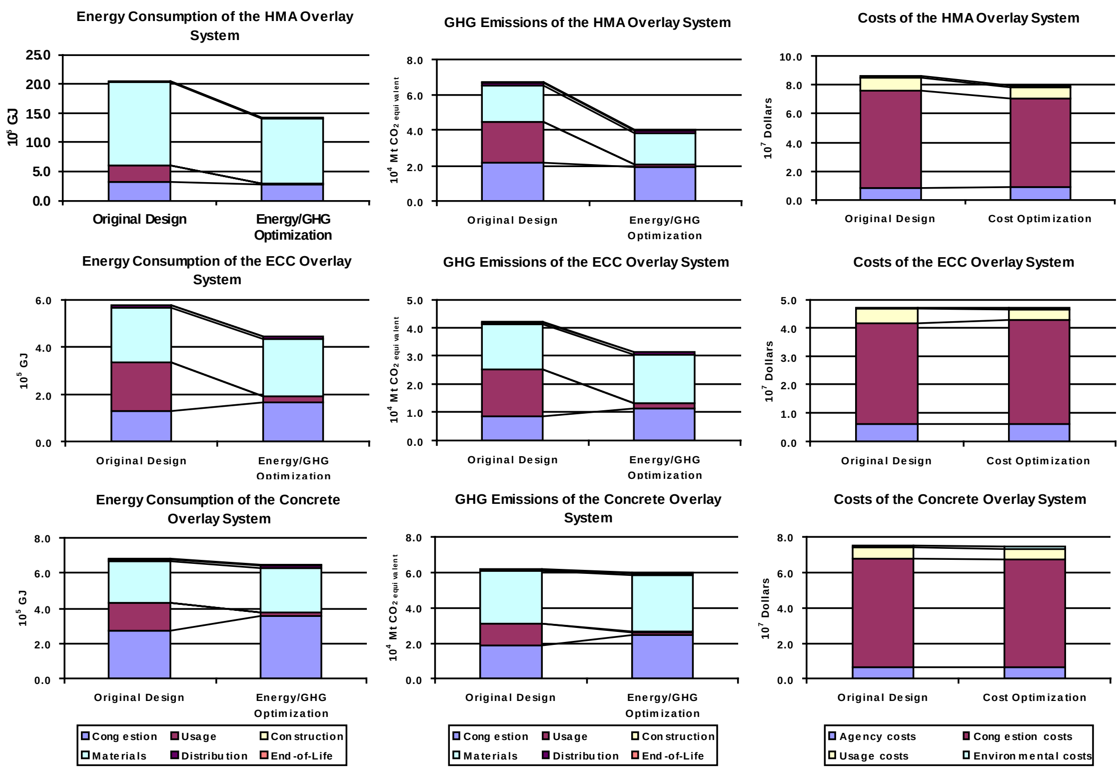

Figure 3.3 Comparison of energy consumption, GHG emissions and costs for MDOT preservation strategies and optimal strategies for a. HMA, b. ECC, and c. Concrete overlay systems

3.3.2 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 costs, traffic related energy consumption, and pollutant emissions by increasing total vehicle miles traveled and overall system congestion. These factors will change the optimal preservation strategy for each overlay system. Figure 3.4 shows the optimal preservation strategies with a 2% annual traffic growth rate. The maintenance and rehabilitation frequency decreases and preservation activities occur earlier avoiding higher costs from future high traffic volumes.

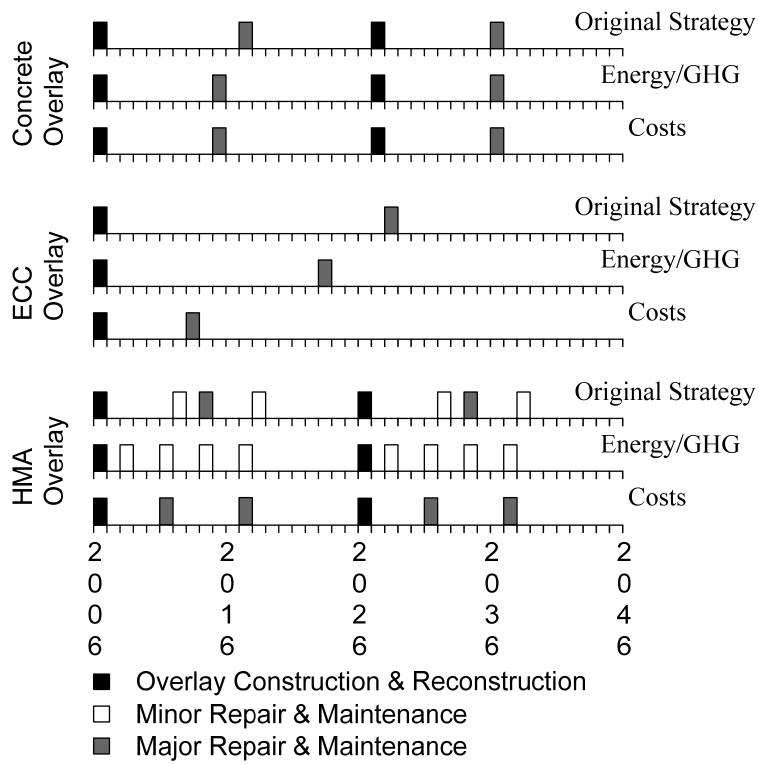

Figure 3.4 Optimal preservation strategies for three overlay systems with 2% annual traffic growth rate

Figure 3.5 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 with increased traffic flow. 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.

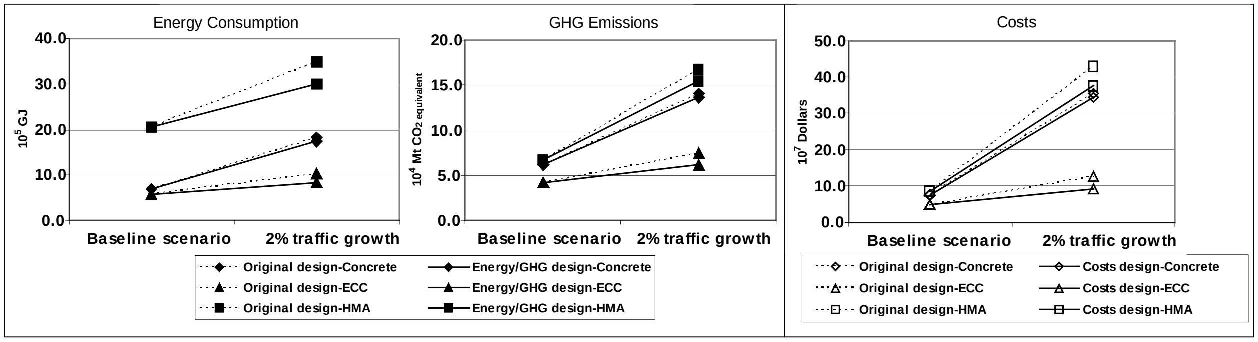

Figure 3.5 Life cycle results with different annual traffic growth rate

3.4 Conclusion

This chapter describes the development of a new life cycle optimization model and its application to a project-level pavement asset management system. Three potential 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 by 5%-30% the total life cycle energy consumption, 4%-40% the GHG emissions, and 0.4%-12% the cost for concrete overlay system, ECC overlay system, and HMA overlay system, respectively, when no traffic growth is considered. Since MDOT has incorporated LCCA into pavement design already, total life cycle costs have been controlled nearly to the optimal results.

However, MDOT's pavement designs cannot dynamically capture 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 more advantage when compared to original preservation strategies (MDOT strategies for the concrete and HMA overlay systems, experimental planning for the ECC overlay system).

Due to improved material properties and extended service life, under any traffic growth scenario, the ECC overlay system shows superior advantages in energy consumption, GHG emissions, and cost, compared to the concrete overlay system and HMA overlay system.

The application of dynamic programming as an optimization tool in life cycle optimization 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.

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 costs and roughness effects in pavement management and accounting. The methodology developed during this study should lead to more cost effective and environmentally sensitive pavement asset management system.

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CHAPTER 4

MULTI-OBJECTIVE AND MULTI-CONSTRAINT OPTIMIZATION IN PROJECT-LEVEL PAVEMENT ASSET MANAGEMENT: INFORMING POLICY AND ENHANCING SUSTAINABILITY

ABSTRACT

Pavement preservation (maintenance and rehabilitation) requires large resource investments and generates significant environmental impacts. Multi-constraint and multi-objective optimization was conducted to study the impact of agency budget constraints on user costs and total life cycle cost, identify the trade-offs between energy consumption and costs, and understand the relationships among material consumption, traffic congestion, and pavement roughness effects. A case study of a hot mixed asphalt (HMA) overlay system shows that a reduction in total agency preservation budget from $2 million to $0.5 million increases the total life cycle cost from $54 million to $61 million over a 20 year service life. A Pareto optimal solution that minimizes energy and cost objectives was also developed to enhance the preservation strategies. The influence of fuel taxes and government subsidies on a PAMS is explored and specific policy recommendations are provided. For example, proposals by presidential candidates Clinton and McCain to temporarily suspend the gas tax in the summer of 2008 would have had a detrimental life cycle societal cost impact.

4.1 Introduction

The national highway system is an important public investment designed to support the national economy by transporting goods and people. The American Society of Civil Engineers (ASCE) estimates that $54 billion is invested in pavement preservation each year (ASCE, 2005). However, the Federal Highway Administration estimates that an additional $27 billion in pavement preservation is needed to ensure adequate improvement in highway condition and performance (ASCE, 2006). The budgetary pressure delays many pavement projects and decreases the pavement serviceable level (OECD, 1994). Thus, an effective pavement asset management system (PAMS) is needed to facilitate highway agencies to allocate their limited budgets cost efficiently.

Researchers and practitioners have developed applied mathematical models to pavement asset management. 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. Later, the Organization for Economic Cooperation and Development (OECD) examined the use of life cycle cost principles for allocating resources to road maintenance (OECD, 1994). Fwa et al. applied genetic algorithms for solving multi-objective pavement maintenance problems (Fwa et al., 2000). In their research, the concept of Pareto efficiency was adopted to perform two and three objective optimization. Currently, the Michigan Department of Transportation (MDOT) relies on the Michigan Road Quality Forecasting System (RQFS) to develop preservation strategies for regional DOT management districts. This RQFS software package uses current pavement condition data from the pavement management system to predict future network conditions at different levels of investment. However, besides the economic costs, those studies do not consider other sustainability indicators (e.g., energy consumption and GHG emissions) in pavement asset management system. Accordingly, the literature addressing the relationship among pavement preservation strategy, policy making, and economic factors is very limited.

The objective of a project-level PAMS is to plan for the implementation of appropriate pavement preservation activities at an optimal time using several mathematical programming techniques. An effective project-level PAMS incorporates a full range of preservation strategies with the goal of enhancing pavement performance (ride quality, safety, service life, etc.) in an overall cost-effective framework. To improve sustainability, modern pavement asset management systems need to analyze innovative materials and technologies; account for energy consumption and environmental impacts; and quantify the impacts of specific policy decisions, such as taxation, subsidies, and budget allocation schemes. Figure 4.1 shows the framework for a modern pavement asset management system.

