Probabilistic Characterization of Life-Cycle Agency and User Costs

Case Study of Minnesota

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Life-cycle cost analysis (LCCA) is a commonly used approach by pavement engineers to compare the economic efficiency of alternative pavement design and maintenance strategies. Over the past two decades, the pavement community has augmented the LCCA framework used in practice by explicitly accounting for uncertainty in the decision-making process and incorporating life-cycle costs not only to the agency but also to the users of a facility. This study represents another step toward improving the LCCA process by focusing on methods to characterize the cost of relevant pay items for an LCCA as well as integrating costs accrued to users of a facility caused by pavement–vehicle interaction (PVI) and work zone delays. The developed model was implemented in a case study to quantify the potential implication of both of these components on the outcomes of an LCCA. Results from the construction cost analysis suggest that the proposed approaches in this paper lead to high-fidelity estimates that outperform current practice. Furthermore, results from the case study indicate that PVI can be a dominant contributor to total life-cycle costs and, therefore, should be incorporated in future LCCAs.

Life-cycle cost analysis (LCCA) is an analytical framework frequently used by decision makers to compare the total cost to construct, maintain, and operate alternative pavement design and maintenance strategies (*1*). The importance of taking a life-cycle approach toward transportation investments continues to grow as planning agencies search for effective ways to maintain an aging infrastructure network that spans more than 8.5 million lane miles and supports over 3 trillion vehicle miles per year in the United States (*2, 3*). Consequently, academics have developed several new tools for LCCA that can now account for uncertainty in the decision-making process as well as, to some extent, the costs accrued to users of a pavement facility (*4–6*).

Despite this progress, several opportunities remain to augment the current LCCA frameworks utilized by planners. In particular, a previous study by Swei et al. demonstrated that estimates of the unit price of pay items within an LCCA are a major contributor to both total agency expected life-cycle costs (LCC) and variation across a series of case studies (*7*). Therefore, it is of paramount importance that estimates of expected construction costs as well as associated variation that enter an LCCA appropriately represent available empirical data. Additionally, current LCCA frameworks generally account for user costs only as they relate to traffic delays caused by work zone closures (*8*). Several previous pavement life-cycle assessment (LCA) studies have suggested, however, that pavement–vehicle interaction (PVI), the implication of pavement condition and design on vehicle fuel economy, is a much larger contributor to the overall environmental burden of a pavement (*9*). No studies exist, to the authors' knowledge, which have accounted for PVI or quantified its relative contribution to total LCC.

As a result, this study focuses on (*a*) enhancing the fidelity of current approaches to characterize both initial and future costs used in an LCCA and (*b*) developing an LCCA approach that encompasses user costs as they relate to PVI in addition to traffic delays. The study subsequently implements the model in a case study to characterize the potential implication of both of these factors on the outputs of an LCCA.

LITERATURE REVIEW

LCCA provides transportation planners the opportunity to compare the economic cost of competing maintenance and design strategies (*1*). Although early research efforts typically assumed deterministic estimates for relevant inputs, over the past two decades several case studies have emerged that explicitly consider the probabilistic nature of the decision-making process (*10–13*). A benefit of the probabilistic approach for LCCA is that it allows decision makers to select a maintenance and design strategy that corresponds to their willingness to accept risk (*14*).

Although both pavement deterioration and, to some extent, the selection of discount rate are well-studied topics among the pavement management community, few studies have addressed the issue of cost estimation for such systems (*1, 15*). Previous studies that have focused on the cost for pay items in pavement projects include Sanders et al. (*16*), who developed a series of bivariate regression models between bid unit price and quantity, and Shrestha et al. (*17*), where a similar analysis was conducted to characterize the degree of dependence between the two. Furthermore, an even smaller subset of the LCCA literature has considered the evolution of the cost for construction activities over time, with the only known example being the work of Swei et al. (*7*). Several studies have accounted for user costs associated with alternative investment strategies (*6, 18*). Such studies, as well as examples in practice, typically calculate user costs only as they relate to traffic delays associated with maintenance

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events by FHWA's work zone user cost method (*19*). No LCCA studies have accounted for other forms of user costs, such as PVI, that are now commonly accounted for in existing environmental LCAs (*20*).

Considering the state of the literature, the contribution of this study is twofold. First, the authors propose a new approach for cost estimation that generally leads to higher-fidelity estimates of expected costs and associated uncertainty as compared with the status quo. Second, this study develops a methodology to account for user costs from PVI within an LCCA. The authors subsequently integrate both of these contributions within an LCCA and apply their model to a case study. Results from the case study indicate that the new approach for cost estimation can influence the preferred alternative within an LCCA and, furthermore, that user costs from PVI are significant contributors to the total LCC for a given project.

METHODOLOGY

The following section is divided into three parts. First, the authors review current methods to estimate the unit price of pay items that enter an LCCA and propose alternative approaches that overcome their shortcomings. Subsequently, a brief overview is presented that details the method used to estimate user costs associated with a pavement design and maintenance alternative, particularly as they relate to PVI. Finally, this paper summarizes the case study implemented as part of this research to assess (*a*) the implication of the enhanced unit price estimation techniques proposed in this study on the outputs of an LCCA and (*b*) the relative contribution of PVI to the total LCC of a pavement.

