Economic and Environmental Evaluations of Life Cycle Cost Analysis Practice: A Case Study of Michigan DOT Pavement Projects

by

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Abstract

This thesis investigated the economic and environmental aspects of Life-Cycle Cost Analysis (LCCA) practiced by Michigan Department of Transportation (MDOT). From the economic perspective, it analyzed MDOT's accuracy in projecting the actual costs over pavement service life and choosing the lowest-cost pavement alternative. The estimated and actual accumulated costs and maintenance schedules of ten highway sections were compared. From the environmental perspective, it incorporated pollution damage cost (an external cost element) which is currently overlooked by states DOT into LCCA. A life-cycle assessment model was developed to compare and monetize the environmental impact of asphalt and concrete pavement alternatives for thirteen MDOT projects.

While results indicated that MDOT LCCA procedure correctly predicted the pavement type with lower initial construction cost, actual costs were usually lower than estimated in the LCCA. This outcome was partly because the cost estimation module in MDOT's model was not site-specific enough. Refinements to its pavement construction and maintenance cost estimating procedures would assist MDOT in realizing the full potential of LCCA in identifying the lowest cost pavement alternative for the studied pavements. Alternatively, asphalt alternatives looked better than concrete alternatives in some environmental indicators (GHG, NO_x, SO_2 and Pb) but worse in others (energy, VOC and carcinogens), with material production as the major source of emissions. The pollution damage cost ranged from \$1,900-\$76,000/4-lanes-km, but the lowest-damage-cost alternative varied across projects. More importantly, it contributed to only 0.8% to 9.2% of total life-cycle costs, and did not alter the results recommended in the original MDOT LCCA documents. Further expansion of the external cost boundary would make it more significant in LCCA.

Acknowledgments

Table of Contents

List of Figures

List of Tables

Acronyms

Below is a list of acronyms that appeared frequently in this thesis report.

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphaltic concrete
ASCE	American Society for Civil Engineers
AORC	Asphalt on rubblized concrete
CO	Carbon monoxide
DOT	Department(s) of Transportation
FHWA	Federal Highway Administration
GHG	Greenhouse gases (e.g. carbon dioxide, methane and nitrous oxide)
HMA	Hot-mix asphalt
LCA	Life-cycle Assessment
LCCA	Life-cycle Cost Analysis
LCI	Life-cycle Inventory
MDOT	Michigan Department of Transportation
MUSES	Material Use: Science, Engineering and Society
NO_x	Nitrogen oxides
NSF	National Science Foundation
Pb	Lead
PM	Particulate matter ($<10\mu m$)
PCC	Portland cement concrete
VOC	Volatile organic compounds

1. Introduction

1.1 Sustainability of Road Infrastructure

Roads are one of the most important infrastructures in moving people and goods around the world. In the United States alone, more than 6.5 million kilometers of public roads are stretching across the country (FHWA 2006a) with values exceeding $2 trillion (BEA 2006). In spite of its vitality to the national economy, the extensive road infrastructure in the US poses a massive financial burden to the federal, state and local governments. Huge investments are made annually to maintain and improve their functions by expanding the network and carrying out routine maintenance and rehabilitation on existing road infrastructure.

Unfortunately, inadequate funding to maintain the road infrastructure has been observed. All levels of governments spend over $153 billion in highway-related activities every year, of which $75 billion represents capital outlays (FHWA 2006a). According to the American Association of State Highway and Transportation Officials (AASHTO), annual capital outlay spending should be increased by 42% and 94%, respectively, to maintain and improve the physical conditions of roads (ASCE 2005). The situation is expected to become more severe as many of the components of the interstate highways built in the 1960s under the Federal-aid Highway Act of 1956 approach the end of service life and need reconstruction. The failure to provide adequate funding to improve the substandard road conditions will lead to serious roadway safety and operational concerns and affect the national economy. Effective management of roadway investment becomes exceptionally important.

Besides the financial management issue, huge resource use and environmental impacts are associated with maintaining and expanding the road infrastructure. Over 1,500 million metric tons (Mt) of natural aggregates, 48 Mt of cement, 35 Mt of asphalt and 6 Mt of steel have been in use as of 2006 for the Interstate Highway System alone, which constitutes only 73,000 km out of 6.5 million km of the road network nationwide (USGS 2006). Portland cement is one of the major constituents in concrete pavement

(12-14% by weight), but cement production uses large amounts of electrical and thermal energy. It is also associated with significant emissions of carbon dioxide (CO_2), which is a greenhouse gas, during limestone calcination[1] and fuel combustion for kiln heat. In fact, cement production alone contributes to almost 5% of anthropogenic CO_2 emissions worldwide (WBCSD 2002). Also, the production process generates significant emissions of criteria air pollutants including nitrogen oxides, sulfur dioxide and particulates (ibid). Alternatively, one of the concerns of asphalt pavement is the emission of volatile organic compounds (VOC) and hazardous air pollutants. They result from the evaporation of petroleum distillate solvent used to liquefy the cutback asphalt in the process of application and curing (ERG 2001). These pollutants pose serious risks to both environmental and human health.

As the two major types of pavement, asphalt and concrete have been compared intensively in terms of life-cycle economic and environmental impacts. Research efforts have come from governments, academia, cement manufacturers, asphalt and concrete paving industries. Mixed results have been observed, with one type of pavement more favorable than the other in different studies. Many of these studies were widely cited by the asphalt and concrete paving industries. In terms of financial management, the Federal Highway Administration (FHWA) has been actively promoting the use of life-cycle cost analysis (LCCA) in the pavement selection process (mainly asphalt vs. concrete alternatives) as a way to achieve more efficient investment in road infrastructure.

1.2 Life-cycle Cost Analysis as an Asset Management Tool

Actively promoted by FHWA, life-cycle cost analysis (LCCA) has become a common practice in road construction at the state level during the past decade in the US. Many states' Departments of Transportation (DOT), including Michigan DOT, have incorporated LCCA into their respective pavement selection processes. LCCA provides an analytical framework that goes beyond the upcoming construction event. It evaluates

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[1] Calcination is the process of converting limestone (calcium carbonate) to calcium oxide. It accounts for over 60% of total CO_2 emissions in cement production. The chemical reaction is an unavoidable process, thus the industry has focused on reducing the CO_2 emissions through energy use

not only the initial construction costs of pavement, but also all the associated maintenance costs over the course of the pavement service life (life cycle). By conducting a comprehensive assessment of long-term costs, it enables pavement engineers to select the pavement alternative that has the lowest life-cycle costs. Hence, agency highway funding can be allocated more optimally in the long run. Because FHWA does not prescribe specific forms for LCCA, states apply LCCA at various levels from brief instructional guidelines to well-established procedures (ERES 2003, Ozbay et al 2004).

In practice, most applications of LCCA focused primarily on assessing the direct economic costs incurred by the government agency on road construction, and sometimes the social costs to the road user. While sustainability requires the balance of economic, social and environmental issues, the environmental elements are totally left out by LCCA. Yet, pavement engineers in states DOTs are well aware of the need to incorporate these elements into the LCCA (MDOT 2006).

More importantly, the full contribution of LCCA to the asset management process is based upon accurate estimation of the initial and future pavement costs and performance. This is a challenging task to pavement engineers as there are often uncertainties over future pavement performance and maintenance needs.

1.3 Thesis Objectives

The research that leads to this thesis is funded through the National Science Foundation (NSF) with a Materials Use: Science, Engineering, and Society (MUSES) grant. The objective of the MUSES program is to reduce "adverse human impact on the total, interactive system of resource use, as well as maximizing the efficient use of individual materials throughout their life cycles." (NSF 2004)

Based on the issues discussed in the previous section, this thesis dedicates two separate chapters looking into the economic and environmental aspects of LCCA

respectively. Realizing the differences of LCCA practices, pavement designs and pavement service life in different parts of the US, this thesis only focuses on the LCCA practice in the pavement selection process of Michigan Department of Transportation (MDOT). To investigate the economic aspect of LCCA, Chapter 4 analyzes MDOT's accuracy in projecting the actual costs over pavement service life and choosing the lowest-cost pavement alternative. The analyses are expected to provide useful insights and guidance on the actual application of LCCA for road infrastructure management.

To explore the environmental implications of LCCA, Chapter 5 compares the environmental impacts of proposed asphalt and concrete pavement alternatives in thirteen Michigan highway projects. Estimates on pollution damage costs (one of the external costs) of pavement alternatives are computed by benefit transfers and matched against the agency and user costs currently considered in MDOT LCCA procedure. The analyses would indicate the importance of incorporating external costs into current LCCA practices. In both chapters, actual Michigan highway projects are utilized to help analyze the problem.

2. Background and Literature Review

2.1 Road Infrastructure in the US

Road infrastructure is one of the prominent land covers in the US. According to Highway Statistics series (FHWA 2006a), there are over 6.5 million km of public roads stretching across the US. About 0.14 million km of them are designated as the National Highway Systems, including the 73,000 km of Interstate Highways (Figure 1). Most of the mileages are owned and managed by counties, townships and municipalities (77%). States highway agencies own another 20%, while federal agencies have possession of merely 3% of public roads mainly in national forests, parks and reservations (ibid). In terms of pavement surface type, over 83% of paved roads are paved with asphalt, and the rest are in composite[2] (11%) or concrete (6%). If only the Interstate highway systems are counted, there is a higher percentage of roads with concrete pavement (30%) (ibid).
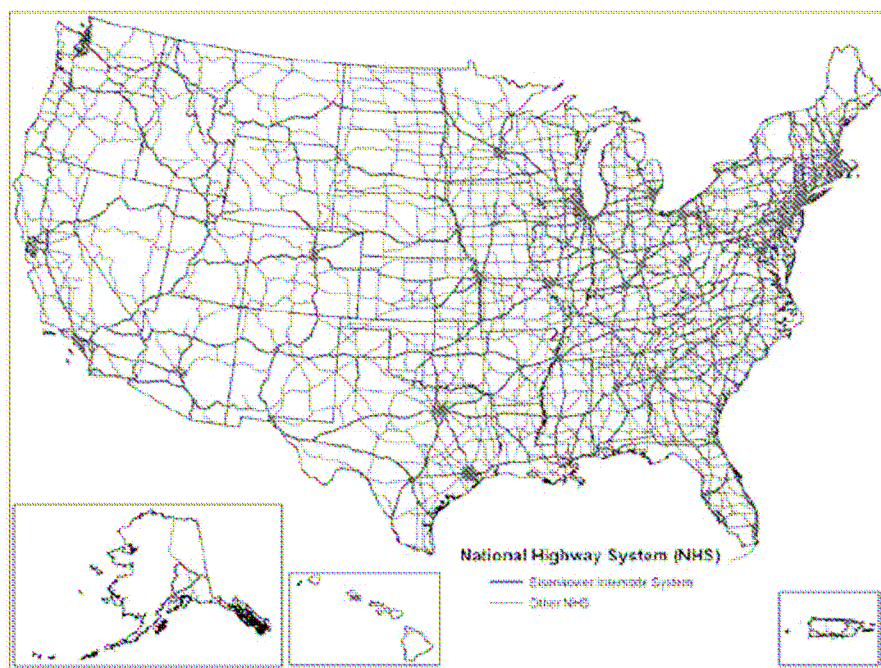
Figure 1: Map showing the National Highway System.
Interstate highways are drawn in darker grey. (FHWA 2006b)

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[2] Composite-- a mixed bituminous or bituminous penetration roadway of more than 1" compacted material on a rigid base (Portland cement concrete) with a combined surface and base thickness of 7" or more (FHWA 2006a)

The extensive road infrastructure in the United States has become a massive financial responsibility for the federal, state and local governments. Every year, all levels of governments spend over $150 billion in highway-related activities, of which $75 billion represents capital outlays (FHWA 2006a). Nonetheless, the American Association of State Highway and Transportation Officials (AASHTO) advises that annual capital outlay spending should be increased by 42% and 94%, respectively, in order to maintain and improve the physical conditions of roads (ASCE 2005). In fact, more than one-third of major roads in the US are in poor or mediocre condition (TRIP 2006). That includes more than 11,000 miles of National Highway Systems pavements (FHWA 2004). Also, the road infrastructure was graded "D" and listed as the top infrastructure concern in the US in the latest Report Card released by the American Society of Civil Engineers (ASCE) (ASCE 2005). The situation is expected to become more severe as many of the components of the interstate highways built in the 1960s under the Federal-aid Highway Act of 1956 approach the end of service life and need reconstruction.

The failure to provide adequate funding to improve the substandard road conditions will lead to serious roadway safety and operational concerns and affect the national economy. It was estimated that poor road conditions in the US cost road users $54 billion annually in extra vehicle repairs and operating costs, which is equivalent to around $275 per road user (ASCE 2005). In addition, motor vehicle accidents cost another $230 billion every year (ibid). Effective management of road infrastructure becomes crucial from the investment standpoint as well as national economy and public safety standpoint.

2.2 LCCA and its Development

Federal Highway Administration (FHWA) has been actively promoting life-cycle cost analysis (LCCA) as an asset management tool to explore the possibility for more efficient investment in road infrastructure. Life-cycle cost, by definition, means "the total cost of the initial project plus all anticipated costs for subsequent maintenance, repair, or resurfacing over the life of the pavement" (Michigan legislation PA 79 of

1997). As a result, when used in the pavement selection process, pavement engineers are able to choose the pavement type and design with the lowest cost in the long run.

The concept of LCCA was first discussed in the 1960s in the AASHTO "Red Book" (Wilde et al 2001). Yet, it did not come into the legislation until the Inter-modal Surface Transportation Efficiency Act (ISTEA) of 1991[3]. ISTEA required consideration of "the use of life-cycle costs in the design and engineering of bridges, tunnels, or pavement". The National Highway System Designation Act of 1995 further imposed a new requirement making LCCA compulsory for National Highway System (NHS) projects costing more than $25 million. The requirement was annulled under Transportation Equity Act for the 21st Century (TEA-21) in 1998, but FHWA and AASHTO remain active in assisting the states in developing their own LCCA procedures. Life-cycle costs must still be considered as part of the FHWA's Value Engineering process for NHS projects costing more than $25 million (see 23 CFR Part 627). States including Michigan have enacted similar legislations in the past decade as well.

In general, life-cycle cost of pavement is usually categorized into three major components: agency cost, user cost and external cost (Figure 2). Agency cost is the cost directly paid by the construction agency for the project, which includes the initial construction/rehabilitation and future maintenance costs of pavement. User costs are social costs incurred by the road users, which include user travel delay cost during construction, maintenance and rehabilitation events. External costs pertain to the remaining indirect costs incurred by the non-user public. Its boundary is not well-defined, but pollution damage cost, noise-pollution cost, agricultural crops damage from pollutants and visibility losses are examples of external costs. Basically, they are referred to "externalities" of road construction that are not reflected in market prices but incurred by the non-user public.

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[3] The current highway-related funding at the federal level is authorized under the "Safety, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU)". It was signed into law by the President on Aug 10, 2005, and replaced the Transportation Equity Act for the 21st Century (TEA-21) of 1998. SAFETEA-LU guaranteed funding for highways, highway safety and public transportation totaling $244 billion through FY 2009
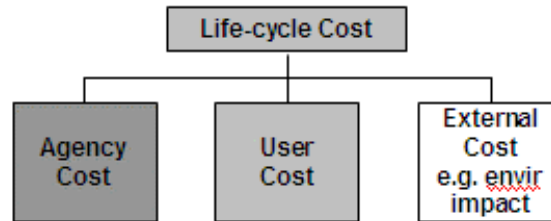
Figure 2: LCCA framework for pavement-type selection
(Darker boxes represent elements more emphasized by states DOTs)

FHWA does not prescribe specific forms for LCCA, but provides guidance to states through publications such as the "Life-Cycle Cost Analysis in Pavement Design" Interim Technical Bulletin (FHWA 1998) and the "Life Cycle Cost Analysis Primer" (FHWA 2002) and by organizing workshops. FHWA also provides the "RealCost" LCCA software with a User Manual, but the use of this software is at the discretion of each state. Accordingly, states apply LCCA at various levels and often use state-developed methods and tools. Different estimation methods are used. In fact, the LCCA procedure of states DOTs varies from brief instructional guidelines to well-established procedures (ERES 2003, Ozbay et al 2004).

Literature review and interviews with states DOT officials indicated that over 80% of the states carry out LCCA in the pavement selection process, at least for some projects (Appendix VI). While all of them consider initial construction and future rehabilitation costs (agency cost), only 70% and 40% of them incorporate routine maintenance cost (agency cost) and user costs associated with maintenance activities (e.g., user delay at work zones), respectively (Figure 3). External cost such as environmental damage cost is not considered by any state. User cost is more likely to be considered in the more densely populated states or urban areas where user delay cost is more significant. States DOTs use slightly different analysis periods and discount rates as well (Wilde et al 2001, Ozbay et al 2004). Figure 3 provides a general picture of the different components considered by states DOTs in LCCA as part of pavement selection as of September 2006.

When both agency cost and user cost are considered, agency cost is usually dominant for road projects with low traffic volume. However, as revealed by the 150 plus MDOT LCCA documents, the magnitude of user cost can be comparable to that of agency cost if the volume of traffic reaches 40,000 AADT (average annual daily traffic) for a 4-lane divided freeway.
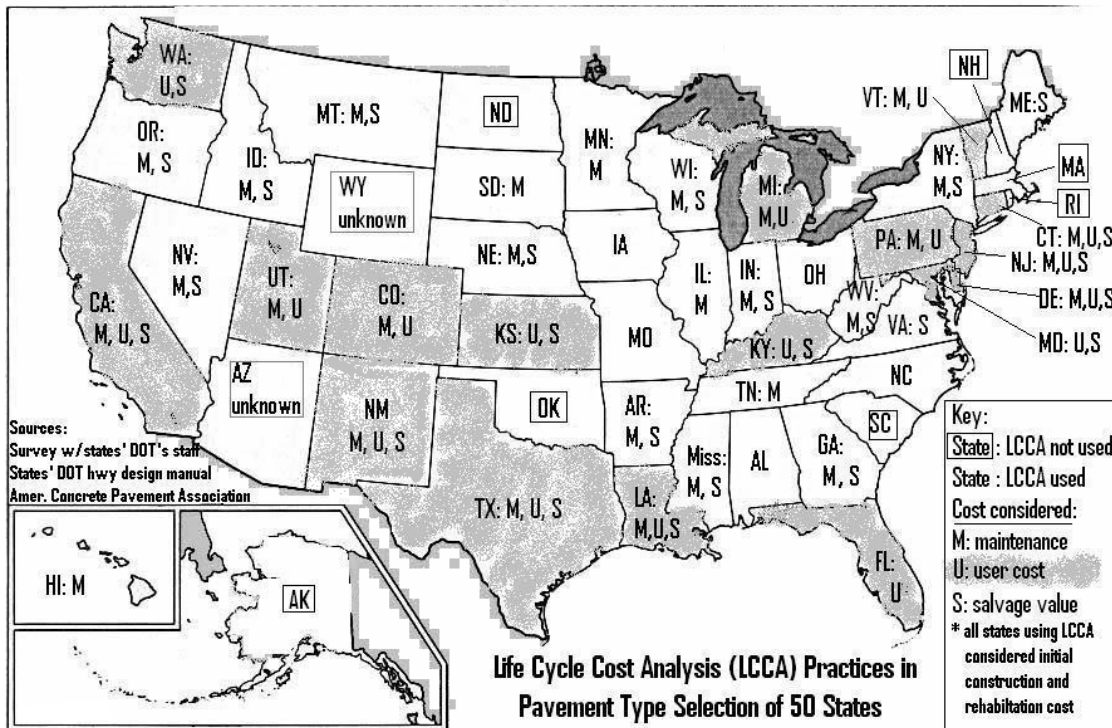
Figure 3: Life-cycle cost analysis practices in pavement type selection in the US (As of September 2006)

2.3 Previous Research

Life-cycle costs and environmental impact between asphalt and concrete pavements is a hotly debated topic. Both the asphalt and concrete industries have strongly argued that their products last longer and cost less in the long run than the other. Both industries often cite and publish links to studies that favor their "claims" and disvalue the others as "noise".

Several empirical studies have compared the actual life-cycle cost of asphalt and concrete pavements in various states. Embacher et al (2001) have studied the life-cycle costs of a number of low-volume roads in Olmsted and Waseca Counties in Minnesota. The author concluded that Portland cement concrete (PCC) pavement is generally more cost-effective than hot-mix asphalt (HMA) pavement if costs are normalized for traffic volumes, and PCC pavement has significantly lower maintenance costs over the pavement service life than HMA pavement. A more comprehensive study was done in Michigan as well. Snook et al (1998) compared the overall costs of 1,900 lane miles of asphalt and concrete pavements along Michigan routes, US routes and interstate highways for the past 80 years. It demonstrated that concrete pavements in Michigan were generally much cheaper than asphalt ones for rehabilitation and reconstruction projects ($2,400 vs. $1,300 per lane-mile year in 1997 dollars). The study was submitted to Michigan Concrete Paving Association and American Concrete Paving Association.

Contrasting results appeared for rural interstate highways in Kansas (Cross et al 2002). Life-cycle costs of PCC pavements were found 80% higher than HMA pavements ($1.25 million per 4-lane mile in 2001 dollars, 35 years). In addition to that, while PCC pavements had lower annual maintenance costs for the first 15 years of service life, their annual expenditures reached as much as 2.4 times that of HMA pavement for the next 20 years. Villacres (2005) cited Cross et al's (2002) and a few other studies in Iowa and Ohio. The author then asserted that HMA pavements were overall more economical than PCC pavements without acknowledging any studies that suggested otherwise. These studies, along with others not discussed in this section, can be found at the Asphalt Pavement Alliance website (http://www.asphaltalliance.com/library.asp?MENU=543). Appendix III contains a leaflet endorsed by Minnesota Asphalt Pavement Association and Dakota Asphalt Pavement Association Inc.

The 150 plus MDOT LCCA files provided more microscopic details: PCC pavement was the lowest-cost alternative for 60% of road projects, while the rest were HMA pavements. PCC pavements tended to be more economical in the long run for roadways with really high traffic volumes. Variations in pavement designs, preservation

strategy and cost estimation methodology across states over time may explain the different results shown in these papers. More importantly, climate can play a major role in affecting the performance of pavement alternatives, as Minnesota and Kansas are located in different climate zones.

There were also studies focused on the LCCA practice itself. Numerous surveys were conducted on the nationwide LCCA practices and wide range of practices developed by different states DOTs were realized (ERES 2003, Ozbay et al 2004) as discussed in Section 2.2. Other studies have attempted to make LCCA model more comprehensive and accurate. For example, sophisticated models to estimate user costs (Carr 2000, NJDOT 1999, Wilde et al 2001) have been developed, although they are not used by many state DOTs. Uncertainties in LCCA parameters can be incorporated into LCCA by using probabilistic models (Gerke et al 1998, FHWA 1998, Herold 2000), yet deterministic models (i.e., models that do not model risk and variability) are mostly adopted by state DOTs, including MDOT. However, the literature is limited in examining how LCCA is actually applied by states DOT and how effective their respective LCCA procedures are in projecting the pavement type or design with the lowest life-cycle cost. Chapter 4 of this thesis attempts to answer these questions for the case of MDOT.

Awareness of the environmental aspect of road construction is on the rise as well. Wilde et al (2002) has proposed a comprehensive LCCA framework for Portland cement concrete pavements that includes external cost such as environmental damage cost. Environmental impact is in fact one of the discussion topics at the LCCA peer exchange, a meeting of which many states come together and discuss a broad range of topics concerning LCCA (MDOT 2006). In the field of comparative assessment between pavement alternatives, Stripple (2000, 2001) carried out a life-cycle assessment on asphalt and concrete pavement alternatives in Europe, and concluded that 37% more energy was consumed for concrete than asphalt pavement. In contrast, Horvath et al (1998) studied the environmental implications of asphalt and steel-reinforced concrete pavements (CRCP) in the US with an economic input-output life cycle assessment (EIO-

LCA) approach[4]. Their study, however, suggested that asphalt and concrete pavements have similar resource input requirements and environmental impacts when no recycled material is used. The variation is the result of the difference in system boundaries considered in their analyses (See Chapter 5.5). It can also be due to the differences in material processing requirements and road designs between Europe and the US. Chapter 5 of this thesis will apply the life-cycle assessment (LCA) framework in comparing the asphalt and concrete pavement alternatives for Michigan pavement projects.

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[4] The approach was developed by the Green Design Initiative (GDI) of Carnegie Mellon University. It uses the 491x491 economic input–output matrix (commodity-by-commodity) of the US economy to identify the entire chain of both direct and indirect suppliers to a commodity (GDI 2006)

3. Life-cycle Cost Analysis Practice of Michigan DOT

3.1 The History and Development

Michigan DOT has a long history of using life-cycle cost analysis (LCCA) in its daily operations. MDOT first utilized LCCA as part of its pavement selection in a highway project in 1985 (EOC 1985). In the late 1980s and early 1990s, LCCA was used in selecting pavement type for more highway projects, and an "Ad-hoc Life-cycle Costing Task Group" was formed to make recommendations on better incorporating LCCA into the pavement selection process.