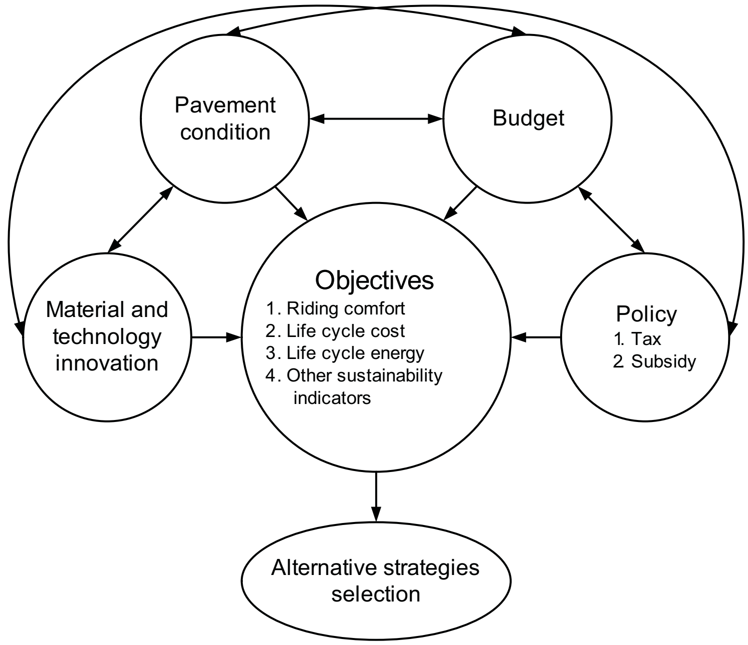

Figure 4.1 Pavement asset management system framework

An integrated LCA-LCCA model expands the scope of a conventional life cycle cost analysis which can generally account for agency costs (internal costs), such as construction costs and maintenance costs (Kendall et al., 2008). The integrated model also can estimate social costs including user costs and environmental damage costs.

LCA and LCCA models have limited management capabilities. A pavement segment can be managed through a variety of different preservation methods and frequencies, which will lead to a variety of different life cycle energy requirements, environmental impacts, and costs (Zhang et al., 2008). A life cycle optimization model is necessary to identify a unique, optimal pavement preservation strategy based on a specific objective(s) and constraint(s). Life cycle optimization techniques mathematically minimize the energy consumption, environmental impacts, and costs associated with all stages of a product or system's life cycle (Kim et al., 2003).

The objective of this chapter is to develop a project-level pavement asset management system which incorporates integrated LCA-LCCA and LCO models. Multi-objective and multi-constraint optimization is applied to balance the complex interactions among material consumption, traffic congestion, and pavement roughness effects. The application of this research to policy making is also explored. The impacts of fuel taxes, government subsidies, and fuel prices on pavement preservation strategies and the resulting energy consumption and life cycle costs are calculated.

4.2 Methodology

4.2.1 Expanded Project-Level Pavement Asset Management System

To improve the flexibility of a decision making process, the project-level pavement asset management system developed in the Chapter 3 is expanded to incorporate budget constraints and objective selection consideration. Figure 4.2 shows the process flowchart of the expanded project-level pavement asset management system. Previous developed project-level pavement asset management system using LCA model, LCCA model, and LCO model evaluates the sustainability indicators and optimizes the preservation strategy based on single constraint (pavement condition) and single objective (energy consumption, environmental impacts, or costs). This single criteria optimization gives highway agencies a limited ability to allocate economic resources under budgetary constraints and develop a global optimal preservation strategy to achieve maximum benefit. To solve this problem and further enhance sustainability, multi-constraint optimization and multi-objective optimization models are developed in the following sections.

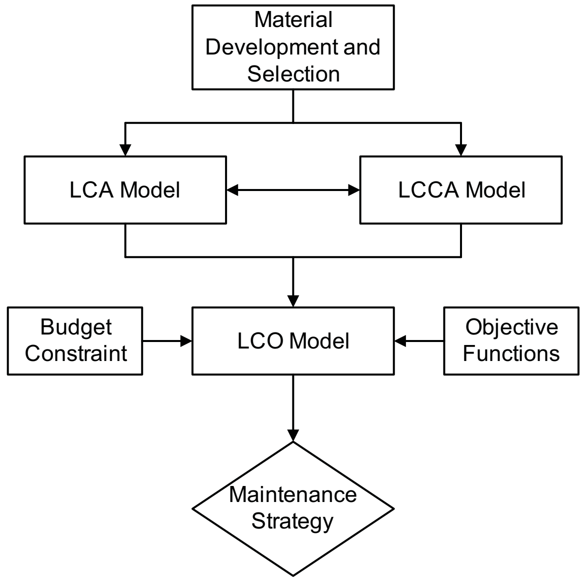

Figure 4.2 The process of project-level pavement asset management system

4.2.2 Multi-Constraint Optimization Model

Generally, highway agencies face at least two constraints: a minimum level of allowable pavement condition (i.e. roughness) and a budgetary ceiling that cannot be exceeded. For illustration, in Michigan the pavement condition is measured by a distress index (DI). The DI value starts at 0 which indicates perfect pavement condition. Although there is no upper limit for the DI value, the Michigan Department of Transportation (MDOT) uses a threshold DI of 50 to indicate the need for pavement rehabilitation or reconstruction (Ahmed et al., 2006). The budget represents the total available resources for a highway agency to allocate among various maintenance and rehabilitation activities for a set of pavement assets in any given year.

Figure 4.3 shows the hypothetical relationship between pavement condition and costs. At lower budget levels, highway agencies have limited resources to perform necessary maintenance and rehabilitation activities. This existing poor pavement condition causes higher user costs and environmental costs through reduced fuel efficiency. With a relaxed budget constraint, necessary maintenance and rehabilitation activities can be implemented. Agency costs increase, however, pavement conditions are improved. As a result, both user costs and environmental costs decrease because a smoother pavement surface is provided to the users. However, if too many maintenance and rehabilitation activities are performed or highway agencies apply inappropriate maintenance and rehabilitation methods at sub-optimal times which interrupt normal traffic flow and cause traffic congestion, generally, user costs, environmental costs, and as a consequent, total life cycle cost increase. Together, pavement condition and available budget determine the total life cycle cost for a pavement system. The objective of multi-constraint optimization is to determine the minimum total life cycle cost at point O and the associated preservation strategy to reach this point.

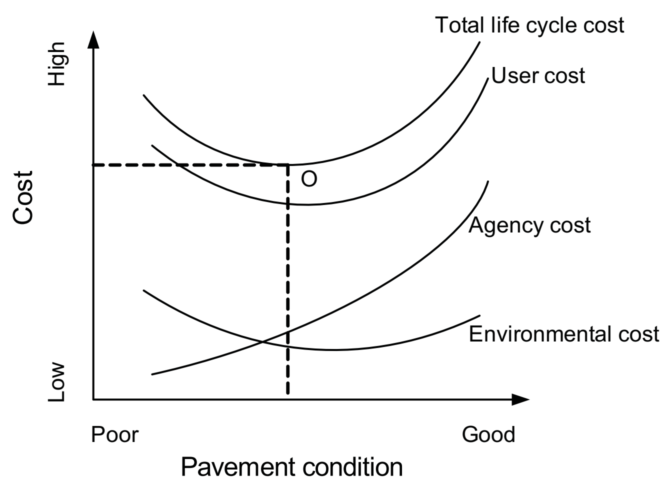

Figure 4.3 A hypothetical relationship between pavement condition and cost

The objective function of the multi-constraint optimization is:

$$C = \min\left[\sum_{t=0}^{N} R_t(q_t, m_t)\right] \quad (4.1)$$

Subject to

$$\sum_{t=0}^{N} q_t = S_0$$
$$m_t < Max\ DI\ (50) \qquad (4.2)$$

where C is the total life cycle cost (or other objective, such as energy consumption). R_t is the total life cycle cost at year t. q_t is the agency cost at year t. S_0 is the budget constraint, m_t is the DI value at year t, and m_0 equals to 0 (new pavement condition).

In order to solve the problem, a Lagrange multiplier is used to reduce the dimension of formulation (Dreyfus and Law, 1977). The following four steps are employed:

(1) Choose a positive value of the Lagrange multiplier λ. λ is also called the shadow price at the optimal solution. The shadow price represents the change in objective function due to an infinitesimal change in the budget constraint. Each budget constraint in an optimization problem has a unique shadow price. The value of the shadow price can provide decision makers useful insight into resource allocation problems. The mathematical interpretation of shadow price is:

$$\lambda = \frac{\text{Marginal change in objective function}}{\text{Marginal change in constraint}}$$

(4.3)

(2) Use dynamic programming to solve the following one-dimensional problem:

$$f_t(\lambda) = \min_{\substack{m_t=0,1,......50 \\ t=0,1,......N}} [R_t(q_t, m_t) + \lambda q_t(m_t) + f_{t+1}(\lambda)] \qquad (4.4)$$

where $f_t(\lambda)$ is the minimum life cycle cost accumulated from year t to the end of year N given a particular maintenance alternative. For a given λ, an optimal set of q_k and m_k are calculated. However, this solution may not be unique. There may be n distinct solutions denoted by $\left\{q_k^1(\lambda), m_k^1(\lambda)\right\},...,\left\{q_k^n(\lambda), m_k^n(\lambda)\right\}$.

(3) Compute

$$A(\lambda) = \min_{j=1,......m} \sum_{t=0}^{N} q_t^j \text{ and } B(\lambda) = \max_{j=1,......,m} \sum_{t=0}^{N} q_t^j \tag{4.5}$$

(4) If $\sum_{t=0}^{N} q_t^j = S_0$ for some j, then the original problem is solved;

If $B(\lambda) < S_0$, then decrease λ and go to step 2;

If $A(\lambda) > S_0$, then increase λ and go to step 2;

If $A(\lambda) < S_0 < B(\lambda)$ and for every j, $\sum_{t=0}^{N} q_t^j \neq S_0$, then stop. The Lagrange multiplier method fails.

A computer program using Visual Basic (VBA) and running within Microsoft Excel software is coded to implement this multi-constraint optimization model.

4.2.3 Multi-Objective Optimization Model

In a single objective optimization problem, the optimal solution is unique. This is not the case for a multi-objective optimization problem (Fwa et al., 2000). The situation of a two objective optimization problem is illustrated in Figure 4.4. Points A, B, and C represent feasible solutions for two objectives, f_1 and f_2. Smaller values are preferred to larger ones for each objective. Given a set of alternative solutions, any movement from one solution to another that can improve at least one objective without making any other worse off is termed a Pareto improvement. For example, moving from solution C to solution A or solution B is a Pareto improvement. If no further Pareto improvement can be made (i.e. moving from solution A to solution B along an indifference curve), Pareto efficiency has been reached. The Pareto frontier is the set of choices that are Pareto efficient.

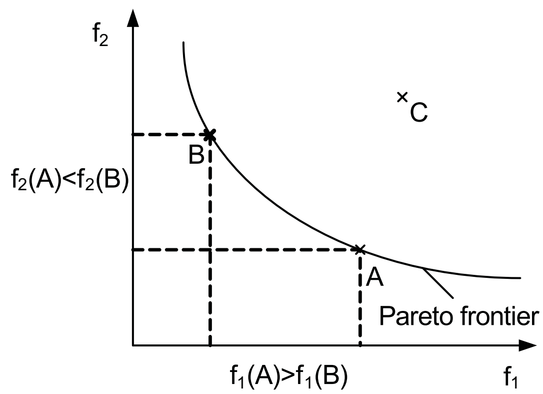

Figure 4.4 Multi-objective optimization and Pareto efficiency

Decision makers may choose different Pareto optimal solutions based on a specific objective function. Life cycle cost and energy consumption are two important sustainability indicators. The Pareto optimal solution for cost and energy consumption objectives is obtained by combining the multiple objectives into one weighted objective function as following:

$$Z = C + \alpha E \tag{4.6}$$

where C is the life cycle cost, E is the life cycle energy consumption, α is the weight factor, and Z is the weighted objective.

Variation of weight factors with the aim of minimizing the weighted objective can be investigated. Though computationally intensive, this approach gives an idea of the shape of the Pareto frontier and provides decision makers with more information about the trade-offs among various objectives.

4.3 Pavement Asset Management System Results – Pavement Overlay Case Study

The project-level pavement asset management system integrated with multi-objective and multi-constraint optimization models is applied to a pavement overlay system to develop the optimal preservation strategy. Pavement overlays are the most prevalent pavement rehabilitation method which utilizes the structure of an existing pavement to reduce the rate of new pavement deterioration and extend pavement service life. A common hot mixed asphalt (HMA) overlay design is analyzed. The HMA overlay system is modeled as 10 km long freeway sections in two directions. Each direction has two 3.6 m wide lanes, a 1.2 m wide inside shoulder, and a 2.7 m wide outside shoulder. The thickness of the HMA overlay is 190 mm which is typical of pavement overlay designs (Huang, 2004). In the PAMS system, the HMA overlay system is designed for a 20 year service life by the Michigan Department of Transportation (MDOT, 2005). The annual average daily traffic (AADT) is approximately 70,000 vehicles with 8% truck fraction (MDOT, 1997). In the baseline scenario, the annual traffic growth rate is 0%.

