HIGHWAY PROJECT LEVEL LIFE-CYCLE BENEFIT/COST ANALYSIS UNDER CERTAINTY, RISK, AND UNCERTAINTY: A METHODOLOGY WITH CASE STUDY

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ABSTRACT

One of the key steps in the highway investment decision-making process is to conduct project evaluation. The existing project level life-cycle cost analysis approaches for estimating project benefits maintain limited capacity of probabilistic risk assessments of input factors such as highway agency costs, traffic growth rates, and discount rates. However, they do not explicitly address cases where those factors are under uncertainty with no definable probability distributions. This paper introduces an uncertainty-based methodology for highway project level life-cycle benefit/cost analysis that handles certainty, risk, and uncertainty inherited with input factors for the computation. A case study is conducted to assess impacts of risk and uncertainty considerations on estimating project benefits and on network-level project selection. First, data on system preservation and expansion, usage, and candidate projects for state highway programming are used to compute project benefits using deterministic, risk-based, and uncertainty-based analysis approaches, respectively. Then, the three sets of estimated project benefits are implemented in a stochastic optimization model for project selection. Significant differences are revealed with and without uncertainty considerations.

CE Database Subject Headings: Highway; Life cycles; Benefit cost ratios; Risk management; Uncertainty principles

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INTRODUCTION

Risk and Uncertainty Considerations in Highway Project Level Life-Cycle Benefit/Cost Analysis

One of the key steps in the highway investment decision-making process is to realistically estimate project-level life-cycle costs and benefits of different types of highway projects. Different highway facilities such as pavements and bridges have different useful service lives. In order to compare the merit of different projects on an equal basis, the life-cycle cost analysis approach needs to be adopted to evaluate the total economic worth of the initial construction cost and discounted future maintenance and rehabilitation costs in the facility life-cycle.

Over the last decade, the life-cycle cost analysis approach has been widely used for evaluating highway pavement and bridge projects. As related to pavement project evaluation, the Federal Highway Administration (FHWA) made a concerted effort for the use of life-cycle cost analysis in highway pavement design (FHWA, 1998). Hicks and Epps (1999) explored alternative pavement life-cycle design strategies with a logical comparison between conventional mixtures and the mixture containing asphalt rubber pavement materials. Wilde et al. (1999) introduced a life-cycle cost analysis framework for rigid pavement design. Abaza (2002) developed an optimal life-cycle cost analysis model for flexible pavements. Falls and Tighe (2003) enhanced life-cycle cost analysis through the development of cost models using the Alberta roadway maintenance and rehabilitation analysis application. Labi and Sinha (2005) and Peshkin et al. (2005) studied systematic preventive maintenance and the optimum timing strategies to achieve minimum pavement life-cycle costs. Chan et al. (2008) evaluated life-cycle cost analysis practices in Michigan. For bridge project evaluation, Purvis et al. (1994) performed life-cycle cost analysis of bridge deck protection and rehabilitation. Mohammadi et al. (1995) introduced the concept of incorporating life-cycle costs into highway bridge planning and design. Hawk (2003) developed a bridge life-cycle cost analysis software tool for bridge project evaluation.

In recent years, researchers began to utilize the risk-based life-cycle cost analysis approach to establish mathematical expectations of highway project benefits. For instance, Tighe (2001) performed a

probabilistic life-cycle cost analysis of pavement projects by incorporating mean, variance, and probability distribution for typical construction variables, such as pavement structural thickness and costs. Reigle et al. (2005) incorporated risk considerations into the pavement life-cycle cost analysis model. Setunge et al. (2005) developed a methodology for risk-based life-cycle cost analysis of alternative rehabilitation treatments for highway bridges using Monte Carlo simulation.

Motivation and Study Objectives

Due to lacking of pertinent information, in many instances it might not be possible to establish a meaningful probability distribution to possible outcomes of a specific input factor such as construction, rehabilitation, and maintenance costs and traffic growth in risk-based life-cycle benefit/cost analysis. That is, the input factors are under uncertainty with no definable probability distributions. Consequently, the mathematical expectation of the input factor cannot be established. Further, risk and uncertainty inherited with input factors for project level life-cycle benefit/cost analysis may vary from project to project. Some projects may only involve risk cases for some input factors, whereas other projects may only experience uncertainty cases for some input factors. In more general situations, a project may face mixed cases of certainty, risk, and uncertainty concerning all input factors for the computation. This necessitates developing a new uncertainty-based methodology for highway project level life-cycle benefit/cost analysis that could rigorously handle such general situations.