Nevertheless, LCCA was not a mandatory requirement in all multi-million dollar road projects until 1998. In 1997, state legislation PA 79 of 1997 stated that "the department shall develop and implement a life cycle cost analysis for each project for which total pavement costs exceed one million dollars funded in whole, or in part, with state funds. The department shall design and award paving projects utilizing material having the lowest life cycle costs. All pavement design life shall ensure that state funds are utilized as efficiently as possible." In response, MDOT revised its pavement selection policy in 1998. According to its "Pavement Design and Selection Manual", all projects with paving costs greater than one million dollars have to carry out LCCA in the design stage (MDOT 2005). Therefore, new construction, reconstruction and rehabilitation events[5] on the major Michigan trunklines generally require LCCA. Prior to 1998, MDOT carried out LCCA for about 30 road projects (the source of the four case studies selected for Chapter 4 of this thesis). The number has almost tripled since then. Unfortunately, this requirement applies only to the 9,700 miles of MDOT-managed National Highway System and the State Trunkline system highways within the state boundary. This requirement does not extend to roads owned by county and city governments nor local projects receiving federal and state funding (ibid).

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[5] Rehabilitation refers to "structural enhancements that extend service life of an existing pavement and/or improve its loading carrying capacity. Rehabilitation techniques include restoration treatments and structural overlays" (FHWA 2005). Construction or reconstruction refers to building a whole new pavement from base to surface.

3.2 Components of the Deterministic LCCA Model Used by MDOT

MDOT's pavement selection procedure requires evaluating the life-cycle costs of both concrete and asphalt alternatives. Different pavement design alternatives are based on the 1993 AASHTO "Guide for Design of Pavement Structures", and life-cycle costs are calculated for these designs. After several reviews and modifications, the Engineering Operations Committee, which is the senior technical committee in MDOT, approves the pavement alternative that has the lowest life-cycle cost for a project. Appendix I describes the whole MDOT pavement selection process in detail.

MDOT is one of the many states that include initial and future agency and user costs in their LCCA. The basic analysis unit of MDOT LCCA includes a one-mile (1.6km) road section without crossovers, underpasses or ramps. It is a common practice among state DOTs that environmental damage cost is not considered, partly because environmental impacts are addressed separately as part of the National Environmental Policy Act (NEPA) process. Agency cost includes initial construction/rehabilitation and future maintenance costs. Only work items with varying cost between alternatives are considered. These include mainline pavement and shoulder materials, joints, sub-base, aggregate base, future pavement repairs, underdrains and traffic control devices (Figure 4). The future pavement preservation strategy and the unit prices of work items are estimated based on historical MDOT project data, and the plan quantity of each work item is site-specific (MDOT 2005). User costs include user travel delay cost incurred during construction, maintenance and rehabilitation events. Construction Congestion Costs (CO3), a program developed by Carr at the University of Michigan, is used by MDOT to compute the user delay cost at initial construction phase, while user costs during future maintenance activities are obtained from tabulated data (ibid).

All costs are in "real" dollars (also called "constant" dollars), reflecting the purchasing power of dollars in the base year of the analysis. All future costs are converted to base-year present value by real discount rate and then annualized into per year equivalents. The discount rate is revised according to the rate published by the Federal Government's Office of Management and Budget (OMB) (ibid).

The analysis period depends on the nature of the project. For new construction events, the analysis period is 26-30 years, which is the expected service life of the new pavement with scheduled maintenance; for rehabilitation events, the period used is 20-21 years (MDOT 2005). It is somewhat different from FHWA recommendations, which suggest a >35-year analysis period to include at least one major rehabilitation event for each alternative being considered. Once an analysis period of a certain length is selected, however, MDOT uses it to evaluate all of the alternatives being considered for that project.
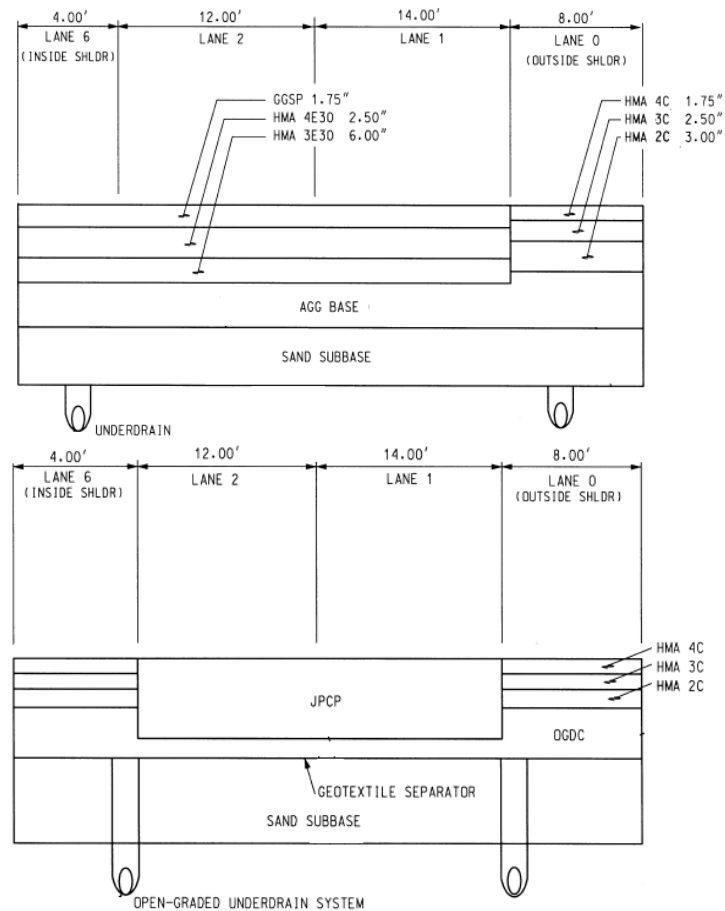
Figure 4: Typical cross-section of pavements
(Top: hot-mix asphalt "HMA" design, bottom: jointed plain concrete "JPCP" with asphalt "HMA" shoulder design)
(Drawings excerpted from MDOT Pavement Design and Selection Manual)

4. Evaluating the Actual Application of MDOT LCCA

4.1 Introduction

The effectiveness of LCCA in road infrastructure management depends on the accuracies on predicting future pavement performance and therefore maintenance schedules and costs. Literature is limited in reviewing the actual application of LCCA in choosing the lowest-cost alternative correctly. MDOT has incorporated LCCA into its pavement selection process for about 20 years. This study takes the opportunity to evaluate the effectiveness of its LCCA procedure as an asset management tool and provide an objective and quantitative assessment on the LCCA performance.

4.2 Case Studies Methodology

A case study approach was adopted. Figure 5 illustrates the general framework of the study, in which two aspects were considered. First, for each case, the actual accumulated costs of two different pavement types (A and B) were compared to determine if the LCCA method used by MDOT in the design stage correctly predicted the pavement type with the lowest life cycle cost. Second, the actual service-life costs and maintenance schedules were compared with the values estimated by LCCA to evaluate its accuracy in estimating these parameters.
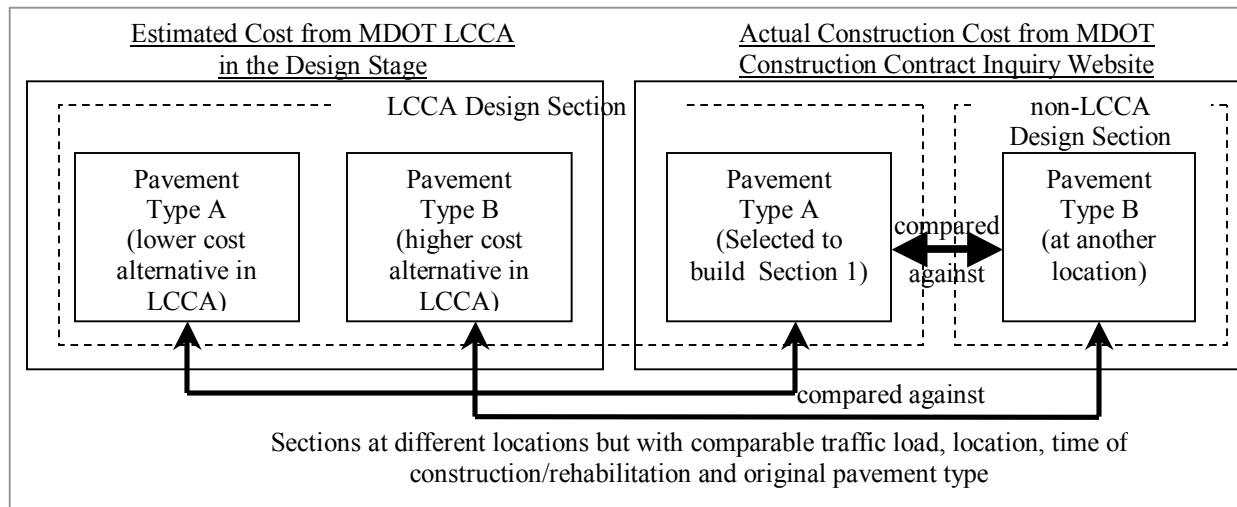
Figure 5: Diagram of study framework

Selection of Road Sections for Direct Comparison

In each case, at least two road sections with different pavement types (asphalt overlay, asphalt over rubblized concrete, or concrete) were chosen. The road section of interest (labeled "LCCA design section" in each case) was the one on which LCCA was carried out by MDOT in the design stage, and for which the pavement alternative with the lowest estimated cost (Type A) was eventually built (Table 1 and Figure 5). The other comparative road sections (termed "Non-LCCA design sections") are at similar locations, but were built with the alternative (Type B) that would have been the higher-cost alternative of the LCCA design section. LCCA was not conducted during the design stage for these sections, hence the "Non-LCCA design sections" designation. Because there are factors other than pavement type that would affect pavement condition and service life, the following factors were strictly controlled when selecting these comparable sections.

- Similar traffic load (±10,000 Average Annual Daily Traffic (AADT)). The data are collected from the MDOT Average Daily Traffic Map series.
- Located within the same or adjacent county so that the geology and climate are similar for both road sections.

17

- The time difference of the initial construction or rehabilitation events among road sections was within 5 years so that the similar construction technology or knowledge should have applied.

- Both road sections had the same original pavement type and similar pavement conditions before the construction/rehabilitation events.

Based on these criteria, four case studies were identified, consisting of a total of 10 highway sections among them. Three of them were rehabilitation projects and one was a reconstruction project. All of the studies pre-date 1998, when user costs were first incorporated into the MDOT LCCA process. The ten highway sections studied are located on I-94, US-131, I-96 and M-37 in the University Region and Southwest Region (Table 1 and Figure 6). It is assumed that in each case, if LCCA were carried out for the non-LCCA design sections, it would have yielded the same LCCA estimates as the LCCA design section.

Table 1: **Road segments selected for case studies**

Road Section #	LCCA Design Section?	Control Section	Starting/ Ending Milepost	Section Length (km)	Surface Type	Initial Con/ Rehab Year (Project #)	Traffic Vol. (2004)
Case 1: I-94 (rehabilitation) [Jackson and Washtenaw County] 4 lanes divided, restricted access							
1	Y	38103	EB: 0-9.9, WB: 0-4.1	11.3	UCOV#	1995 (29582)	46000-49000
2	N	81104	6.14-11.98	9.3	asphalt overlay	1990 (28218)	50900-53000
Case 2: M-37 (reconstruction and widening) [Kent County] 4 lanes divided							
1	Y	41031	8.42-10.70	3.6	asphalt	1997 (34695)	27800
2	N*	41031	6.28-8.42	3.4	concrete w/asphalt shoulder	1996 (34694)	27400
Case 3: US-131 (rehabilitation) [Allegan County] 4 lanes divided, restricted access							
1	Y	3112	3.07-8.56	8.8	AORC^	1993 (28143)	28900-30300
2	N	3112	8.6-16.17	12.1	asphalt overlay	1989 (26713/28525)	29700-36400
Case 4: I-96 (rehabilitation) [Eaton and Ingham County] 4 lanes divided, restricted access							
1	Y	23151/ 33083/ 33084	23151: 0-2.86, 33083: 0-3.69, 33084: 0-2.97	16.9	AORC^	1995 (29581)	32100-55300
2	Y**	33084	8.89-11.49	13.9	AORC^	1993 (28213)	48700
3	N	33084	3.67-8.89	8.4	asphalt overlay	1987 (25203)	50700
4	N	33085	0-2.65	4.3	asphalt overlay	1989 (26758)	50800
* LCCA was carried out for this section, but the estimated higher-cost alternative (concrete) was built. ^ AORC: Asphalt on Rubblized Concrete, # UCOV: Unbonded Concrete Overlay ** LCCA was not carried out for this section, but the lower-cost alternative was built.							
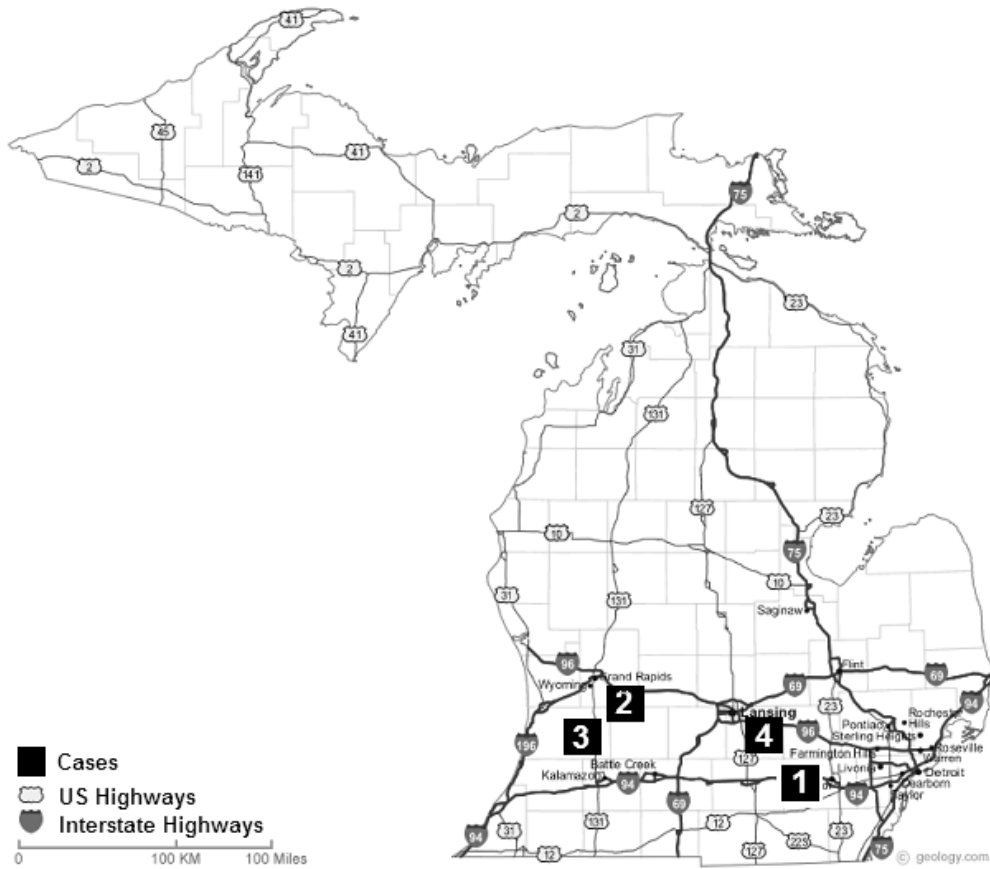
Figure 6: Location of selected road sections for case studies
      (Original map provided by www.geology.com)

Data Collection

      For each road section, actual initial construction & maintenance costs and maintenance schedule data related to the mainline and shoulder were collected. Such "accumulated" costs were transformed to 2005 dollars using Michigan Surface Index and were presented on a "per kilometer" basis. The actual construction and maintenance costs were collected from the finalized construction contracts, while actual maintenance schedules were obtained from databases managed by MDOT staff. Construction contracts before mid-1990s were obtained from microfilms in MDOT Construction & Technology (C&T) complex and the State Record Center in Lansing. Later construction contracts were downloaded from MDOT Construction Contract Inquiry Website (http://mdotwas1.mdot.state.mi.us/public/trnsport/). For the road projects with LCCA

estimates, the cost estimations were obtained from LCCA documents located in the MDOT C&T complex.

4.3 Findings and Discussions

Figure 7a-d depict the estimated and actual cost increments and maintenance activities for the selected road sections since construction. The cost estimating procedure used to inform the MDOT LCCA was able to predict the pavement alternative with lower initial construction costs, but the actual costs of each alternative were over-estimated in most cases. While the actual occurrence of maintenance events on some road sections roughly followed the estimated schedules, the actual maintenance procedures carried out (e.g. micro-surfacing, joint repair) were rather different from the estimation. Such observation could explain the reason that MDOT no longer specifies particular types of future maintenance events in their post-1998 LCCA documents.
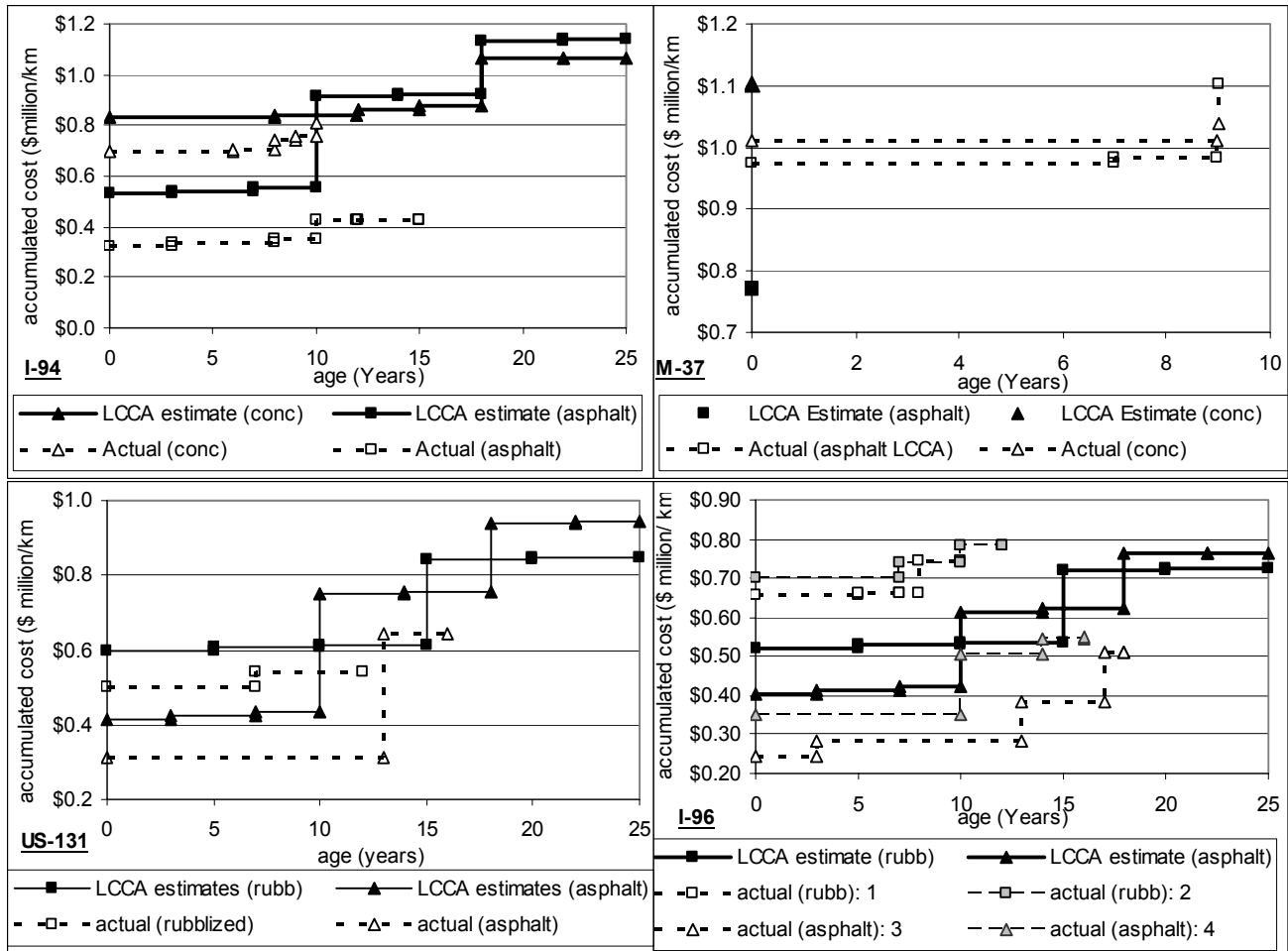
Figure 7a-d: Estimated vs. actual cost accumulations over pavement service life for I-94, M-37, US-131 and I-96 sections (From left to right, top to bottom)

Case 1: Rehabilitation on I-94: concrete overlay vs. asphalt overlay over existing concrete

The LCCA design section was rehabilitated in 1995 using an unbonded Portland cement concrete (PCC) overlay (estimated lowest-cost alternative) while the non-LCCA section was rehabilitated with an asphaltic concrete (AC) overlay in 1990. The LCCA PCC section required maintenance sooner than expected in the LCCA, while the actual maintenance timeline of the non-LCCA AC section was similar to that which would have been estimated (Figure 7a). The actual initial construction cost (in 2005 dollars) of the

22

LCCA PCC section ($0.70 million/km) was 16% less than had been projected in the LCCA ($0.83 million/km), while that of the non-LCCA AC section ($0.32 million/km) was 40% lower than the cost estimation for the AC alternative in the LCCA ($0.53 million/km). More importantly, the assumption in the LCCA that the cost of AC rehabilitation in year 10 would cause the accumulated cost of AC alternative to begin to exceed the accumulated cost of the PCC alternative is not borne out by the actual results of the non-LCCA section. The "mill and recycling" event on the non-LCCA AC section at year 10 cost only 20% of what had been estimated for the AC alternative in the LCCA.

In point of fact, then, the actual accumulated cost of the non-LCCA AC section has been lower than that of the LCCA PCC section to date. The source of error in the LCCA findings seems to be largely attributable to the disproportionate overestimation of the costs of AC overlay relative to the cost of the unbonded PCC overlay. The reason for poorer performance of the LCCA PCC section compared to the non-LCCA AC section is uncertain. Traffic loading on the non-LCCA section (51,000-53,000 AADT in 2004) was actually higher than that of the LCCA section (46,000-49,000 AADT in 2004). As noted, estimates for the costs both materials (PCC and AC) considered in the LCCA were too high. Over-estimation of initial construction cost of the unbonded PCC overlay in the LCCA section is partly due to the over-estimation of the quantity of PCC needed in road and shoulder construction, underdrains, joint repair and concrete repair (Figure 8a). While the quantity of concrete used in road and should construction is only around 15% less than estimated, underdrains and other items are as much as 90% lower. For the non-LCCA AC section, the estimated and actual asphalt consumption are about the same (Figure 8b), but the actual weighted-average unit price for asphalt (~$34/tonne in 2005 dollars) (tonne = 10^3 kg) is at least 35% less than estimated when the LCCA was conducted (~$54/tonne). Given that the to-date accumulated cost of the non-LCCA AC section is half that of the LCCA section, it is quite possible that unbonded PCC overlay will not turn out to have been the actual lowest-cost alternative by the end of service life for this particular highway. This possibility does not mean, of course, that the AC overlay is inherently more cost effective than the unbonded PCC overlay, but only that in this instance the former may have been the lower cost application.

It is also important to note that the discrepancy in the LCCA estimates versus the actual accumulated costs to date does not mean that LCCA did not work as a methodology in this example. Rather, the cost estimate used in the LCCA for the AC section should be reviewed to see why it was so high. If a cause can be found, this should be corrected so that later analyses could be more accurate. Similarly, the PCC overlay should be studied to see why it did not perform as estimated by MDOT historical maintenance data when the LCCA was conducted.
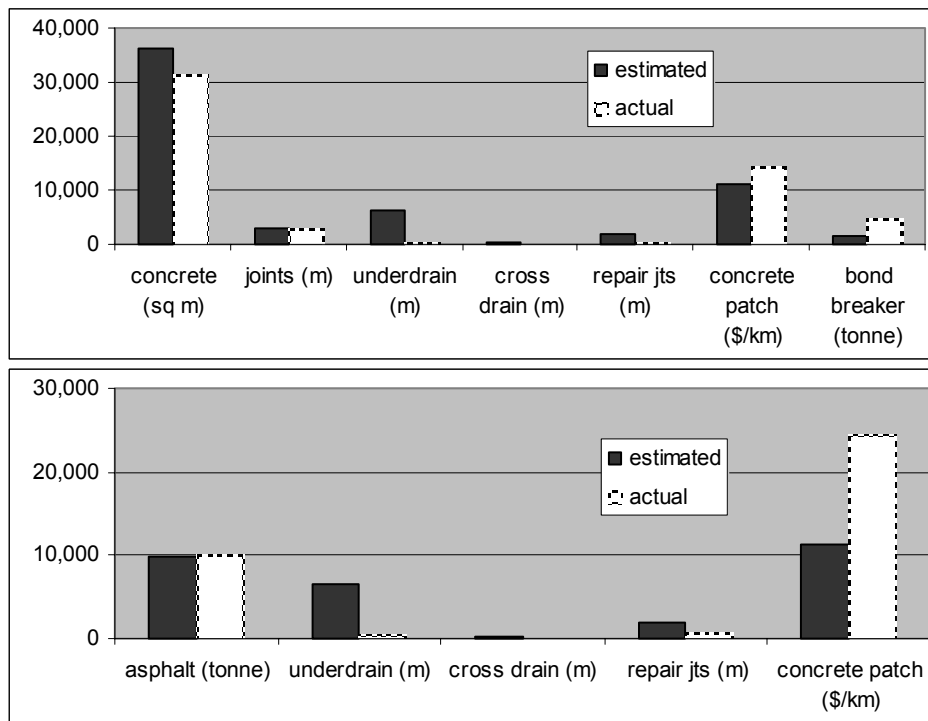
Figure 8a-b: I-94: Estimated vs. actual material use in initial construction phase for the LCCA design section (unbonded Portland cement concrete overlay) and non-LCCA design section (asphalt overlay) (Top to bottom)

Case 2: Reconstruction and Widening of M-37: asphalt vs. concrete

Two M-37 sections were reconstructed in 1997 and 1996 respectively, adjacent to each other south of Grand Rapids. LCCA was carried out for both sections. The former section was built with the estimated lowest-cost alternative (AC), while the latter was

built with the estimated highest-cost alternative (PCC mainline and AC shoulders). The reasons for this departure from recommended lowest-cost alternative are unclear.