4.3.1 Multi-Constraint Optimization Result

Multi-constraint optimization is applied to determine optimal preservation strategies to minimize total life cycle costs based on various preservation budget constraints. In the analysis, the preservation budget (initial construction costs are not included) over the 20 year pavement life is decreased from $2 million to $0.5 million which is the minimum to keep the pavement overlay under a threshold of DI of 50

(MDOT, 2005). Figure 4.5 shows the impact of this budget reduction on optimal overlay preservation strategies. As the budget decreases, expensive major maintenance activities are replaced by numerous, lower cost, minor maintenance activities. However, this more frequent maintenance and rehabilitation schedule associated with a lower budget increases traffic interruptions, traffic congestion, and user delay.

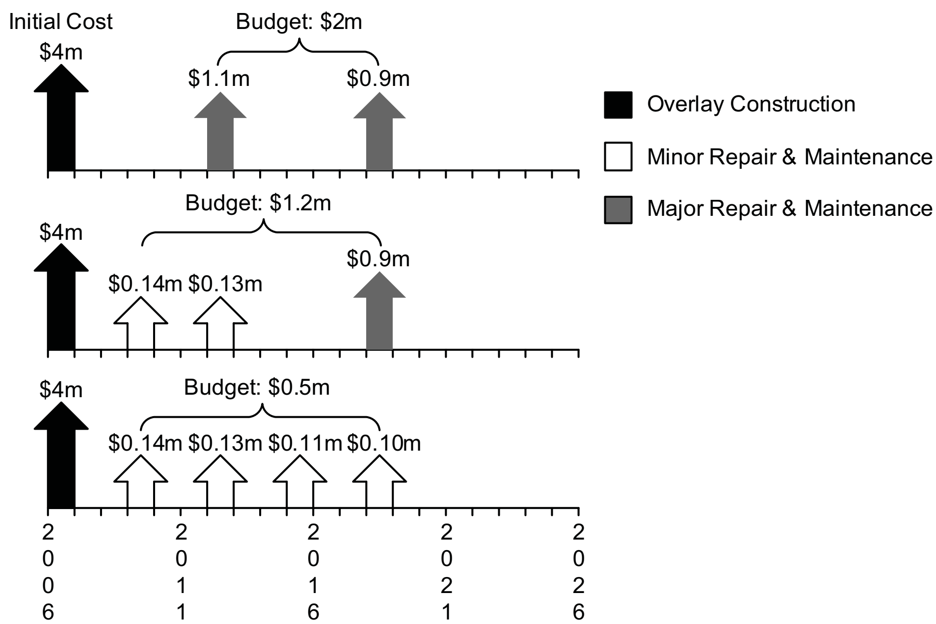

Figure 4.5 Optimal maintenance strategies based on different budget constraints

Figure 4.6 shows the total life cycle cost broken down into user cost, agency cost and environmental cost, using the optimal preservation strategies under three budget levels ranging from $0.5 to $2 million. As expected, agency costs decrease as the budget constraint tightens. However, user costs, which are about 8 times higher than agency costs over the 20 year life time of a pavement overlay system, increase as the budget decreases. The unitless shadow prices for $2 million, $1.2 million, and $0.5 million budget constraints are 5, 5.5, and 6, respectively.

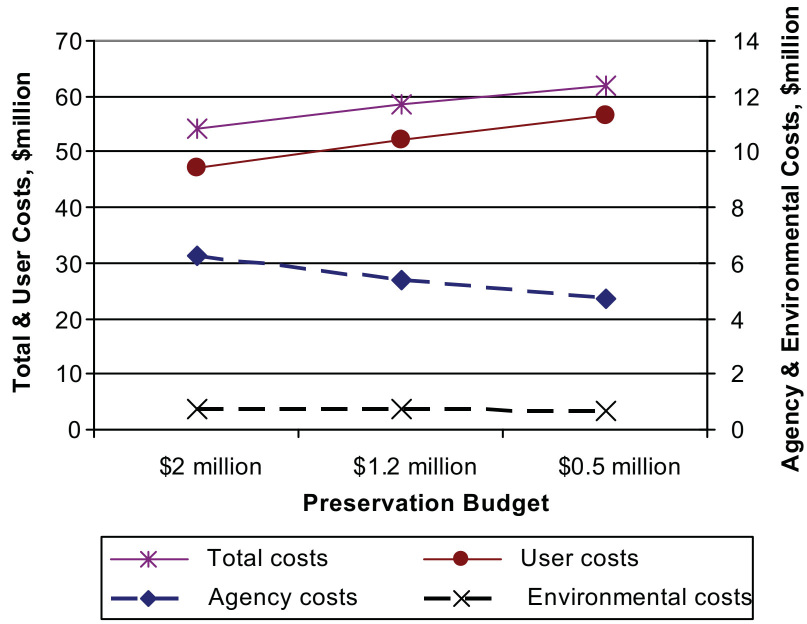

Figure 4.6 Total life cycle cost based on different budget constraints for a 20 year analysis period

4.3.2 Multi-Objective Optimization Result

The optimal Pareto frontier of energy consumption and life cycle costs objectives under \$2 million budget constraint is shown in Figure 4.7. The weight factor α ranges from \$0.01/MJ to \$0.10/MJ. Most of the energy consumption in the pavement overlay system comes from additional fuel burned in traffic congestion caused by maintenance and rehabilitation activities along with poorer vehicle fuel efficiency caused by increased pavement roughness. Therefore, gasoline cost is a major factor. The weight factor α is equivalent to \$0.32/l (\$1.22/gal) to \$3.22/l (\$12.18/gal) using the lower heating value of gasoline (32.2 MJ/l). One potential application of this weight factor will be discussed in following section.

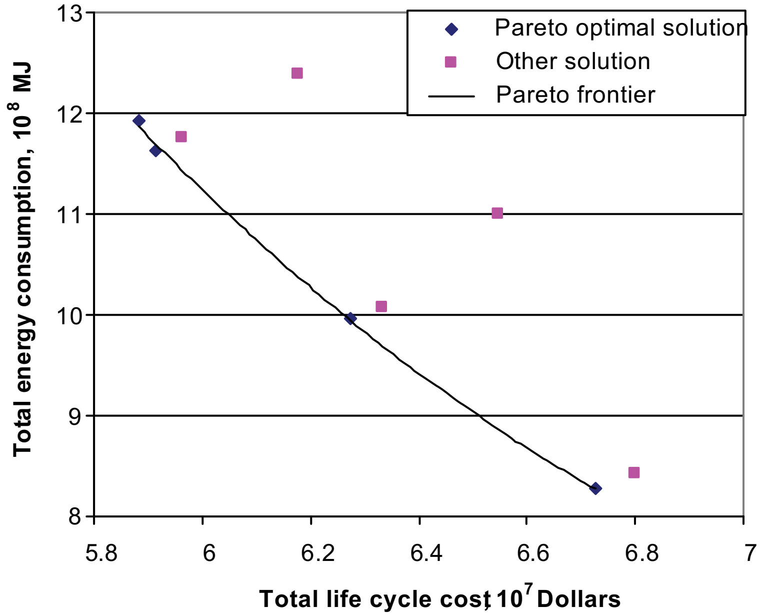

Figure 4.7 Pareto frontier for total energy consumption and total life cycle cost objectives for a 20 year analysis period

4.4 Discussion

In 2008, presidential candidates McCain and Clinton both proposed suspending the \$0.049/l (\$0.184/gal) federal gas tax for 3 months during the peak summer travel season to counteract soaring gas prices (Broder, 2008). The federal motor fuel tax is used to partially fund the National Highway Trust Fund which is distributed to states to maintain roads and bridges. While this tax reduction would benefit users in the short run (Summer 2008), the long term impacts are more complex and require further analysis. In the pavement overlay system described previously, the user tax benefit (which is also the total 3 month gasoline tax loss for that summer due to the tax reduction plan) is:

$$User\ tax\ benefit = \frac{\overbrace{70000_{vehicle/day} \times 10_{km} \times 30_{days/month} \times 3_{month}}^{Total\ Kilometer\ Traveled}}{\underbrace{10.7_{km/l}}_{Average\ Fuel\ Economy}} \times \overbrace{\$0.049_{/l}}^{Tax\ Reduction} = \$287,945 \tag{4.7}$$

In Michigan, 30% of the Highway Trust Fund is used to do pavement rehabilitation and reconstruction (MDOT, 2007). Thus, the budget decrease would be:

$$\$287,945 \times 0.3 = \$86,384 \qquad (4.8)$$

An immediate budget decrease will have a much larger impact in the future. For example, the reduced budget will postpone necessary maintenance and rehabilitation activities and may also force highway agencies to substitute one high-cost major maintenance activity with several low-cost minor maintenance activities. These changes in preservation strategy ultimately change the total life cycle cost, especially user costs. Postponed essential maintenance and rehabilitation activities accelerate the deterioration of pavement overlay and increase overlay surface roughness thereby adding fuel consumption for users. More frequent minor maintenance activities interrupt normal traffic flow and cause traffic congestion and detouring which will increase user time delay and travel mileage. To quantify the impact of current budget constraint change on future total life cycle cost, an average shadow price 5.5 is used.

As described previously, the shadow price, λ, is the partial derivative of total life cycle cost with respect to agency cost. Therefore, the total life cycle cost increase associated with this proposed plan is:

$$\textit{Budget change} \times \textit{Shadow price}\ (\lambda) = \$86,384 \times 5.5 = \$475,109 \qquad (4.9)$$

Since 85% of total life cycle cost for a pavement overlay system is borne by users (Zhang et al., 2008), the total user cost increase for a 3 month suspension of the federal gasoline tax (paid over the 20 year analysis period) is:

$$\textit{Total life cycle cost} \times 85\% - \textit{User tax benefit} = \$475{,}109 \times 0.85 - \$287{,}945 = \$115{,}898 \tag{4.10}$$

Conversely, if the government increases discretionary transportation budget spending, highway agencies will have more resources to improve preservation strategies and even promote the application of new materials and technologies. HMA is a common material used in pavement overlay applications. However, asphalt, which is a petroleum byproduct, poses significant environmental challenges. Additionally, the physical limitations of asphalt, which are factors in pavement overlay failure and higher preservation frequency, have driven the research of alternative materials, such as ECC.

ECC is a promising candidate material for road repairs, pavement overlays, and bridge deck rehabilitation (Li, 2003). Previous research has shown that the required thickness of an ECC overlay is half that compared to an HMA overlay while the life of an ECC overlay is estimated to be twice that of an HMA overlay. However, the initial construction cost of ECC overlay is higher than that of an HMA overlay. The construction duration of an ECC overlay is also longer than an HMA overlay. The initial construction costs and construction related congestion costs for an ECC overlay are \$7 million higher to an HMA overlay (\$36 million and \$29 million initial costs for an ECC overlay and an HMA overlay, respectively) (Zhang et al., 2008). If the government can subsidize ECC for \$7 million, it will make ECC material competitive with HMA material. This subsidy will reduce the total life cycle costs by:

$$\textit{Budget change} \times \textit{Shadow price}\ (\lambda) = \$7{,}000{,}000 \times 5.5 = \$38{,}500{,}000 \tag{4.11}$$

An independent study of life cycle costs for an ECC and HMA overlay system shows a similar result. The total life cycle costs of an ECC and HMA overlay system for a 40 year lifetime are $48.8 million and $92.5 million, respectively. Details of life cycle cost analysis model for each overlay system are described in Zhang et al (2008).

