Evaluation of Life-Cycle Cost Analysis Practices Used by the Michigan Department of Transportation

Arthur Chan[1]; Gregory Keoleian[2]; and Eric Gabler[3]

Abstract: Life-cycle cost analysis (LCCA) has become a common practice in road construction at the state level during the past decade in the United States. It enables pavement engineers to conduct a comprehensive assessment of long-term costs, and ideally agency highway funding can be allocated more optimally. Michigan Department of Transportation (MDOT) has adopted LCCA in the pavement selection process since the mid-1980s, yet its application in actual projects has not been reviewed. Using case studies, this paper seeks to analyze MDOT's accuracy in projecting the actual costs over the pavement service life and choosing the lowest-cost pavement alternative. Ten highway sections in Michigan were chosen and grouped into four case studies. Their estimated and actual accumulated costs and maintenance schedules were compared. While results indicate that MDOT LCCA procedure correctly predicts the pavement type with lower initial construction cost, actual costs are usually lower than estimated in the LCCA. This outcome may be partly because the cost estimation module in MDOT's model is 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 alternatives for the pavements studied.

DOI: 10.1061/(ASCE)0733-947X(2008)134:6(236)

CE Database subject headings: Cost control; Estimation; Life cycles; Pavement management; Policies; Michigan; Road construction; Government agencies.

Introduction

The extensive road infrastructure in the United States is a massive financial responsibility for the federal, state, and local governments. The 6.4 million km of public roads stretching across the United States require routine maintenance and rehabilitation to maintain their functions, and more new lane miles of roads are under construction. Every year, all levels of governments spend over $147 billion in highway-related activities, of which $70 billion represents capital outlays (FHWA 2005a). 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. With more than one-third of major roads in the United States in poor or mediocre conditions (TRIP 2006), the American Association of State Highway and Transportation Officials AASHTO advises that annual capital outlay spending should be increased by 42 and 94%, respectively, to maintain and improve the physical conditions of roads (ASCE 2005). 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 crucial as highway funding at all levels of government continues to fall short of infrastructure needs.

In this regard, life cycle-cost analysis (LCCA) is applied in road construction to explore the possibility for more efficient investment. It evaluates not only the initial construction cost of the pavement, but also all the associated maintenance costs during its service life. Therefore, pavement engineers are able to choose the pavement type and design with the lowest cost in the long run.

The concept of LCCA in road construction was first discussed by AASHTO "Red Book" in the 1960s (Wilde et al. 2001), but it did not appear in the federal legislation until the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991. 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 the Transportation Equity Act for the 21st Century (TEA-21) in 1998, but the Federal Highway Administration (FHWA) and AASHTO remain active in assisting the states in developing their own LCCA procedures. FHWA is required by TEA-21 to fund research that "expands the knowledge of implementing LCCA" (23 USC 502). Life-cycle costs must still be considered as part of the FWwA's value engineering process for NHS projects costing more than $25 million (23 CFR Part 627) (GPO 2001). States including Michigan have enacted similar legislation in the past decade as well.

---

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

[2] Codirector, Center for Sustainable Systems, and Associate Professor, School of Natural Resources and Environment, Univ. of Michigan, 440 Church St., Ann Arbor, MI 48109 (corresponding author). E-mail: gregak@umich.edu

[3] Economist, Office of Asset Management, Federal Highway Administration, Washington, D.C 20590.

Note. Discussion open until November 1, 2008. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on December 19, 2006; approved on August 27, 2007. This paper is part of the ***Journal of Transportation Engineering***, Vol. 134, No. 6, June 1, 2008. ©ASCE, ISSN 0733-947X/2008/6-236–245/$25.00.