Both sections have undergone one maintenance activity to-date. The AC section underwent crack-fill operations at year 7 and micro-surfacing project at year 9, while the PCC section received joint-sealing treatment at year 9 (Figure 7b). The MDOT LCCA predicted that the life-cycle cost of AC pavement would never exceed the initial construction cost of concrete pavement for this particular section. After the completion of the micro-surfacing project on the asphalt section, however, its accumulated cost surpassed the accumulated cost of the PCC section (Figure 7b). In terms of initial construction costs, the difference between the AC ($0.98 million/km) and the PCC sections ($1.01 million/km) was much smaller than was estimated (AC: $0.77 million/km; PCC: $1.10 million/km). This is partly because less PCC (for mainline pavement) and AC (for shoulder) were used in the PCC section, while more than the estimated materials were consumed in the AC section (Figure 9a-b).

A longer time frame is needed to study if the life-cycle cost of the AC section will actually be lower than that of the PCC section. AC pavements usually receive more maintenance over their life cycle and thus have higher maintenance costs than PCC pavements. Unfortunately, the original LCCA documents for both the AC and PCC sections only provide a lump sum future maintenance cost. The future maintenance schedule is therefore not available for comparison.

Again, the LCCA method will only be as accurate as the cost estimates entered into it. In this particular example, our review of the LCCA would have benefited from more documentation of the process, including the assumptions made about future maintenance costs and an explanation how the LCCA results supported the selection of two different designs.
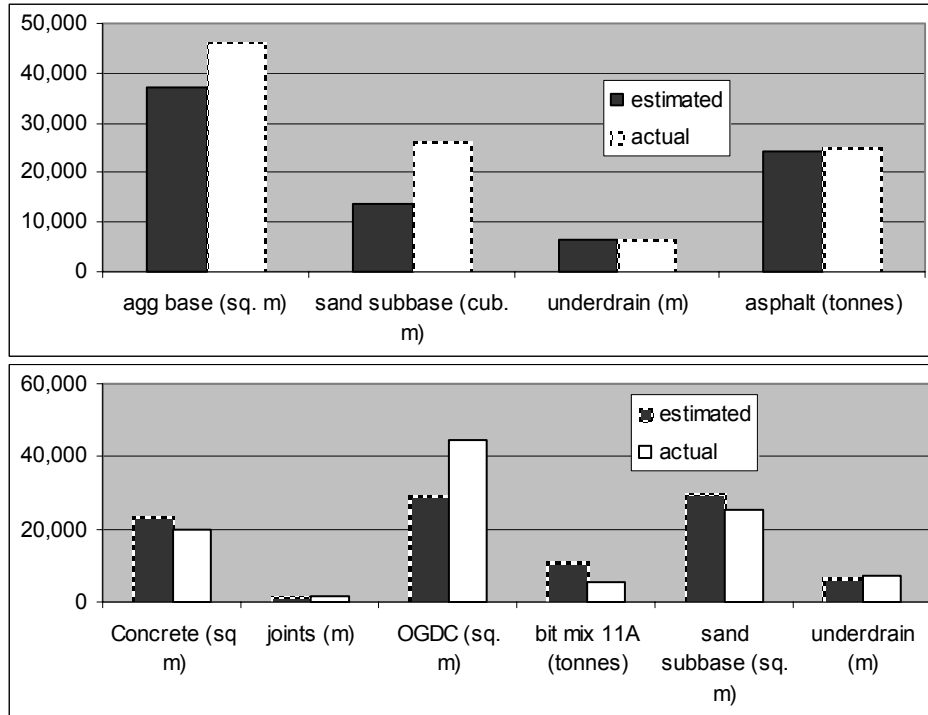
Figure 9a-b: M-37: Estimated vs. actual material use in initial construction phase for the asphalt section and the Portland cement concrete section (Top to bottom)

Case 3: Rehab of US-131: AC overlay on rubblized concrete (AORC) vs. AC overlay over existing concrete

The original PCC pavement in the LCCA design section was rubblized and overlaid with AC (the estimated lowest-cost alternative) in 1993, whereas the non-LCCA section was rehabilitated only with an AC overlay after repairs to the original PCC pavement in 1989. Both sections went through fewer maintenance events than estimated, although the actual maintenance costs per event were higher than estimated for the LCCA section (Figure 7c). The first actual resurfacing event for the non-LCCA AC overlay section was carried out at the age of 13, but would have been estimated to be carried out in year 10 in the assumptions used in the LCCA. The traffic loadings of both sections (LCCA: 28,900-30,300 AADT, non-LCCA: 29,700-36,400 AADT) in 2004 were close to the projections assumed in the LCCA (32,000 AADT). Some other factors may contribute to the difference in maintenance needs.

26

The actual initial construction cost of the LCCA rubblized section ($0.50 million/km) was higher than that of the non-LCCA asphalt section ($0.31 million/km), confirming the estimate in the LCCA that AORC would be more expensive than an AC overlay initially. However, the estimated figures of both pavement types were around $0.10 million/km higher than actual costs (Figure 7c). For the LCCA section, less concrete was rubblized (Figure 10a) than estimated in the LCCA exercise, and the weighted-average unit price of AC layer was 20% cheaper ($40/tonne vs. $48.5/tonne) than estimated. For the non-LCCA section, fewer concrete substrate repair operations were done than estimated (Figure 10b) and the unit price for asphalt was 10% lower than the engineering estimate that informed the LCCA would have estimated. Maintenance activities for the LCCA section were less frequent, but the crack fill operation at the age of 7 was more expensive than the sum of expected maintenance ($45,400/km vs. $15,500/km in 2005 dollar) for this section. The actual to-date maintenance cost of the non-LCCA section ($0.33 million/km) is similar to that which had been estimated for the LCCA, although the present value of this maintenance event as of year 0 would be less than originally estimated due to its being deferred by 3 years, from year 10 (estimated for the LCCA exercise) to year 13 (actual).

As no major maintenance is scheduled on the LCCA rubblized section in 2006, the accumulated constant dollar cost of the non-LCCA section would begin to exceed that of the LCCA section (as of this point, however, the present value of cost comparison between the non-LCCA section and the LCCA section would still favor the non-LCCA section at a 3% real discount rate). In this case, it seems that the pavements are following the maintenance schedules estimated in the LCCA documents. In addition, LCCA estimated that the final accumulated constant dollar cost of AC overlay would exceed that of AORC after the age of 18. While the relative cost trends are conforming to those projected in the LCCA, it is too early to conclude that AORC chosen by LCCA is the actual lowest cost alternative for this particular highway section, particularly with regard to the present value of costs of the section's life cycle.
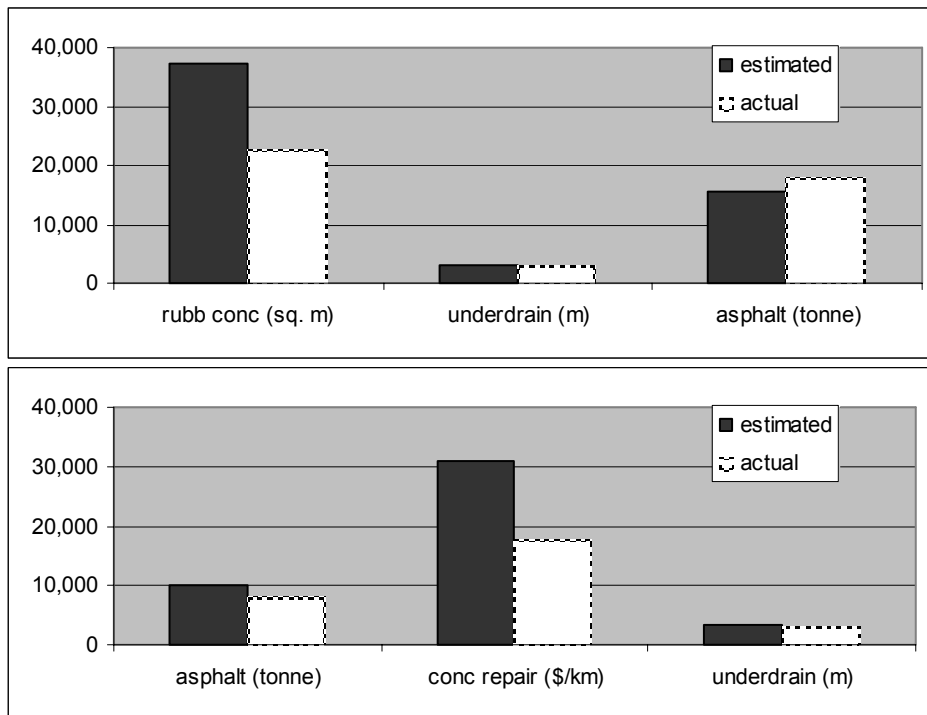
Figure 10a-b: US-131: Estimated vs. actual material use in initial construction phase for the LCCA design section (asphalt overlay over rubblized concrete) and non-LCCA design section (asphalt overlay) (Top to Bottom)

Case 4: Rehabilitation of I-96: AORC vs. AC overlay over existing concrete

Four sections were chosen on I-96 around Lansing. Two LCCA design sections were rehabilitated with AORC (estimated lowest-cost alternative) in 1995 and 1993 respectively, while the non-LCCA design sections were rehabilitated with an asphalt overlay in 1987 and 1989 correspondingly. The two LCCA sections appear to be performing worse than expected, as they require more frequent maintenance activities and were more expensive to install (Figure 7d).

The actual initial construction costs of both LCCA AORC sections (both around $0.68 million/km) were higher than those of both non-LCCA AC sections ($0.25 to $0.37

million/km). This finding supports the estimation used in the LCCA that AORC is more expensive than asphalt overlay in terms of initial construction cost. However, the costs of the two AORC pavements were underestimated by over 20% in the LCCA, in part because the weighted-average unit prices of asphalt were higher than expected. For the non-LCCA sections, actual initial costs were 15% to 40% lower than would have been estimated in the same LCCA exercise, which was contributed by less consumption of aggregate bases and underdrains during construction (Figure 11b). In terms of cost increments over time, the accumulated costs of the non-LCCA asphalt-overlay sections were increasing at a faster rate (4% to 6%/year) than the LCCA AORC sections (1%/year), which agrees with the expected trend. However, to-date maintenance costs for both LCCA sections ($0.08 to $0.09 million/km) were much higher than expected ($16,200/km) since more frequent maintenance were carried out. In addition to the crack-fill operations estimated in LCCA, micro-surfacing events (~$74,600/km) were also carried out. The situation is similar for the non-LCCA sections. Despite the costs of minor maintenance events (crack fill) being lower than would have been estimated using LCCA, the costs of major "asphalt milling and recycling" event were as much as 50% higher.

The empirical data are consistent with the industry experience that asphalt overlay requires more maintenance than AORC over the pavement service life. In this case, however, it remains uncertain if the accumulated constant dollar cost of AC overlay would catch up and surpass that of AORC.
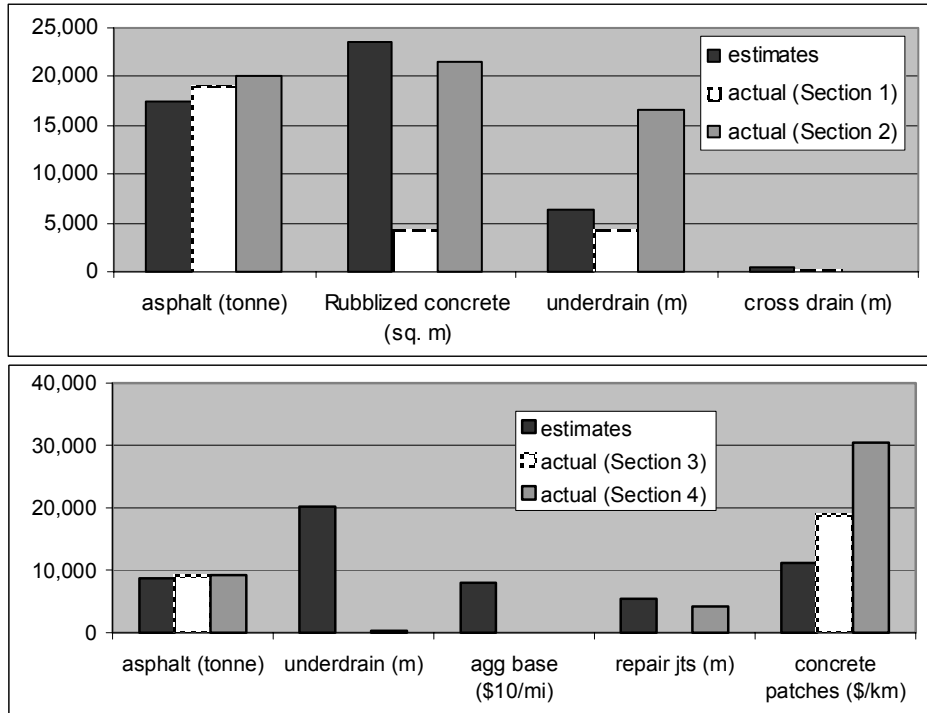
Figure 11a-b: I-96: Estimated vs. actual material use in initial construction phase for the LCCA design section (asphalt overlay over rubblized concrete) and non-LCCA design section (asphalt overlay) (Top to Bottom)

The Differences between Estimated and Actual Cost and Material Consumption

The variations between estimated and actual construction material in the LCCA examples reviewed in this analysis are, to a large extent, the result of the difficulty in developing accurate pavement installation and maintenance cost estimates. This problem is not unique to LCCA, of course, in that actual costs of highway projects often vary from engineering cost estimates.

For all of the cases, the LCCA cost estimating module includes a one-mile road section without intersections, underpasses and crossovers. In reality, roads are constructed differently when they are under a bridge or at an intersection. For example, AC or PCC overlays cannot be applied to road sections below the bridge because it would reduce the clearance height. Instead, that section must be reconstructed from base

to surface (MDOT 2006). Moreover, more differences were observed for work items related to joint repair, original pavement repair and underdrains. This is normal because these items were usually rough estimates in LCCA documents. Construction engineers may find more or less repair is needed for the pavement once the road section is under reconstruction or rehabilitation.

Other site-specific conditions can account for the observed differences as well. In Case 2, a different aggregate base was substituted for the open-graded drainage course originally included in the LCCA (MDOT 2006). The unit price and plan quantities of both materials were different than used in the original cost estimation (ibid). Furthermore, construction plans can be changed after LCCA was carried out and approved (ibid). A thinner shoulder may be built, or different asphalt mixes might be used for the road project. In Case 4, although AORC was the lowest-cost alternative, part of the LCCA-designed rubblized section (Section 1) (Table 1) was reconstructed or resurfaced without rubblizing the substrate concrete pavement.

Lastly, the observed maintenance schedules of the studied road sections do not usually match up with the ones estimated by MDOT LCCA model. In most cases, the actual unit costs of work items (e.g. AC and PCC) and types of maintenance events are also different from the estimation. Despite the MDOT pavement preservation strategy are estimated based on the historical asphalt and concrete pavement performance in Michigan, ERES (2003) argued that most pavements in Michigan nowadays are constructed differently from the past.   For example, short jointed plain concrete pavement design replaced the jointed reinforced concrete pavement design used in the past. MDOT has revised the hot-mix asphalt specifications a few times in the last few decades and have also implemented Superpave Mixtures (Superpave stands for "SUperior PERforming Asphalt PAVEments") (MDOT 2000).   Thus, the historical pavement performance does not necessarily coincide with the ones with new designs and construction methods. On the other hand, the actual pavement material consumption and costs may deviate from the original estimation. All these factors suggest that the LCCA process used by MDOT could benefit from additional reviews of actual case studies, the

results of which can be used to target improvements to the LCCA cost estimation process and pavement preservation strategies. In time, it would be expected that the accuracy of the overall process would improve.

4.4 Limitations of the Study

It is rather difficult to compare pavement performance over time between two different pavement alternatives, only one of which was actually built. In this paper, strict selection criteria were adopted to control factors affecting the pavement conditions, so that direct comparison among road sections became possible. Still, in Cases 1 and 4, non-LCCA design sections have quite different quantities of underdrains and repair items (e.g. joint repair, concrete patches) than would have been estimated if LCCA had been applied (Figure 8a-b, Figure 11a-b). In case 4, those items contributed to more than 55% of the estimated initial construction cost, but less than 30% in the non-LCCA AC sections.

More significantly, this study involves only four case studies. Based on the small sample, it is difficult to make general conclusions about the overall accuracy of the LCCA process in Michigan. Maintenance schedule can also be changed because of external factors including political or financial reasons. More extensive research, based on a larger number of studies, would allow better insight into the accuracy of the process, particularly potential improvements in LCCA since 1998, when MDOT made significant changes to its LCCA process.

4.5 Conclusion

The author is a strong proponent of practicing LCCA in road construction because LCCA can be one of the most important asset management tools for road infrastructure, the value of which exceeds $2 trillion nationally (BEA 2006). The process of doing LCCA requires that designers and engineers carefully specify their assumptions about pavement properties and costs in a manner that is informative in its own right. Yet, the full contribution of LCCA to the asset management process is based upon the pre-

requisites that initial and future pavement costs and performance can be estimated accurately within the LCCA process. Because the results from LCCA inform the decision making in the pavement selection process of the DOTs, it is therefore important that its findings be reviewed periodically for accuracy. By the use of before-and-after analysis, such as conducted for this study, researchers can improve cost estimating methods and develop more refined estimates of total life-cycle costs to provide more reliable estimates to decision makers.

The primary purpose of this study is to evaluate the accuracies of the LCCA procedure used by MDOT in the pavement design stage in projecting the life-cycle costs and maintenance schedules of different pavement types, and thereby choosing the lowest-cost pavement type. Based on the four case studies, all the LCCA procedures in the case studies were able to predict the pavement type with lower initial construction cost, although the amount of the initial costs were subject to estimation error. Improvement in initial cost estimation could yield important and immediate benefits to the accuracy of the process because initial construction cost contributes to more than half of the life-cycle cost of a pavement. In addition, the actual to-date accumulated costs are generally over-estimated by more than 10%. The expected and actual maintenance schedules are similar in some cases, yet the actual maintenance procedures carried out differ from the estimation.

In the four case studies, most non-LCCA design sections have the lower to-date accumulated costs than the LCCA design sections. This result appears largely to be the result of the cost estimation process, particularly the initial costs. It remains to be seen if the non-LCCA design sections will undergo additional major maintenance activities in the future and thus have higher life cycle cost toward the end of pavement's service life. Although the studied sections are midway (8-16 years) through their service life and a longer time frame is necessary to conclude the accuracies of the original LCCA, the current analysis does not suggest that benefits would definitely be realized at the expected level in the future for these case studies, particularly once the costs are discounted into present value dollars.

The cost estimation module used in the MDOT LCCA model would likely benefit from more site-specific capabilities. As discussed in the previous section, the model estimates the life-cycle costs of different pavement alternatives based on a simplified one-mile stretch of road without intersections, underpasses and crossovers. This approach facilitates the speed of conducting an analysis but can introduce estimation errors for roads with many intersections and highways with many ramps, underpasses and crossovers, because the construction method and the quantities of material consumption can be quite different. Hence, future research can investigate the effect of incorporating these site-specific parameters (e.g. ramps) into the MDOT LCCA model. Fortunately, any improvements to the accuracy of the initial cost estimating portion of the model can be tested quickly based on ongoing construction experience, and need not await the completion of the project's life cycle.

Lastly, the maintenance schedules provided in the LCCA documents are based on historical averages of the whole state, and the unit price for different work items used in LCCA are estimated from a few previous road projects. As demonstrated in the case studies, the timeline and types of maintenance activities did not completely follow the predicted schedules. As discussed in last section, it is probably because the historical pavement performance cannot totally reflect the ones nowadays that are built with different designs and/or materials (ERES 2003). Work item unit costs can also differ substantially by road projects carried out in the same year (MDOT 2006). A greater emphasis should be paid to developing more accurate engineering estimates of future maintenance events and costs, as well as establishing a process to monitor actual cost experience and make adjustments to the cost estimating processes based on actual results.

The incorporation of probabilistic capabilities to the model could also provide better information on the range of life-cycle costs of different pavement alternatives by capturing the variability of work item costs and schedules. Moreover, it is possible to look back further into the historical data on maintenance schedules and types, and

observe the differences among different regions in Michigan. Different schedules can be developed and used to carry out LCCA for roads in different regions.

In summary, continued refinements to the cost estimation methods and data used in the LCCA will contribute to increased accuracy of results in the future. Progress in the LCCA process can only be established by periodic reviews of analyses in which estimated outcomes are compared to actual results.

5. Incorporating Pollution Damage Costs into MDOT LCCA

5.1 Introduction

From the sustainability perspective, it is important to adopt a holistic approach that integrates economics, social and environmental issues into the decision-making process of pavement selection processes. States DOTs are required by the National Environmental Policy Act to prepare Environmental Impact Statement (EIS) for transportation projects. The EIS disseminates information to the public about the overall economic, community and environmental impact of the project, yet it covers a broader scope in terms of transportation (e.g. transportation mode, project alignment) than simply comparing the impact of two pavement alternatives.

This chapter serves two purposes. The first one is to evaluate and compare the life-cycle environmental impact of asphalt and concrete pavement alternatives proposed in the LCCA documents of MDOT road projects. The second one is to incorporate pollution damage costs, part of the external costs, into the current MDOT LCCA model. Environmental impacts will be monetized by benefits transfer, and their significance compared with other components of life-cycle cost model will be explored.

5.2 Methodology

Pavement designs are site-specific (e.g. different thickness of pavement layers). Following the AASHTO 1993 Guideline for Design of Pavement Structures, MDOT designs pavement by considering various site parameters, including but not limited to landscape, geology, traffic volume and existing infrastructure (MDOT 2005). To capture the variations in results due to different pavement designs in different locations, this study analyzed multiple real MDOT projects. Such an approach would yield a more representative picture of the general situation in Michigan. It also became possible to look for correlations among pavement types, pavement life-cycle agency and user costs, and life-cycle environmental impact.