The multi-objective optimization analysis gives highway agencies more flexibility to control and manage their pavement systems. Figure 4.8 shows different optimal HMA overlay preservation strategies with a weight factor ranging from $0.32/l ($1.22/gal) to $3.22/l ($12.18/gal) (calculated in the previous section). Generally, fuel prices reflect the relationship between fuel demand and supply. Higher fuel price indicates the insufficient fuel supply relative to increasing demand. Thus, at a higher fuel price, highway agencies can adjust the preservation strategy to an energy saving strategy (higher weight factor), which increases maintenance and rehabilitation frequency to reduce pavement surface roughness. On the contrary, if fuel price is relatively low and economic costs are more important, the highway agencies can focus on optimizing agencies costs, which result in reducing maintenance and rehabilitation frequency to decrease construction related congestion and user time delay cost.

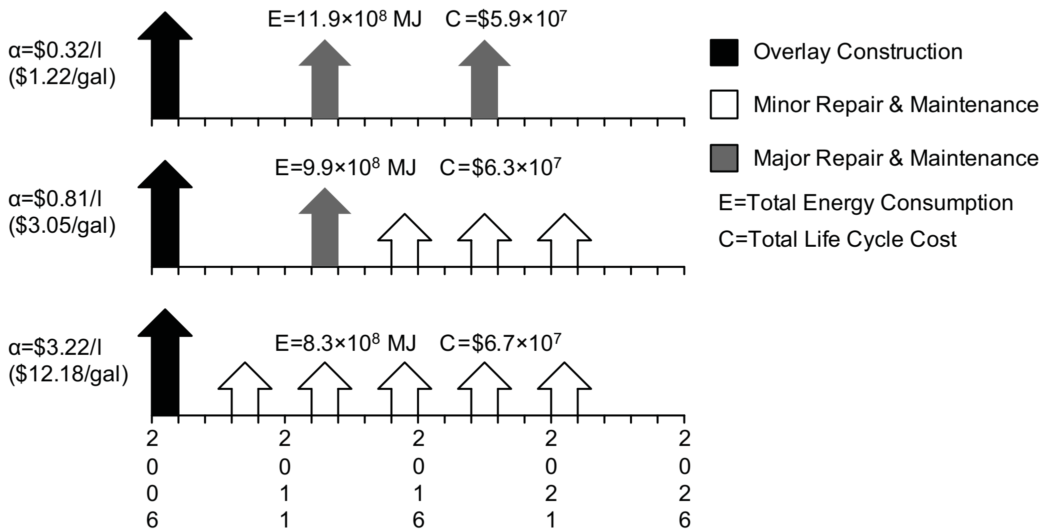

Figure 4.8 Optimal maintenance strategies based on different fuel prices

4.5 Conclusion

This study demonstrates the feasibility of applying mathematical programming methods to a pavement asset management system. A multi-constraint model and a multi-objective model are incorporated in a project-level PAMS model to enable decision makers to evaluate pavement infrastructure projects from a more holistic, long term perspective while providing criteria for more sustainable infrastructure material selection.

Multi-constraint and multi-objective analysis provides a quantitative base for pavement preservation policy making. The results of multi-constraint analysis show that the total life cycle cost of an HMA overlay system increases from $54 million to $61 million as the agency budget decreases from $2 million to $0.5 million. Suspending the gas tax will not benefit highway users from a long term perspective. The shadow price of the HMA overlay system shows that a $0.29 million suspension of the gas tax for 3 months will cost about $0.40 million to highway users over 20 year period. Additionally, a government subsidy can be helpful to promote the application of new materials and technologies which can further decrease life cycle costs compared to those of conventional low initial cost techniques. A $7 million subsidy to implement ECC overlay technologies can reduce life cycle costs by $38.5 million in the future.

Multi-objective optimization enables highway agencies to develop their preservation strategy based on weighted objectives to achieve maximized benefit. A series of weight factors between energy consumption and life cycle cost objectives are generated. These weight factors are converted to fuel prices ranging from $0.32/l ($1.22/gal) to $3.22/l ($12.18/gal). At a higher fuel price, a more frequent preservation strategy that decreases pavement surface roughness and saves energy is preferred. If the fuel price is relatively low, decreasing the pavement maintenance and rehabilitation frequency will decrease the user time delay caused by construction activities and then decrease the total life cycle cost.

The multi-constraint and multi-objective optimization models developed here represent a new set of tools to guide policy making that can enhance transportation infrastructure sustainability.

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CHAPTER 5

NETWORK-LEVEL PAVEMENT ASSET MANAGEMENT SYSTEM INTEGRATED WITH LIFE CYCLE ANALYSIS AND LIFE CYCLE OPTIMIZATION

ABSTRACT

A network-level pavement asset management system (PAMS) utilizing life cycle analysis and life cycle optimization methods was developed. Three priority selection methods were developed based on benefit, benefit cost ratio, and binary integer programming to allocate the limited preservation budget. A geographic information system (GIS) model was utilized to enhance the network-level PAMS by collecting, managing, and visualizing pavement condition data. The new network-level pavement asset management system allows decision makers to preserve a healthy pavement network and minimize total life cycle cost, while also meeting budget constraints and other agency constraints. A case study application to Washtenaw County, Michigan, compared the optimal preservation strategies with the Michigan Department of Transportation's current preservation practice. The results show that the optimal preservation strategies can reduce total life cycle cost by 9%-13% compared to the current preservation plan. The impact of annual preservation budget on total life cycle cost was analyzed. A $3 million annual preservation budget reduction will significantly increase user costs by $450 million for a 40 year analysis period.

5.1 Introduction

Highway agencies are faced with the challenges of an aging and deteriorating highway networks and inadequate preservation budget. While the Federal-aid highway program is undergoing a significant transition from its original focus on building the Nation's highway network to preserve and improve the existing pavement infrastructure, a network-level pavement asset management system (PAMS) is necessary to allow highway agencies to allocate their limited budgets efficiently (FHWA, 1998).

There are two major administrative levels of any pavement asset management system: network-level PAMS and project-level PAMS (Mbwana, 2001). Project-level PAMS is intended to predict the pavement deterioration, select the appropriate preservation activity, and develop the optimal preservation schedule for a specific pavement segment. Network-level PAMS determines the pavement segment preservation priority and budget allocation strategy. Network-level PAMS policy will guide project-level PAMS to ensure that each individual pavement segment preservation strategy will result in an overall optimal solution for the entire pavement network.

Network-level pavement asset management system has become an important part of the decision making process for state highway agencies, because of limited highway preservation funds. 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. In 1989 Federal Highway Administration (FHWA) issued a policy that requires each state highway agency to have a pavement asset management system (FHWA, 1989). After that, a number of network-level pavement asset management models have been developed during the past two decades. Mbwana used Markov decision model to predict pavement network condition and applied linear programming to determine the optimal pavement maintenance and rehabilitation strategy (Mbwana and Turnquist, 1996). Chootinan et al. developed a network-level pavement maintenance program using genetic algorithm to maximize pavement performance and minimize pavement maintenance cost (Chootinan et al., 2006). Currently, the Michigan Department of Transportation (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 at different levels of investment. However, to improve sustainability, modern pavement asset management systems should also have the ability to account for other sustainability indicators, such as user time delay caused by preservation activities, additional fuel consumption caused by pavement surface deterioration, and 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).

Another challenge in developing a network-level PAMS is the ability of managing and analyzing the large pavement condition dataset. A network-level PAMS relies on pavement condition information for identifying pavement construction sections, developing preservation strategy, and allocating budget. Geographic information system (GIS), with its unique spatial analysis capability, allows highway agencies to integrate, manage, query, and visualize pavement conditions. A number of researchers and highway agencies have applied GIS platform for enhancing pavement asset management. Medina et al. developed a prototype low-volume roads pavement management system using GIS tool for Fountain Hills, Arizona (Medina et al., 1999). The Illinois Department of Transportation 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 decision making process involved in managing pavement networks.

An innovative network-level pavement asset management system is developed in this chapter. Figure 5.1 shows the framework of the network-level PAMS. The integrated LCA-LCCA model evaluates the life cycle energy consumption, environmental impacts, and costs for a pavement network. User time delay caused by preservation activities, pavement surface roughness effects, and environmental damage costs are captured by the life cycle analysis model. Details of this model are described in the Chapter 2. The GIS model initializes the pavement network and provides the pavement condition data to the integrated LCA-LCCA model. The network-level PAMS model develops the optimal pavement network preservation strategy to minimize one or multiple sustainability indicators (costs and energy consumption, etc.) based on current pavement network condition and budget constraint. The optimal preservation strategy is fed back to the integrated LCA-LCCA model to calculate the optimized sustainability indicators. The results are stored in the GIS model and can be retrieved quickly and accurately.

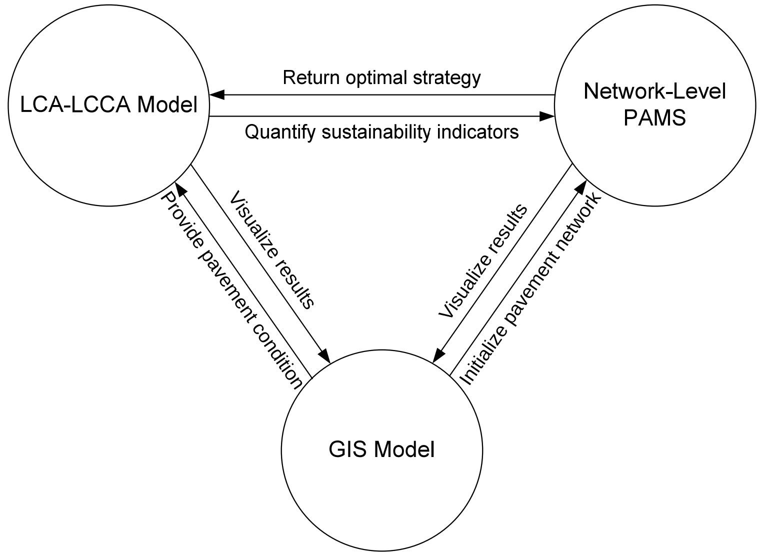

Figure 5.1 The integrated framework of the network-level PAMS

5.2 Methodology

5.2.1 Network-Level Pavement Asset Management System

The network-level pavement asset management process starts from a previously developed project-level PAMS. This project-level PAMS divides a pavement system into several stage and state variables (Zhang et al., 2009). The stage variable represents each year in the analysis period. The state variable is the pavement condition. In Michigan, the pavement condition is measured by a distress index (DI). The DI value starts at 0 which indicates perfect pavement condition. Although there is no upper limit for the DI value, the Michigan Department of Transportation (MDOT) uses a threshold DI of 50 to indicate the need for pavement rehabilitation or reconstruction (Ahmed et al., 2006). At each stage and each possible state, a set of preservation decisions can be made for each pavement segment.

A burden function $B(i, j)$ is defined as the current burden (energy consumption, GHG emissions, or total cost) caused by a certain preservation activity for a specific pavement segment. The burden function can be described by Equation 5.1.

$$B(i, j) = \begin{cases} B_M(i, j) + B_C(i, j) + B_D(i, j) + B_{CG}(i, j) + B_E(i, j) + B_U(i, DI(i)) & \text{if } i > 0 \\ 0 & \text{if } i = 0 \end{cases} \quad (5.1)$$

where i is the current stage (year), j is the preservation alternative, $B_M(i, j)$ is the burden associated with the material module at year i with decision j. Similarly, $B_C(i, j)$, $B_D(i, j)$, $B_{CG}(i, j)$, and $B_E(i, j)$ are the burdens of construction, distribution, traffic congestion, and end of life processes, respectively, at year i with decision j. $B_U(i, DI(i))$ is the burden of pavement usage which is caused by pavement surface roughness effects at year i with a particular distress index.

A backward dynamic programming procedure was developed to select the optimal preservation strategy from all candidate decisions (Zhang et al., 2009).