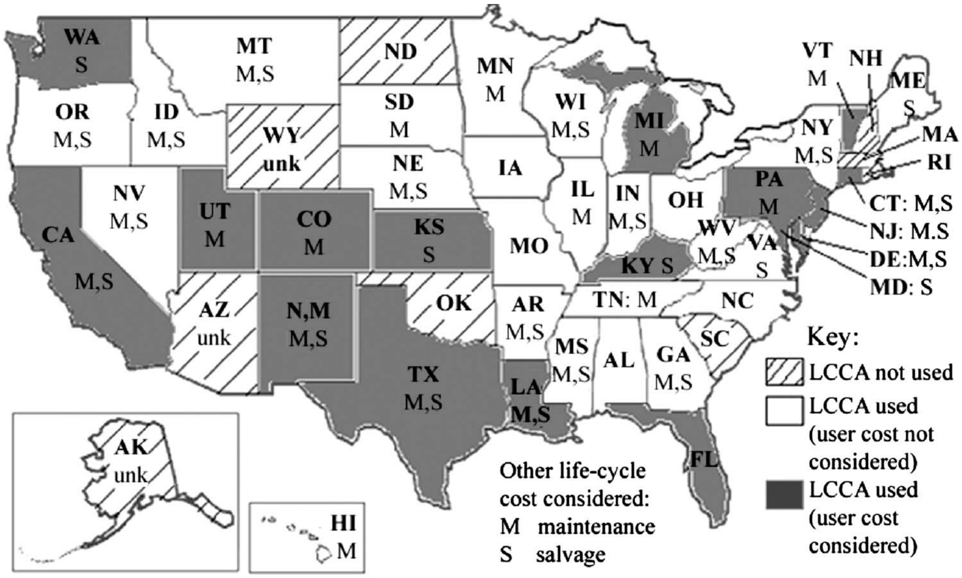

Fig. 1. Life-cycle analysis practices in pavement type selection in the United States (based on survey of state DOTs completed by the writer in 2006)

FHWA does not prescribe specific forms for LCCA, but provides guidance to states such as publishing the "Life-cycle cost analysis in pavement design" interim technical bulletin (FHWA 1998), the "Life-cycle cost analysis primer" (FHWA 2002), "Economic analysis primer" (FHWA 2003a), and organizing workshops. These publications discussed topics from the general possible applications of LCCA to the treatment of individual cost components. 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.

Literature review and interviews conducted in 2005–2006 with state DOT officials indicated that over 80% of the states carry out LCCA in the pavement selection process, at least for some projects. While all of them consider initial construction and future rehabilitation costs, only 40% of them incorporate user costs associated with road construction activities (e.g., delay at work zones) (Fig. 1). Nonuser social costs such as environmental damage are not considered. This finding supports the general perception among LCCA experts that state DOTs' LCCA procedures have long been focused primarily on agency costs. User cost is more likely to be considered in the more densely populated states or urban areas where user delay cost is more significant. State DOTs use slightly different analysis periods, pavement maintenance strategies, and discount rates as well (Wilde et al. 2001; Ozbay et al. 2004).

ERES Consultants (2003) and Ozbay et al. (2004) reported that most states do not have well-established procedures but brief instructional guidelines. They added that gaps exist between theoretical and actual LCCA applications. For example, sophisticated models to estimate user costs (Carr 2000; NJDOT 1999) have been developed, but many state DOTs use simple tabular data to estimate user costs. Uncertainty in LCCA parameters can be incorporated into LCCA by using probabilistic models (Gerke et al. 1998; FHWA 1998; Herbold 2000; Wilde et al. 2001), yet deterministic models (i.e., models that do not model risk and variability) are mostly adopted by state DOTs. Pavement performance prediction models (Wilde et al. 2001) are able to forecast maintenance needs based on a number of criteria (e.g., economic or engineering aspects), but it is a general practice that state DOTs establish their respective pavement maintenance strategies based on historical maintenance records. As pavement technologies and designs advance over time, pavements constructed today, although of the same type (e.g., asphaltic or portland cement concrete), would have different optimal maintenance schedules from pavements constructed decades ago. Finally, models are available to quantify and monetize the social impact of road construction, including health impacts of pollutants emissions, noise, etc. (Delucchi and McCubbin 1996; Wilde et al. 2001). While nonuser social costs are seldom considered by state DOTs, pavement engineers will soon be aware of the need to incorporate these elements into LCCA in order to capture the full costs incurred by the general public (personal communication with B. Krom & M. Eacker, MDOT Pavement design engineers, Aug. 2005–May 2006).