Thirteen MDOT highway projects were randomly picked and the environmental impacts of asphalt and concrete pavement alternatives proposed in the respective LCCA documents were evaluated. They included five rehabilitation, seven reconstruction and one new construction projects located around Michigan. Asphalt and concrete were the lowest-cost pavement type for seven and six of the projects respectively. The majority of the projects (ten of them) are divided freeways because they are more likely to cost over $1 million, the minimum figure for which LCCA is mandatory. The LCCA of these selected road projects were carried out after MDOT made a major revisions in its pavement selection policy in 1998. Table 2 and Figure 12 describe the location and general characteristics of the road projects chosen in this study.
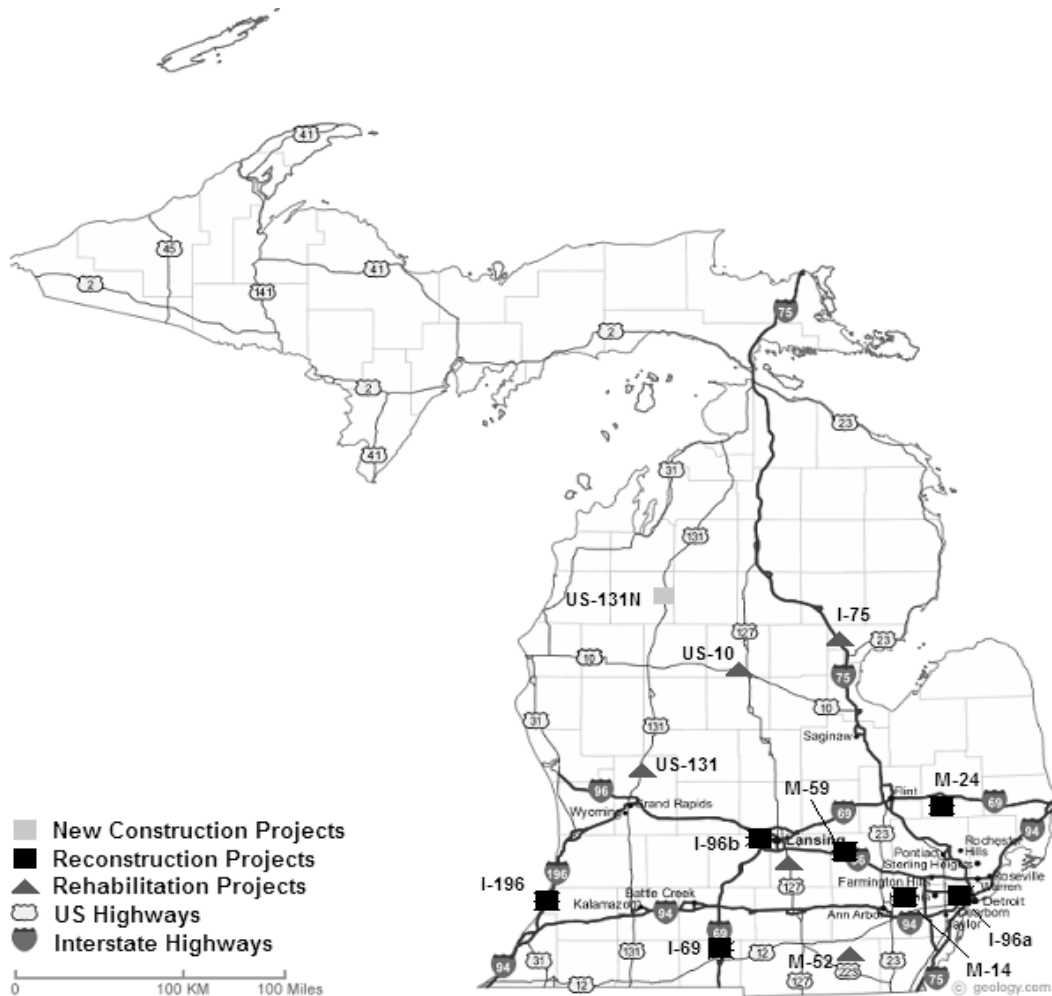
Figure 12: Location of reconstruction and rehabilitation projects studied
(Original map from www.geology.com)

Table 2: Characteristics of case study projects

							Traffic Vol. (2005) (AADT)	Mainline Thickness (mm)	
Project ID	Route	Region	Sched. Constr. Year	Lowest-cost alternative	Project Length (km)	# of lanes		Asphalt	Concrete
Rehabilitation Projects									
38209	US-131	Kent County	2001	UCO	13.31	4	29,900-50,500	188	160
43521	M-52	Lenawee County	2005	AORC	8.92	2	7,800	164.7	165.1
50629/ 53304	US-10	Clare County	2005	AORC	11.76	4	9,000-9,700	165.1	165.1
60450	US-127	Ingham County	2006	AORC	10.61	4	31,200	164.7	165.1
55125	I-75	Arenac County	2006	AORC	21.24	4	17,800	182.9	152.4
Reconstruction Projects									
45640	I-96#	Lansing	2002	JRCP	7.37	4	37,000-62,300	302	280
45711	M-14	Wayne County	2006	JPCP	6.21	4-6	83,300	273.1	279.4
48608	I-96#	Detroit	2006	JPCP	1.93	10	105,000	284	279.4
48762	M-59	Livingston County	2008	HMA	5.87	4	21,780	200.66	215.9
50775	I-69	Branch County	2004	JPCP	14.71	4	19,200	279.4	279.4
55908	M-24	Lapeer County	2006	HMA	7.88	4	20,267	190.5	228.6
60471	I-196	van Buren County	2008	JPCP	14.32	4	17,200-21,200	260.35	279.4
New Construction Project									
34682	US-131*	Wexford County	2003	Asphalt	12.85	4	7,300-8,300	156	200

*: This project will be referred to as US-131N in this paper

#: I-96 48608 and I-96 45640 will be referred as I-96a and I-96b in this paper respectively

AORC: asphalt on rubblized concrete

HMA: hot-mix asphalt

JPCP: jointed plain concrete pavement

JRCP: jointed reinforced concrete pavement

UCO: unbonded concrete overlay

5.3 Environmental Impact of Pavements: The LCA Model

Modeling Approach

There are two popular approaches to perform life-cycle assessment (LCA). Instead of the EIO-LCA model (Horvath et al 1998) as mentioned in Section 2.3, this study utilized the approach intensively developed by the Society of Environmental Toxicology and Chemistry (SETAC 1993) and the US Environmental Protection Agency (EPA 1993). The SETAC-EPA method is a conventional process-based approach that divides each product or system into individual process flows (including upstream flows) and quantifies their environmental impacts (ibid). This method was chosen ahead of EIO-LCA method because this is adopted by International Organization for Standardization (ISO) as a standard procedure for LCA (Zapata et al 2005). More importantly, the SETAC-EPA method is more convenient in tracking the contribution of different processes to environmental impacts, and the results from this study can be compared with the Horvath's study which uses the EIO-LCA approach. LCA of this study was developed in accordance with ISO 14040, 14041, and 14042 methods (ISO 1997, ISO 1998, and ISO 2000).

Life-Cycle Inventory and the System Boundary

A life-cycle inventory (LCI) was built to calculate the environmental impact of asphalt and concrete alternatives proposed in the MDOT LCCA documents. The model was referenced from similar models developed and described in a thesis written by Alissa Kendall titled "A Dynamic Life Cycle Assessment Tool for Comparing Bridge Deck Designs" (2004) and a research paper by Han Zhang (2007). The LCCA documents contained most of the primary data, and the model computed environmental impact categories including resource use, primary energy consumption, greenhouse gas emissions and conventional air pollutants emissions and carcinogenic substances

emissions[6]. In terms of systems boundary, the following activities associated with road construction were considered in the model (Figure 13):

- Material production and waste treatment (i.e. recycling or landfill);
- Material/waste transportation to/from construction site;
- Construction and maintenance processes, which is dominated by fuel consumption by on-site construction equipment and machinery; and
- Traffic delay in the work zone area and detour, which lead to changes in total tailpipe emissions (it is different from the user cost due to traffic delay)
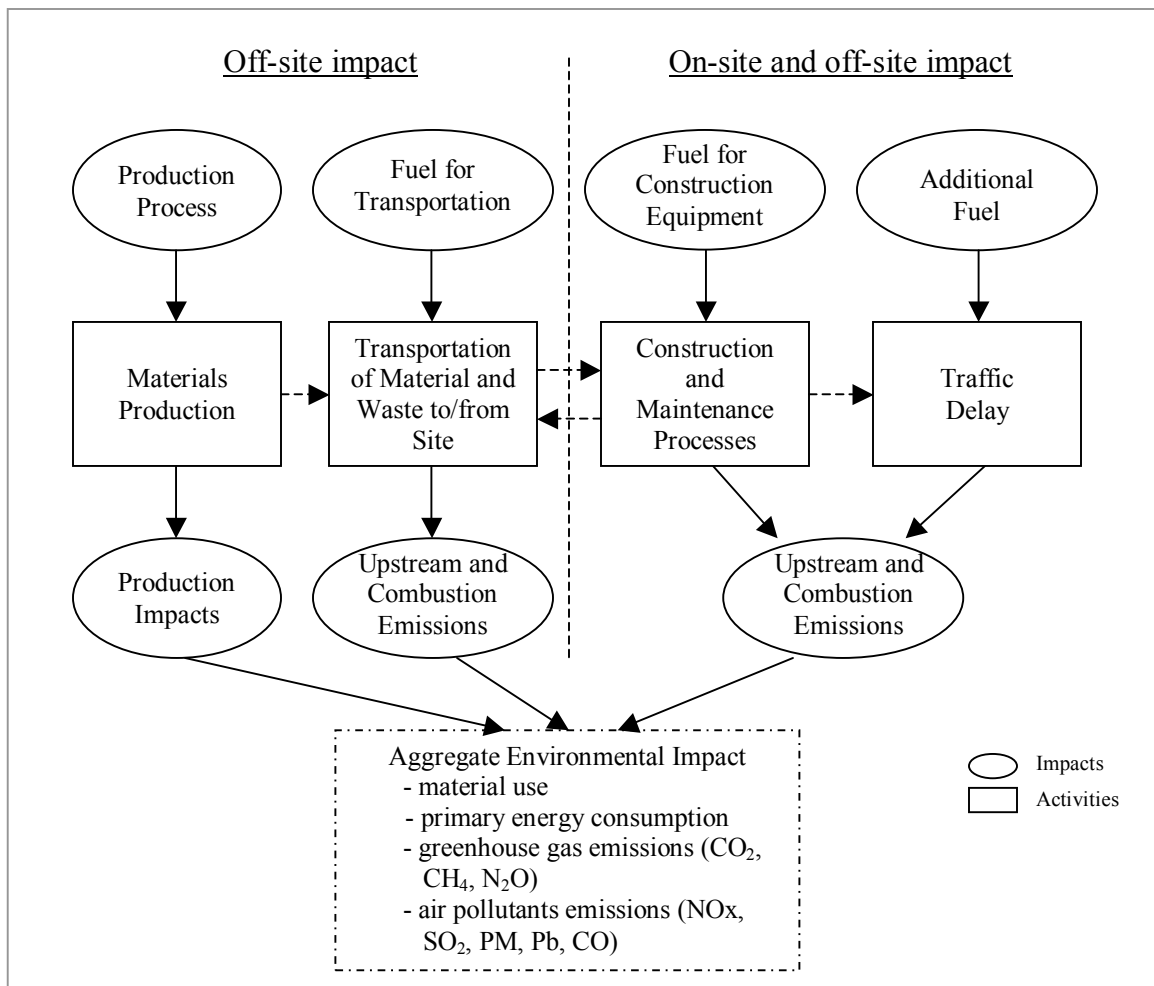
Figure 13: System boundary of LCA model

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[6] Definition of carcinogenic substances is based on the list published by the International Agency for Research on Cancer (IARC) and the National Toxicology Program (NTP). (DEHS 2007)

Material Production and Transportation Sub-model

This sub-model computed the environmental impacts of manufacturing and distributing the materials for the structural component of roads over the pavement service life. The structural components, referred to as "work items" by MDOT, included in this model were consistent with what appeared in the MDOT LCCA documents in calculating the life-cycle cost. They included mainline pavement, shoulder, joints, sub-base, and aggregate base.

The quantities of these "work items" used per lane-mile were specified in the LCCA documents of each road project, but only for the initial construction phase. The post-1998 LCCA documents only specified future maintenance costs but not types, thus the quantities of work items used in future maintenance events were estimated from both pre-1998 LCCA documents and the latest annual "Weighted Average Item Price Report" released by MDOT (MDOT 2006). Appendix II exemplifies preservation strategies excerpted from the latest MDOT Pavement Design and Selection Manual (MDOT 2005). Based on the material mix designs published in the MDOT "Standard Specifications for Construction" and similar manuals from other states, the consumption quantities of raw materials (i.e. bitumen, cement, limestone, etc) were estimated (Appendix IV). The model assumed the use of recycled materials in each project. For example, the recycled asphalt content in asphalt pavement in Michigan can reach as high as 50% (FHWA 1997). By default, the model assumed 25% of recycled asphalt in asphalt, and 2% fly ash content by weight in concrete. While wastes were produced during road construction, additional impacts were considered if they were not recycled but sent to landfill. It was estimated that the nationwide recycling rate of asphalt and concrete wastes were around 80% and 50% respectively (FHWA 1993, EPA 2003).

Besides production impacts, the model accounted for the impacts from transporting materials and wastes from and to the construction site. Transportation distances and mode, comprised of truck, rail and barge combinations, were estimated based on potential material suppliers around the construction sites. Environmental impacts due to fuel combustion and upstream production were analyzed. Data sets from

the Portland Cement Association, the Athena Sustainable Materials Institute, SimaPro 6.0, and IVL Swedish Environmental Research Institute were used to calculate environmental impacts of pavement alternatives in material production and distribution processes (Table 3).

Table 3: References of LCI and Design Mix Information for major materials

Material	Data Source
Bitumen	Athena Sustainable Material Institute (1999) IVL Swedish Environmental Research Institute SimaPro 6.0
Portland cement	Athena Sustainable Material Institute (1999) Portland Cement Association (PCA 2002) SimaPro 6.0
Crush aggregate	Athena Sustainable Material Institute (1999) Portland Cement Association (PCA 2002) SimaPro 6.0
Limestone	IVL Swedish Environmental Research Institute SimaPro 6.0
Sand	SimaPro 6.0
Gravel	SimaPro 6.0
Epoxy	Ecobilan DEAM database (Ecobilan 2001)
Steel	International Iron and Steel Institute (IISI 2000)

Construction Process Sub-model

For the construction process, the model evaluated the environmental impacts from fuel combustion and upstream production of on-site construction equipments. The type, productivity and operating time of construction equipment were estimated by referencing the proposed schedule of each construction process in the LCCA documents and the construction manuals of states DOT. Fuel consumption and fuel-related emissions data was generated using EPA NONROAD2005 model of diesel engine emissions in Michigan (EPA 2006), while the environmental impact of upstream fuel production process was determined using SimaPro 6.0 fuel production data.

Traffic Delay Sub-model

Lastly, environmental impact of additional fuel consumption due to construction-related traffic delay was analyzed. Multiple existing models were used in computing the impact. First, the traffic pattern in the work zone was simulated using a traffic model adopted from the KyUCP model. KyUCP was developed by Kentucky Transportation Center (KTC 2002) to estimate traffic delays in the work zone. In this study, the traffic model assumed that half of the lanes were closed for construction and maintenance, and the speed limit in the work zone dropped to 40mph from 70mph, unless otherwise specified in LCCA documents. The model also assumed that 12% of traffic would be detoured during construction. Using data such as hourly traffic, annual traffic growth rate and work zone length that are available in the LCCA documents, the road capacity, vehicle traveling speed and vehicle miles of travel (VMT) in the work zone during both the construction and an equivalent non-construction period were computed by the traffic model. With these outputs, EPA MOBILE6 model (EPA 2006) was utilized to estimate the vehicle tailpipe and evaporative emissions (except CO_2) for construction and non-construction periods.

CO_2 emissions were not available from MOBILE6, thus it was estimated from fuel consumption. Vehicle fuel economy data of 2003 was obtained from the Vision Model developed by Center for Transportation Research Argonne National Laboratory (DOE 2004), and projections of fuel economy improvement over time were obtained for heavy trucks and passenger vehicles from Langer 2004 and Heywood et al 2004, respectively. For trucks, fuel economy was assumed to be improved by 1.5% per annum (Langer 2004). For light trucks and passenger vehicles, an algorithm[7] was derived from a study by Heywood et al (2004). Total fuel consumption was calculated from fuel economy and VMT data to estimate CO_2 emissions at both construction and an equivalent non-construction period. Furthermore, environmental impact from upstream fuel production process was evaluated using data sets from SimaPro 6.0. The environmental impact of additional fuel consumption due to traffic delay and detour was

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[7] $FE_n = -4.96 \times 10^{-4} \times (n-n_0)^3 + 4.08 \times 10^{-2} \times (n-n_0)^2 - 0.23 \times (n-n_0)^1 + FE_0$

  where FE_n = fuel economy of year n

          n = year, n_0 = base year (2003)

the difference between that during construction period and an equivalent non-construction period. Figure 14 and Figure 15 show the schematic of estimating environmental impacts of construction-related traffic delay.
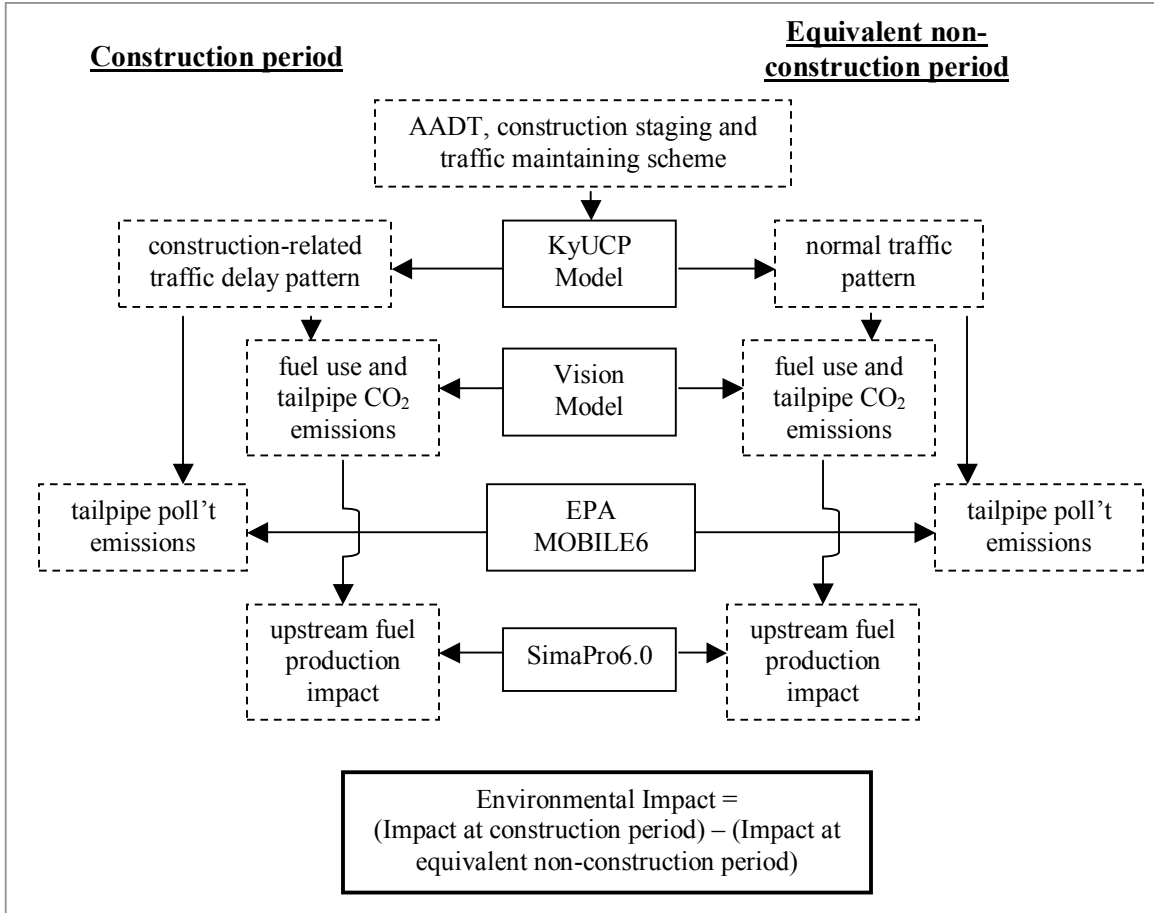
Figure 14: Models and dataset used in computing the environmental impact of construction-related traffic delay
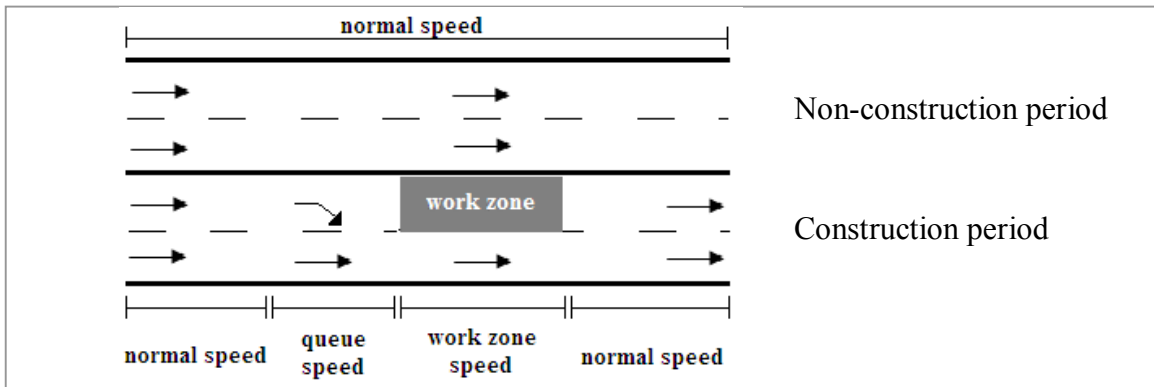
Figure 15: Model traffic pattern during construction and equivalent non-construction periods

5.4 Incorporating Pollution Damage Costs into LCCA

Introduction

Environmental impact cannot be directly compared with other LCCA elements unless it is represented in the same metric. Using the pollutant emissions data from the previous section and marginal damage cost estimates of pollutants, the pollution damage costs (an external cost element) of different alternatives were calculated. Pollution damage costs from the emissions of carbon dioxide, methane, nitrous oxide, sulfide dioxide, nitrogen oxides, carbon monoxide, lead, volatile organic compound, and particulates were considered because these estimates are relatively more common in the peer-reviewed literature. Damage costs of conventional air pollutants are mainly from human health impacts, while those of greenhouse gases reflect the possible social and economic effect of global warming. Realizing the uncertainties associated with the estimates of marginal damage cost, low and high estimates were reported.

Benefit Transfer Method

There are two major methods to monetize the environmental impacts. One is to carry out an original valuation study, which is often expensive and time-consuming. The other method is to adopt the estimates from existing studies, which is referred to as "benefit transfer". By definition, benefit transfer is "the application of monetary values obtained from a particular non-market goods analysis to an alternative or secondary policy decision setting" (Brookshire et al 1992). The method has been extensively used in estimating the perceived benefits or costs of environmental public goods (e.g., recreational use, pollution damage cost, etc). There are primarily two types of benefit approach: value transfer and function transfer. Value transfer uses a unit value estimate, unadjusted or adjusted, from another study (e.g., marginal damage cost of CO_2 emission in an urban setting equals $2.03/metric ton), while function transfer uses a benefit/cost or regression analysis function derived from another study (e.g., cost per metric ton equals factor A + β factor B + γ factor C).

However, benefit transfer is viewed as the less ideal strategy compared to carrying out an original valuation study. The estimates obtained from existing studies might not be totally specific to the context of research question being evaluated. For example, the estimates can be derived based on a different region, population structure or time frame. Rosenberger et al (2001) added that most primary researches are not designed for benefit transfer purposes, and the quality of benefit transfer method has a "garbage-in, garbage-out" factor. Therefore, results will only be as accurate as the estimates obtained from another study. The error can even be magnified if the estimates are not totally suitable for the research question being evaluated. Nonetheless, the error can be minimized by carefully choosing the appropriate sets of estimates from existing literatures. This study has drawn marginal damage costs estimates of conventional air pollutants from multiple studies looking at specific emission sources in order to better reflect the situations concerned.

Marginal Damage Costs Used

Two major emission pathways are related to road construction. There are stationary sources of emissions from chimneys of power plants and factories due to material production processes, and mobile sources of emissions from on-site construction equipment operations, user vehicles and trucks transporting the materials to site at the ground level. It is expected that the same amount of pollutants would lead to different levels of health impacts for the two dispersion pathways. As a result, different estimates were used for conventional air pollutants from the two pathways. They were taken from a major study of air pollution externalities of electricity generation in Minnesota (Banzhaf et al 1996, Matthews et al 2000) and a nationwide study on the social cost of motor vehicle air pollution (Delucchi 1996) respectively. The Banzhaf et al (1996) and Delucchi et al (1996) studies were based on health effects and have developed different marginal damage costs for rural and urban scenarios. It is unsurprising that the Delucchi's estimates are higher than that of Banzhaf et al (1996) as the public are more exposed to the vehicle emissions at ground level. However, the difference can be as much as three orders of magnitude for the high estimates (Table 4). Marginal damage cost

estimate for lead was not evaluated by Delucchi et al (1996), and the estimate from Banzhaf et al (1996) was used for both sources.

Climate change impact of greenhouse gases occur on a global scale and one estimate from Tol (2005) was used. The study summarized the 123 estimates of marginal damage costs of carbon dioxide emissions from 28 published studies. Estimates derived from a pure rate of time preference of 3% – corresponding to 4% to 5% of social discount rate used by US governments for long-term investment – were used. Neglecting the negative marginal damage cost at the lower bound of the interval, the median of the probability density function was used as the low estimate, while $50/tC was used as the high estimate as suggested by Tol (2002, 2005) and Pearce et al (1996). Marginal damage costs of nitrous oxides and methane were approximated by multiplying that of carbon dioxide by a global damage potential[8] (nitrous oxide: 348 tN_2O/ tCO_2, methane: 14 tCH_4/ tCO_2) (Tol 1999). Table 4 reports the marginal damage costs used in this study.

Table 4: Marginal damage cost used in this study

Air Emissions \Locality		Urban		Urban fringe		Rural	
		low	high	low	high	low	high
CO_2		2.03	14.48	2.03	14.48	2.03	14.48
CH_4		28.38	202.73	28.38	202.73	28.38	202.73
N_2O		705.51	5,039.38	705.51	5,039.38	705.51	5,039.38
Pb		4,516.74	5,591.21	2,383.11	2,879.02	580.09	645.90
VOC		228.77	6,291.09	228.77	6,291.09	228.77	6,291.09
NOx	Stat.	535.70	1,411.19	202.04	384.18	26.02	146.94
	Mobile	2,209.25	32,520	1,620.12	23,874	1,620.12	23,874
SO_2	Stat.	162.24	272.44	65.81	159.18	13.78	36.73
	Mobile	6,480.47	51,961	4,123.94	33,286	4,123.94	33,286
CO	Stat.	1.53	3.28	1.10	1.93	0.31	0.60
	Mobile	14.73	147.28	14.73	132.56	14.73	132.56
PM_{10}	Stat.	6,437.62	9,266.13	2,866.77	4,163.18	811.21	1,233.65
	Mobile	18,012	233,046	12,931	170,863	12,931	170,863
Stat. Emissions associated with material production (Stationary) Mobile Emissions associated with fuel combustion and upstream production process (presented in 2006 dollars per metric ton)							

[8] Global damage potential is defined as the time integral of time-discounted environmental impact per unit emission divided by the same integral by carbon dioxide. It was argued that it should be used instead of global warming potential (GWP) because radiative forcing, as considered in GWP, does not hold a linear relationship with environmental damage (Tol 1999)

5.5 Results and Discussion: Life-cycle Environmental Impacts

Life-cycle environmental impacts of asphalt and concrete alternatives for thirteen actual highway rehabilitation and reconstruction projects in Michigan were computed. The results included impacts from material production and distribution, construction equipment use and construction-related traffic delay over the pavement service life. Environmental indicators included resource use, energy consumption, greenhouse gas emissions and air pollutants emissions. In general, CO_2 and NO_x were the two most significant gaseous emissions. The majority of environmental impact originated from the initial construction period as material production contributed to most of these emissions. As for pavement alternatives, asphalt pavements looked better in some environmental indicators but worse in others. For better representation, the results in this section are presented based on a functional unit of a 4-lane kilometer section.