In this paper, we will first introduce a methodology for highway project level life-cycle benefit/cost analysis that considers certainty, risk, and uncertainty associated with input factors for the computation. A case study is then conducted to assess impacts of risk and uncertainty considerations in estimating project level life-cycle benefits and on network-level project selection. Discussions of usefulness of the proposed methodology and directions to its refinement are provided in the last section.

FRAMEWORK OF THE PROPOSED METHODOLOGY

The section starts with the discussion of common agency cost and user cost categories for pavement and bridge facilities, respectively. It then introduces a project level life-cycle cost analysis approach for

computing agency costs and user costs, as well as estimating overall project level life-cycle benefits for pavements and bridges. Next, risk and uncertainty issues associated with input factors for the computation are addressed. The last part of this section provides a generalized framework for uncertainty-based highway project level life-cycle benefit/cost analysis where the input factors are under certainty, risk, and uncertainty.

Pavement and Bridge Life-Cycle Agency Costs and User Costs

In this study, the pavement or bridge life-cycle is defined as the time interval between two consecutive construction events. Maintenance and rehabilitation treatments are performed within the pavement or bridge life-cycle. The pavement and bridge life-cycle agency cost and user cost components are briefly discussed in the following:

Pavement Life-Cycle Agency Costs

Cost analysis is a cardinal element of any highway project life-cycle benefit/cost analysis. All costs incurred over pavement life-cycle including those of construction, rehabilitation, and maintenance treatments need to be included into the analysis.

Bridge Life-Cycle Agency Costs

Bridge agency costs are primarily involved with costs of bridge design and construction/ replacement, deck and superstructure rehabilitation and replacement, and maintenance treatments.

Pavement/Bridge Life-Cycle User Costs

User costs are incurred by highway users in the pavement or bridge life-cycle. User cost components mainly include costs of vehicle operation, travel time, vehicle crashes, and vehicle air emissions (FHWA, 2000; AASHTO, 2003). Each user cost component consists of two cost categories: user cost under normal operation conditions and excessive user cost due to work zones (FHWA, 1998).

Pavement/Bridge Life-Cycle Activity Profiles and User Cost Profiles

Pavement/Bridge Life-Cycle Activity Profiles

The pavement or bridge life-cycle activity profile refers to the frequency, timing, and magnitude of construction, rehabilitation, and maintenance treatments within its life-cycle. A typical life-cycle activity profile represents the most cost-effective way of implementing strategically coordinated treatments to achieve the intended service life. In practice, pavement life-cycle activity profiles are determined using preset time intervals for treatments and condition triggers for treatments, respectively. Many state transportation agencies currently use preset time intervals because of lacking consensus in condition trigger values and consistency in pavement condition data. With respect to bridge life-cycle activity profiles, the preset time interval approach is also commonly used. Table 1 lists the typical frequency and timing of major treatments in pavement and bridge service lives used by the FHWA, American Association of State Highway and Transportation Officials (AASHTO), and state transportation agencies (FHWA, 1987, 1991; Gion et al, 1993; INDOT, 2002; AASHTO, 2003).

Table 1. Typical Frequency and Timing of Major Treatments in Pavement and Bridge Life-Cycles

Facility (1)	Material Type (2)		Service Life (Year) (3)	Treatment Frequency (4)	Timing (5)
Pavement	Flexible		40	Thin overlay +	15th year
				Thick HMA overlay	30th or 33rd year
	Rigid		40	PCC joint sealing +	7th year
				PCC joint sealing +	15th year
				PCC repair techniques +	23rd year
				Thick HMA overlay +	30th year
				HMA crack sealing	37th year
				PCC overlay +	30th year
				PCC joint sealing	35th year
Bridge	Concrete	Channel Beam	35	Deck rehabilitation	20th year
		T-Beam/ Girder	70	Deck rehabilitation +	20th, 55th year
				Superstructure replacement	35th year
		Slab	60	Deck rehabilitation	30th, 45th year
	Prestressed Concrete	Box-Beam	65	Deck rehabilitation +	20th, 50th year
				Deck replacement	35th year
		Box Girder	50	Deck rehabilitation	20th, 35th year
	Steel	Box-Beam/ Girder	70	Deck rehabilitation +	20th, 55th year
				Deck replacement	35th year
		Truss	80	Deck rehabilitation +	25th, 65th year
				Deck replacement	40th year