The literature is limited in examining the effectiveness of state DOTs' LCCA in projecting and picking the pavement alternative with the lowest life-cycle costs. FHWA (2003b) published a case study on the LCCA experience of the Pennsylvania DOT. The authors argued that LCCA promotes transparency in pavement selection process to the industry groups as well as the public. The new pavements in general performed better than those built before the implementation of LCCA, but quantitative assessment was not available. On the other hand, empirical studies have been carried out to compare the actual life-cycle cost of concrete and asphalt pavement in different states. While some studies favor asphalt over concrete (Cross and Parsons 2002; Villacres 2005), others favor other materials (Snook and Buch 1998; Embacher and Snyder 2001).

This study seeks to evaluate the effectiveness of the MDOT LCCA procedure as an asset management tool. The MDOT LCCA procedure is reviewed, and case studies are performed in order to provide an objective and quantitative assessment on the LCCA performance. The analyses are expected to provide useful insights and guidance on the actual application of LCCA for road infrastructure management.

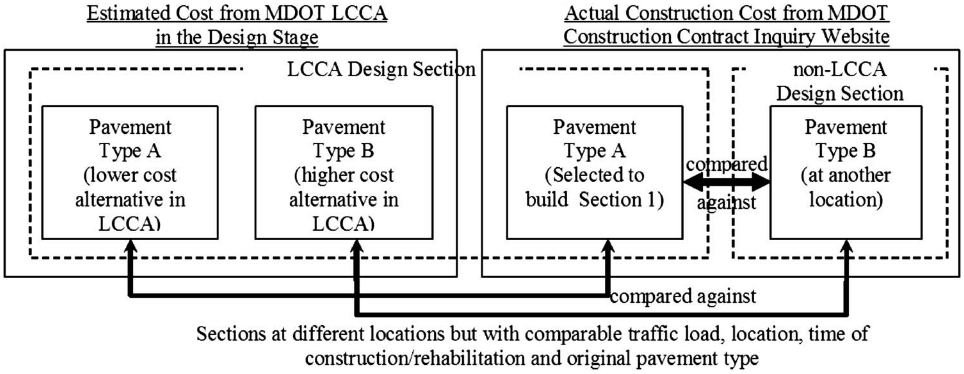

Fig. 2. Diagram of study framework

LCCA Practices of Michigan Department of Transportation

History and Development

MDOT first utilized LCCA for pavement selection in 1985 (EOC 1985), and the procedure was last revised in 1998 to meet new federal and state legislative requirements. Prior to 1998, LCCA was not performed in all multimillion dollar road projects. However, state legislation PA 79 of 1997 states that "the department shall develop and implement a life-cycle cost analysis for each project for which total pavement costs exceed 1 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." 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 1 million dollars require LCCA in the design stage. Therefore, new construction, reconstruction, and rehabilitation events on the major Michigan trunklines generally require LCCA. Rehabilitation refers to "structural enhancements that extend the service life of an existing pavement and/or improve its load carrying capacity. Rehabilitation techniques include restoration treatments and structural overlays" (FHWA 2005b). Construction or reconstruction refers to building a whole new pavement from base to surface. Prior to 1998, MDOT carried out LCCA for about a total of 30 road projects (the source of the four case studies selected for this paper). The number has almost tripled since then. However, this requirement does not extend to roads owned by county and city governments (MDOT 2005).

Components of 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.

Inputs to LCCA include initial and future agency and user costs. The basic analysis unit includes a 1 mi (1.6 km) 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, subbase, aggregate base, future pavement repairs, underdrains, and traffic control devices. 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 (Carr 2000), 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 (MDOT 2005).

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) (MDOT 2005).

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 (FHWA 1998).

Case Studies Methodology

A case study approach was adopted. Fig. 2 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.