Resource Use

Road construction is material-intensive. The model calculated that 18,000-28,000 metric tons (Mt) of materials were used for construction and reconstruction projects per 4-lanes-km, while 8,000-13,000 Mt/4-lanes-km for rehabilitation projects (Table 5). For rehabilitation projects, the surface course material (i.e. asphalt or concrete) contributed to over 99% of the tonnage; for construction and reconstruction projects, slightly more than half of the tonnage went to subbase materials, with the rest mainly surface course materials. The asphalt alternative had higher material use requirements than the concrete alternative. The reasons are that asphalt pavement usually requires a thicker new aggregate base, and the upper layer of asphalt is milled and repaved in the middle of pavement service life.

Table 5: Material requirement of pavement alternatives

Fix	Time\ Type	Asphalt alt.	Concrete alt.
Rehabilitation	Initial	9,100-10,000	8,000-10,000
	maintenance	2,600-3,000	10-35
New Construction	initial	24,000-37,000	18,000-28,000
& Reconstruction	maintenance	2,200-4,300	35-105
In metric tons per 4-lanes km			

Energy Consumption

Bitumen is a product of crude oil. Because of its high feedstock (embodied) energy content, the primary energy consumption of asphalt pavements in all studied projects were one to three times higher than that of concrete pavements. For rehabilitation projects, the primary energy consumption for asphalt and concrete alternative ranged from 30-46 and 11-14 million MJ respectively; for reconstruction projects, they were 30-98 and 14-53 million MJ respectively. However, when only process energy was considered, the energy requirement of asphalt and concrete alternatives were comparable (Appendix V). Figure 16 shows the primary energy consumption of asphalt and concrete alternatives of studied projects. Feedstock energy in the concrete alternative was primarily due to the asphalt shoulder design.
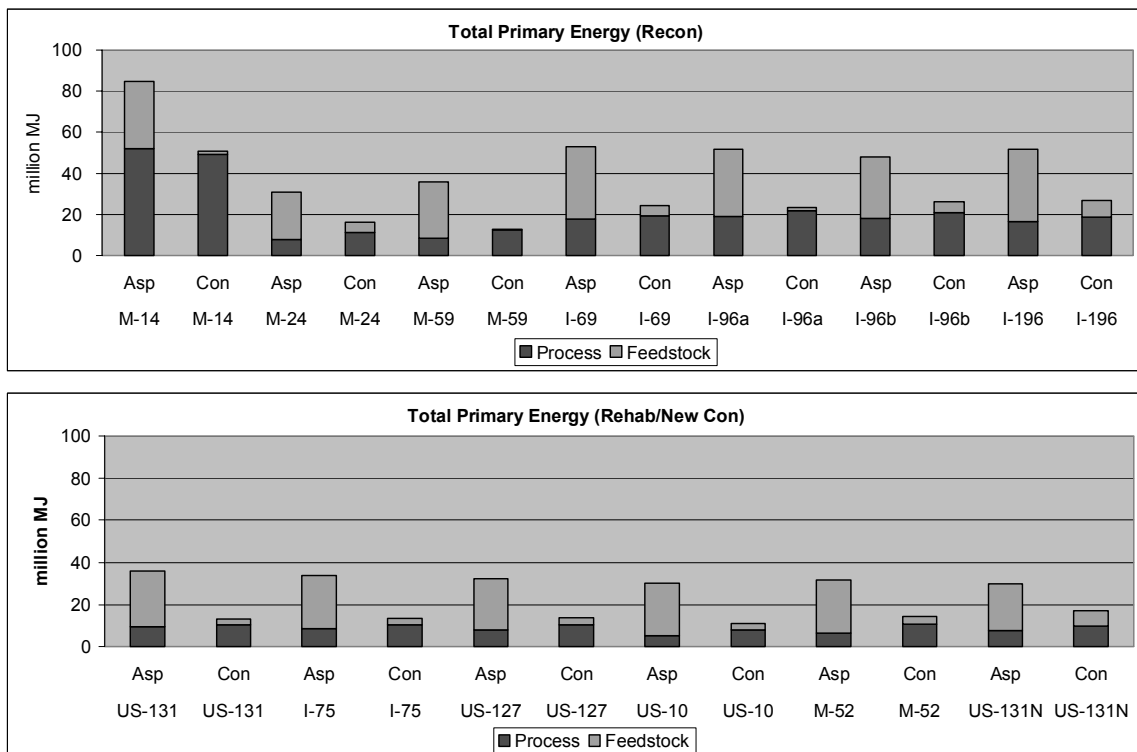
Figure 16: Life-cycle process and feedstock energy consumption of reconstruction (top), rehabilitation and new construction projects (bottom) (Results were normalized by 4-lane km)

In terms of construction activities, material production dominated the primary energy consumption. Contribution from construction-related traffic delay was related with the road capacity and traffic volume. Its contribution was comparable to material production in M-14 but was low in most cases primarily because traffic volumes of most case study projects were low (< 20,000 AADT). The traffic was traveling at the work-zone speed limit for most of the time. Figure 17 shows the primary energy consumption categorized by construction activities. Lastly, the initial construction period was responsible for 73% to 98% of the primary energy consumption (asphalt: 73% to 87%, concrete: 88% to 98%), which is related to the resource use pattern over the pavement service life.
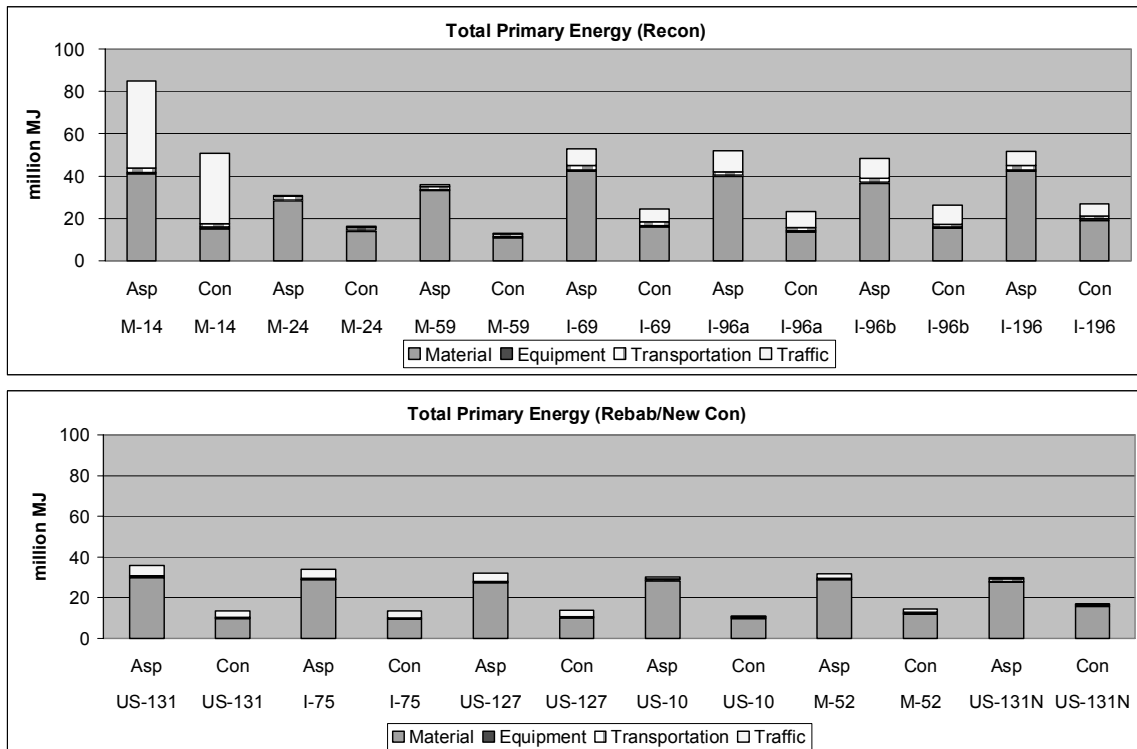
Figure 17: Life-cycle primary energy consumption of reconstruction (top), rehabilitation and new construction projects (bottom) by activities

Greenhouse Gas Emissions (GHG)

General trends were observed for greenhouse gas emissions (CO_2, N_2O, CH_4) among case study projects. Weighed by global warming potential, CO_2 emission was the major greenhouse gas emission (90% to 99%). Methane was slightly more prominent in asphalt alternatives, while nitrous oxide had negligible impact (Appendix V). Concrete alternatives had higher GHG emissions than asphalt alternatives, and reconstruction projects yielded more GHG emissions than rehabilitation projects. For reconstruction projects, asphalt and concrete alternatives led to 1,000-4,000 and 1,500-4,400 Mt of CO_2 equivalents per 4-lanes-km of greenhouse gases emissions respectively; for rehabilitation projects, they were 580-1,000 and 1,100-1,300 Mt CO_2 eq. correspondingly. Despite asphalt and concrete alternatives having comparable process energy consumption, the latter caused more GHG emissions. It is primarily because cement production releases enormous amount of CO_2 in both calcination and fuel combustion processes (WBCSD 2002).

Material production contributed to the majority of GHG emissions, but to a lesser extent than that in primary energy consumption (Figure 18). Again, construction-related traffic delay became more significant if traffic volume is higher (i.e. M-14 case). Lastly, 64% to 90% and 91% to 99% of GHG emissions were originated from initial construction period for asphalt and concrete alternatives respectively. Asphalt alternatives were expected to carry out more maintenance activities in terms of both numbers and intensity. For example, up to 76mm (3 inches) of upper asphalt layer would be milled and repaved in the middle of pavement service life.

Figure 18: Life-cycle greenhouse gas emissions of reconstruction (top), rehabilitation and new construction projects (bottom right) by activities

Conventional Air Pollutants and Hazardous Substances

CO, NO$_x$, Pb, PM$_{10}$, SO$_2$, VOC and carcinogenic substances were considered in this study, and different trends were found. NO$_x$ and SO$_2$ emissions were the highest among other air pollutant emissions (2.5-8.0 and 1.7-5.7 Mt/4-lanes-km). Net emission reduction was observed for CO (-4.5-38 Mt). Higher life-cycle SO$_2$, Pb and NO$_x$ emissions were found for the concrete alternatives, while higher life-cycle VOC and carcinogenic emissions were noticed for the asphalt alternatives. The VOC emissions for asphalt alternatives originate from the evaporation of petroleum distillate solvent during application of emulsified asphalt at maintenance (ERG 2001). Figure 19 to Figure 25 illustrate the levels of air pollutant emissions of the alternatives considered in the case study projects.

Activity-wise, material production processes were the biggest contributors in most emission categories (10% to 98%), especially for SO$_2$ (87% to 98%) and Pb (92% to

52

98%) (Figure 20 and Figure 24). As well, construction-related traffic delay became a more crucial factor at higher traffic volumes in NO_x, CO, VOC and carcinogens categories (e.g. M-14, I-96a, and I-96b cases). Particularly, traffic delay actually reduced NO_x and CO emissions in most projects except M-14, which is related to the assumption made in the EPA MOBILE6 model. In the model, NO_x and CO emission rates have a U-shaped relationship with vehicle traveling speed. At very low speed (i.e. highly congested traffic as in M-14 case), the emission rate of CO and NO_x is the highest. The rate drops with increasing speed and reaches the lowest at around 30-35 mph (the vehicle traveling speed in work zone for most of the projects), then it increases afterwards. For other activities, construction equipment operation was not the major source of emissions for most categories except particulate matter (PM_{10}). It is especially true for rehabilitation projects where the material consumption was lower and thus the material production process emitted fewer pollutants. Transportation of materials did not have noticeable impact on the environmental indicators except for NO_x. Lastly, in terms of temporal distribution of emissions, 90% to 99% of emissions were generated during the initial construction except for VOC. VOC were emitted during maintenance operations on asphalt pavement (e.g. reseal crack, micro-surfacing, crack fill) when emulsified asphalt was applied.
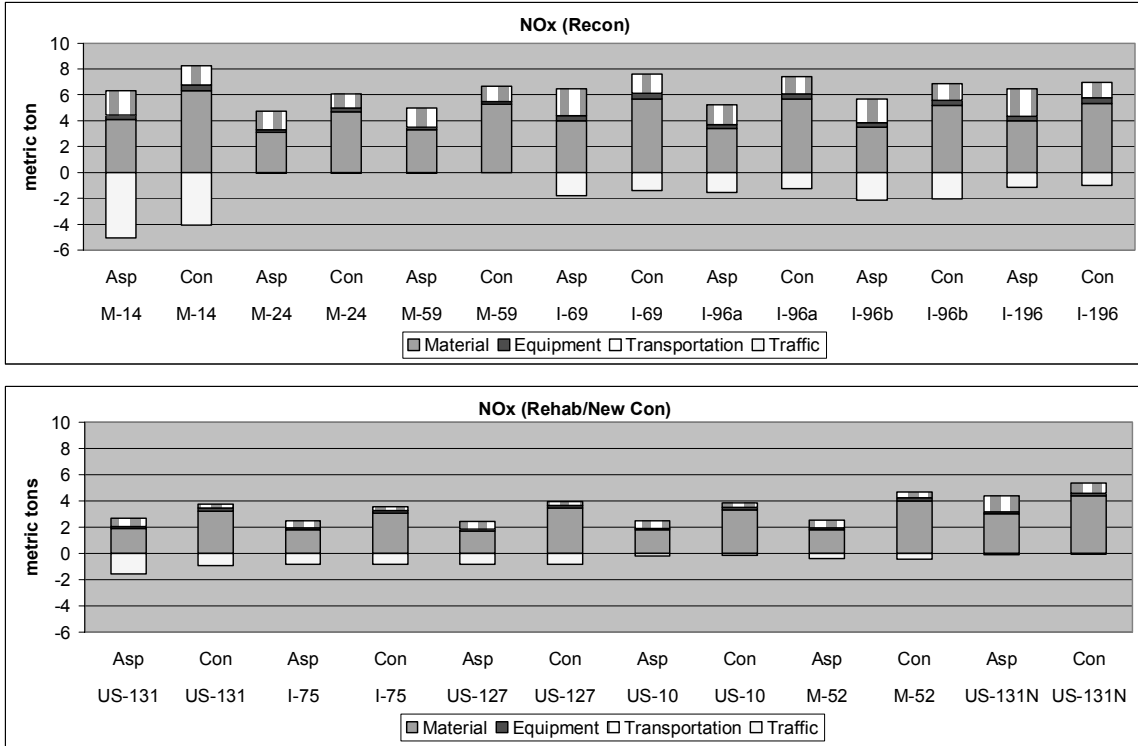
Figure 19: Life-cycle nitrogen oxides emissions of reconstruction (top), rehabilitation and new construction projects (bottom right) by activities
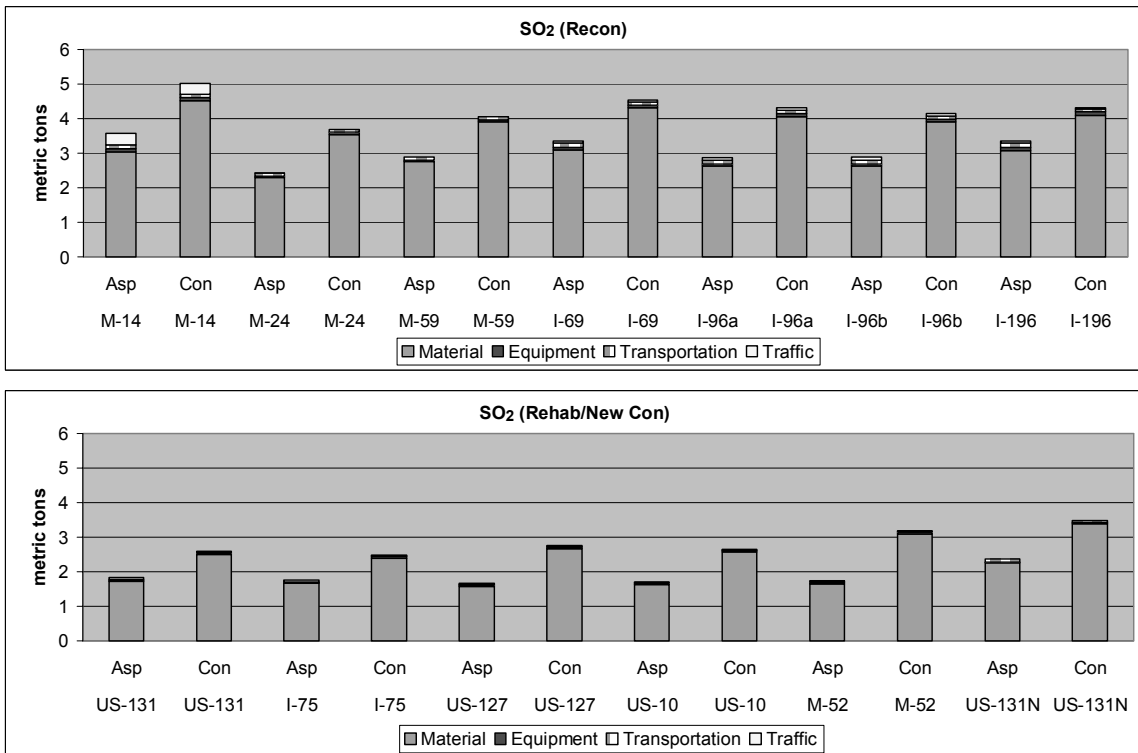
Figure 20: Life-cycle sulfur dioxide emissions of reconstruction (top), rehabilitation and new construction projects (bottom right) by activities
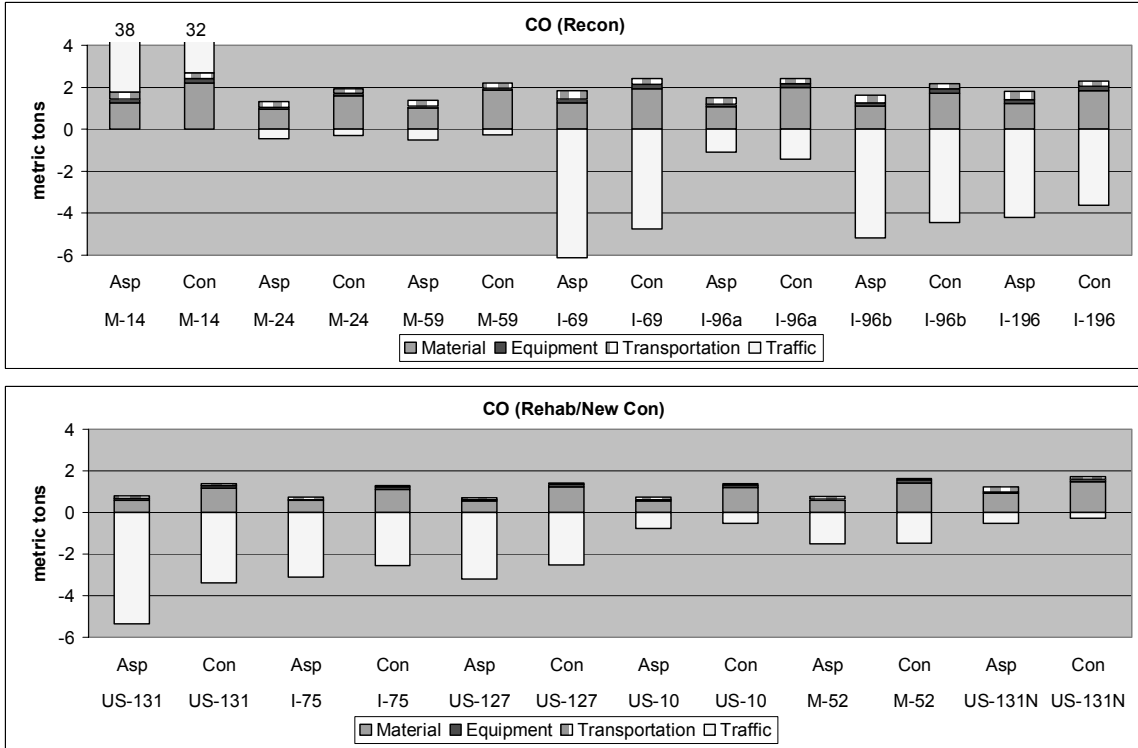
Figure 21: Life-cycle carbon monoxide emissions of reconstruction (top), rehabilitation and new construction projects (bottom right) by activities
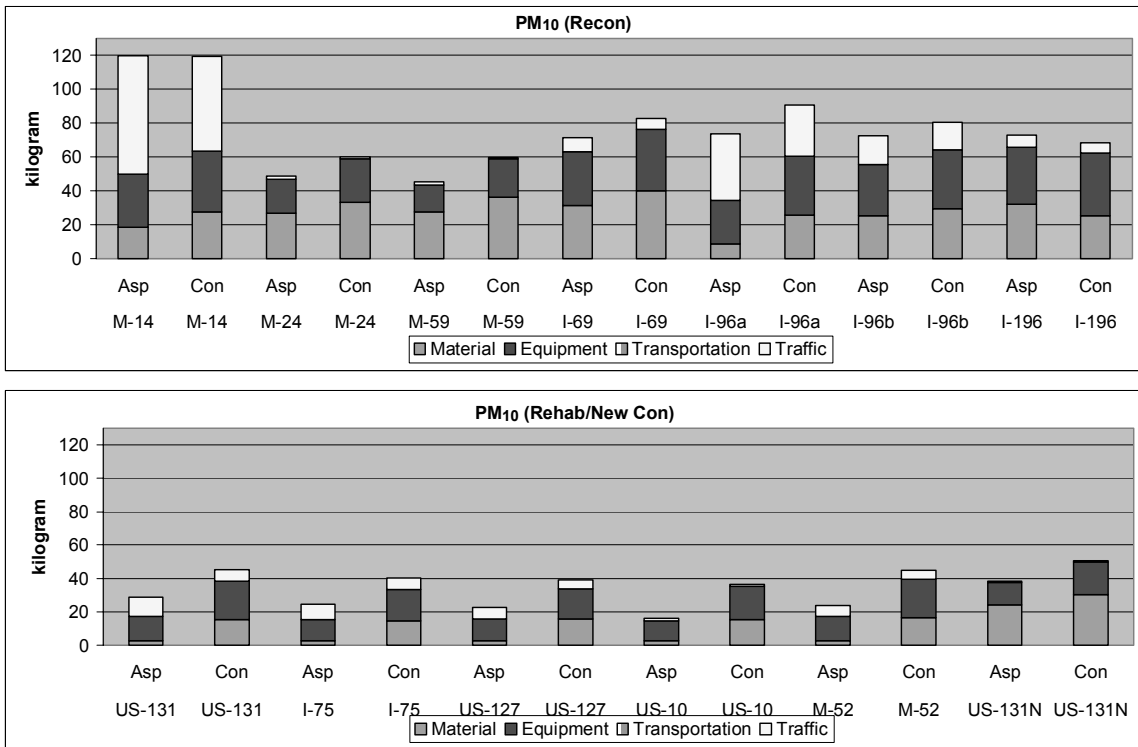
Figure 22: Life-cycle particulate matter emissions of reconstruction (top), rehabilitation and new construction projects (bottom right) by activities
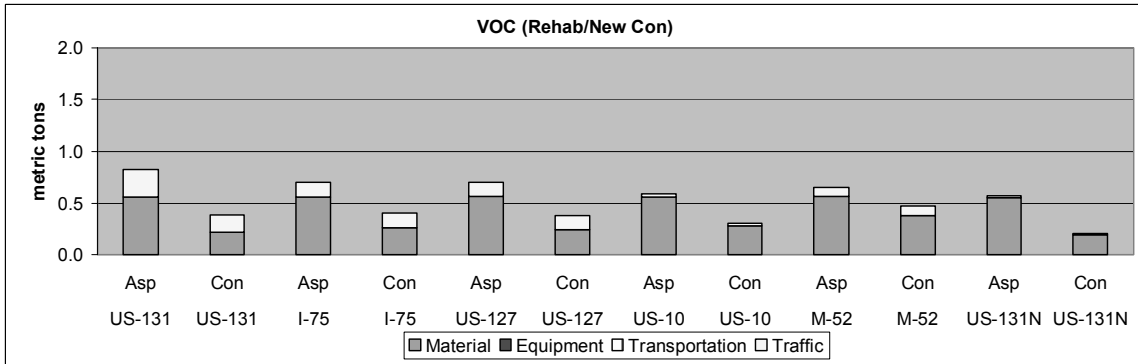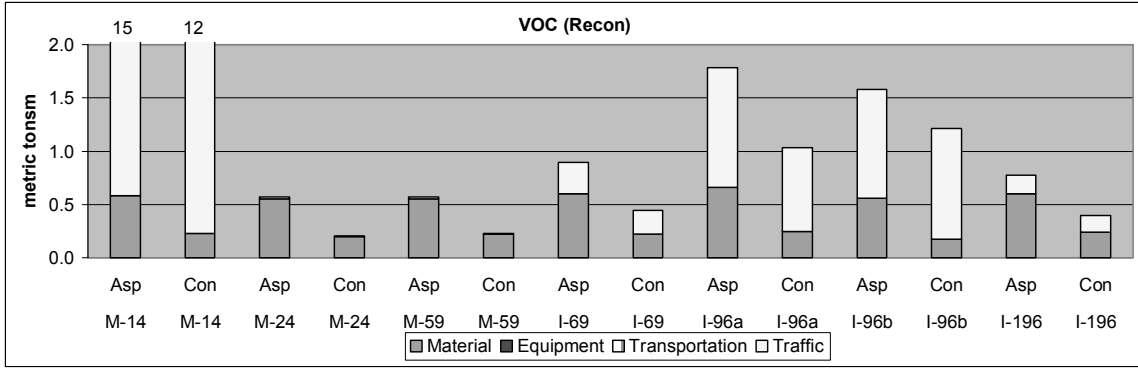
Figure 23: Life-cycle VOC emissions of reconstruction (top), rehabilitation and new construction projects (bottom right) by activities