The life-cycle agency costs for each type of pavements or bridges can be quantified on the basis of the proposed life-cycle activity profile as Table 1. For a specific pavement or bridge project, the construction, rehabilitation, and maintenance costs in the pavement or bridge life-cycle can be estimated using historical data on the unit rates of construction, rehabilitation, and maintenance treatments multiplied by the project size. A geometric growth rate represented by a constant percent of annual growth can be used to establish annual routine maintenance costs for future years based on the first year routine maintenance cost within an interval between two major treatments.

Pavement/Bridge Life-Cycle Annual User Cost Profiles

For each user cost component, the first year user costs under normal operation conditions within an interval between two major treatments can be calculated. A geometric growth rate can be used for estimating annual user costs in future years within the same interval based on the first year user costs. The excessive user costs caused by project work zones such as delay costs need to be considered for the year involving major treatments.

Estimation of Project Level Life-Cycle Benefits

The typical life-cycle activity profile for pavements or bridges represents the most cost-effective investment strategy to manage pavement or bridge facilities. If any needed treatment fails to be timely implemented as per the typical life-cycle activity profile, an early termination of the service life is expected. As such, the typical life-cycle activity profile can be used as the base case activity profile and the case with early service-life termination can be considered as an alternative case activity profile. For each type of pavements or bridges, the reduction in life-cycle agency costs of the base case activity profile compared with the alternative case activity profile can be computed as project level life-cycle agency benefits of timing implementing the needed project. Similarly, the decrease in life-cycle user costs according to the base case activity profile against the alternative case activity profile can be estimated as the project level life-cycle user benefits.

Figure 1 illustrates an example of base case and alternative case activity profiles for the steel-box beam bridge and the method for estimating project level life-cycle agency benefits and user benefits by keeping the typical life-cycle activity profile for the bridge. For the base case life-cycle activity profile, agency costs in the T-year bridge service life consist of initial bridge construction cost C_{CON} in year 0, first deck rehabilitation cost $C_{DECK\ REH1}$ in year t_1, deck replacement cost $C_{DECK\ REP}$ in year t_2, second deck rehabilitation cost $C_{DECK\ REH2}$ in year t_3, and annual routine maintenance costs. The annual routine maintenance costs between two major treatments in the bridge life-cycle will gradually increase over time due to the combined effect of higher traffic demand, aging materials, climate conditions, and other non-load related factors. Different geometric gradient growth rates are used for intervals between year 0 and t_1, t_1 and t_2, t_2 and t_3, and t_3 and T, respectively.

For the alternative life-cycle activity profile, it is assumed that the deck replacement project (with the cost of $C_{PROJECT}$) is actually implemented y_1 years after year t_2 as the base case profile, namely, $C_{DECK\ REP}$ in year t_2 is replaced by $C_{PROJECT}$ in year t_2+y_1. This will defer the second deck rehabilitation by y_1 years. Due to postponing deck replacement and the second deck rehabilitation, the bridge service life may experience an early termination of y_2 years. As for the annual routine maintenance costs, different geometric gradient growth rates are used for intervals between year 0 and t_1, t_1 and t_2+y_1, t_2+y_1 and t_3+y_1, and t_3+y_1 and $T-y_2$, correspondingly. In particular, the annual routine maintenance cost profiles for the base case and alternative case profiles are identical from year 0 to year t_2. The project level life-cycle agency benefits are estimated as the reduction in bridge life-cycle agency costs quantified according to the base case activity profile compared with the alternative case activity profile.