If the highway agency has enough budget, all segments in the pavement network should follow the optimal preservation strategy developed by the project-level PAMS to achieve the optimal results (minimizing life cycle energy consumption, environmental impacts, or costs). However, if the total budget of the highway agency cannot cover the entire pavement network, the network-level PAMS is necessary to adjust the optimal preservation strategy developed from the project-level PAMS and allocate the limited budget to specific pavement segments based on a priority selection process. Thus, priority selection model is the key part in the network-level PAMS.

5.2.2 Priority Selection Model

To decide the priority of each pavement segment, three selection methods are developed. The first method is based on benefit. Benefit is defined as $B(i,0)-B(i,\ j)$, where $B(i,0)$ is the current burden without applying any preservation activity at year i and $B(i,\ j)$ is the current burden with applying preservation activity j at year i. If applying preservation activity j to pavement segment k has a larger benefit than the benefit of applying the same preservation activity to the other pavement segments, pavement segment k will have a higher priority to do preservation activity j. The second method is based on benefit cost ratio. The benefit cost ratio is defined as $(B(i,0)-B(i,\ j))/C(i,\ j)$, where $C(i,\ j)$ is the agency cost of preservation activity j at year i. Similarly, if applying preservation activity j to pavement segment k has a larger benefit cost ratio than the benefit cost ratio of applying the same preservation activity to the other pavement segments, pavement segment k will have a higher priority to do preservation activity j.

However, these two methods are not based on mathematical programming. They may not always identify the global optimal result. To solve this problem, a third method is developed based on binary integer programming. The objective is to minimize the overall burden for the entire pavement network at year i. So the objective function is defined as:

Minimize $B_1X_1^T+B_2X_2^T+......+B_nX_n^T$ (5.2)

where $B_k=\left[b_{k1},b_{k2},......,b_{km}\right]$ and $X_k=\left[x_{k1},x_{k2},......x_{km}\right]$. B_k is the burden matrix of pavement segment k, from current state to the last state; X_k is the preservation activity matrix of pavement segment k. T means transpose. b_{kj} is the burden of doing preservation activity j of pavement segment k, from current state to the last state ; x_{kj} is the preservation activity j of pavement segment k.

Subject to:

$$C_1X_1^T + C_2X_2^T + ... + C_nX_n^T \le C \tag{5.3}$$

where $C_k = [c_{k1}, c_{k2}, ..., c_{km}]$. C_k is the agency cost matrix of pavement segment k, C is the total annual budget. c_{kj} is the agency cost of preservation activity j of pavement segment k.

Also, the other constraints include:

$$DI \le Max\ DI\ (50) \tag{5.4}$$

$$x_{kj} \ge 0, \quad k = 1, 2, ..., n; \quad j = 1, 2, ..., m \tag{5.5}$$

$$x_{kj} \in \text{int}, \quad k = 1, 2, ..., n; \quad j = 1, 2, ..., m \tag{5.6}$$

$$\sum_{j=1}^{m} x_{kj} = 1, \quad k = 1, 2, ..., n \tag{5.7}$$

A computer program using Visual Basic Application (VBA) and running within Microsoft Excel software was coded to implement the priority selection model and link it to the network-level PAMS. Three network-level pavement asset management systems based on benefit, benefit cost ratio, and binary integer programming selection methods are developed and named as PAMS1, PAMS2, and PAMS3, respectively.

5.2.3 GIS Model

To integrate GIS application with the network-level pavement asset management system, several GIS base map layers are created which contain multiple sets of attributes. Attributes are data in digital map layer that are linked to linear pavement features, such as control section (CS), pavement type (concrete or asphalt), pavement remaining service life (RSL), annual average daily traffic (AADT) and commercial average daily traffic (CADT), and pavement condition (distress index). Linear referencing method provides an intuitive way to associate these attributes to the portions of pavements. These attributes can be further displayed, queried, edited, and analyzed without affecting the underlying linear feature's geometry (ESRI, 2004). In linear referencing, a route is created to model the linear feature using a one-dimensional measuring system. The measuring system records the data by using a relative position along an already existing linear pavement feature. For example, route US-23, kilometer point 11.5, uniquely identifies a position in a map without using two-dimensional (x, y) geographic coordinates. Route event tables are used to store linearly referenced attributes. Event table is a relational database management system table supported by GIS platform. Because events simply reference measure locations along linear features, they are edited and maintained independently of the pavement features. Event rows are composed of a route identifier, measure values indicating a location, and one or more attributes associated with the location. As shown in Figure 5.2, along a route, beginning and ending meter points (BMP and EMP, respectively) of different attributes rarely match. To generate the final pavement segments and visualize them on map, a dynamic segmentation method is used.

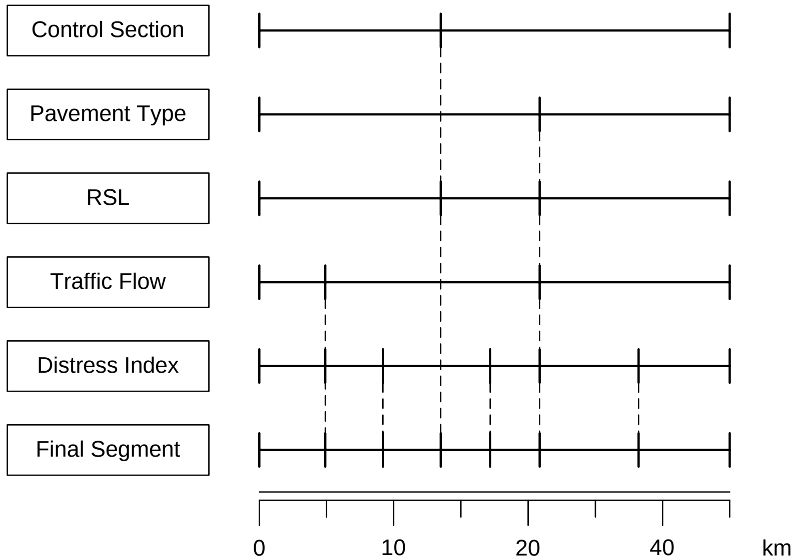

Figure 5.2 Route event segmenting process

Dynamic segmentation is a process of computing the map location of events stored in an event table and allows multiple sets of attributes to be associated with any portion of a linear feature. Figure 5.3 shows how the dynamic segmentation method overlays two route event tables to produce a single route event table. The route event table (a) stores traffic flow information (AADT). The route event table (b) stores pavement condition data (DI). The two event tables are unioned to a third event table. The output event table (c) contains all of the input events, which have been split where they intersected.

CS	BMP	EMP	AADT
81041	0	3219	85600
81041	3219	3791	70000
81062	0	3219	55900
81062	3219	4828	62400

(a)

CS	BMP	EMP	DI
81041	0	1609	25.4
81041	1609	3219	19.0
81041	3219	3791	7.9
81062	0	1609	10
81062	1609	4828	21

(b)

CS	BMP	EMP	AADT	DI
81041	0	1609	85600	25.4
81041	1609	3219	85600	19.0
81041	3219	3791	70000	7.9
81062	0	1609	55900	10
81062	1609	3219	55900	21
81062	3219	4828	62400	21

(c)

Figure 5.3 Union of two route event tables using dynamic segmentation

The commercially available GIS software ArcGIS 9.2 has been used to create the digital pavement network map and conduct the linear referencing process. A Visual Basic program is developed to implement data transfer between ArcGIS and network-level PAMS.

5.3 Case Study: Washtenaw County Pavement Network

5.3.1 Pavement Network Initialization

Washtenaw County, Michigan, was selected for the case study. Washtenaw County covers 1,871 km^2 and has almost 350,000 residents (Census Bureau, 2008). Several major highways cross Washtenaw County, including I-94 (Interstates), US-23 (US highways), and M-14 (Michigan State Trunklines). The pavements in Washtenaw County are preserved by the Michigan Department of Transportation. They also collect and maintain the pavement information data. These data provide the length, width, location, pavement type, pavement distress index, and traffic flow of each pavement.

Query analysis is conducted in the GIS model for identification of the pavement sections which satisfy the following predefined intervention criteria:

(a) All pavement sections are freeways

(b) AADT $\geq$ 30000

(c) CADT $\geq$ 4000

Linear referencing and dynamic segmentation methods are applied to the initial dataset. A total number of 32 pavement segments (total 120 km long) are generated. The description of each pavement segment is listed in Table 5.1.

Table 5.1 Pavement segments information list

ID	Name	CS	BMP	EMP	Type	AADT	CADT	RSL	DI
1	I-94	81041	0	3790.8	Concrete	85233	9200	10	17.4
2	I-94	81062	0	4828.0	Asphalt	55900	7900	12	15.5
3	I-94	81062	4828.0	11265.4	Asphalt	70650	7900	12	11.6
4	I-94	81062	11265.4	14661.0	Asphalt	85433	8633	9	3.9
5	I-94	81063	0	3128.7	Asphalt	106900	11600	9	2.0
6	I-94	81063	3128.7	4828.0	Asphalt	103500	11600	3	2.0
7	I-94	81063	4828.0	5809.6	Asphalt	103500	11600	7	6.4
8	US-23	81074	0	6437.4	Concrete	73850	6950	6	9.3
9	US-23	81074	6437.4	12028.0	Concrete	70500	6900	6	4.1
10	M-14	81075	0	1810.0	Concrete	56100	5500	11	25.3
11	US-23	81075	0	4828.0	Asphalt	64300	6000	11	21.1
12	US-23	81075	4828.0	11748.2	Asphalt	65820	6000	11	20.0
13	US-23	81075	0	1209.8	Asphalt	63100	7900	11	24.5
14	US-23	81076	0	1609.3	Concrete	36900	6300	12	9.4
15	US-23	81076	1609.3	11265.4	Asphalt	41817	6300	7	13.2
16	US-23	81076	11265.4	15922.9	Asphalt	57233	6833	8	16.8
17	M-14	81103	0	1609.3	Asphalt	70100	6900	13	5.8
18	M-14	81103	1609.3	4828.0	Asphalt	63600	5500	7	13.9
19	M-14	81103	4828.0	6437.4	Asphalt	63600	5500	16	4.1
20	M-14	81103	6437.4	8046.7	Asphalt	62200	5500	9	8.3
21	M-14	81103	8046.7	9656.1	Asphalt	62200	5500	1	9.8
22	M-14	81103	9656.1	11265.4	Asphalt	62200	5500	4	8.6
23	M-14	81103	11265.4	12874.8	Asphalt	62200	5500	6	5.6
24	M-14	81103	12874.8	13850.0	Asphalt	61700	5500	8	5.2
25	I-94	81104	0	9656.1	Asphalt	49067	8600	7	6.1
26	I-94	81104	9656.1	19312.1	Asphalt	55500	9200	3	21.1
27	I-94	81104	19312.1	28968.2	Asphalt	61050	8983	7	9.3
28	I-94	81104	28968.2	29396.3	Asphalt	46600	7900	12	5.7
29	M-14	81105	0	5886.9	Concrete	32750	4400	3	1.7
30	US-23	81103	0	1609.3	Concrete	63100	7900	7	9.1
31	US-23	81103	1609.3	3128.7	Concrete	63100	7900	11	3.6
32	US-23	81103	3128.7	3863.0	Concrete	63100	7900	10	3.2

Figure 5.4 shows the GIS map and the initial pavement network condition.