Characterization of Unit Cost for Relevant Construction Pay Items

Initial Unit Cost

Several studies have demonstrated that estimates of the unit price of pay items for an LCCA influence the accompanying results (*7*). For the most part, existing research typically develops representative parametric estimates of the unit price of relevant pay items by fitting available data with a best-fit distribution (*14*). In particular, previous research has demonstrated that much of the variation in the unit price of pay items for pavements can be attributed to economies of scale, where an increase in production levels reduces the average unit cost of construction (*16, 17*). Consequently, this paper extends the strategy of Shrestha et al. (*17*) by considering a few simple data transformation techniques and selecting the transformation that causes the data set to conform, as best as possible, to the underlying assumptions of linear regression. Although other frameworks, such as Box–Cox transformations, would allow for a greater amount of flexibility in the data transformation process, the authors find that the described approach is sufficient for the study at hand.

Projection of Future Prices

Current LCCA practice assumes that the future cost of relevant maintenance actions will change in accordance with the general rate of inflation (*21–23*). Although such an assumption simplifies the analysis, it potentially leads decision makers toward selecting the less economically efficient maintenance and design strategy given that existing empirical data demonstrate that the costs of different construction inputs have evolved both differently from inflation and, perhaps more important, from one another (*24*). As a result, the authors of this study have developed probabilistic price projection models for inputs relevant to the pavement community, with a particular focus on paving materials given (*a*) their significant contribution to the total cost of a maintenance event and (*b*) their high level of volatility (*25*).

A novel probabilistic approach was developed for projecting future paving material prices that convolves conventional forecasts for underlying constituent prices and a long-term price equilibrium relationship between commodities of interests and constituents (*24*). To do so, this research assumes that individual states exhibit differential cost structures such that the cross-sectional price level for a paving commodity may differ across states, yet the relative change in cost growth is similar. Subsequently, historical real-price data were collected for paving materials for the location of the LCCA case study. Similar to Swei et al. (*24*), out-of-sample forecasts were conducted, in which price projection models were constructed set back in time and compared to what actually occurred. Data used for parameter estimation serve as the training set for the model, whereas data made available following the year of forecasts act as the validation set. The errors of the forecasts are aggregated to provide a measure of the overall efficacy of the proposed price modeling technique. For the purposes of this study, the mean absolute percentage error (MAPE), a common metric used in the forecasting community, is estimated to measure the fidelity of the modeling approach set forth (*26*). The MAPE of the proposed price projection approach is compared to the current assumption that the future real price of paving commodities will remain constant over a given analysis period.

Incorporation of User Costs

Aside from the agency cost associated with construction and maintenance of roads, pavement design and management policies have impacts on the user cost of transportation for vehicles throughout the pavement life cycle. These user costs are related with pavement impacts on fuel consumption through PVI, as well as value of time and idling cost caused by traffic delay during the maintenance and rehabilitation (M&R) of roads. Aside from fuel consumption impacts, another form of pavement-induced user cost caused by road roughness is that of the vehicle wear and tear, which is beyond the scope of this study.

Pavement–Vehicle Interaction

Pavements contribute to vehicle rolling resistance and fuel consumption through their surface condition and structural properties. These rolling resistance forces result from three mechanisms of texture-, roughness-, and deflection-induced PVIs, where energy is dissipated in the vehicle tires, suspension, and the pavement material, respectively. Simply, to maintain constant speed in the presence of such resistive forces, the vehicle engine has to compensate by outputting extra power and consuming excess fuel in the process.

Although these PVI impacts are small for a single vehicle, their aggregated impact for a high-volume roadway have been shown to surpass other factors contributing to the pavement life cycle (*27*). Despite decades of empirical studies on PVI, only recently have PVI models been able to quantitatively assess this change in fuel consumption as a function of pavement characteristics and design, as well as climatic and traffic conditions (*28, 29*). These advances in modeling of deflection- and roughness-induced PVI enable comparison of user costs to initial and M&R costs (*30–32*). The PVI models used for this study are briefly presented. The impact of texture on vehicle fuel consumption, however, has not been taken into account because of the lack of available pavement information.

Recent developments in deflection-induced PVI research provide a fundamental understanding of dissipation through bench-top experiments of PVI and enable the quantitative assessment of pavement impacts on vehicle fuel consumption through models that represent pavement, vehicle, and climate characteristics (*20, 30, 31*). The excess fuel consumption caused by deflection-induced PVI is evaluated for asphalt and concrete pavements as a function of subgrade stiffness, pavement stiffness, thickness, width, temperature, vehicle axle load, speed, and relaxation time. Relaxation time represents the pavement viscoelasticity and its relationship with temperature is captured for asphalt and concrete materials.