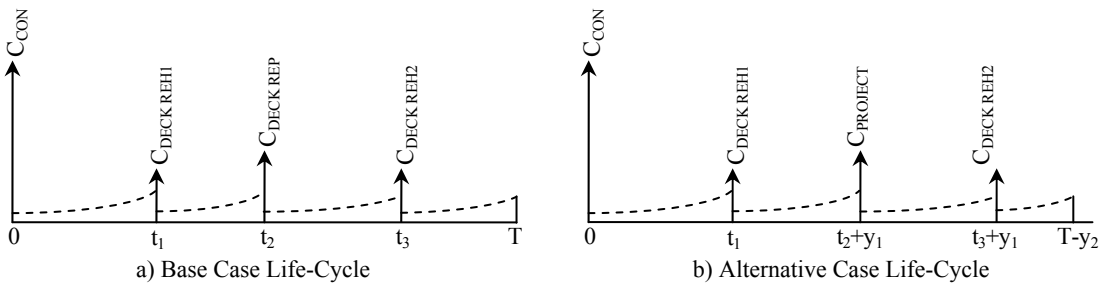

Fig. 1. Illustration of Base Case and Alternative Case Life-Cycles for the Steel- Box Beam Bridge

The primary user cost items include vehicle operating costs, travel time, vehicle crashes, and vehicle air emissions. For each user cost item, the base case and alternative case annual user cost profiles in bridge life-cycle follow a pattern similar to the profile of annual routine maintenance costs in bridge life-cycle. In either the base case profile or alternative case profile, the "first year" user cost amounts immediately after the major treatments including bridge construction, first deck rehabilitation, deck replacement, and second deck rehabilitation are directly computed on the basis of the unit user cost in constant dollars per vehicle mile of travel (VMT) and the annual VMT. The unit user cost per VMT is estimated according to average travel speed and roadway condition as in Li and Sinha (2003). Geometric growth rate is then applied to the "first year" user cost amount for each interval between two major treatments to establish the annual user cost amounts for subsequent years within the interval. Additional work zone related costs are estimated using the procedures in FHWA (1988, 2000) and AASHTO (2003), and added to the annual user cost amounts for the years in which major treatments are implemented. This ultimately establishes the base case and alternative case annual user cost profiles for vehicle operating costs, travel time, vehicle crashes, and vehicle air emissions, respectively.

For each user cost item, the annual user cost profiles for the base case and alternative case are identical from year 0 to t_2 and are different for the remaining years in the bridge life-cycle. The travel demand in terms of annual VMT for a specific year after year t_2 could be different between the base case and alternative case due to the fact that the traffic volume, i.e., annual average daily traffic (AADT) and/or travel distance associated with the bridge might change for the two cases. The consumer surplus concept is employed to

separately compute the user benefits by comparing the base case and alternative case annual user cost profiles for intervals from year t_2 to t_2+y_1, t_2+y_1 to t_3, t_3 to t_3+y_2, t_3+y_2, $T-y_2$, and $T-y_2$ to T. The total project level life-cycle user benefits are the aggregation of individual user benefit items associated with reductions in vehicle operating costs, travel time, vehicle crashes, and vehicle air emissions in the bridge life-cycle. With equal weights assigned for agency benefits and user benefits, the total project level life-cycle benefits by keeping the typical life-cycle activity profile for the bridge are established by combining the two sets of benefits.

Estimation of Project Level Life-Cycle Benefits in Perpetuity

The project level life-cycle benefits in perpetuity can be quantified on the basis of the base case and alternative life-cycle activity profiles. As the base case life-cycle activity profile represents the most cost-effective investment strategy, investment decisions are always made with the intention to keep abreast of the base case life-cycle activity profile. For the base case life-cycle activity profile in perpetuity, the base case typical facility life-cycle is assumed to be repeated an infinite number of times. For the alternative case life-cycle activity profile in perpetuity, early termination of service life may occur in the first life-cycle, in the first and second life-cycles or in the first several life cycles. After experiencing early service life terminations, the base case typical facility life-cycle is expected to be resumed back for the subsequent life cycles in perpetuity horizon. This is because that the base case life-cycle profile represents the most cost-effective investment strategy that the decision-maker always aims to achieve. Without loss of generality, the alternative case life-cycle profile in perpetuity in this study adopts early terminations for the first two life-cycles and the base case life-cycle profile is used for subsequent life cycles in perpetuity horizon. The reduction in project level life-cycle agency costs between the base case and the alternative case life-cycle activity profiles in perpetuity is computed to establish project level life-cycle agency benefits in perpetuity.