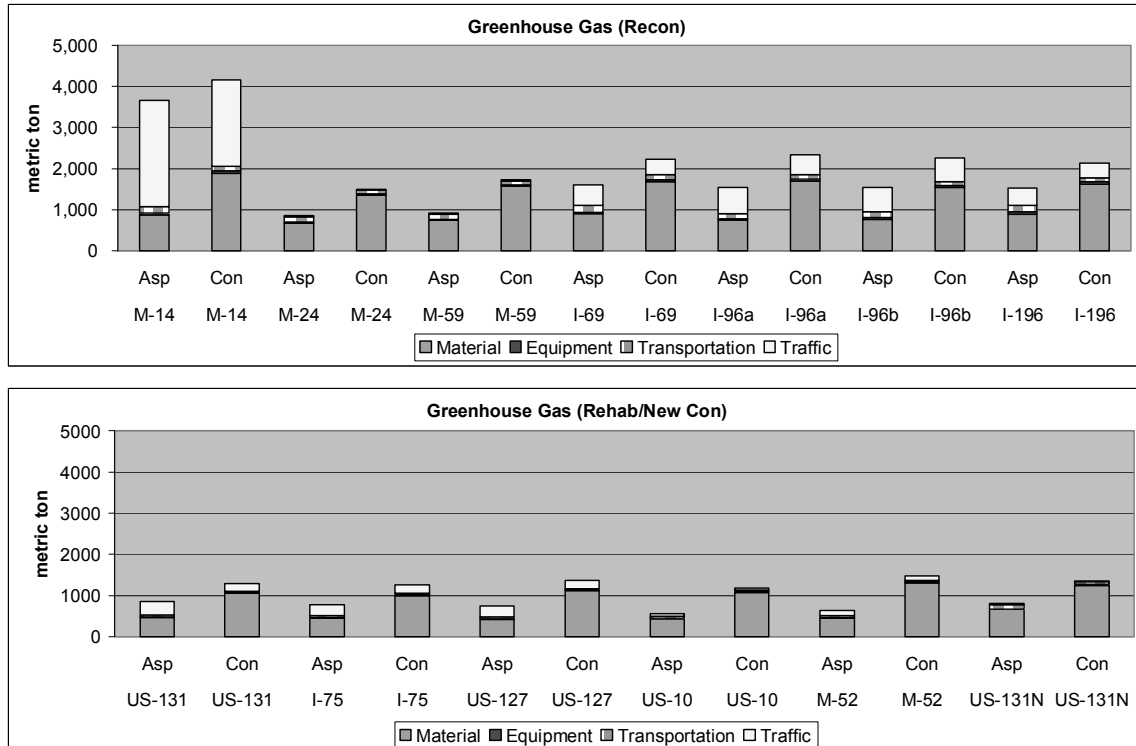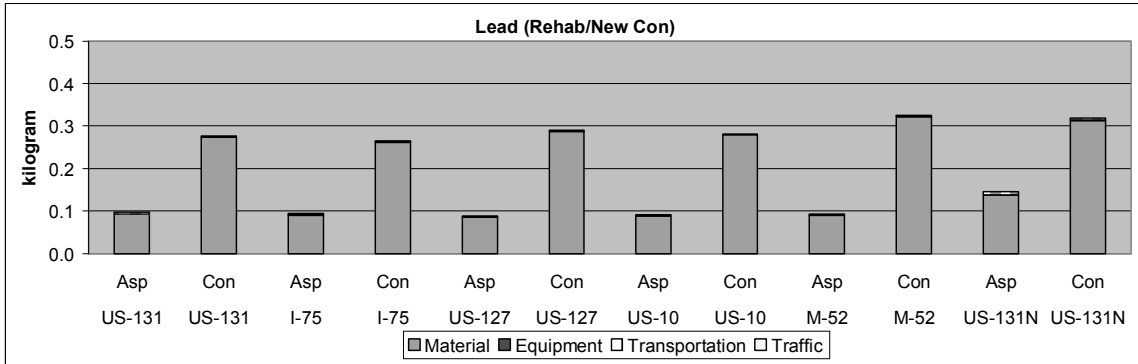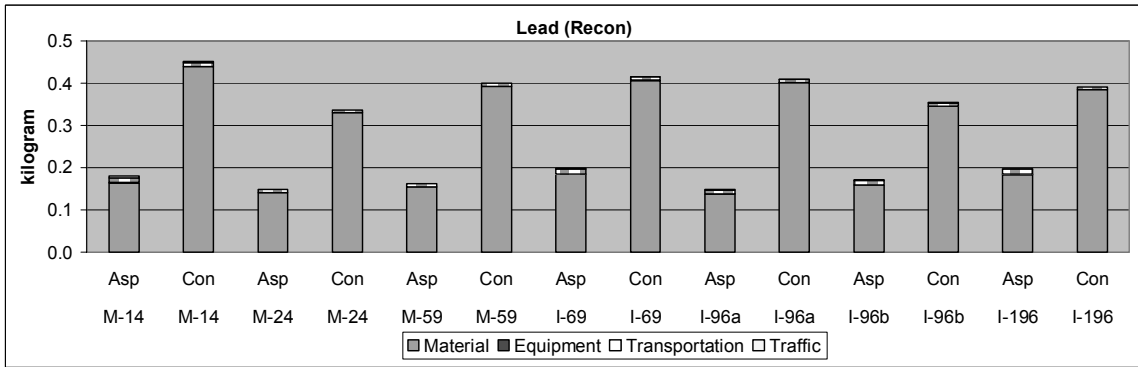**Figure 24: Life-cycle lead (gaseous) emissions of reconstruction (top), rehabilitation and new construction projects (bottom right) by activities**
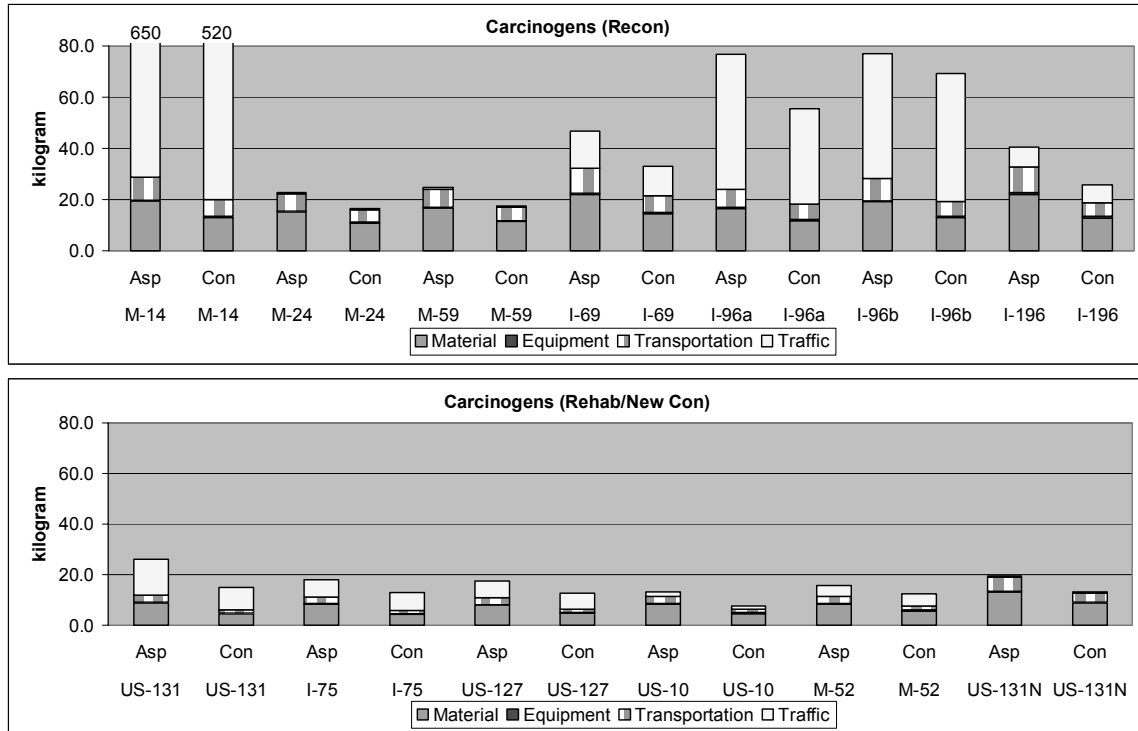
Figure 25: Life-cycle carcinogenic (gaseous) emissions of reconstruction (top), rehabilitation and new construction projects (bottom right) by activities

Production Impact of Surface Course Materials

Results from the case study projects suggested that material production processes were the dominant positive contributor in all environmental indicators. While asphalt and concrete are the major surface-paving materials, their contributions to different environmental impact varied from 1% to 95%, depending on the environmental indicators concerned, fix type and pavement type (Table 6). For example, asphalt and concrete production accounted for 3% to 12% and 10% to 25% of PM_{10} emissions, and 1% to 3% and 5% to 30% of VOC emissions respectively. VOC emissions in asphalt alternatives were predominantly from cracks-sealing maintenance activities (ERG 2001) and/or from traffic delay (Figure 23); for concrete pavements, they were primarily emitted during the production of petroleum-based pavement joints-filling materials. On the other end of spectrum, production of surface course materials was responsible for the major proportion of primary energy consumption (asphalt: 65% to 95%, concrete: 35% to 85%),

Table 6: Contributions of major surface course materials (asphalt or concrete) to environmental indicators studied

Fix Type Indicators\Alternatives	Recon/Construction		Rehabilitation	
	Asphalt	Concrete	Asphalt	Concrete
Primary Energy	65-85%	35-65%	85-95%	65-85%
CO	25-50%	40-75%	65-75%	70-80%
GHG	30-60%	40-70%	55-75%	80-90%
NOx	30-60%	55-85%	70-75%	80-85%
Pb	50-70%	65-75%	90-95%	70-80%
PM_{10}	3-7%	10-20%	8-12%	15-25%
SO_2	55-60%	65-75%	90-95%	70-80%
VOC	1-3%	5-30%	1.3-1.6%	10-15%
Carcinogens	10-35%	10-30%	30-45%	30-60%

lead emissions (asphalt: 50% to 95%, concrete: 65% to 80%) and SO_2 emissions (asphalt: 55% to 95%, concrete: 65% to 80%). The lower end often represented the case study projects that had more impacts from traffic delay.

Pavement types and fix types accounted for the differences as well. For example, 35% to 85% of primary energy consumption was contributed to concrete production. It was 65% to 95% for asphalt production, reflecting the high feedstock energy of bitumen. Higher contribution percentages were also found in rehabilitation compared to reconstruction and new construction projects, although the impacts were lower quantitatively. It is possibly because a new road base is not required for rehabilitation projects, making asphalt or concrete the primary new material to be produced. Additionally, rehabilitation projects take less time to complete, thereby reducing the total work-zone-induced traffic delay.

Sensitivity Analysis

Differences in the amount of energy consumption and air pollutants emissions were observed among case study projects. While the results were presented in a normalized fashion, the differences were not due to the number of lanes of the projects but a number of factors. Infrastructure-wise, the projects had different pavement designs, with various shoulder widths and pavement thickness (

Table 2). Therefore, the material requirements were different as well. The other important factor is the difference in road capacity and traffic volume, which determines the level of traffic delay during the construction period. For example, a maintenance activity which closes two driving lanes is expected to cause less delay on a 10-lane highway than a 4-lane highway with the same traffic volume. Alternatively, slight changes in maintenance schedules would not pose major changes in environmental impacts as 75% to 99% of emissions were emitted during the initial construction period.

Differences can also arise from differences in material mixes. By default, this study assumed that the asphalt layers have 25% recycled asphalt content for asphalt pavement, and 2% fly-ash content in concrete pavement. If no recycled materials are used, the energy consumption and pollutants emissions rose by as much as 52% (NO_x). Net CO emissions can change from being negative to positive. Nonetheless, the qualitative results remained the same when asphalt alternatives were compared against concrete alternatives for all environmental indicators concerned. Table 7 illustrates the maximum extent to which the values of environmental indicators increase.

Table 7: Maximum percentage increase in environmental impacts for pavements using no recycled material

Environmental Indicators	Max %
Primary Energy	30%
CO	from negative to positive
GHG	25%
NOx	52%
SO$_2$	31%
Pb	31%
PM	4%
VOC	2%
carcinogens	20%

N.B. The maximum percentages were achieved by separate projects

Comparison with other LCA studies

As discussed in Section 2.3 Previous Research, Stripple (2000, 2001) and Horvath et al (1998) have both studied the life-cycle environmental impact of newly-constructed

asphalt and concrete pavements. Stripple (2001) concluded that 37% more energy is required for concrete than asphalt pavement, while Horvath et al (1998) suggested that both pavement types have comparable environmental inputs and outputs. This study yielded results that are quite different from those in the two studies. It is not surprising as the conceptual roadways in the two studies were two-lane wide, while the results in this study were normalized by a 4-lane highway. More importantly, the two studies had different systems boundaries and data sources. Both did not include road base and pavement shoulders in their assessments, which contributed more than half of the material input requirements for reconstruction projects. Data sources used in this study have in general higher pollutant emission rates per material output than the sources used by Stripple (2001). For example, SO_2 emissions associated with bitumen production are 2.05 and 0.02 kg/kg of bitumen in this study and that of Stripple (2001) respectively.

The difference in conclusion between Horvath et al's (1998) and this study is primarily due to the different assumptions over pavement service life. This study used the MDOT observations that asphalt and concrete pavements have similar service life (20-21 years for rehabilitation projects and 26 years for reconstruction projects) (Appendix II), while Horvath et al (1998) assumed that asphalt and concrete pavement lasted 13-15 and 20-25 years respectively. If environmental impacts were not annualized, Horvath et al's (1998) studies showed that asphalt alternatives would have higher energy consumption, lower SO_2 and NO_x emissions than concrete alternatives, which are qualitatively the same as this study indicated.

Similar conclusions were reached by Stripple (2001) and this study. Asphalt alternatives were found to have higher energy consumption and lower emissions of CO_2, SO_2 and NO_x than concrete alternatives. However, maintenance activities had a higher contribution to the environmental impacts. Stripple's results were based on a 40-year analysis period, thus more maintenance activities were carried out over a longer time frame to maintain the serviceability of the road.

5.6 Results and Discussions: Pollution Damage Costs of Pavements

Life-cycle pollution damage costs were calculated for the thirteen studied projects based on the environmental indicators presented in Section 5.5. The costs included the potential global warming and human health impacts of GHG, CO, NO_x, SO_2, PM_{10} and VOC emissions respectively. They varied across projects, ranging from \$1,500-\$14,000 per km for the asphalt alternative of 2-lanes M-52 to \$23,000-\$175,000 per km for the concrete alternative of 10-lanes I-96a (in 2006 dollars). Figure 26 compared the average pollution damage costs of asphalt and concrete alternatives of studied projects (the costs in figure and this section were normalized as per 4-lane km).

Reconstruction projects (asphalt: \$6,200-\$76,000/4-lanes-km, concrete: \$7,500-\$70,000) incurred higher pollution damage costs than rehabilitation (asphalt: \$1,900-\$29,000, concrete: \$3,800-\$39,000) and new construction projects (asphalt: \$5,300-\$53,000, concrete: \$6,200-\$53,000). Most of the pollution damage costs were incurred at initial construction period, with 47% to 90% for asphalt alternatives and 85% to 95% for the concrete alternatives. The result is expected as 70% to 75% and 95% to 99% of materials were produced and transported to the site for asphalt and concrete alternatives at the initial construction period respectively.

Contributions by Activities

Unlike the environmental indicators, pollution damage costs showed a somewhat different pattern (Figure 26). Material production (14% to 40%) was no longer the dominant factor. Instead, material transportation (26% to 65%) and construction equipment operation (13% to 32%) became the more important contributors. It is primarily due to the use of higher marginal damage costs of air pollutant emissions for these sources. For example, NO_x emissions from these sources cost 8 to 62 times (for low and high estimates respectively) more than that from material production (Table 4). It made a huge difference as NO_x emission was one of the major emissions and had a high marginal damage cost. Between the two pavement alternatives, pollution damage

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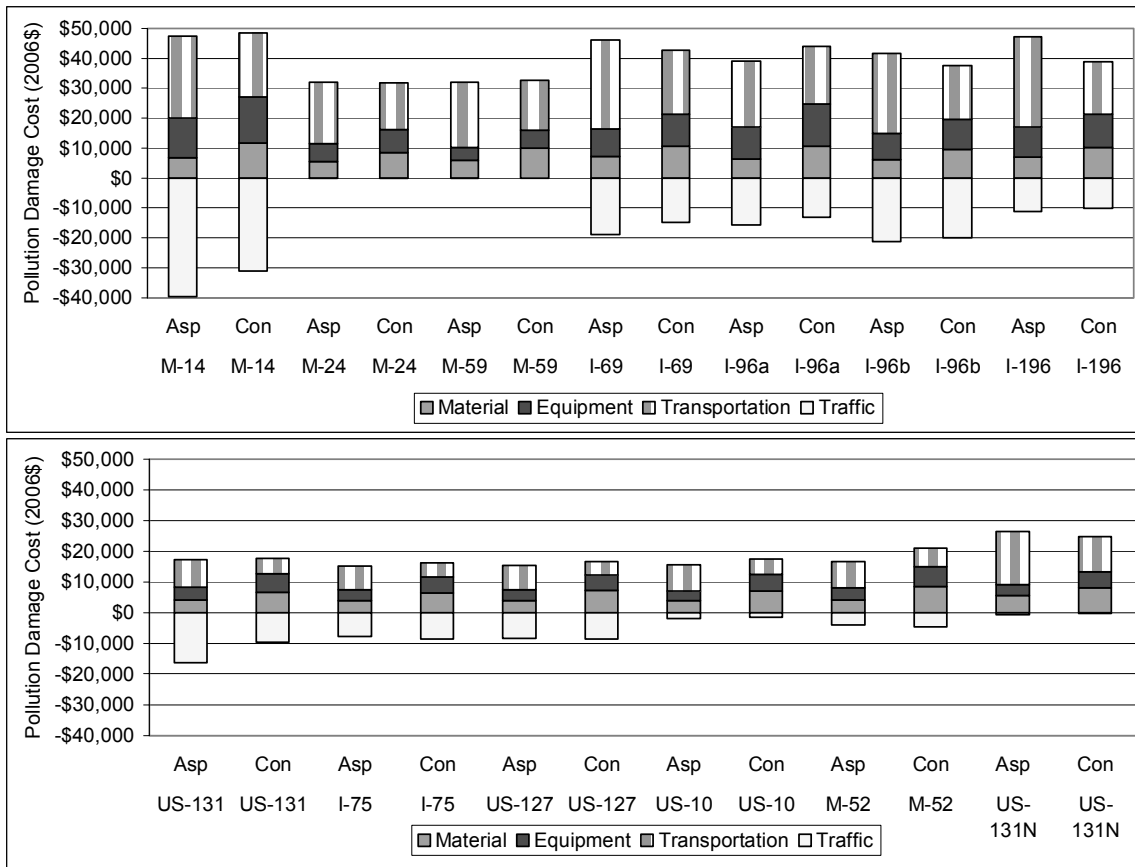
Figure 26: Avg. pollution damage costs of asphalt and concrete alternatives of reconstruction (top), rehabilitation and new construction projects (bottom) by activities
(Costs are normalized per 4-lane km in 2006 dollars)
(Appendix V showed the results for low and high estimates)

costs from material transportation were usually higher for the asphalt than the concrete pavements, for the reason that asphalt pavements consumed more materials over pavement service life (Table 5).

Contribution from construction-related traffic delay was again highly dependent on the traffic volume and road capacity. However, it yielded negative pollution damage costs (except for M-14) because small traffic delay curtailed NO_x and CO emissions. Asphalt alternatives tended to be more influenced by traffic delay as the maintenance

activities for the asphalt alternatives took longer periods than those for the concrete alternatives. This is also true for reconstruction projects in comparison with rehabilitation projects. By and large, traffic delay reduced the overall pollution damage costs by 1% to 80% depending on the level of traffic delay. If traffic delay was not considered, pollution damage costs would range from $3,100-$18,000/4-lane-km (asphalt alt. of US-127) to $11,000-$101,000/4-lane-km (concrete alt. of M-14) (low and high estimates).

Contributions by Air Pollutants Emissions

Pollution damage costs were characterized by GHG and NO_x being the major components (with 40% to 80% of costs combined), SO_2 and PM contributing comparably (10% to 20%) and CO having negligible contribution. The contribution of NO_x is tied to construction-related traffic delay. It was usually negative when NO_x reductions from traffic delay offset the NO_x emissions from construction equipment operation and material transportation (Figure 19). NO_x, SO_2 and PM emissions had more substantial contribution to pollution damage costs than in environmental impacts because they have much higher marginal damage costs than GHG, particularly CO_2. Figure 27 depicts the general contributions to pollution damage costs by GHG and air pollutants.
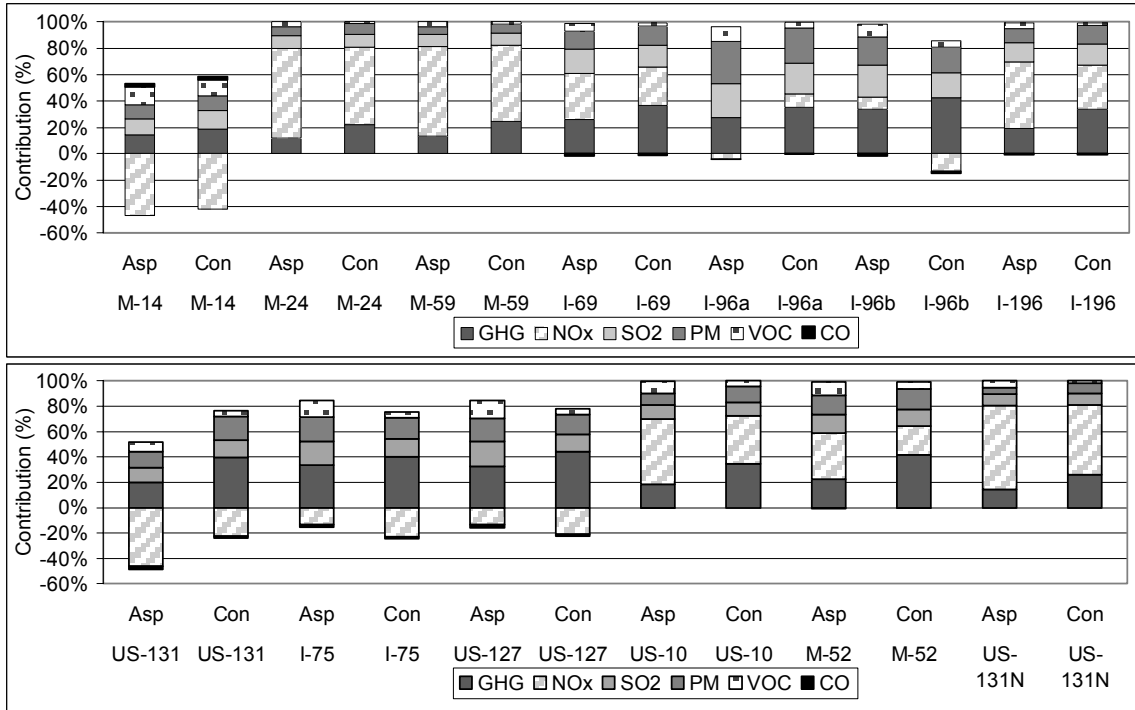
Figure 27: Contributions to pollution damage costs (average) by GHG and air pollutants emissions for reconstruction (top), rehabilitation and new construction projects

Contributions by Major Surface Course Materials

Production of asphalt and concrete had less impact on pollution damage costs, while indirect impacts (i.e. transportation of material/wastes to/from construction sites) were more substantial. Overall, asphalt and concrete production generated 5% to 39% of pollution damage costs. Higher percentages of contributions were observed for concrete compared with asphalt alternatives (19% to 39% vs. 5% to 18%). The same was found for rehabilitation than reconstruction and new construction projects (9% to 30% vs. 5% to 24%). Asphalt alternatives had lower percentages because they have higher material input requirements (Table 5). Given that marginal damage costs used to monetize impact from material transportation were much higher than those from material production (Table 4), pollution damage costs from material transportation increase faster than those from material production for each unit increase in material input requirement. The same

explanation applies to rehabilitation vs. reconstruction projects as well, as rehabilitation projects consumed fewer materials (Table 5).

Asphalt vs. Concrete

Asphalt alternatives incurred higher pollution damage costs in six of the thirteen case study projects, but only one of them was a rehabilitation project. For the rehabilitation projects, the lowest-cost alternative proposed in the original LCCA documents coincided with the lowest pollution damage costs calculated in this study; for reconstruction and construction projects, only half of them followed the same trend (Table 8). The alternative with the lowest pollution damage costs did not necessarily have a thinner surface paving layer. Nonetheless, the difference in pollution damage costs between alternatives was not very prominent. The smallest and the largest differences were $100 and $44,000 per km (2006 dollars) respectively (Table 8). A larger difference was expected for I-96a as it is a 10-lane highway.