The impact of roughness-induced PVI on vehicle fuel consumption is evaluated using the Highway Development Management 4 (HDM-4) model, originally developed by the World Bank in 2001 and later calibrated to represent U.S. vehicle conditions in 2012 (*32, 33*). The road roughness metric in HDM-4 is the international roughness index (IRI), evaluated from pavement profile measurements as the accumulated vertical motion along the road length, with units of slope. In addition to IRI, the HDM-4 model requires a reference roughness after construction or maintenance (IRI_0) here selected as 1 m/km (63 in./mi) to remain consistent with HDM-4's calibration baseline. Moreover, the roughness model accounts for vehicle type and vehicle speed in estimating the instantaneous increase in fuel consumption caused by roughness [a simplified form of the HDM-4 model and the calibration factors are provided in Akbarian (*20*)]. The assumed cost of excess gasoline and diesel consumption for deflection- and roughness-induced PVI are consistent with HDM-4 model assumptions and are respectively equal to $3.63 and $3.97 per gallon.

Traffic Delays Caused by Work Zone Closures

During the lifetime of the pavement, M&R activities involve work zones, lane closures, and on-site construction activities and can result in significant economic, mobility, and safety impacts. This paper employs the FHWA's work zone road user cost economic analysis concepts to calculate traffic delay and the vehicle operating costs (*19*). The analysis contains traffic delay contributions from the time required to decelerate into and accelerate out of the work zone, the time added because of lower speeds in the work zone, the time spent stopping, and the time spent in queue. The number of passenger cars and trucks affected by each delay type during the M&R activity is calculated on the basis of the hourly demand, free-flow capacity, work zone capacity, and queue rate to determine the total delay time for all vehicles. The associated added cost is calculated on the basis of the hourly value of travel time, equal to $17 and $27 per person-hour for a passenger car and truck, respectively (*34*).

LCCA Model and Application

Overview of Probabilistic LCCA Methodology

The probabilistic LCCA model used in this study follows that of Swei et al. (*7*, *13*) except that the scope of the analysis now incorporates user costs. The approach accounts for uncertainty not only as it relates to construction and user costs described previously, but also other relevant inputs that underlie the model. The total probabilistic cost for a given pavement design and maintenance strategy is computed through Monte Carlo simulations, where inputs for the model are randomly sampled on the basis of their underlying distribution. Sampling as part of the Monte Carlo simulations takes into consideration both correlations and dependences as described in Swei et al. (*7*). Results from the model report both the cumulative distribution of outcomes for each alternative investment, as well as the "comparison indicator," which computes the probability that a given investment will cost more with respect to total LCC than a competing alternative (*13*). In addition, the authors determine the parameters that contribute most significantly to total variance by calculating Spearman's correlation coefficient, which captures the degree to which a monotonic relationship exists between an individual input and total LCC.

Description of Data Sets and Case Study

In collaboration with the Minnesota Department of Transportation (DOT), two case studies were selected to study the initial cost characterization of paving activities, incorporation of uncertainty in the LCCA process, and calculation of user impacts for alternative pavement constructions. The case study presented here, Case 1, is a 7.25-mi pavement that is in need of major rehabilitation planned in two lengths of 0.97 and 6.28 mi. Three possible rehabilitation scenarios are studied for each project length: an asphalt pavement with asphalt shoulders, a concrete pavement with asphalt shoulders, and a concrete pavement with concrete shoulders. The six scenarios, 1A to 1C for the 0.97-mi sections and 1D to 1F for the 6.28-mi sections, are presented in Table 1 along with their M&R schedules. The section designs and maintenance data are used in initial and life-cycle cost analyses, as well as traffic delay and deflection-induced PVI calculations. Moreover, predictions of pavement roughness in its life were provided by the Minnesota DOT with respect to IRI for the six scenarios, calculated on the basis of historical pavement performances for thick asphalt and concrete pavements. These values were used to calculate the cost impacts of roughness-induced PVI.

Estimates of the current unit price for relevant pay items are based on publicly available bid data for the state of Minnesota for the period of 2012 to 2015 (*35*). Measurements of the long-run fidelity of the price models integrated into the LCCA model use historical price indexes, made available by the Minnesota DOT, which are a weighted average of the historical cost of different pavement materials (*36*). Out-of-sample forecasts are constructed between 1987, the earlier point in which data exist, and 2000. The probabilistic LCCA results are compared with the results of the Minnesota DOT LCCA spreadsheets for calculating project initial and maintenance costs for District 7 (*37*).

TABLE 1 Life-Cycle Scenario Definition for Case 1

Preparation	Construction	Maintenance
Scenarios 1A and 1D[a]		
2.5 in. mainline and inside shoulder milling	4 in. mainline and inside shoulder HMA (4,E) 1.5 in. outside shoulder HMA (2,B)	Year 3: 32% crack sealing Year 7: 31% chip sealing Year 14: 2 in. milling 3.5 in. overlay Year 17: 32% crack sealing Year 21: 31% chip sealing Year 27: 2 in. milling 3.5 in. overlay Year 30: 32% crack sealing Year 34: 31% chip sealing
Scenarios 1B and 1E[b]		
Mainline geotextile fabric 8 in. inside shoulder reclamation 9 in. outside shoulder reclamation	6 in. mainline PCC 4 in. shoulder HMA (2,B)	Year 20: 1% type BA Year 20: 1% type B3 Year 20: 7% type CD-HV Year 20: 3% type CX Year 20: 23% diamond grind Year 20: 1.5 in. milling and fill shoulder
Scenarios 1C and 1F[b]		
Mainline and shoulder geotextile	6 in. mainline PCC 6 in. shoulder PCC	Year 20: 1% type BA Year 20: 1% type B3 Year 20: 7% type CD-HV Year 20: 3% type CX Year 20: 23% diamond grind