Similarly, the reduction in project level life-cycle user costs between the base case and the alternative case life-cycle annual user cost profiles in perpetuity for vehicle operating costs, travel time, vehicle crashes, and

vehicle air emissions can be separately computed and summed up to establish project level life-cycle user benefits in perpetuity. With equal weights considered for agency benefits and user benefits, they can be directly added to establish overall project level life-cycle benefits in perpetuity.

Risk Considerations in Estimating Project Level Life-Cycle Benefits

Primary Input Factors under Risk Considerations

Project construction, rehabilitation, and maintenance costs may not remain as predicted. Traffic demand may not follow the projected path. Discount rate may fluctuate over time during the pavement or bridge life-cycle. Such variations will in turn result in changes in the overall project level life-cycle benefits. In this study, the unit rates of project construction, rehabilitation, and maintenance treatments, traffic growth rates, and discount rates are primary input factors considered for probabilistic risk assessments.

Selection of Probability Distributions for the Input Factors under Risk Considerations

The minimum and maximum values of above input factors under risk considerations are bounded by non-negative values. For each of the risk factors, the distribution of its possible outcomes could be either symmetric or skewed. Such distribution characteristics can be readily modeled by the Beta distribution that is continuous over a finite range and also allows for virtually any degree of skewness and kurtosis. The Beta distribution has four parameters- lower bound (L), upper bound (H), and two shape parameters α and β, with density function given by

$$f(x|\alpha, \beta, L, H) = \frac{\Gamma(\alpha+\beta)\cdot(x-L)^{\alpha-1}\cdot(H-x)^{\beta-1}}{\Gamma(\alpha)\cdot\Gamma(\beta)\cdot(H-L)^{\alpha+\beta-1}} \quad (L \le x \le H) \tag{1}$$

where the Γ-functions serve to normalize the distribution so that the area under the density function from L to H is exactly 1.

The mean and variance of the Beta distribution are given as

$$\mu = \frac{\alpha}{\alpha+\beta} \text{ and } \sigma^2 = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}. \tag{2}$$

Using Simulation for Probabilistic Risk Assessments

Simulation is essentially a rigorous extension of sensitivity analysis that uses randomly sampled values from the input probability distribution to calculate discrete outputs. Two types of sampling techniques are commonly used to perform simulations. The first type is the Monte Carlo sampling technique that uses random numbers to select values from the probability distribution. The second type is the Latin Hypercube sampling technique where the probability scale of the cumulative distribution curve is divided into an equal number of probability ranges. The number of ranges used is equal to the number of iterations performed in the simulation. The Latin Hypercube sampling technique is likely to achieve convergence in fewer iterations as compared to those of the Monte Carlo sampling technique (FHWA, 1998).

Uncertainty Considerations in Estimating Project Level Life-Cycle Benefits

As a practical matter, the input factors under risk considerations may not be readily characterized using reliable probability distributions. Consequently, a meaningful mathematical expectation for each factor cannot be established and this invalidates risk-based analysis. Shackle's model introduced herein is well suited to handle each input factor under uncertainty where no probability distribution can be readily established for a number of possible outcomes (Shackle, 1949).

In general, Shackle's model overcomes the limitation of inability to establish the mathematical expectation of possible outcomes of each input factor for project level life-cycle benefit/cost analysis according to the following procedure. First, it uses degree of surprise as a measure of uncertainty associated with the possible outcomes in place of probability distribution. Then, it introduces a priority index by jointly evaluating each known outcome and the associated degree of surprise pair. Next, it identifies two outcomes of the input factor maintaining the maximum priority indices, one on the gain side and the other on the loss side from the expected outcome $X_{(E)}$. The expected outcome could be the average value or the mode of all known possible outcomes, but it is not the mathematical expectation as outcome probabilities are unknown. The two outcomes need to be standardized to remove the associated degrees of surprise. The absolute deviations of two outcomes relative to the expected outcome are terms as standardized focus gain x_{SFG} and

standardized focus loss x_{SFL} from the expected outcome $X_{(E)}$. This model yields a triple < x_{SFL}, $X_{(E)}$, x_{SFG}> for each input factor under uncertainty. More details of Shackle's model are in Ford and Ghose (1998), Young (2001), and Li and Sinha (2004, 2006).