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 con-

Table 1. Road Segments Selected for Case Studies

Road section number	LCCA design section?	Control section	Starting/ending milepost	Section length (km)	Surface type	Initial con/ rehab year (project number)	Traffic volume (AADT[e] in 2004)
(a) Case 1: I-94 (rehabilitation) (Jackson and Washtenaw Counties) 4 lanes divided, restricted access							
1	*Y*	38103	EB: 0–9.9, WB: 0–4.1	11.3	UCOV[c]	1995 (29582)	46,000–49,000
2	*N*	81104	6.14–11.98	9.3	Asphalt overlay	1990 (28218)	50,900–53,000
(b) Case 2: M-37 (reconstruction and widening) (Kent Counties) 4 lanes divided							
1	*Y*	41031	8.42–10.70	3.6	Asphalt	1997 (34695)	27,800
2	*N*[a]	41031	6.28–8.42	3.4	Concrete w/asphalt shoulder	1996 (34694)	27,400
Case 3: US-131 (rehabilitation) (Allegan Counties) 4 lanes divided, restricted access							
1	*Y*	3112	3.07–8.56	8.8	AORC[b]	1993 (28143)	28,900-30,300
2	*N*	3112	8.6–16.17	12.1	Asphalt overlay	1989 (26713/28525)	29,700–36,400
Case 4: I-96 (rehabilitation) (Eaton and Ingham Counties) 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[b]	1995 (29581)	32,100–55,300
2	*Y*[d]	33084	8.89–11.49	13.9	AORC[b]	1993 (28213)	48,700
3	*N*	33084	3.67–8.89	8.4	Asphalt overlay	1987 (25203)	50,700
4	*N*	33085	0–2.65	4.3	Asphalt overlay	1989 (26758)	50,800

[a] LCCA was carried out for this section, but the estimated higher-cost alternative (concrete) was built.

[b] AORC=asphalt overlay on rubblized concrete.

[c] UCOV=unbonded concrete overlay.

[d] LCCA was not carried out for this section, but the lower-cost alternative was built.

[e] AADT=annual average daily traffic.

crete) 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, Fig. 2). 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:

1. Similar traffic load [±10,000 average annual daily traffic (AADT)]. The data are collected from the MDOT average daily traffic map series;
2. Located within the same or adjacent county so that the geology and climate are similar for both road sections;
3. The time difference of the initial construction or rehabilitation events among road sections was within 5 years so that similar construction technology or knowledge should have applied; and
4. 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 ten highway sections among them. Three of them were rehabilitation projects and one was a reconstruction project. All of the studies predate 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 R and Southwest regions (Table 1). 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.

Data Collection

For each road section, actual initial construction and 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