NOTE: All scenarios have two 12-ft-wide lanes, with 4-ft inner and 10-ft outer shoulders. Initial annual average daily traffic and annual average daily truck traffic are equal to 10,100 and 1,360 vehicles, respectively. The traffic growth rate is 1.1%. The analysis period is 35 years and the associated discount rate is 2%. The maintenance work zone is in place from 7 a.m. to 7 p.m. HMA = hot-mix asphalt; PCC = portland cement concrete; type BA = partial depth repair; type B3 = joint and crack repair; type CD-HV = full depth repair; type CX = pavement replacement.

[a] Salvage life (4/12 of rehab #6).

[b] No remaining service life.

RESULTS

The results section details the characterization and fidelity of the approaches proposed to model the cost of construction actions before presenting the outcomes of the case study discussed.

Characterization of Unit Cost for Relevant Construction Pay Items

Characterization of Unit Price for Pay Items

Developing early and unbiased cost estimation of transportation investments requires accurate characterization of the unit price of pay items. Here, the distributions of 3 years of winning bids for the state of Minnesota for all pay items associated with Case 1A to 1F sections are analyzed. In particular, the relationship between the unit price and the quantity of pay items is studied.

The logarithmically transformed independent and dependent variables are used to fit each data set into a power model of the following form:

$$\ln(P_i) = \beta_0 + \beta_q \ln(X_{i,q}) + u_i$$

where

P_i = bid unit price,
$X_{i,q}$ = bid quantity,
u_i = standard error, and
β_0 and β_q = coefficients of the fit.

Table 2 presents estimates of u_i, β_0, β_q, and the coefficient of determination R^2 for 22 data sets used in the analysis that exhibit economy-of-scale behavior. The only bid items represented through a mean and a standard deviation are microsurfacing and crack sealing of asphalt pavements, where bid data were limited and distributions of cost and quantity could not be obtained.

Demonstration of Efficacy of Long-Run Material Price Forecasts

Figure 1 plots the MAPE of the out-of-sample forecasts constructed between 1987 and 2000 for the Minnesota DOT paving cost index. Over a multidecade time horizon, the proposed hybrid methodology for price forecasting significantly outperforms the current assumption that future material prices will grow with inflation. One obvious issue in the estimation of the MAPE for the model is that the sample size is significantly smaller for higher years in the future, potentially reducing the robustness of test results. Nevertheless, such findings provide evidence that the methodology proposed by the authors works well not only at the national level but also for a specific state.

LCCA Case Study Results

The life-cycle cost estimates of Case 1 scenarios are presented here.

TABLE 2 Probabilistic Pay Item Cost Characterization Through Power Law Fit of Economy-of-Scale Relationship or Using Normal Distribution

Item Description	Unit	Economy of Scale	Intercept, β_0	Slope, β_q	SE, u_i	R^2	Mean	SD
HMA grade (4,E)	Ton	Yes	4.87	–0.07	0.10	.56		
HMA grade (2,B)	Ton	Yes	4.42	–0.04	0.14	.46		
HMA grade (3,B)	Ton	Yes	5.08	–0.11	0.14	.72		
HMA grade (3,C)	Ton	Yes	4.94	–0.09	0.14	.62		
HMA grade (4,C)	Ton	Yes	4.87	–0.07	0.10	.63		
PCC pavement	yd^3	Yes	6.68	–0.19	0.27	.71		
Placement of PCC	yd^3	Yes	6.57	–0.31	0.51	.65		
Removal of PCC	yd^2	Yes	3.63	–0.20	0.53	.43		
Select granular material	yd^3	Yes	4.36	–0.19	0.36	.56		
Class 6 aggregate base	yd^3	Yes	4.14	–0.11	0.37	.34		
Standard milling, 1.5 in	yd^2	Yes	3.76	–0.35	0.50	.57		
Standard milling, 2 in	yd^2	Yes	3.49	–0.31	0.53	.64		
Standard milling, 2.5 in	yd^2	Yes	1.75	–0.13	0.38	.43		
Reclaiming shoulders	yd^2	Yes	3.51	–0.28	0.51	.32		
Geotextile fabric	yd^2	Yes	2.16	–0.17	0.43	.34		
Partial depth repair	yd^2	Yes	6.31	–0.14	0.35	.33		
PCC replacement	yd^2	Yes	5.40	–0.10	0.28	.31		
Full-depth repair	ft	Yes	4.97	–0.08	0.21	.33		
Saw seal joints	ft	Yes	4.22	–0.10	0.29	.35		
Chip sealing	yd^2	Yes	5.21	–0.33	0.23	.49		
Fog sealing	yd^2	Yes	2.39	–0.13	0.17	.32		
Diamond grinding	yd^2	Yes	4.32	–0.27	0.21	.59		
Microsurfacing	yd^2	No					2.82	0.42
Crack sealing	yd^2	No					0.47	0.07

NOTE: SE = standard error.