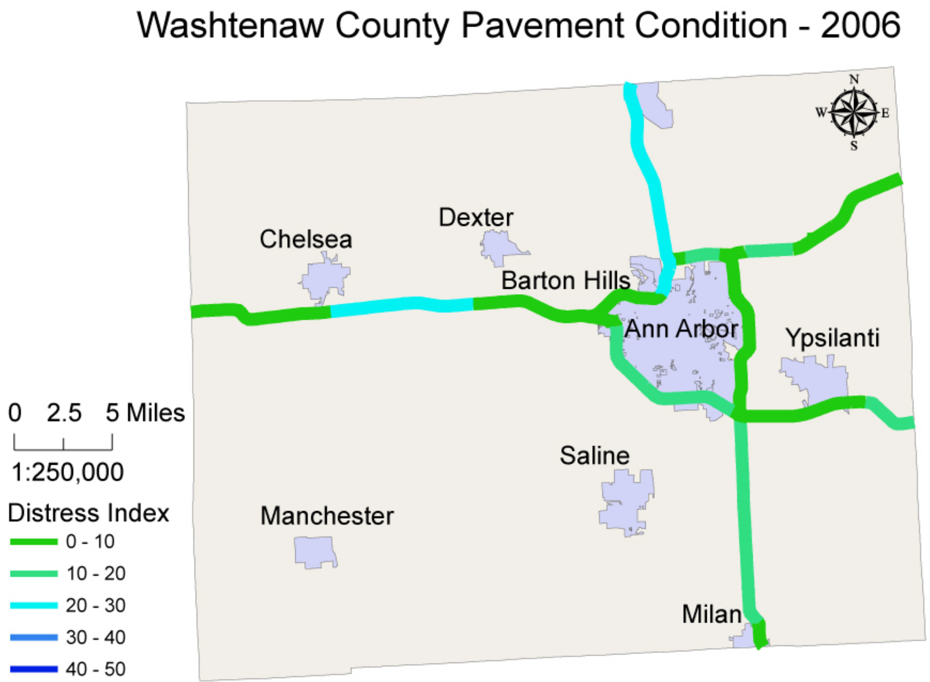

Figure 5.4 GIS map and pavement network condition

5.3.2 Network-level pavement asset management results

The network-level PAMS is applied to the above pavement network to develop the optimal preservation strategy for a 40 year analysis period. The annual budget for the entire pavement network is derived from the Michigan Five-Year Transportation Program (MDOT, 2007). In the 2007 to 2011 Five-Year Transportation Program, Washtenaw County and other nine nearby counties can receive approximately $368 million for 2,150 km road preservation. The annual budget allocated to the pavement network in this research is estimated to be $4 million/year.

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 5.2.

Table 5.2 Alternative preservation methods and unit costs

Method	Unit cost, $/lane-km
Do nothing	0
Minor Maintenance	4000-5000
Major Maintenance	28750-36250
Overlay	106550-106860

Using the network-level PAMS, 3 sets of optimal preservation strategies based on the three priority selection methods (PAMS1, PAMS2, and PAMS3) are developed. Another case based on the MDOT preservation plan is also generated to compare to the optimal preservation strategies. Figure 5.5 shows the pavement surface condition which is represented by the distress index in the 40 year analysis period using different preservation strategies. Due to allocate the resource efficiently, the pavement surface conditions of preservation strategies using PAMS1, PAMS2, and PAMS3 methods are generally better than the conditions of MDOT plan. This better pavement surface condition will decrease the fuel consumption for highway drivers and decrease the user fuel costs.

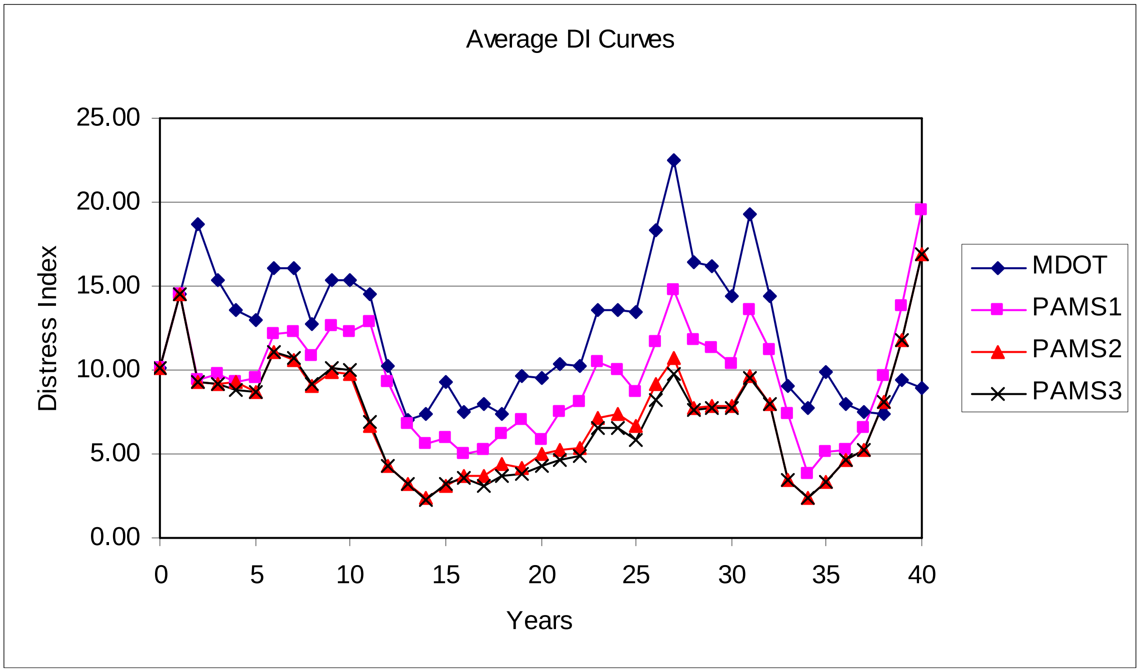

Figure 5.5 Average DI curves based on different preservation strategies

The network-level PAMS also optimizes the preservation method selection and preservation frequency. It decreases the congestion caused by the interruption of normal traffic flow and decreases the user time delay. The user time delay has been identified 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). Thus, decreasing the user time delay cost will further decrease the total life cycle cost. Figure 5.6 shows the total life cycle cost broken down into agency cost, user congestion cost (caused by preservation activity), user roughness cost (caused by pavement surface roughness), and environmental cost based on different preservation strategies. The results of PAMS1, PAMS2, and PAMS3 methods reduce 9%, 12%, and 13% total life cycle cost, respectively, compared to current MDOT preservation plan.

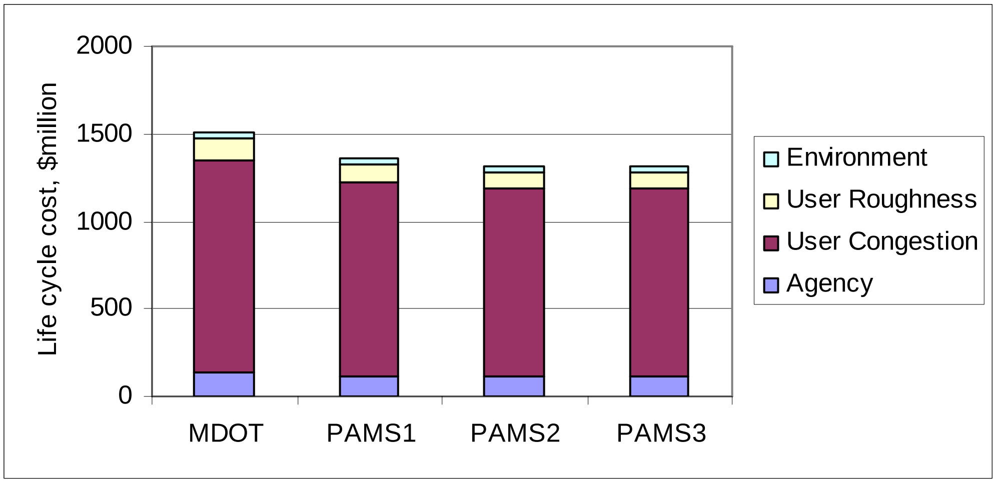

Figure 5.6 Total life cycle cost of different preservation strategies

Annual preservation budget is an important factor which determines the total resource that the highway agency can use for pavement preservation. To identify the impact of annual preservation budget on total life cycle cost, a sensitivity analysis is conducted using PAMS3 method. The result is shown in Figure 5.7. While the annual budget decreases from $4 million to $1 million, the total life cycle cost (present value) increases from $1310 million to $1690 million over a 40 year service life. As expected, agency costs decrease as the budget constraint tightens. However, user congestion cost and user roughness cost, which combined are about 8 times higher than agency costs over the 40 year life time of a pavement overlay system, increase as the annual preservation budget decreases. The model indicates that for a budget less than $1 million/yr is not enough to preserve the entire pavement network without failure (DI > 50).

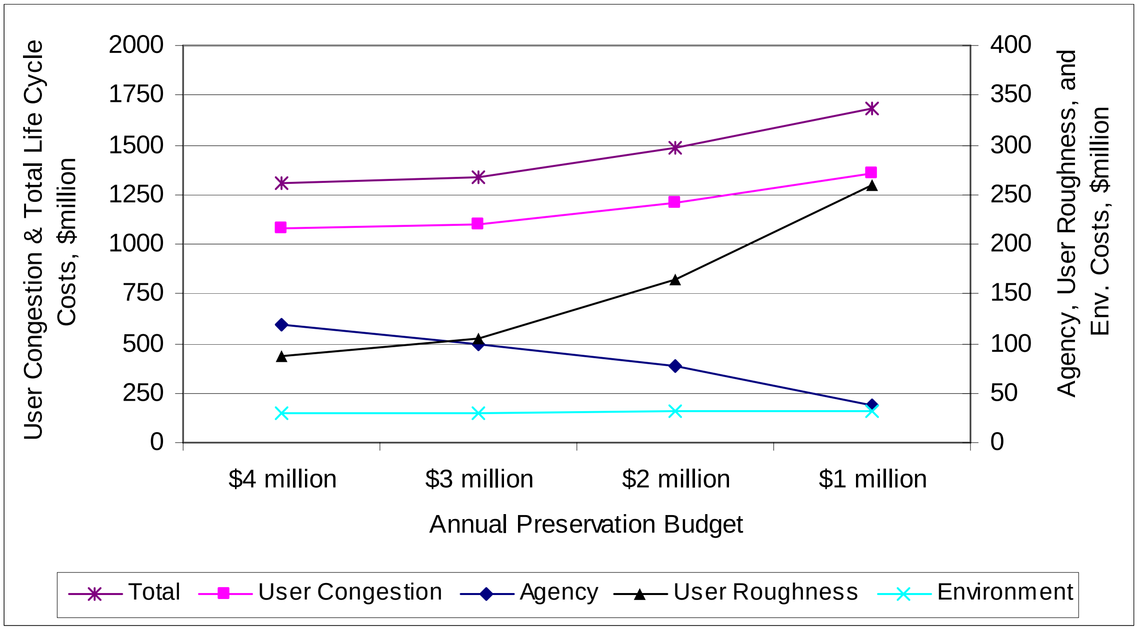

Figure 5.7 Total life cycle cost based on different annual budget

The results obtained through network-level pavement asset management system have been imported to the GIS model and visualized on the digital map created before. Figure 5.8 shows an example of the different attributes illustrated on the map. All other attributes associated with any pavement section can be selected and visualized on the graphical map.