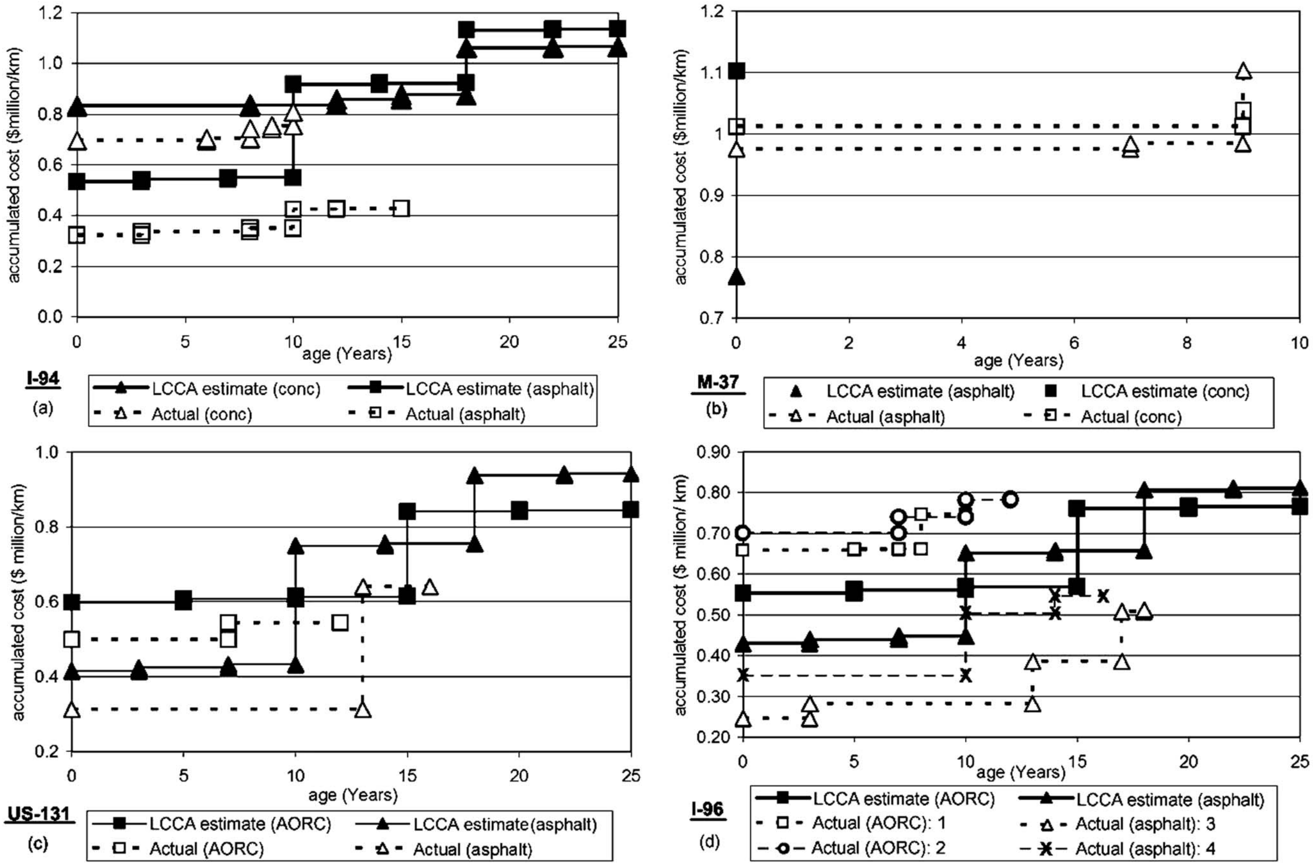

Fig. 3. (a–d) (From left to right, top to bottom) Estimated versus actual cost accumulations over pavement service life for I-94, M-37, US-131, and I-96 sections

the mid-1990s were obtained from microfilms in the MDOT Construction & Technology (C&T) complex and the State Record Center in Lansing, Mich. Later construction contracts were downloaded from the MDOT Construction Contract Inquiry Website (MDOT 2006). For the road projects with LCCA estimates, the cost estimations were obtained from LCCA documents located in the MDOT C & T complex.

Findings and Discussion

Figs. 3(a–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 overestimated 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., microsurfacing, 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.

Case 1: Rehabilitation on I-94: Concrete Overlay versus 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 [Fig. 3(a)]. The actual initial construction cost (in 2005 dollars) of the 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 the 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. Such difference from 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 of both materials (PCC and AC) considered in the LCCA were too high.

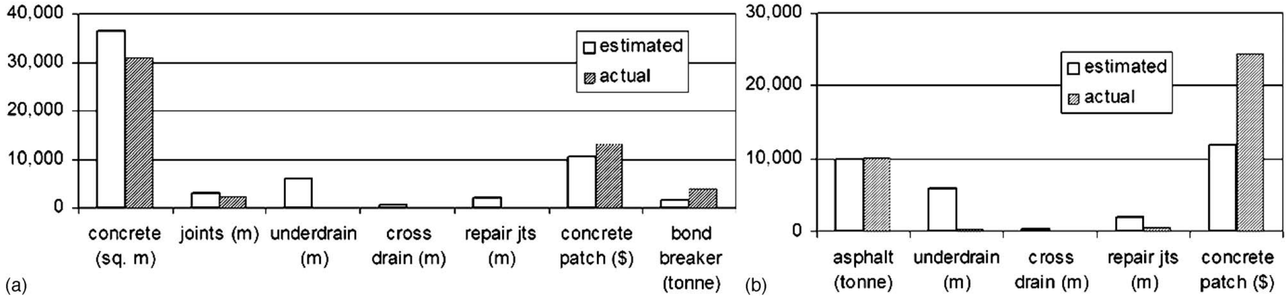

Fig. 4. (a–b) I-94: estimated versus actual material use in initial construction phase for LCCA design section (unbonded portland cement concrete overlay) and non-LCCA design section (asphalt overlay)

Overestimation of initial construction cost of the unbonded PCC overlay in the LCCA section is partly due to the overestimation of the quantity of PCC needed in road and shoulder construction, underdrains, joint repair, and concrete repair [Fig. 4(a)]. While the quantity of concrete used in road and shoulder 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 [Fig. 4(b)], but the actual weighted-average unit price for asphalt (~$34/t in 2005 dollars) ($t=10^3$ kg) is at least 35% less than estimated when the LCCA was conducted (~$54/t). 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 the 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. Clearly, future MDOT applications of LCCA to similar projects would benefit from additional investigation into the causes of the cost-estimation errors noted above.