Table 8: Comparison between the lowest-cost alternative proposed in the LCCA documents and the alternative with the lowest pollution damage cost

Project ID	Route	Lowest-cost alt. in LCCA	Alt. with lowest pollution damage cost	Difference in pollution damage. cost from higher-cost alt. (2006$/km)
Rehabilitation Projects				
38209	US-131	UCO	UCO	$1,900-$15,000
43521	M-52	AORC	AORC	$1,100-$5,600
50629/ 53304	US-10	AORC	AORC	$1,600-$7,100
60450	US-127	AORC	AORC	$1,400-4,600
55125	I-75	AORC	AORC	$1,000-$2,400
Reconstruction Projects				
45640	I-96b	JRCP	JRCP	$1,700-$1,900
45711	M-14	JPCP	HMA	$2,500-$23,000
48608	I-96a	JPCP	HMA	$6,700-$44,000
48762	M-59	HMA	HMA	$1,700-$5,300
50775	I-69	JPCP	JPCP	$1,400-$3,800
55908	M-24	HMA	JPCP	$1,300-$2,500
60471	I-196	JPCP	JPCP	$210-$11,000
New Construction Project				
34682	US-131	Asphalt	JPCP	$100-$1,000

AORC: asphalt on rubblized concrete
HMA: hot-mix asphalt
JPCP: jointed plain concrete pavement
JRCP: jointed reinforced concrete pavement
UCO: unbonded concrete overlay

Sensitivity Analysis

The original analysis was based on the assumption that recycled contents are present in the materials. Additional analysis was done for the case study projects when no recycled material was used for surface course materials. It was computed that pavements with no recycled material would only increase the overall damage costs by as much as $900 per 4-lane-km. The extra costs mainly came from the increase in greenhouse gas emissions (70-80%) to mine virgin materials.

The cost patterns observed in this study were partly dependent upon the choice of different marginal damage costs for air pollutants. As a result, two extra scenarios were

done using either set of marginal damage costs for conventional air pollutants (Banzhaf et al 1996 or Delucchi et al 1996 marginal damage costs data). When only Banzhaf et al (1996) data was used, the pollution damage costs ranged from $1,700-$156,000 per 4-lane-km; when Delucchi et al (1996) data was applied, the pollution damage costs rose to $12,000-$410,000 per 4-lane-km. It is expected as marginal damage costs estimated by Delucchi et al (1996) were up to 64 times higher than those by Banzhaf et al (1996). Negative pollution damage costs due to NO_x emissions reduction from construction-related traffic delay were reduced because pollution damage costs from all emission pathways were weighed equally in the two scenarios and material production was the major source of NO_x emissions.

5.7 Significance of Pollution Damage Costs

Figure 28 contrasted the pollution damage costs with agency and user costs which are currently considered in the MDOT LCCA procedure. Even when the high estimates were considered, pollution damage costs were only 0.8% to 9.2% of the total life-cycle costs. There were no major differences in the range of percentages among reconstruction, rehabilitation and new construction projects. Moreover, pollution damage costs weighed less in projects with high user costs. While the traffic delay in the construction zone induced user delay costs, the reduction in speed actually lowered total NO_x emissions and reduced the pollution damage costs. The reduction was indeed sizeable especially for studied projects including M-14 and US-131 (Figure 26). For example, 80% of the pollution damage costs were offset for M-14.

More importantly, the lowest-cost alternatives proposed in the MDOT LCCA documents remained the same even if the pollution damage cost component was incorporated. The pollution damage costs of asphalt and concrete alternatives for the case study projects differed by $100 to $44,000 per km as calculated (Table 8), but the difference in life-cycle agency and user costs between alternatives (as listed in LCCA documents) were in the range of $30,000 (I-69) to $0.9 million per km (I-96a). If all the MDOT projects with LCCA documents were considered, the range was $3,000 to $0.9

67

million, or 0.45% to 54% of life-cycle agency and user costs of the highest-cost alternatives. The differences were more than $0.1 million for 75% of the road projects, and less than $10,000 for only 5% of the projects. For the case study projects, the pollution damage costs were not substantial enough to make the original higher-cost alternative cheaper than the other.
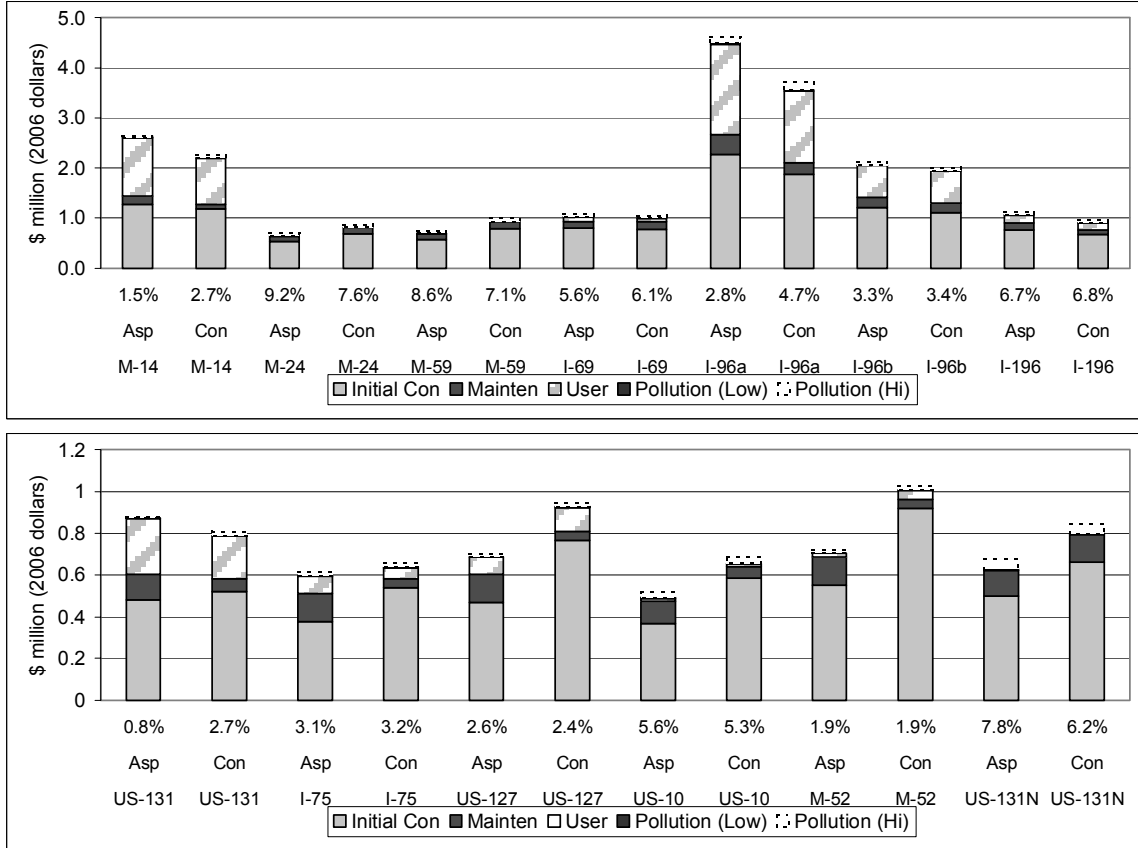
Figure 28: Significance of pollution damage costs compared with other costs for reconstruction (top), rehabilitation and new construction projects (bottom)
(Percentage denoted contribution from pollution damage cost when hi estimates were considered)

5.8 Limitations of the Study

Pavement performance and service life are highly dependent on the site-specific factors such as climate, traffic loadings and maintenance routines practiced by the states DOTs. This study looked at thirteen MDOT road projects constructed in the late 1990s and afterwards. All of the parameters and assumptions on pavement design, material mixes and preservation schedules used in the study were based on Michigan situation. The LCA model used in this study had more than 50 adjustable parameters from pavement thicknesses to maintenance schedules, and the parameters were changed accordingly to represent the differences among the thirteen case study projects. While the results apply to the Michigan highways, it may not completely reflect the situation in other parts of the US, as well as the local roads. The same situation arises, as discussed in Chapter 2, when different results were found by comparing the life-cycle agency costs of asphalt and concrete pavements in different states.

There were limitations with regard to the LCA model itself. Several mixes are usually approved for asphalt or concrete in the construction project (MDOT 2006), but this study only assumed that one mix was used to construct the whole section in each project (Appendix I). Material production impacts and construction techniques were assumed constant over the pavement service life (20-26 years), which is not necessarily true. Technological advancement can reduce future material production impacts and construction time. For example, FHWA's Highways for LIFE[9] program, funded by SAFETEA-LU, took an integrated approach to advance the road construction practices. The program aimed at promoting and incentivizing the use of proven state-of-the-art practices, technologies and innovations in order to build highways and bridges faster, safer and better. The pilot projects in California, Colorado, New Mexico and Virginia constructed pavements with prefabricated slabs. The time of on-site construction was reduced by as much as 97%, when compared to conventional cast-in-place construction technique (FHWA 2004). As a result, the construction-related traffic impacts can be reduced by 97% as well.

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[9] LIFE is an acronym for Long lasting highways using Innovative technologies and practices to accomplish Fast construction of Efficient and safe pavements and bridges.

MDOT preservation strategies were used to help predict the future maintenance needs of the pavement alternatives. In the real world, however, actual maintenance activities do not always coincide with the proposed schedule in terms of both time and scale as shown in Chapter 4. Maintenance can be moved forward or deferred for political and financial reasons, and the service life of pavements will be affected. Fortunately, the impact of such uncertainty was not too decisive in this study, at least for the concrete alternatives. For instance, 85 to 95% of the pollution damage costs were incurred for the concrete alternatives during the initial construction phase. However, it can be problematic when most of the other states DOTs use an analysis period of more than 30 years in their respective LCCA procedures.

Lastly, monetizing the environmental impacts is controversial and full of uncertainty. The study deliberately limited the boundary to only monetize the impacts from greenhouse gas and conventional air pollutants emissions because there were more peer-reviewed papers related to these pollutants. Damage costs estimates on other pollutants, such as water pollution, were not abundant and the estimates can be highly site-specific. According to Tol (2005), there have been over 100 estimates of marginal damage costs of CO_2 and greenhouse gas emissions around the world. The mean of estimates is around \$97 per metric ton of carbon (tC) with a standard deviation of \$297/tC. In fact, some studies estimated a negative marginal damage cost for CO_2. On the other hand, there were few studies regarding the pollution damage costs of vehicle use in the US but the widely-cited research by Delucchi of the University of California at Davis (Delucchi et al 1996). The marginal damage costs suggested in his study was used to evaluate the pollution damage costs of emissions from material transportation, construction equipment operation and traffic delay. They are many times higher than Banzhaf's that were used to estimate pollution damage costs of emissions from material production, although they refer to different emission pathways (Table 4). This study presented the results with low and high estimates in order to capture some of the uncertainties, but the results remain dependent on the choice of marginal damage costs.

5.9 Conclusion

The original purpose of life-cycle costs analysis (LCCA) in road construction is purely about effective investment of government agency funds in the long run. The "externality" associated with road construction is becoming more recognized, and "user cost" has been incorporated into LCCA procedures by more than 40% of the states DOTs including MDOT nowadays. Because of the complexity and uncertainty of monetizing the environmental impact and assigning the boundaries, external costs are yet to be considered by any states DOTs. Nonetheless, a more holistic LCCA is needed to capture the "real" cost of road construction, and states DOTs officials have since realized the importance of incorporating external costs (i.e. human health impact, noise, crops damage, etc) into the LCCA procedures (MDOT 2006).

This study evaluated the environmental impact and pollution damage costs of asphalt and concrete alternatives, as a means to examine the importance of incorporating external costs into the LCCA of the pavement selection process. Based on the thirteen Michigan highway projects studied, carbon dioxide, nitrogen oxides and sulfur dioxide were the major emissions associated with road construction activities, from material production and transportation to on-site construction equipment operation and work-zone traffic delay. The model showed that asphalt alternatives performed worse in some environmental indicators (e.g. material use, primary energy, volatile organic compounds and carcinogens emissions) but better in others (e.g. greenhouse gases, nitrogen oxides, sulfur dioxide and lead emissions) than concrete alternatives. Material production was the major source of energy consumption and greenhouse gases and pollutants emissions, but contributions from traffic delay increased when the usual traffic volume approached normal road capacity. Additionally, the initial construction phase was the major contributor to the environmental indicators, because at least 80% of the materials were consumed in this phase.

Slightly different patterns were observed for pollution damage costs. For the studied projects, the costs ranged from $1,900-$76,000 per functional unit (4-lanes-km)

71

in 2006 dollars (Figure 26). Because marginal damage costs for conventional air pollutants were different by source, material transportation became the major contributor in pollution damage costs. Alternatively, construction-related traffic delay had negative effect on damage costs as NO_x emissions were reduced by slower traffic in the work zone. If this negative effect was not considered, the pollution costs could be increased by 1% to 280% depending on the original contribution by traffic delay. Most importantly, in the cloud of conflicting claims from the asphalt and concrete industries, the thirteen case studies did not show that one pavement alternative is always less environmental-costly than the other. The alternative with the lowest life-cycle agency and user costs did not necessarily have the lowest pollution damage costs either.

When compared with other components of life-cycle costs, pollution damage cost was rather small. It contributed to only 0.8% to 9.2% of total life-cycle costs even when the high estimates were used. The percentage decreased when traffic delay impact increased. Besides, the lowest-cost alternative remained the same for the case study projects if pollution damage costs were incorporated. Nonetheless, the importance of external costs in the LCCA procedure cannot be undermined. From the broader societal point of view, it is important to capture the "real" costs of road constructions as the externalities will be realized by the governments and the public eventually. From the pavement selection point of view, there still can be instances that the pollution damage costs alter the lowest-cost alternative. The difference in life-cycle agency and user costs of pavement alternatives was less than $10,000/km for 5% of the MDOT LCCA projects, which is the range of pollution damage costs difference among asphalt and concrete alternatives. It is also possible that pollution damage costs will become more important in future as construction techniques, traffic patterns and the associated environmental impacts may change and the marginal damage costs of pollutants emissions will be revised.

Besides, the LCA model did not capture all the associated external costs of road construction. For example, it did not take into the account the possible difference in fuel

economy between driving on asphalt and concrete roadways[10], and the possible drop in fuel economy when pavements deteriorate over service life. The accidents induced by road construction were not included. It did not consider the monetary impacts of water pollution from road construction as well. If these costs from the use phase were included, the external costs would have become more significant at least numerically in comparison with agency and user costs. In fact, Stripple (2001) calculated that the "total" energy consumption of traffic was nine times that for construction and maintenance of roads in a 40-year analysis period. Such dominance should be observed for external costs. Future work can look into this matter by expanding the boundary of external costs and studying more actual projects with small differences in life-cycle agency and user costs. Focus can also be shifted to studying projects in different states in order to generalize the findings.

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[10] Fuel economy depends on numerous factors such as rolling resistance, air resistance, inertia and gradient resistance. It is believed that the viscoelastic behavior of asphalt pavement might increase rolling resistance of heavy trucks and thereby reducing the fuel economy in comparison with rigid concrete pavement. Some studies have showed that there were either no differences or the differences were likely to be less than 1%. They added that surface roughness had more significant effect in fuel economy than pavement type (APA 2003, EAPA 2004). Yet, a few studies in Canada concluded a 1-6% difference (TC 2002, NRC 2006).

6. Conclusion and Future Directions

This thesis has investigated the economic and environmental aspects of life-cycle costs analysis (LCCA) practiced by the Michigan DOT pavement selection process. Chapter 4 looked at the actual application of LCCA by MDOT and evaluated the accuracies of MDOT LCCA procedures in predicting the pavement alternatives with the lowest life-cycle costs (agency and user costs). Chapter 5 computed the pollution damage cost, a component of external costs, associated with road construction and examined the impact of incorporating it into the current MODT LCCA procedure. The detailed conclusions were addressed at the end of Chapter 4 and 5 respectively.

All in all, the future development of LCCA is going in two directions. One is to refine the current LCCA parameters, and the other is to incorporate more elements of external costs. As shown in the previous chapters, the uncertainties related to predicting pavement performance and monetizing the pollution impacts of road construction presented a difficult modeling challenge. This thesis took an initial attempt to look at such issues by studying how current LCCA procedures projected life-cycle costs of pavements and how the incorporation of external costs into LCCA procedures would impact the current practices. Future work can focus on performing more empirical studies of the actual life-cycle costs and performance of pavements, developing better cost-estimation methods, expanding the systems boundary of the LCA model, or refining the monetary impacts of pollutant emissions. The LCA model developed for this thesis was designed solely to compute the environmental impact and external costs. The model can be merged into the LCC model currently used by the states DOTs to evaluate the life-cycle agency and user costs of pavement alternatives. A fully-integrated LCA-LCC model – considering economic, social and environmental elements – would serve as a more comprehensive tool to streamline the evaluation processes and promote road infrastructure sustainability.

Appendix

Appendix I: MDOT Pavement Selection Process

This appendix is an excerpt of Chapter 4: Pavement Selection Process in MDOT Pavement Design and Selection Manual (2005)

Pavement selection is determined using the life cycle cost analysis method when the project pavement costs exceed one million dollars. Pavement costs are determined by calculating the cost of the HMA and concrete necessary for paving the mainline pavement. When the cost of either the HMA or concrete exceeds $1 million a life cycle cost analysis is required. The process required for projects meeting these criteria is as follows:

Step 1 - Each Region Office identifies mainline pavement costs for upcoming projects in that Region. The Associate Region Engineer (Development) requests a pavement selection analysis from either the Region pavement designer or the Lansing Pavement Management Unit, using the following guidelines:

The Lansing Pavement Management Unit is responsible for preparing a pavement design and selection package for the following project types:

a) All new/reconstruction projects with mainline pavement costs greater than $1 million.

b) Major rehabilitation projects (unbonded concrete overlays & rubblized with HMA surfacing) with mainline pavement costs greater than $1 million.

The Region pavement designer is responsible for preparing a pavement design and selection package for the following project types:

a) Rehabilitation projects (other than major rehabilitations)

b) Local roads being redesigned due to an MDOT project. Pavement designs for local roads require the concurrence of the local agency.

c) New, reconstruction and major rehabilitation projects when the mainline pavement cost is less than $1 million.

Steps 2-5 pertain to projects where pavement selection is the responsibility of the Lansing Pavement Management Unit. Otherwise, assistance will be given to the Regions on an as-needed basis.

Step 2 - The appropriate Region personnel will request, assemble and provide all necessary information for projects requiring the Pavement Management Unit to prepare the pavement design and Life Cycle Cost Analysis. This information includes existing soils information, traffic data, maintenance of traffic scheme, as well as other miscellaneous information listed on the Life Cycle Cost Analysis Checklist, found in the appendix.

Step 3 - The pavement designer prepares multiple pavement designs to be used in the Life Cycle Cost Analysis (LCCA). A design life is selected based on the pavement fix life that is assigned to the project in the Region or Statewide program. The alternates considered should include both a concrete and HMA alternate. In the event that either a standard concrete or HMA alternate do not exist for the specified fix life, the pavement designer will consider multiple pavement alternates using the same surfacing material.

Step 4 - The pavement designer submits design alternates to the Pavement Selection Engineer, who prepares the LCCA package. The LCCA package should include:

-A cover memo indicating the alternate with the lowest life cycle cost and a project summary explaining the project location, existing and proposed typicals, existing pavement condition (including RSL and RQI), traffic volumes, construction staging and maintaining traffic scheme.

-An appendix should also be attached which includes all of the detailed information that was used in the analysis. Items such as unit prices, production rates, soil boring logs and

recommendation memos, traffic memos, construction scheduling analysis, pavement design information and life cycle cost calculations should all be included in the appendix.

Step 5 - The Pavement Management Engineer along with the Pavement Selection Engineer, Lansing Pavement Design Engineer and any other necessary Lansing/Region personnel review the pavement selection package. Corrections, if necessary, are made, and an updated package is forwarded to the Engineering Operations Committee (EOC) for a preliminary review. Once the LCCA package is preliminarily approved, it is sent out for industry review. Again, corrections, if any, are made, and the final package is submitted to EOC for final review and approval.

The Engineering Operations Committee approves the pavement selection based on the alternate that has the lowest life cycle cost. EOC is the senior technical committee in MDOT. The committee membership includes the Chief Engineer, representatives from the Design Division, Construction & Technology Division, Maintenance Division, Traffic & Safety Division, Region Offices and the Federal Highway Administration. The committee is chaired by the Chief Operations Officer.

Step 6 - Region Office or Bureau of Planning finalize the Scope of Work for the proposed project.

Step 7 - Region or Bureau of Planning program the project and the project is assigned to a Design Engineer with a Plan Completion Date

Projects having pavement costs less than one million dollars are not required to follow the above process. However, the pavement designer should use some form of objective analysis for these projects to determine pavement type selection. The analysis technique should document that the decision supports cost-effective use of the Department's pavement preservation dollars.

Appendix II: MDOT Pavement Preservation Strategy

This appendix describes the pavement preservation strategies excerpted from Chapter 7 of the latest MDOT Pavement Design and Selection Manual (MDOT 2005). According to MDOT, the strategies are estimated based on actual historical maintenance and pavement management records, and "reflect the overall maintenance approach that has been used network-wide for a specific fix type (i.e. reconstruction or rehabilitation)." Since the first application of LCCA by MDOT in 1985, the projected preservation strategies were changed several times. The latest version projects a shorter pavement service life than the pre-1998 ones for both asphalt and concrete alternatives.

Table 9.1-2: Preservation strategies of freeways after (re)construction

Facility: Freeway/ Divided Highway
Fix Type: New/Reconstruction - Flexible HMA Pavement

Activity	Distress Index (Before)	Distress Index (After)	Approx. Age	RSL (yrs) (Before Fix)	Life (yrs) Extension	RSL (yrs) (After Fix)	Cost per Lane-Mile
Initial Construction	0		0			13	Computed Computed
Prev. Maintenance	29	6	10	3	5	8	$33,789 See Table A
Prev. Maintenance	18	0	13	5	8	13	$44,730 E10 $54,384 E30 $52,293 E50 See Table A
Rehabilitation or Reconstruction			26				

Facility: Freeway/ Divided Highway
Fix Type: New/Reconstruction - Rigid Concrete Pavement

Activity	Distress Index (Before)	Distress Index (After)	Approx. Age	RSL (yrs) (Before Fix)	Life (yrs) Extension	RSL (yrs) (After Fix)	Cost per Lane-Mile	
Initial Construction	0		0			22	Computed Computed	Agency User Cost
Prev. Maintenance	6	5	9	13	1	14	$13,516 See Table A	Agency* User Cost
Prev. Maintenance	18	10	15	8	3	11	$41,834 See Table A	Agency** User Cost
Rehabilitation or Reconstruction			26					

Facility: Freeway/ Divided Highway
Fix Type: Rehabilitation - Unbonded Concrete Overlay on Repaired Concrete

Activity	Distress Index (Before)	Distress Index (After)	Approx. Age	RSL (yrs) (Before Fix)	Life (yrs) Extension	RSL (yrs) (After Fix)	Cost per Lane-Mile	
Initial Construction	0		0			18	Computed Computed	Agency User Cost
Prev. Maintenance	10	3	11	7	3	10	$25,905 See Table A	Agency* User Cost
Rehabilitation or Reconstruction			21					

Facility: Freeway/ Divided Highway
Fix Type: Rehabilitation - HMA Overlay on Rubblized Concrete

Activity	Distress Index (Before)	Distress Index (After)	Approx. Age	RSL (yrs) (Before Fix)	Life (yrs) Extension	RSL (yrs) (After Fix)	Cost per Lane-Mile	
Initial Construction	0		0			10	Computed Computed	Agency User Cost
Prev. Maintenance	17	15	6	4	1	5	$20,273 See Table A	Agency* User Cost
Prev. Maintenance	23	0	8	3	7	10	$46,661 E10 $56,315 E30 $54,384 E50 See Table A	Agency** Agency** Agency** User Cost
Prev. Maintenance	7	2	12	6	2	8	$4,827 See Table A	Agency* User Cost
Rehabilitation or Reconstruction			20					

Table 10.1-2: Preservation strategies of freeways after rehabilitation

Table 11.1-2: Preservation strategies of low volume roads after (re)construction

Facility: Low Volume
Fix Type: New/Reconstruction - Flexible HMA Pavement

Activity	Distress Index (Before)	Distress Index (After)	Approx. Age	RSL (yrs) (Before Fix)	Life (yrs) Extension	RSL (yrs) (After Fix)	Cost per Lane-Mile	
Initial Construction	0		0			15	Computed Computed	Agency User Cost
Prev. Maintenance	27	7	11	4	5	9	$22,204 See Table A	Agency* User Cost
Prev. Maintenance	20	0	15	5	10	15	$44,891 E3 $45,696 E10 $55,350 E30 See Table A	Agency** Agency** Agency** User Cost
Rehabilitation or Reconstruction			30					

Table 12: Preservation strategies of low volume roads after rehabilitation

Facility: Low Volume (Combined projects with Freeway)
Fix Type: Rehabilitation - HMA Overlay on Rubblized Concrete

Activity	Distress Index (Before)	Distress Index (After)	Approx. Age	RSL (yrs) (Before Fix)	Life (yrs) Extension	RSL (yrs) (After Fix)	Cost per Lane-Mile	
Initial Construction	0		0			11	Computed Computed	Agency User Cost
Prev. Maintenance	10	6	6	5	1	6	$27,192 See Table A	Agency* User Cost
Prev. Maintenance	20	0	9	3	8	11	$44,891 E3 $45,696 E10 $55,350 E30	Agency** Agency** Agency**

Facility: Low Volume **(Combined projects with Freeway)**
Fix Type: New/Reconstruction - Rigid Concrete Pavement

Activity	Distress Index (Before)	Distress Index (After)	Approx. Age	RSL (yrs) (Before Fix)	Life (yrs) Extension	RSL (yrs) (After Fix)	Cost per Lane-Mile	
Initial Construction	0		0			21	Computed Computed	Agency User Cost
Prev. Maintenance	6	5	8	13	1	14	$13,516 See Table A	Agency* User Cost
Prev. Maintenance	20	5	16	6	8	14	$65,647 See Table A	Agency** User Cost
Rehabilitation or Reconstruction			30					

Appendix III: The Competition between Asphalt and Concrete

The asphalt and concrete industries are fierce competitors in road infrastructure businesses. One of the hotly debated topics is related to the life-cycle costs of asphalt and concrete pavements. Both sides have launched campaigns and drew supporting studies to promote their products as the most economical paving material. An author in one of the articles cited in the attachment below once mentioned in personal communications, "It is a very hotly debated topic and the stakes to the contractors are very high. One side thought I was a hero and the other side called me every name in the book, including questioning my professional ethics and integrity." Attached is a two-page leaflet published by the Minnesota Asphalt Paving Association and Dakota Asphalt Pavement Association Inc with an overwhelming list of facts and references to communicate the idea that HMA is the most economically and environmentally-sustainable paving material. Notice that it is only one of the many fact sheets or articles circulated by the asphalt and concrete industries.