Agency Cost

The probabilistic cost for the given pavement construction and maintenance activities in Table 1 are computed through Monte Carlo simulations and the net present values are presented in Figure 2*a* and Figure 2*b* for Cases 1A to 1C and 1D to 1F, respectively. Cases 1A to 1C are for the shorter segment and Cases 1D to 1F are for the longer segment. Cases 1A and 1D are asphalt and Cases 1B, 1C, 1E, and 1F are concrete. The error bars represent the standard deviation around the mean. It is seen that the lower initial cost of the asphalt scenarios 1A and 1D are offset in the pavement life cycle by their frequent maintenance requirements compared with the concrete alternatives 1B and 1C and 1E and 1F. Moreover, it is shown that the asphalt section 1A is the lowest cost alternative for the short scenarios, while the concrete sections 1E and 1F benefit from lower prices at the larger scale, a testament to the importance of economies of scale in pay item price characterization. Figure 2*c* and Figure 2*d* present the same results for Cases 1A to 1C and 1D to 1F, respectively, calculated using the Minnesota DOT LCCA tool with deterministic pay item prices. It is seen that the deterministic results are insensitive to project scale and the lowest cost alternative for the short and long sections is the concrete pavement with asphalt shoulders (1B and 1E). Furthermore, comparison of the probabilistic and deterministic costs shows agreement between the two approaches for the longer sections 1D to 1F, evidence that the deterministic pay item prices used by Minnesota are evaluated for large-scale projects. Hence neglecting the economy of scale in price characterization in the Minnesota DOT's LCCA tool results in lower than feasible cost estimates for the shorter sections in Figure 2*c*.

In addition to the reported life-cycle costs, the cumulative distribution of the agency costs are computed through the probabilistic approach for each alternative investment and presented in

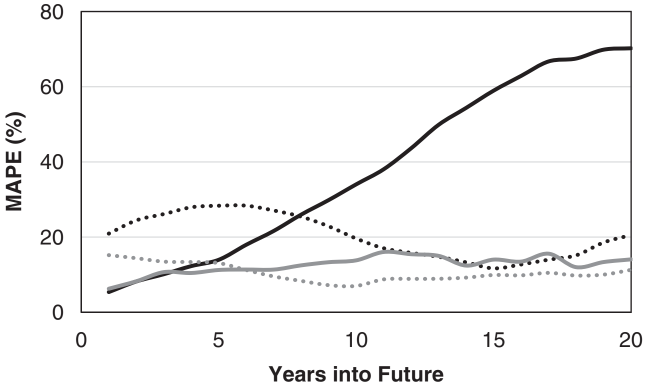
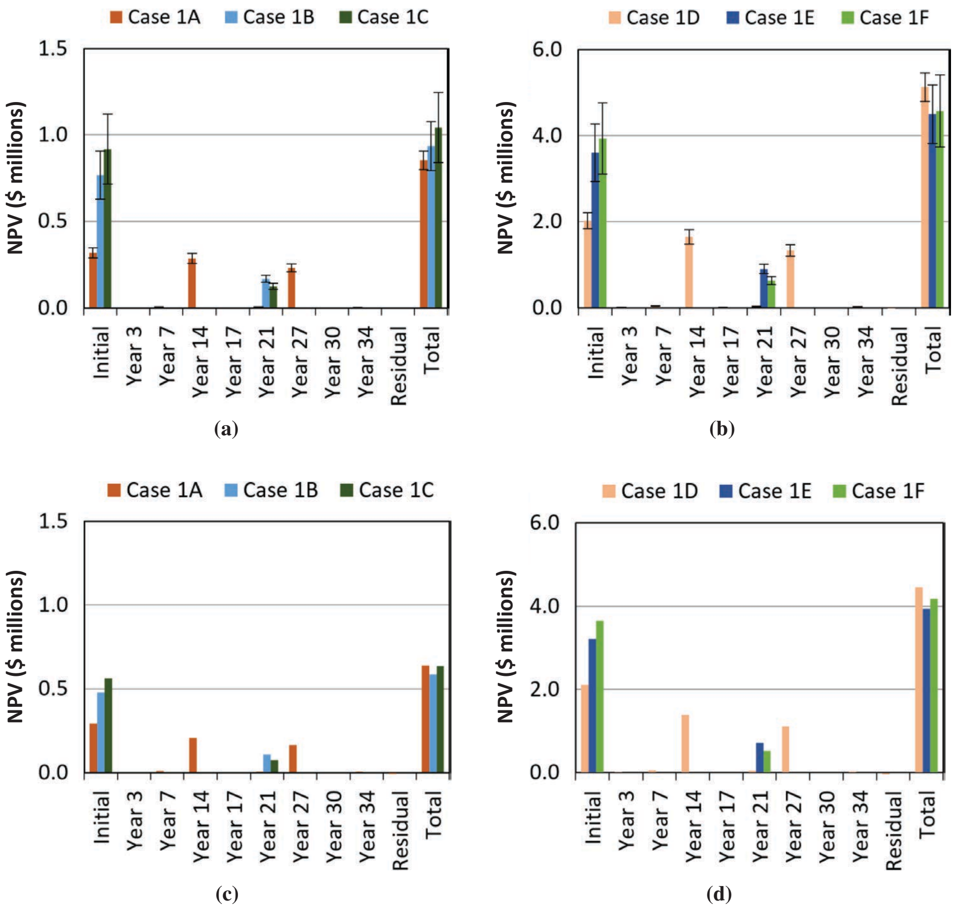


FIGURE 1 MAPE of asphalt (black) and concrete (gray) models using proposed forecasting approach (dashed) of Swei et al. (*24*) and current assumption of constant real prices of materials (solid).