Case 2: Reconstruction and Widening of M-37: Asphalt versus Concrete

Two M-37 sections were reconstructed in 1997 and 1996, respectively, adjacent to each other south of Grand Rapids, Mich. 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 a microsurfacing project at Year 9, while the PCC section received joint-sealing treatment at Year 9 [Fig. 3(b)]. 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 completion of the microsurfacing project on the asphalt section, however, its accumulated cost surpassed the accumulated cost of the PCC section [Fig. 3(b)]. 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 [Figs. 5(a and b)].

A longer time frame is needed to study whether 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. Our review of the LCCA would have benefitted from more documentation.

Case 3: Rehab of US-131: AC Overlay on Rubblized Concrete versus 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 with only an AC overlay after repairs to the original PCC pavement in 1989. The actual maintenance events roughly followed the estimated schedule for both sections [Fig. 3(c)]. The first actual resurfacing event for the non-LCCA AC overlay section was

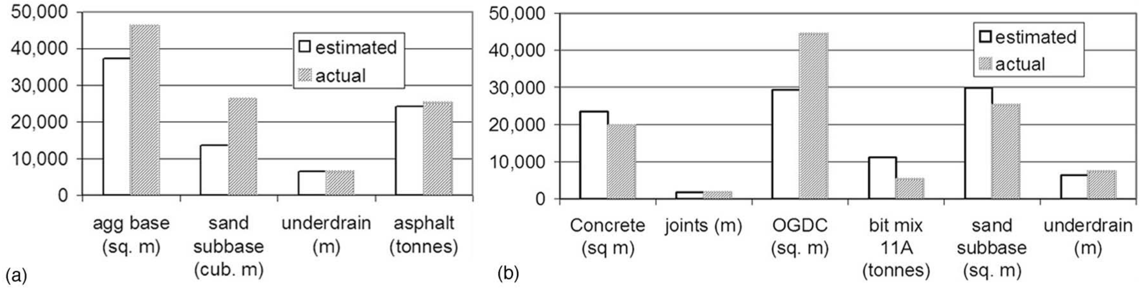

Fig. 5. (a–b) M-37: estimated versus actual material use in initial construction phase for asphalt section and portland cement concrete section

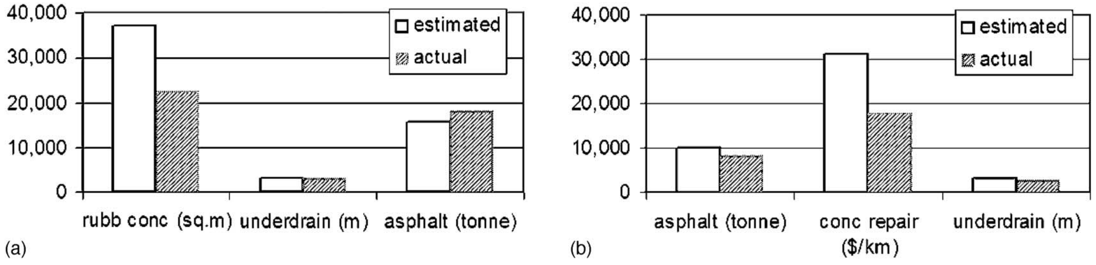

Fig. 6. (a–b) US-131: estimated versus actual material use in initial construction phase for LCCA design section (asphalt overlay over rubblized concrete) and non-LCCA design section (asphalt overlay)

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.

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 asphalt overlay on rubbilized concrete (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 [Fig. 3(c)]. For the LCCA section, less concrete was rubblized [Fig. 6(a)] than estimated in the LCCA exercise, and the weighted-average unit price of AC layer was 20% cheaper ($40/t versus $48.5/t) than estimated. For the non-LCCA section, fewer concrete substrate repair operations were done than estimated [Fig. 6(b)] and the unit price for asphalt was 10% lower than the engineering estimate that informed the LCCA would have estimated. 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.

Case 4: Rehabilitation of I-96: AORC versus AC Overlay over Existing Concrete

Four sections were chosen on I-96 around Lansing, Mich. 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 [Fig. 3(d)].