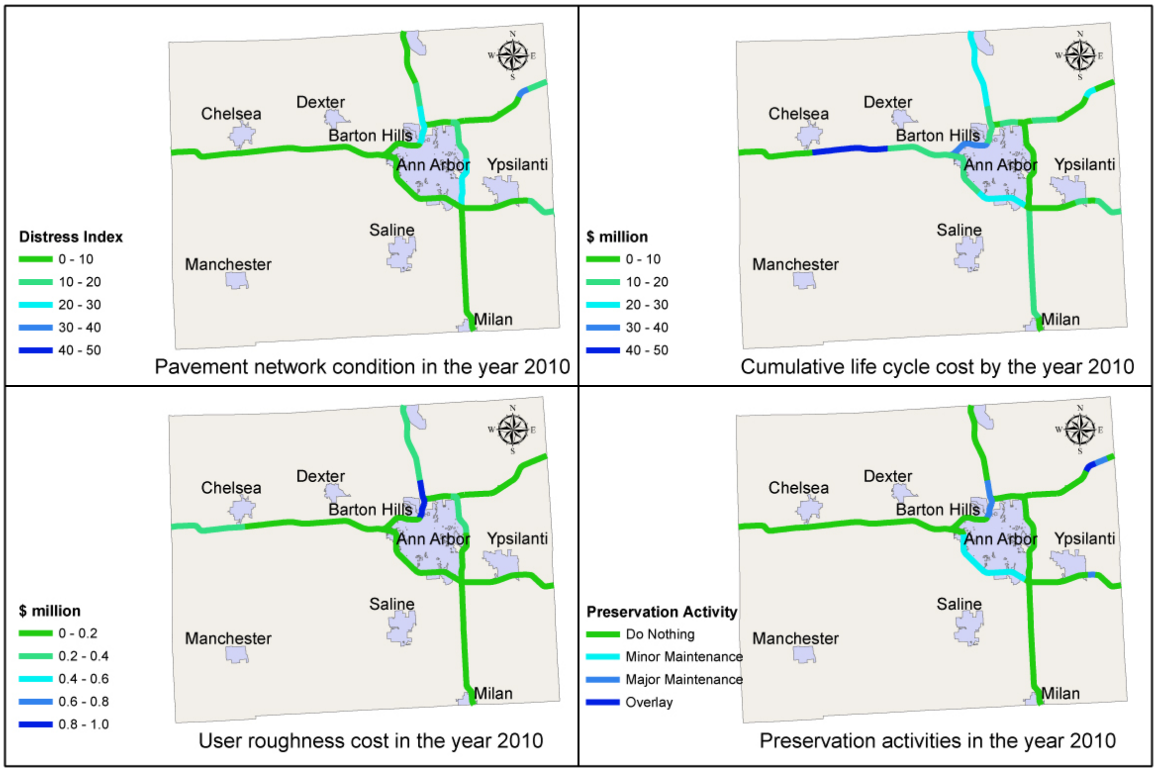

Figure 5.8 Visualization of different attributes in GIS map

5.4 Conclusion

This study describes the development of a network-level pavement asset management system (PAMS) that integrates life cycle analysis, optimization, and GIS. In the network-level PAMS model life cycle analysis captures user congestion cost, user roughness cost, and environmental costs as well as agency costs. Life cycle optimization is applied to determine the optimal preservation strategy for a pavement network and to minimize total life cycle cost within an analysis period. Three priority selection methods are developed based on different criteria to allocate the limited budget efficiently. Binary integer programming performed more accurately than the other methods in this research to reach a global optimal budget allocation result.

A GIS model and interface was developed to enhance the network-level pavement asset management system by collecting, managing, and visualizing pavement condition data. Query analysis was conducted in the GIS model to identify the specific pavement network in the basic digital map. Linear referencing and dynamic segmentation methods are applied to define the pavement segment and associate pavement information with any pavement portion. GIS model integrated with the network-level PAMS provides a unique way to immediately retrieve and visualize all pavement network attributes, such as pavement condition, current pavement preservation activity, and costs, on the graphical map. This unique function enables more effective communication between highway agencies and preservation strategy development.

The case study application to Washtenaw County, Michigan, demonstrated the capability of the PAMS to improve preservation performance. The result showed that the optimal preservation strategies can reduce total life cycle cost by 9%-13% compared to preservation practice used by the Michigan Department of Transportation. Since LCCA has been required by MDOT in the design of all projects with paving costs greater than $1 million since 1998, the improvement of optimal preservation strategies is limited. However, MDOT preservation plan can not anticipate the impacts of constraints changes and dynamically adjust the preservation strategy. Annual preservation budget has significant impact on total life cycle cost. A preservation budget reduction from $4 million/yr to $1 million/yr increases the total life cycle cost from $ 1310 million to $1690 million. It is expected that greater benefits might be realized in states that don’t employ LCCA. In the present application of the PAMS model, the annual budget was fixed but the model can also be implemented with a 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.

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CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

This dissertation has focused on the development of a new framework for evaluating and enhancing the sustainability of pavement systems from alternative material applications, asset management, and policy making perspectives. Ultimately this has produced a unique collaborative platform upon which a variety of analysis methods and tools including life cycle analysis, life cycle optimization, microeconomics, decision making, and spatial analysis interface with the overall goal of improving infrastructure system sustainability. The new methods enable decision makers to evaluate and preserve pavement systems from a more comprehensive, long term perspective and provide criteria for more sustainable infrastructure material selection.

Four main research activities have been divided into individual chapters depending upon their objectives: life cycle assessment and life cycle cost analysis model evaluating the sustainability indicators of pavement systems and comparing new designs and ECC materials to conventional designs and materials; project-level pavement asset management system optimizing the pavement preservation strategy and improving the sustainability; multi-objective and multi-constraint optimization model exploring the impact of policies based on the project-level PAMS; and finally, the network-level pavement asset management system applied to a pavement network minimizing life cycle cost, while also meeting budget constraints and other agency constraints. Significant findings and accomplishments made in individual research tasks are summarized in the following.

6.1.1 Development of the Integrated Life Cycle Assessment and Life Cycle Cost Analysis Model

Chapter 2 focused on the development of life cycle analysis framework. An integrated life cycle assessment and life cycle cost analysis model was developed to compare the sustainability of an unbonded concrete overlay system, a hot mixed asphalt overlay system, and an ECC overlay system. The model captures cumulative traffic flows, overlay deterioration over time, and preservation activities to evaluate life cycle energy consumption, environmental impacts, and costs. The incorporation of pavement overlay roughness effects on fuel consumption and related life cycle environmental burdens represents a significant extension of existing models. Without considering roughness effect, the life cycle energy consumption of concrete, ECC, and HMA overlay systems will decrease 23%, 36%, and 14%, respectively (traffic condition and other system parameters were defined in Chapter 2).

The model results showed that the overlay application of ECC material may effectively reduce the total life cycle energy consumption, environmental impacts, and costs when compared to the conventional materials and designs. While ECC is more energy and cost intensive per unit volume, compared to the concrete and HMA overlay systems, model results indicate the ECC overlay system reduces the total life cycle energy by 15% and 72%, greenhouse gas (GHG) emissions by 32% and 37%, and costs by 40% and 58% over the entire 40 year life cycle, respectively. These advantages are derived from the expected enhanced material properties of ECC which should prevent reflective cracking failures. While the assumption of longer service life of the ECC overlay system is supported by results of experimental tests, FEM simulations, and bridge deck applications, it is necessary to verify the result with the actual application of ECC material in an overlay system and observation of its performance over time.

The analysis also showed the potential of environmentally preferable mixtures which use industrial byproduct as a substitute for energy intensive materials, such as using waste fly ash to replace portions of Portland cement in the ECC overlay system. This substitution results in significantly reduced raw material and energy consumption and decreased environmental burdens while maintaining or improving overlay system performance.

Material consumption, traffic congestion caused by construction activities, and pavement surface roughness effects caused by overlay deterioration are identified as three dominant factors that influence the energy consumption, environmental impacts, and costs of overlay systems. These three factors are determined by the pavement preservation strategy. This result led to the following research on searching for the optimal pavement maintenance and rehabilitation strategy to minimize life cycle energy consumption, environmental impacts, and costs.

6.1.2 Project-Level Pavement Asset Management System

Chapter 3 focused on the development of a project-level pavement asset management system. The project-level PAMS which determines an optimal pavement preservation strategy is identified through the application of life cycle optimization and dynamic programming tools for modeling the sustainability indicators and breaking the complicated system into several sub processes. The integration of modern optimization techniques and life cycle analysis methods improves the management capability of transportation agencies as compared to current pavement asset management practice.

The project-level pavement asset management system is applied to the ECC, concrete, and HMA overlay systems. The results show that the optimal preservation strategies will reduce the total life cycle energy consumption by 5%-30%, the GHG emissions by 4%-40%, and the costs by 0.4%-12% for three overlay systems compared to current the Michigan Department of Transportation preservation strategies. Total life cycle costs of MDOT strategies have been controlled nearly to the optimal levels, because LCCA and user costs have been incorporated into their design.

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, at higher traffic growth rates, the ECC overlay system shows superior advantages in energy consumption, GHG emissions, and cost, compared to the concrete overlay system and HMA overlay system.

The trade-offs between material consumption, traffic congestion, and pavement surface roughness effects are identified in this research. Energy consumption minimization leads to a more frequent preservation strategy, while cost minimization favors a less frequent preservation strategy. This conflicting result on optimal preservation strategy selection highlighted the necessity to implement a more comprehensive optimization model.

6.1.3 Multi-Objective and Multi-Constraint Optimization in Project-Level Pavement Asset Management

Chapter 4 investigated the impact of pavement preservation policies. The multi-constraint model and a multi-objective model were incorporated in the project-level PAMS to provide a quantitative base for policy development. A case study of a hot mixed asphalt overlay system shows that a reduction in total agency preservation budget from $2 million to $0.5 million increases the total life cycle cost from $54 million to $61 million over a 20 year service life. The shadow prices of the HMA overlay system derived from the multi-constraint analysis were used to evaluate the impact of gas tax reduction and subsidy policies. Proposals by presidential candidates Clinton and McCain to temporarily suspend the $0.049/l ($0.184/gal) federal gas tax in the summer of 2008 would cost about $0.40 million to highway users over 20 year period. Additionally, a $7 million subsidy to implement ECC overlay technologies can reduce life cycle costs by $38.5 million in the future.

Motivation for the multi-objective optimization is based upon the observation that minimizing energy consumption and saving total costs are conflicting objectives. The relationship between fuel prices and pavement preservation strategies is identified using weighted objective optimization analysis and microeconomic theory. At a higher fuel price, a more frequent preservation strategy that decreases pavement surface roughness and saves energy is preferred. If the fuel price is relatively low, a less frequent pavement maintenance and rehabilitation strategy is favored which will decrease the user time delay caused by construction activities and then decrease the total life cycle cost. This method enables highway agencies to develop their preservation strategy based on weighted objectives to achieve maximum benefit.

6.1.4 Network-Level Pavement Asset Management

Chapter 5 described the development of the network-level pavement asset management system that integrates life cycle analysis, optimization, and GIS. With limited budget, the optimal preservation strategies developed in Chapter 3 and 4 cannot be applied to all the pavement segments within a pavement network. Three priority selection methods were developed based on benefit, benefit cost ratio, and binary integer programming to allocate the limited preservation budget efficiently. Binary integer programming performed more accurately than the other methods in this research to reach a global optimal budget allocation result.

To manage the large scale pavement network database, a GIS model and interface was developed to enhance the network-level PAMS. GIS model provides a unique way to immediately retrieve and visualize all pavement network attributes, such as pavement condition, current pavement preservation activity, and costs, on the graphical map. This unique function enables more effective communication between highway agencies and preservation strategy development.

The case study application to Washtenaw County, Michigan, demonstrated the capability of the PAMS to improve preservation performance. The result showed that the optimal preservation strategies can reduce total life cycle cost by 9%-13% compared to preservation practices used by the Michigan Department of Transportation. The annual preservation budget has significant impact on total life cycle cost. A preservation budget reduction from $4 million/yr to $1 million/yr increases the total life cycle cost from $1310 million to $1690 million over a 40 year analysis period.

6.2 Future Work

The methodologies and models proposed in this research could be further improved and /or extended in the following directions:

(1) With the flexibility of life cycle analysis and life cycle optimization, the framework discussed in this dissertation can be applied to other long life complex systems and discrete time decision making processes. Compared to other methods, life cycle modeling extends the scope of systems and adequately captures the broader impacts of material and structure performance to evaluate life cycle energy consumption, environmental impacts, and costs. Buildings and other long-lived systems that require maintenance throughout their entire life are excellent candidates for this life cycle modeling approach. Similarly, life cycle optimization framework and optimization models utilized in this research can be applied and modified to investigate the other decision making processes. Some of these include optimal machinery replacement (i.e., vehicle fleet) or alternative material design.

(2) The potential incorporation of industrial waste and recycled materials into alternative design is promising. While fly ash has been used to replace some

portions of Portland cement in ECC and proved to be more environmentally preferable, other materials exist which can be potential candidates to substitute for conventional energy intensive or environmentally harmful materials. The clear message in this dissertation showed that material properties of alternative designs must meet the infrastructure application durability needs. A life cycle analysis and optimization model is necessary to evaluate the sustainability performance of alternative ECC mix designs and study the trade-offs between material properties and material sustainability.