(a) (b)

(c) (d)

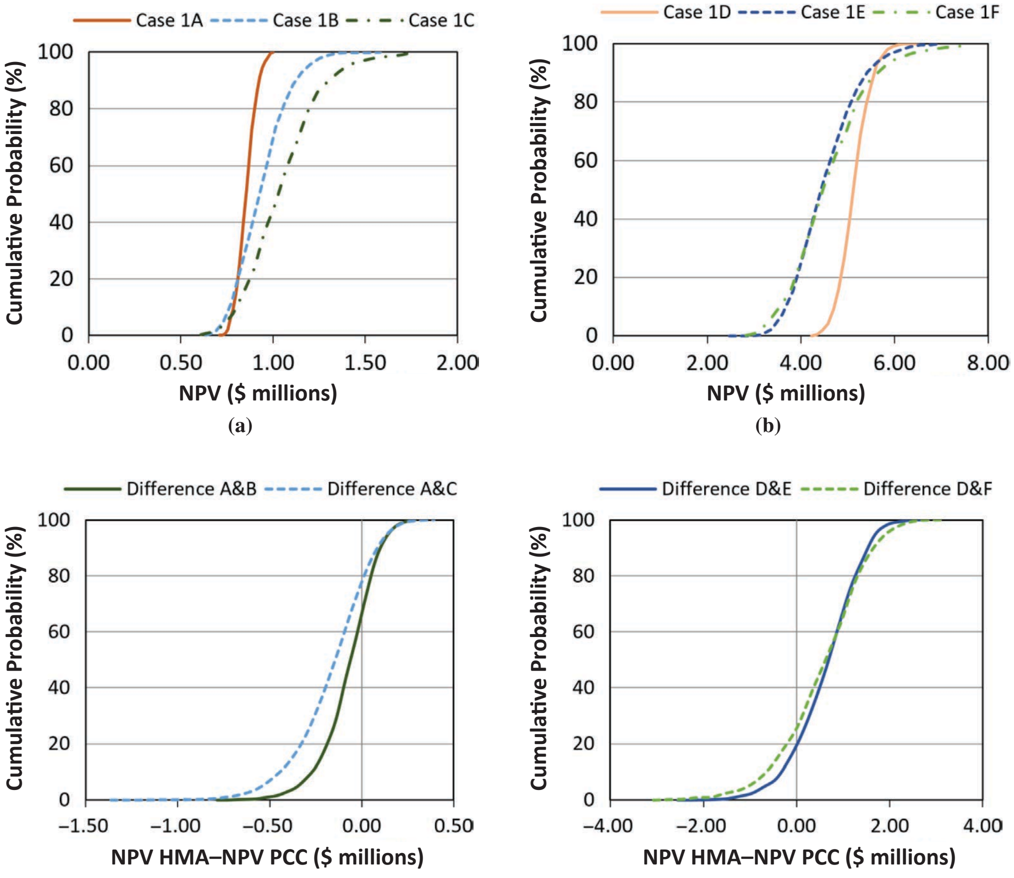
FIGURE 2 Agency LCCA results for Cases 1A to 1F calculated using (*a* and *b*) probabilistic LCCA and (*c* and *d*) deterministic Minnesota DOT LCCA (NPV = net present value).

Figure 3*a* and Figure 3*b*. It is observed in the error bars of Figure 2*a* and Figure 2*b*, as well as through the slope of the cumulative distributions of cost in Figure 3*a* and Figure 3*b*, that asphalt sections (1A and 1D) have a narrower distribution and hence less uncertainty associated with their cost estimates compared with their concrete alternatives. Moreover, the cumulative distributions show that at 50% reliability, the asphalt alternative has the lowest net present value of all short sections (Case 1A in Figure 3*a*), while the concrete scenarios are the lowest cost alternative for the long sections (Case 1E or 1F in Figure 3*b*). An increase in the reliability level to 95%, equivalent to lowering the risk of overrunning the total cost estimate to only 5%, strengthens selection of the asphalt pavement for the short section and closes the gap between the three pavement alternatives for the long sections. To assist with differentiating the lowest cost alternative, the comparison indicator is calculated as the cost difference between the asphalt and concrete scenarios for the short and long sections and is presented in Figure 3*c* and Figure 3*d*, respectively. It represents the probability of overrunning the total LCC estimate compared with a competing alternative. Figure 3*c* shows that there is an 80% probability that the asphalt scenario 1A will have a lower cost than the alternative concrete section 1B, and similarly a 65% probability against 1C for the short pavement scenarios. Conversely, Figure 3*d* shows there is less than a 20% probability that the asphalt scenario 1D will cost less than the concrete alternatives 1E and 1F; or in other words, there is more than an 80% probability that the concrete sections will be the lowest cost alternative for the long pavement scenarios.