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 ($0.25–0.37 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 15–40% lower than would have been estimated in the same LCCA exercise, which was contributed by a lower consumption of aggregate bases and underdrains during construction [Fig. 7(b)]. In terms of cost increments over time, the accumulated costs of the non-LCCA asphalt-overlay sections were increasing at a faster rate (4–6%/year) than the LCCA AORC sections (1%/year),

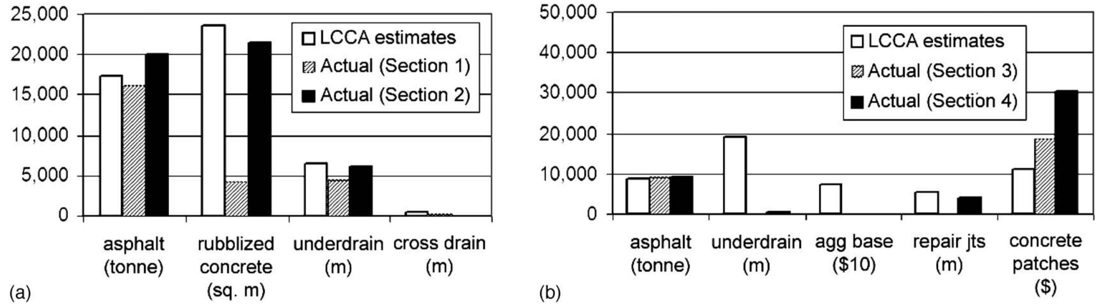

Fig. 7. (a–b) I-96: estimated versus actual material use in initial construction phase for LCCA design section (asphalt overlay over rubblized concrete) and non-LCCA design section (asphalt overlay)

which agrees with the expected trend. However, to date maintenance costs for both LCCA sections (\$0.08–0.09 million/km) were higher than expected (\$16,200/km) since more frequent maintenance was carried out. In addition to the crack-fill operations estimated in LCCA, microsurfacing 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 a 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.

Differences between Estimated and Actual Cost and Material Consumption

The discrepancy in the LCCA estimates versus the actual accumulated costs to date does not mean that LCCA did not work as a methodology. It is, 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 MDOT LCCA cost estimating module includes a 1 mi 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 (personal communication with B. Krom and M. Eacker, MDOT, Aug. 2005–May 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 (personal communication with B. Krom and M. Eacker, MDOT, Aug. 2005–May 2006). The unit price and plan quantities of both materials were different than used in the original cost estimation (personal communication, MDOT, Aug. 2005–May 2006). Furthermore, construction plans can be changed after LCCA was carried out and approved (personal communication, MDOT, Aug. 2005–May 2006). A thinner shoulder may be built, or different asphalt mixes might be used for the road project. In Case 4, part of the LCCA-designed rubblized section (Section 1) (Table 1) was reconstructed or resurfaced without rubblizing the substrate concrete pavement.

Finally, the observed maintenance schedules of the road sections studied do not usually match up with the ones estimated by the 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. As a result, the actual pavement material consumption and costs deviated 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. In time, it would be expected that the accuracy of the overall process would improve.

Limitations of 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 [Fig. 4(a and b), Fig. 7(a and 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. 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.

Conclusions

The writers are strong proponents 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 prerequisites 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 was 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 overestimated 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 the pavement's service life. Although the sections studied 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 1 mi 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.

Finally, 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. Work item unit costs can also differ substantially by road projects carried out in the same year (personal communication, MDOT, Aug. 2005–May 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 use of pavement performance models can yield useful data and help determine the maintenance schedules used for LCCA.

The incorporation of probabilistic capabilities to the model could 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.

Acknowledgments

This research was funded through an NSF MUSES Biocomplexity Program Grant (Grant Nos. CMS-0223971 and CMS-0329416). MUSES (materials use: science, engineering, and society) supports projects that study the reduction of the adverse human impact on the total interactive system of resource use, the design and synthesis of new materials with environmentally benign impacts on biocomplex systems, as well as the maximization of efficient use of materials throughout their life cycles. Most of the data in this study were collected and verified with the help of Benjamin Krom and Michael Eacker, who worked at the Michigan Department of Transportation as pavement selection engineers. The views expressed are those of the writers and do not represent an official policy statement of any government agency.

References

AASHTO. (1986). *1986 guide for design of pavement structures*, Washington, D.C.

ASCE. (2005). *Report card for America's infrastructure*, Reston, Va.