Which of these claims being made about HMA pavement do you find believable?

The competition claims to have:

☐ Lower costs less than HMA
☐ Longer life than HMA with less need for maintenance and repair
☐ A quieter surface than HMA
☐ A safer surface than HMA
☐ More environmental appeal than HMA
☐ Better energy-efficiency than HMA, and
☐ More aesthetically pleasing appearance than HMA.

How about ☑ NONE OF THE ABOVE!

In fact, did you know:

➢ Hot-Mix Asphalt (HMA) is still the best value for pavements. The cost of HMA pavement material has the smallest increase in cost of any construction material over the years and is the most recycled material.

➢ HMA pavements constructed in recent years benefit from the improved design and quality control techniques to demonstrate that it is the best pavement material.

➢ HMA pavements have been and can be designed as "PERPETUAL PAVEMENTS" meaning engineered from the bottom-up to last generations. Minnesota has won four National Perpetual Pavement Awards, which shows that it is a high-tech product. These HMA pavements range from 40 to 47 years of service and are still going strong.

➢ HMA Pavements, either Full-Depth or Aggregate base design have a service life exceeding concrete pavements. Most concrete pavements are either overlaid with HMA, removed from service, or receive major repair work by the time they reach 20 years of age.

➢ Most HMA facilities (highways, local streets, airports ...) receive their first overlay after 15 to 18 years of service (design basis of 20 years) and continue to provide service to the driving public for generations. If maintenance is needed, it is quick, easy, economical, and can be performed with local specifier work force.

➢ HMA offers the quietest driving surface available today. Research shows asphalt surfaces are a cost-effective way to reduce traffic noise, noise walls, and corridor costs.

➢ The riding surface of an HMA pavement is smoother than concrete. Smooth pavements save fuel, reduce damage to roadways and vehicles, and produce less noise.

➢ Aesthetically, HMA is a flexible pavement that is designed to conform to rolling and flat terrain with a smooth surface.

➢ Emissions from HMA facilities are very low and well controlled, leading the EPA to declare that no single facility has the potential to be a major source of hazardous air pollutants.

➢ HMA has demonstrated that it can withstand heavy loads.

➢ The tax-paying public deserves the best in quality and value that HMA pavements provide.

Minnesota Asphalt
Pavement Association
www.asphaltisbest.com

Page 1 of 3
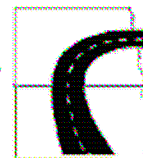
"Build with Asphalt"
Dakota Asphalt Pavement Association Inc.

For More Facts See:

1. ERES, "Bituminous Over Aggregate Base Pavement and Overlaid Bituminous Pavement Performance Study," Minnesota, 2003.
2. ERES, "Full-Depth Asphalt Pavement Performance Study," Minnesota, 2003.
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Appendix IV: Sources for Material Mix Design Used in LCA Model

Hot-mix asphalt

-Mainline and Shoulder Design Mixes:

% by weight	wearing course	base course	road base
bitumen	6.50%	6.00%	5.00%
crushed aggregate	72.10%	73.20%	74.00%
sand	16.90%	17%	17.67%
limestone	4.50%	3.33%	3.33%

- Recycled asphalt pavement (RAP) % allowed in Michigan: 50%

- Recycling percentage of used asphalt: 80-90%

- Specific weight: 110lb/syd-in

Sources: FHWA User guidelines for waste and byproduct materials in pavement

construction, FHWA-RD-97-148 (FHWA 1997)

IVL Swedish Research Institute

MDOT Road Design Manual (MDOT 2000)

MDOT Standard Specifications for Construction, Division 5 and 9 (MDOT 2003)

Portland cement concrete

- Pavement Type P1

Mixes	1	2	3*	4
cement content (lb/cyd)	564	526	517	480
fly ash (lb/cyd)	0	0	78	72
fine aggregate (lb/cyd)	1,409	1,409	1,409	1,409
coarse aggregate (lb/cyd)	1,691	1,691	1,691	1,691
water (lb)	283	283	283	283

*: Mix 3 is the default mix used in this study

- Recycling percentage of waste concrete: 50-60%

Source: EPA "Background Document for Life-Cycle Greenhouse Gas Emission Factors

for Clay Brick Reuse and Concrete Recycling" EPA530-R-03-017 (2003)

MDOT Pavement Design Manual Table 601-2 (MDOT 2000)

Joints and Dowel Bar Specifications

- Dimensions and requirements of steel bars in joints

  dowel bar diameter: 3.2cm, length: 45cm, spacing: 30cm

  tie bar length: 60cm, spacing: 79cm

  epoxy coating thickness: 0.24-0.35mm

Sources: American Concrete Pavement Association (2001)

        MDOT Road Design Manual R-39-E1, R41-C

        MDOT Standard Specifications for Construction, Division 9 (2003)

Subbase and Base

- Subbase material has to be "compacted to not less than 95% of the maximum unit weight"

- Range of maximum unit weight of base materials

      Construction aggregates- 90 to 102 lb/cubic foot

      Gravely soil - 100 to 140 lb/cubic foot

      Sandy soil - 80 to 135 lb/cubic foot

      Silty soil - 75 to 110 lb/cubic foot

      Clayey soil - 80 to 110 lb/cubic foot

Sources: Coduto, D. "Foundation Design" Prentice Hall, NJ p.50 (Coduto 2001)

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Appendix V: Additional Figures for Environmental Indicators and Pollution Damage Costs

This appendix includes additional figures related to the environmental indicators that were not inserted in Section 5.5 and Section 5.6. Results were normalized as per 4-lane km.
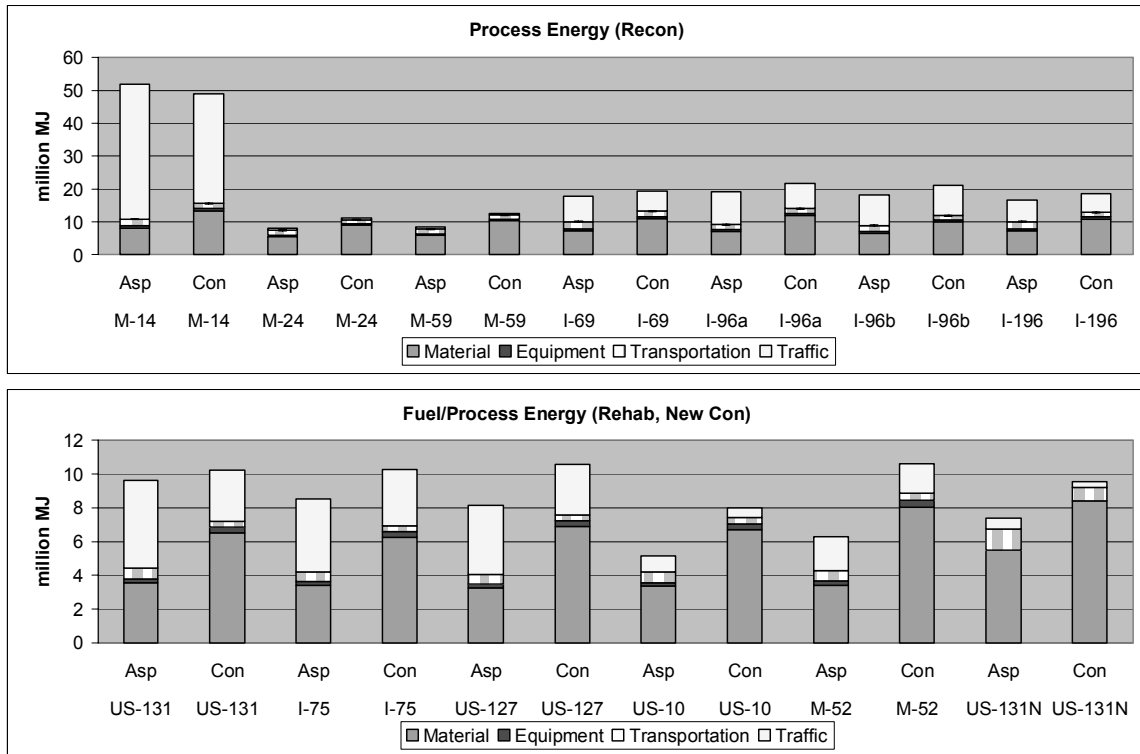

Figure 29: Life-cycle process energy consumption of reconstruction (top), rehabilitation and new construction projects (bottom) by activities

Figure 30: Life-cycle carbon dioxide emission of reconstruction (top), rehabilitation and new construction projects (bottom) categorized by activities

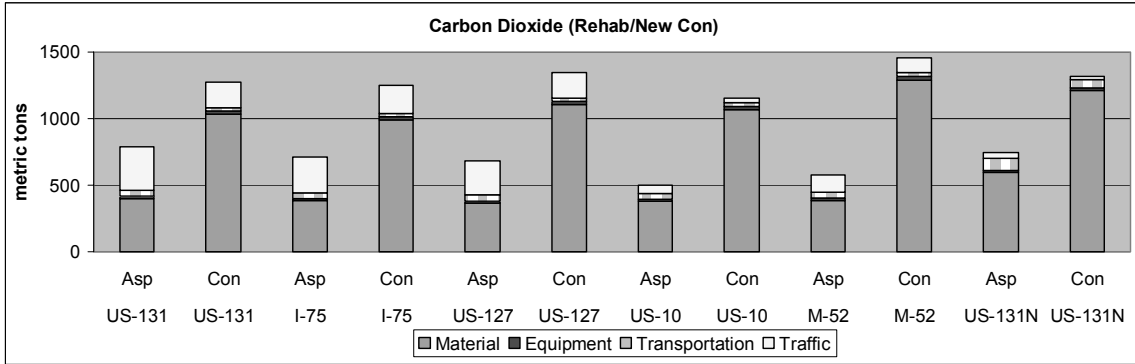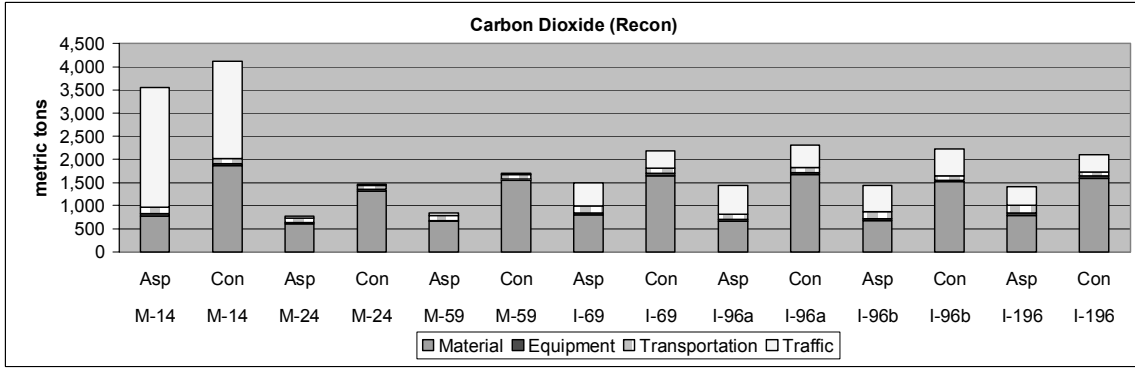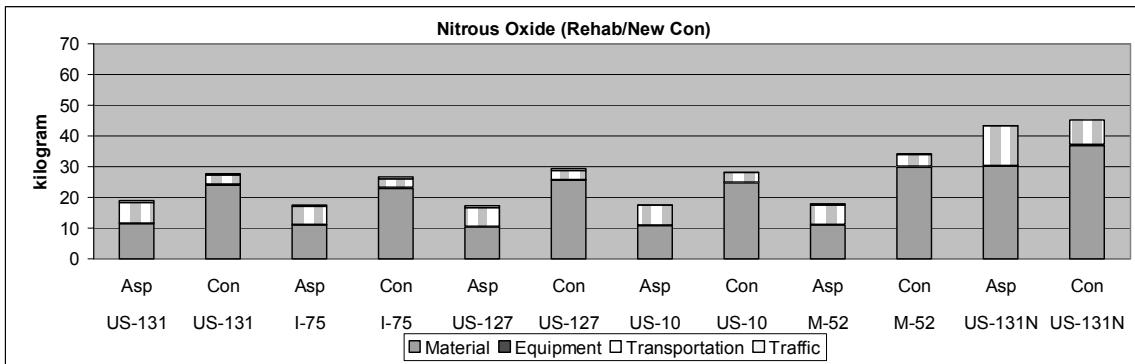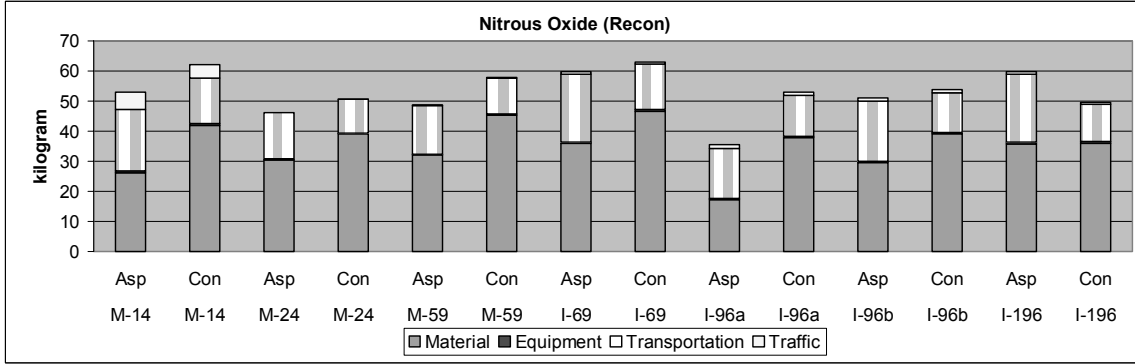**Figure 31: Life-cycle nitrous oxide emission of reconstruction (top), rehabilitation and new construction projects (bottom) by activities**

87
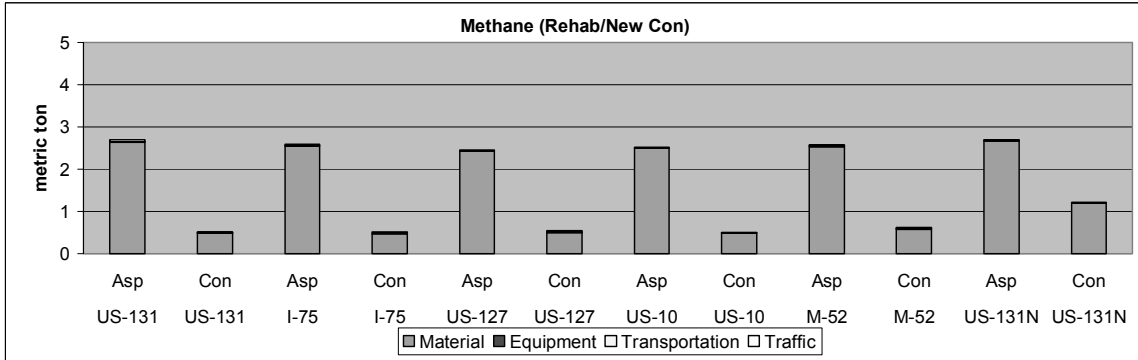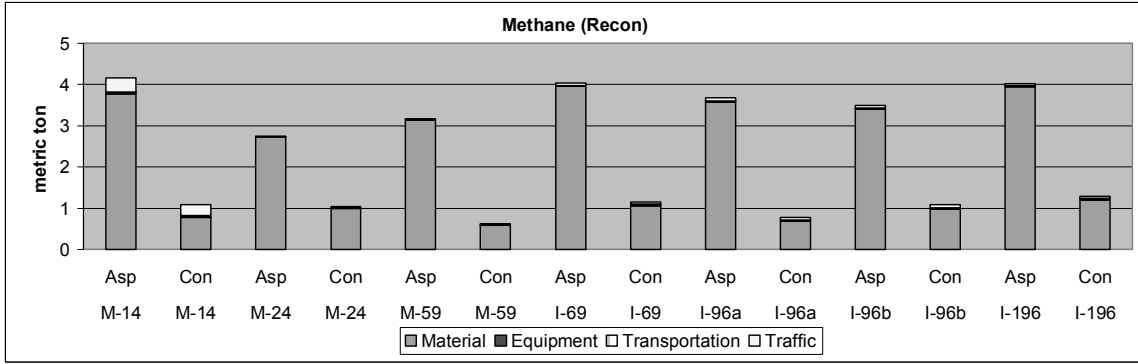
Figure 32: Life-cycle methane emissions of reconstruction (top), rehabilitation and new construction projects (bottom) by activities

Figure 33: Life-cycle pollution damage costs (low estimates) of reconstruction (top), rehabilitation and new construction projects (bottom) by activities

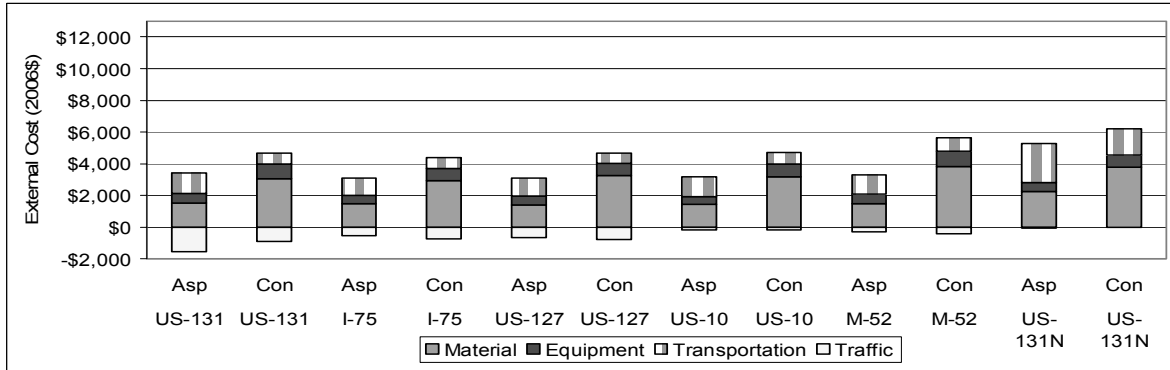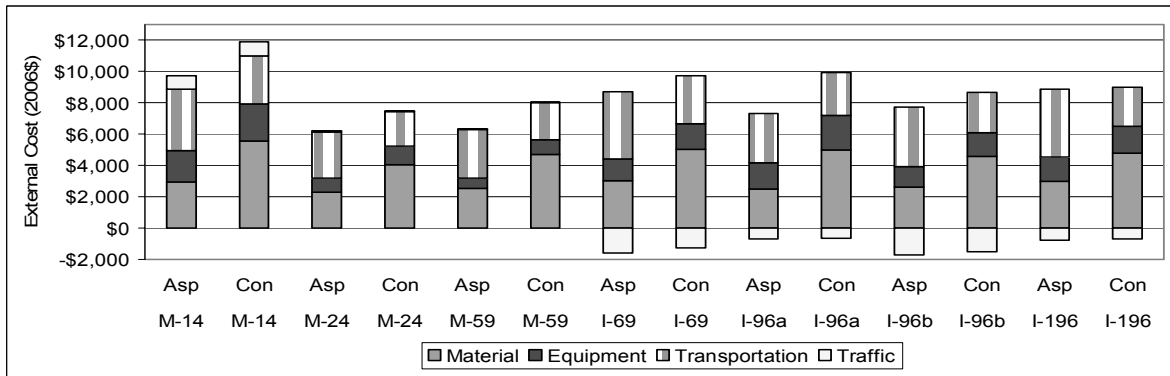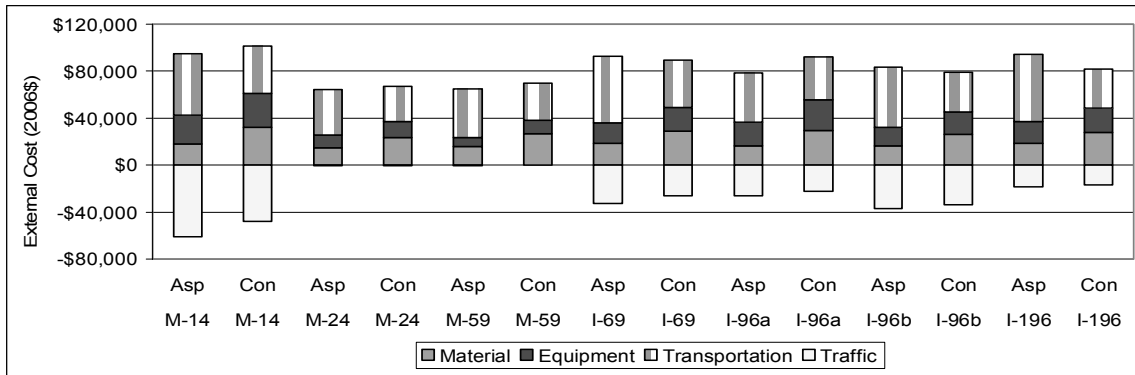**Figure 34: Life-cycle pollution damage costs (high estimates) of reconstruction (top), rehabilitation and new construction projects (bottom) by activities**

Appendix VI: LCCA Practice in Pavement Selection in the US

This is Figure 3 in table form.

Table 13: LCCA Practices in Pavement Selection in the US

State	Analysis used in Pavement Selection*	Analysis Period - Years	Discount Rate - Percent	INIT CONSTR	MAINT	REHAB	USER	SALV
AL	Y	28	4	X		X		
AK	N							
AZ	Unknown							
AR	Y (L)	35	3.8	X	X	X		X
CA	Y (TI>10)	20-50	4	X	X	X	X	X
CO	Y (>1m)	40	4	X	X	X	X	
CT	Y	30-40	4	X	X	X	X	X
DE	Y	30-40	4	X	X	X	X	X
FL	Y	40	5	X		X	X	
GA	Y	30	3	X	X	X		X
HI	Y	30-50	4 to 6	X	X	X		
ID	Y	36	4	X	X	X		X
IL	Y	40	3	X	X	X		
IN	Y	40	4 (0-10)	X	X	X		X
IA	Y	40	3	X		X		
KS	Y	30	2	X		X	X	X
KY	Y	30 - 40	0 to 10	X		X	X	X
LA	Y (L)	40	4	X	X	X	X	X
ME	Y	16	4	X		X		X
MD	Y	40	4 (3-5)	X		X	X	X
MA	N							
MI	Y (>1m)	20 - 30	4	X	X	X	X	
MN	Y	35	4.5	X	X	X		
MS	Y	25	2 to 5	X	X	X		X
MO	Y	15, 25, 35	4	X		X		
MT	Y	35	3	X	X	X		X
NE	Y	50	2.82	X	X	X		X
NV	Y	35	4	X	X	X		X
NH	N							
NJ	Y	40 or 50	3 or 4	X	X	X	X	X
NM	Y			X		X	X	X
NY	Y	50	4	X	X	X		X
NC	Y	30	4	X		X		
ND	N							
OH	Y	35	0 to 6	X		X		
OK	N							
OR	Y	30	4	X	X	X		X

State	Analysis used in Pavement Selection*	Analysis Period - Years	Discount Rate - Percent	INIT CONSTR	MAINT	REHAB	USER	SALV
PA	Y	20 or 40	6	X	X	X	X	
RI	N							
SC	N							
SD	Y	40	4.06	X	X	X		
TN	Y	30	4.5	X	X	X		
TX	Y	30	4 to 7	X	X	X	X	X
UT	Y	40	4	X	X	X	X	
VT	Y	40	3 to 5	X	X	X	X	
VA	Y	50	4	X		X		X
WA	Y	60	4 (2-5)	X		X	X	X
WV	Y (new)	40	4	X	X	X		X
WI	Y	50	5	X	X	X		X
WY	Unknown							

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