Finally, the highest contributors to the total variance of the difference between the asphalt and concrete scenarios are evaluated. In all scenarios, the dominating contribution to variance is due to the uncertainty around the initial cost of portland cement concrete (PCC) and PCC placement, with the contribution of the asphalt concrete pavement recurring throughout its life cycle. While outside the scope of this study, the uncertainty in the initial cost of PCC can be further reduced by cost data filtering and disaggregating PCC costs by geography in Minnesota.

User Cost

Figure 4, *a* through *d*, presents the user costs associated with traffic delay, roughness-induced, and deflection-induced PVI impacts on passenger car and truck fuel consumptions for the six scenarios. The probabilistic analysis of deflection-induced PVI is represented with bars showing the standard deviation around the mean causes by uncertainty in material stiffness. Since the dominating PVI impacts are independent of road shoulder type and are a function of road surface conditions and structural properties, Cases 1B and 1C, as well as 1E and 1F, are assumed to have the same user costs. The small difference in the results of these scenarios is due to the traffic delay



(a) (b)

(c) (d)

FIGURE 3 Agency LCCA results for Cases 1A to 1F with (*a* and *b*) cumulative probabilistic LCCA results and (*c* and *d*) the probabilistic difference between bituminous and concrete scenarios.

caused by maintenance of the asphalt concrete shoulders in Scenarios 1B and 1E. The upward trend of the PVI-induced costs is associated with increasing road IRI levels and passenger car and truck traffic growths. It is observed from Figure 4 that roughness-induced PVI dominates the associated user costs, followed by deflection-induced PVI, and instances of traffic delay during M&R. It should be noted, however, that Case 1 has moderate traffic levels, such that traffic delay and deflection-induced PVI impacts are minimized.