Bureau of Economic Analysis (BEA). (2006). "Table 7.1B. Current-cost net stock of government fixed assets, National economic account." ⟨http://www.bea.gov/bea/dn/FA2004/TableView.asp#Mid⟩ (Dec. 7, 2006).

Carr, R. (2000). "Construction congestion cost (CO^3) basic model." *J. Constr. Eng. Manage.*, 126(2), 105–113.

Cross, S., and Parsons, R. (2002). *Evaluation of expenditures on rural interstate pavements in Kansas*, Kansas Univ. Transportation Center, Univ. of Kansas, Lawrence, Kan.

Delucchi, M., and McCubbin, D. (1996). "The social cost of the health effects of motor vehicle air pollution: Report #11 in the series—The annualized social cost of motor vehicle use in the United States, based on 1990-1991 data." *Rep. No. UCD-ITS-RR-96-3(11)*, Institute of Transportation Studies, Univ. of California, Davis, Calif.

Embacher, R., and Snyder, M. (2001). "Life cycle cost comparisons of asphalt and concrete pavements on low-volume roads." *Transportation Research Record*. 1749, Transport Research Board, Washington, D.C., 28–37.

Engineering Operations Committee (EOC). (1985). "Engineering operations committee minutes, June 1985." Michigan Department of Transportation, Lansing, Mich.

ERES Consultants. (2003). "Neutral third party Ohio pavement selection process analysis." *Rep. Prepared for Ohio DOT Pavement Selection Advisory Council*, Champaign, Ill.

Federal Highway Administration (FHWA). (1998). "Life-cycle cost analysis in pavement design." *HNG-42/9-98(5M)QE*, Washington, D.C.

Federal Highway Administration (FHWA). (2002). "Life-cycle cost analysis primer." *FHWA-IF-02-047*, Washington, D.C.

Federal Highway Administration (FHWA). (2003a). "Economic analysis primer." *FHWA IF-03-032*, Washington, D.C.

Federal Highway Administration (FHWA). (2003b). "Life-cycle cost analysis: The Pennsylvania experience." *FHWA-IF-03-038*, Washington, D.C.

Federal Highway Administration (FHWA). (2005a). "Highway statistics 2004." *FHWA-PL-05-013*, Washington, D.C.

Federal Highway Administration (FHWA). (2005b). "Memorandum: Pavement preservation definitions." *FHWA:HIAM-20:LLAWNDY: 63975:ll:08/22/05*, Washington, D.C.

Gerke, R., Dewald, R., and Gerbrandt, R. (1998). "Use of highway network level data for a project level life cycle analysis." *Proc., 1998 Transportation Conf.*, Iowa State Univ., Ames, Iowa, 135–138.

Herbold, K. (2000). "Using Monte Carlo simulation for pavement cost analysis." *Public Roads*, 64(3), 2, ⟨http://www.tfhrc.gov/pubrds/nov00/lifecycle.htm⟩ (Sep. 25, 2006).

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

Michigan Dept. of Transportation (MDOT). (2006). "Construction contract inquiry." Lansing, Mich., ⟨http://mdotwas1.mdot.state.mi.us/public/trnsport/⟩.

New Jersey Dept. of Transportation (NJDOT). (1999). *Road user cost manual*, Trenton, N.J.

Ozbay, K., Jawad, D., Parker, N. A., and Hussain, S. (2004). *Life cycle cost analysis: State-of-the-practice vs. state-of-the-art*, Rutgers University and the City College of the City University of New York Press, New York.

The Road Information Program (TRIP). (2006). “Key facts: America’s road and bridge conditions and federal funding.” Washington, D.C.

Snook, R., and Buch, N. (1998). *Long term cost comparison of pavement types in Michigan*, Pavement Research Center of Excellence, Michigan State Univ., Lansing, Mich.

US Government Printing Office (GPO). (2001). “Code of federal regulations: Title 23, Chapter I, Part 627—Value engineering.” Washington, D.C.

Villacres, J. (2005). *Pavement Life-Cycle Cost Studies Using Actual Data Cost—A Synthesis, Rep. No. 5672-2/1*, Asphalt Pavement Alliance, Lanham, Md.

Wilde, W., Waalkes, S., and Harrison, R. (2001). “Life cycle cost analysis of portland cement concrete pavements.” *SWUTC/01/167205-1*, Center for Transportation Research, Univ. of Texas at Austin, Austin, Tex.