(3) It will be a useful extension of the research model if uncertainty is included in the pavement deterioration model. While a statistical auto-regressive model was proposed in this research, a probabilistic-based model for predicting the remaining service life and deterioration of different material is needed. A possible method to estimate uncertainties in a pavement system is to apply Monte Carlo simulation to randomly generate deterioration rates and develop a stochastic deterioration function.

(4) Traffic volume has significant impacts on pavement service life. Ultimately, a theoretical method which models the impacts of traffic flow and other factors, such as material property, structure, construction practice, and environment, would significantly improve the accuracy to calculate structures service life and deterioration rate.

(5) In this research several preservation methods were predefined in the pavement asset management system. Different highway agencies may

choose different preservation methods. Alternative preservation methods can be included into the PAMS and their impacts on the sustainability indicators can be evaluated.

(6) Wireless sensing technology can collect the pavement deterioration data and calibrate the optimal preservation strategies derived from pavement asset management system.

APPENDIX A

LOW TRAFFIC VOLUME SCENARIOS

The effect of lower traffic volume on construction related traffic congestion and roughness effect was studied here. This analysis, however, did not model the impact of traffic volume on pavement service life. This is an important limitation to be noted. Lower traffic volume will reduce deterioration which ultimately impacts traffic congestion and roughness effects. Despite the limitation, it was useful to simulate traffic volume impacts for this unrealistic case.

Figure A.1 compares the life cycle energy consumption of 70000 AADT, 35000 AADT, and 10000 AADT cases for concrete and ECC overlay systems. Figure A.2 compares the life cycle cost of 70000 AADT, 35000 AADT, and 10000 AADT cases for concrete and ECC overlay systems. The lower traffic volume will diminish the material advantage of ECC. At 70000 AADT, ECC overlay can save 15% total life cycle energy consumption and 39% cost compared to concrete overlay system. At 35000 AADT, ECC overlay can save 9% total life cycle energy consumption and 29% cost compared to concrete overlay system. At 10000 AADT, ECC overlay can only save 5% total life cycle energy consumption and 21% cost compared to concrete overlay system. With lower traffic volume, material consumption and agency cost become the only dominant factors for life cycle energy consumption and cost, respectively.

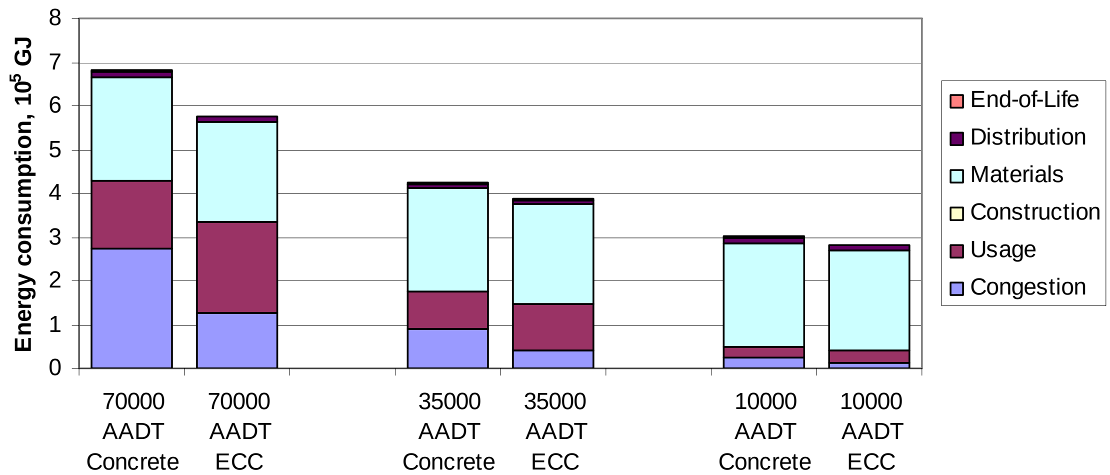

Figure A.1 Total life cycle energy consumption of different AADT cases for concrete and ECC overlay systems

(assumes preservation strategy is independent of traffic volume; this is an unrealistic case but it explores the effect of traffic volume on congestion and usage (e.g., roughness effects))

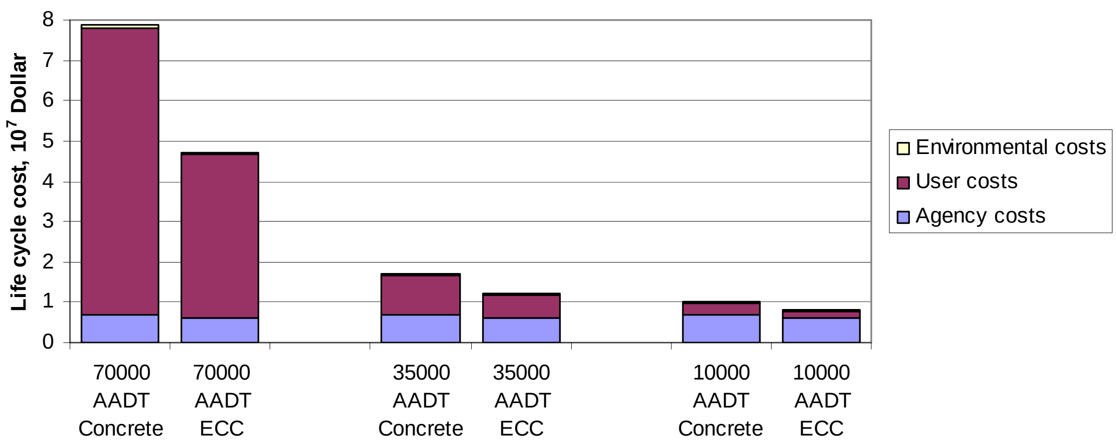

Figure A.2 Total life cycle cost of different AADT cases for concrete and ECC overlay systems

(assumes preservation strategy is independent of traffic volume; this is an unrealistic case but it explores the effect of traffic volume on congestion and usage (e.g., roughness effects))

APPENDIX B

DIFFERENT PAVEMENT CONDITION CONSTRAINTS

Currently, MDOT uses a threshold of DI of 50 to indicate the need for overlay reconstruction. The pavement asset management framework presented in this dissertation also uses DI<50 as a pavement condition constraint. Figure B.1 shows the optimal preservation strategies for an HMA overlay system based on different pavement condition constraints. With stricter pavement condition constraints, the maintenance frequency increases and the life cycle cost increases. The life cycle costs are $\$8.43\times10^7$, $\$9.23\times10^7$, and $\$1.08\times10^8$ for DI<50, DI<30, and DI<20 constraints, respectively.

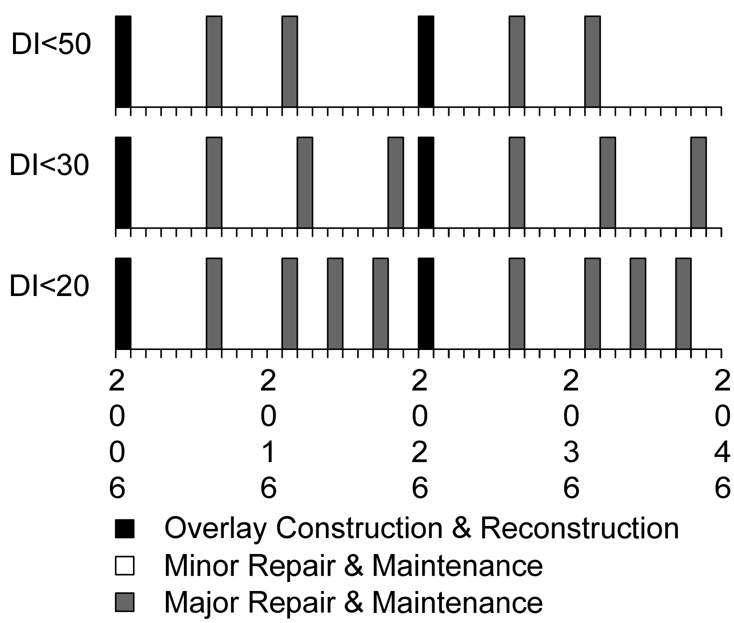

Figure B.1 Optimal preservation strategies for an HMA overlay system based on different pavement condition constraints

APPENDIX C

DIFFERENT ANALYSIS PERIODS

The original analysis period used in the project-level pavement asset management system was based on the overlay service life. For example, the expected service life and the analysis period for the ECC overlay system is 40 years. For the HMA overlay, the expected service life is 20 years. Here we explore the effects of a shorter analysis period (<20 years) with a fixed HMA service life of 20 years.

Figure C.1 shows the optimal preservation strategies and pavement performance for an HMA overlay using different analysis periods. The results show that a shorter analysis period changes the late maintenance activities but has less impact on the early maintenance activities. This result also shows that the optimization model is robust in identifying the optimal preservation strategy for most of an analysis period. At the late stage of the overlay service life, the DOT can estimate the remaining service life of its overlays project based on an inspection and evaluation of the overlay condition and develop an updated optimal strategy for the rest of overlay life.

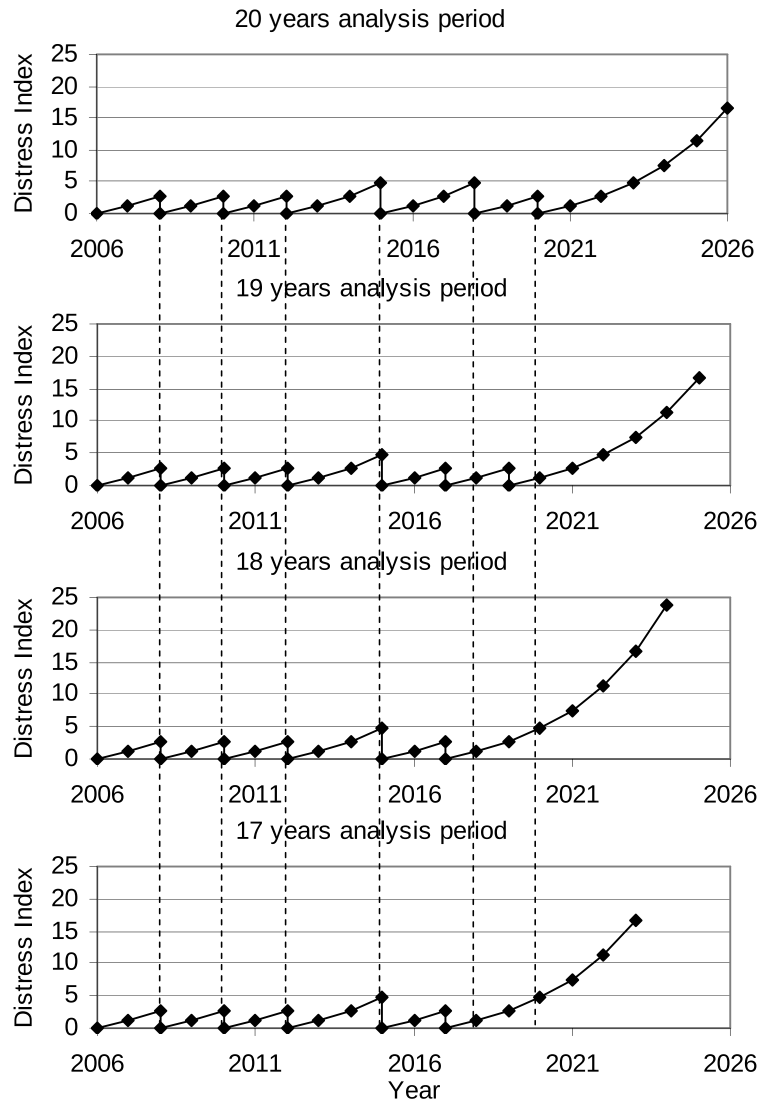

Figure C.1 Different optimal preservation strategies based on different analysis periods