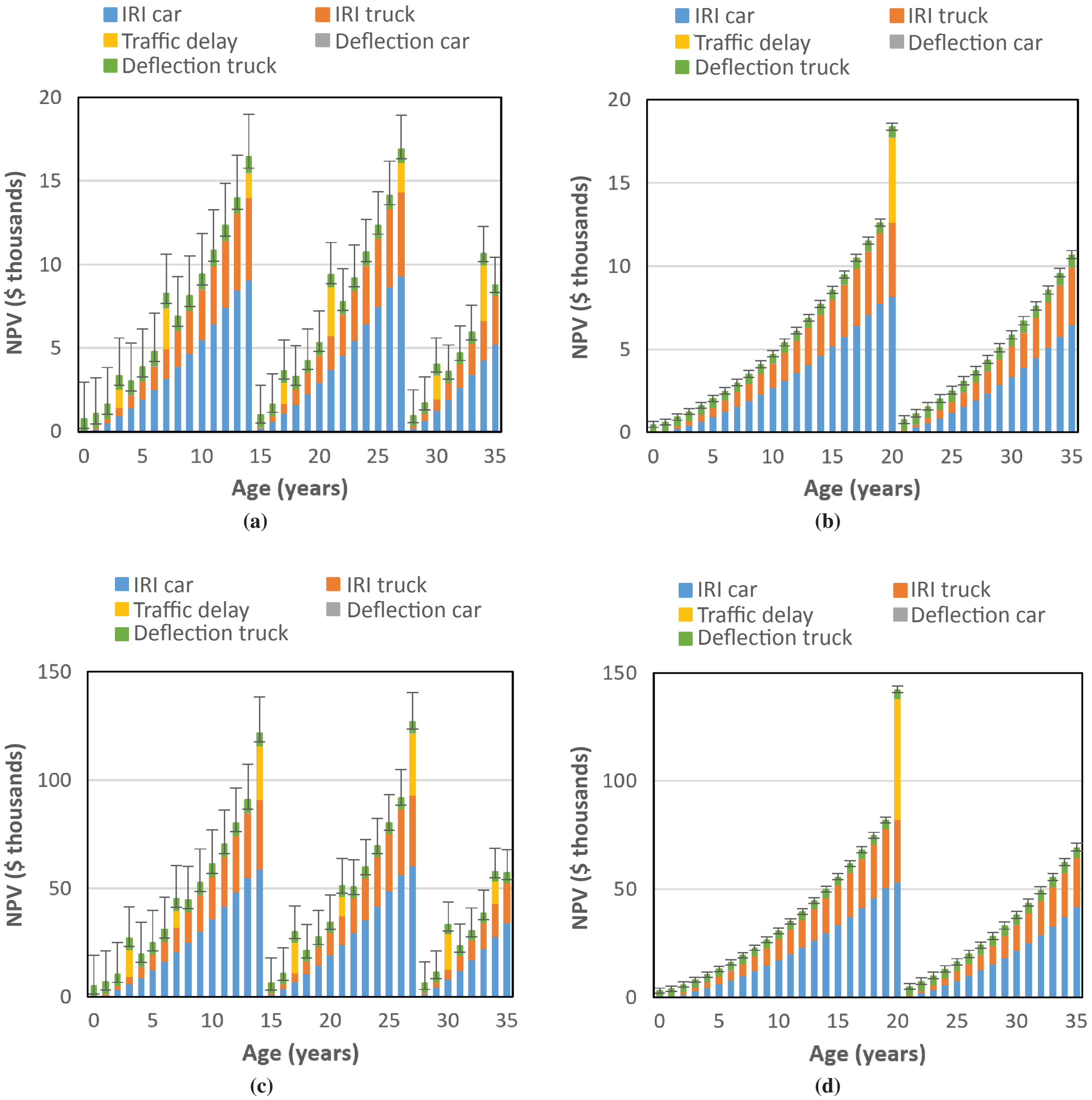
Total Life-Cycle Cost

The probabilistic initial M&R, traffic delay, and PVI user costs are presented in Figure 5*a* for Cases 1A to 1C and in Figure 5*b* for Cases 1D to 1F. The asphalt scenarios, 1A and 1D, have low initial costs and high M&R costs compared with their concrete counterparts, 1B and 1C and 1E and 1F. The user cost is dominated by roughness-induced PVI impacts on fuel consumption, followed by deflection-induced PVI and traffic delay costs. The figure shows the economy-of-scale's impact on the lowest cost alternative for the short sections 1A to 1C and the long sections 1D to 1F, with and without user cost. Although these sections have a medium traffic volume, the user costs are roughly equal to the total M&R costs, potentially justifying more maintenance activities to mitigate user costs.

CONCLUSIONS

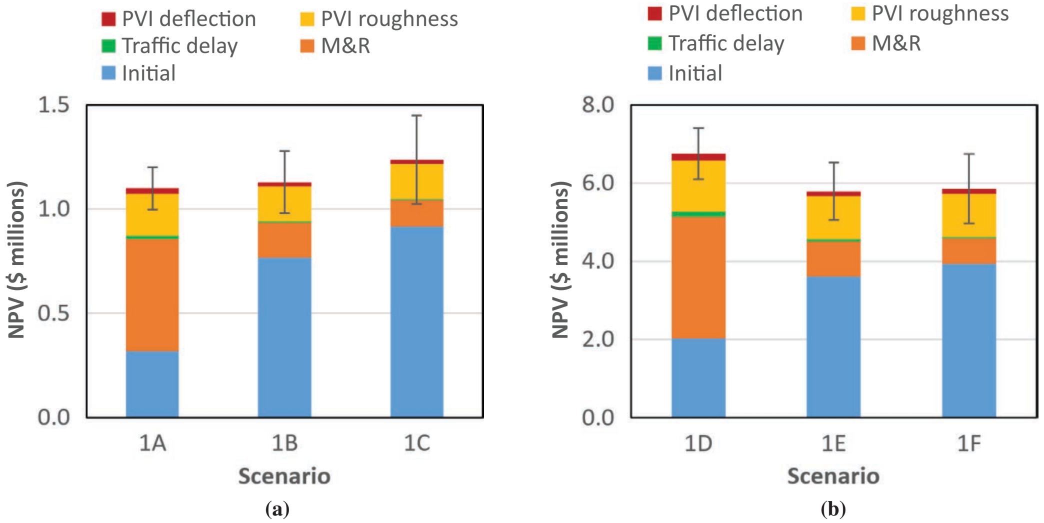
Planning agencies increasingly depend on LCCA to determine cost-effective design and maintenance strategies for pavement projects. Although researchers have improved the LCCA process over the past two decades, several opportunities remain to enhance such frameworks. In particular, this study has focused on understanding the fidelity of current approaches to model the unit price of construction pay items and, furthermore, has quantified, by use of a case study, the potential cost to users associated with PVI.

Results from the analysis of cost data indicate that economies of scale, as suggested by other researchers, explain much of the variation in existing data. Consequently, not accounting for economies of scale leads to incorrect estimates of both expected costs and associated measures of variation, potentially influencing the preferred alternative in an LCCA. Furthermore, this research tested the efficacy of projecting the future cost of material prices at the state level and found that, in general, such forecasts outperform the current assumption that future construction costs grow with the rate of inflation. Finally, the case study results suggest that PVI is a dominant contributor to user costs in LCCA and, furthermore, such costs are of the same order of magnitude as life-cycle costs to the agency. As a result, it is of great importance that future LCCA studies begin to incorporate costs associated with PVI, similar to current pavement LCA studies.



(a) (b) (c) (d)

FIGURE 4 User cost associated with traffic delay, roughness-induced, and deflection-induced PVI for scenarios (*a*) 1A, (*b*) 1B and 1C, (*c*) 1D, and (*d*) 1E and 1F (error bars are standard deviation of probabilistic deflection-induced PVI results).



(a) (b)

FIGURE 5 Total life-cycle cost including agency and user-associated costs for (*a*) short sections 1A, 1B, and 1C and (*b*) long sections 1D, 1E, and 1F (error bars represent standard deviation of probabilistic initial, M&R, and deflection-induced PVI results; traffic delay and roughness-induced PVI values are deterministic).

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