To simplify the application of Shackle's model for uncertainty-based analysis, the grand average of simulation outputs from multiple iterations of replicated simulation runs can be used as the expected outcome $X_{(E)}$ for an input factor under uncertainty:

$$X_{(E)} = \frac{\sum_{m=1}^{M}\sum_{n=1}^{N} X_i}{M \times N} \tag{3}$$

where

X_i = A simulation output representing a possible outcome

N = Number of iterations in each simulation run, and

M = Number of replicated simulation runs.

If higher valued outcomes are preferred for an input factor, the absolute deviation of the average value of simulation outputs that are lower than the expected outcome can used as standardized focus loss value x_{SFL} and the absolute deviation of the average value of simulation outputs that are equal or higher than the expected outcome can used as standardized focus gain value x_{SFG} for the input factor under uncertainty.

$$x_{SFL} = \left| \frac{\sum_{m=1}^{M}\sum_{n=1}^{N_r} X_i}{M \times N_r} - X_{(E)} \right| \tag{4}$$

$$x_{SFG} = \left| \frac{\sum_{m=1}^{M}\left(\sum_{n=1}^{N} X_i - \sum_{n=1}^{N_r} X_i\right)}{M \times (N - N_r)} - X_{(E)} \right| \tag{5}$$

where

N_r = Number of simulation outputs in the rth simulation run such that $X_i < X_{(E)}$ if a higher outcome value is preferred for the input factor.

In some cases, lower outcome values are preferred for an input factor such as the discount rate. The N_r for computing the standardized focus loss value x_{SFL} and the standardized focus gain value x_{SFG} thus refers to number of simulation outputs in the rth simulation run such that $X_i > X_{(E)}$.

As an extension of Shackle's model dealing with the input factor under uncertainty, a decision rule is introduced to help compute a single value X for the input factor based on the triple $< x_{SFL}, X_{(E)}, x_{SFG}>$ that can be used for estimating project benefits. Assuming that the decision-maker only tolerates loss from the expected outcome for the input factor under uncertainty by ΔX and if higher outcome values are preferred, the decision rule is set as

$$X = \begin{cases} X_{(E)}, & \text{if } x_{SFL} \leqslant \Delta X \\ \dfrac{X_{(E)} - x_{SFL}}{[1 - \Delta X / X_{(E)}]}, & \text{otherwise} \end{cases} \tag{6}$$

When lower outcome values are preferred for an input factor, the decision rule is revised to

$$X = \begin{cases} X_{(E)}, & \text{if } x_{SFL} \leqslant \Delta X \\ \dfrac{X_{(E)} + x_{SFL}}{[1 + \Delta X / X_{(E)}]}, & \text{otherwise} \end{cases} \tag{7}$$

If the standardized focus loss x_{SFL} from the expected outcome $X_{(E)}$ does not exceed ΔX, the expected outcome value will be utilized for the input factor for the computation. This will produce an identical input factor value for both uncertainty-based and risk-based analyses. If the standardized focus loss x_{SFL} from the expected outcome $X_{(E)}$ exceeds ΔX, a penalty is applied to derive a unique value for the input factor. Different tolerance levels ΔX's may be used for different input factors under uncertainty.

A Generalized Framework for Uncertainty-Based Project Level Life-Cycle Benefit/Cost Analysis

Figure 2 shows a generalized framework for uncertainty-based highway project level life-cycle benefit/cost analysis with input factors under mixed cases of *certainty* (the input factor is purely deterministic with single value), *risk* (the input factor has a number of possible outcomes with a known probability distribution), and *uncertainty* (the input factor has a number of possible outcomes with unknown probabilities). If an input factor is under certainty, the single value of the factor can be used for the computation. If an input factor is under risk, the mathematical expectation of the factor can be utilized for the computation. If an input factor is under uncertainty, the single value of the factor determined according to the decision rule extended from Shackle's model can be adopted for the computation.

By using values of input factors determined under certainty, risk or uncertainty, the proposed framework helps establish project level life-cycle agency benefits and user benefits concerning decrease in agency costs, reduction in vehicle operating costs, shortening of travel time, decrease in vehicle crashes, and cutback of vehicle air emissions in perpetuity horizon, respectively. The combination of certainty, risk, and uncertainty cases for input factors may vary by project benefit item for the same project and may also vary for different types of highway projects.

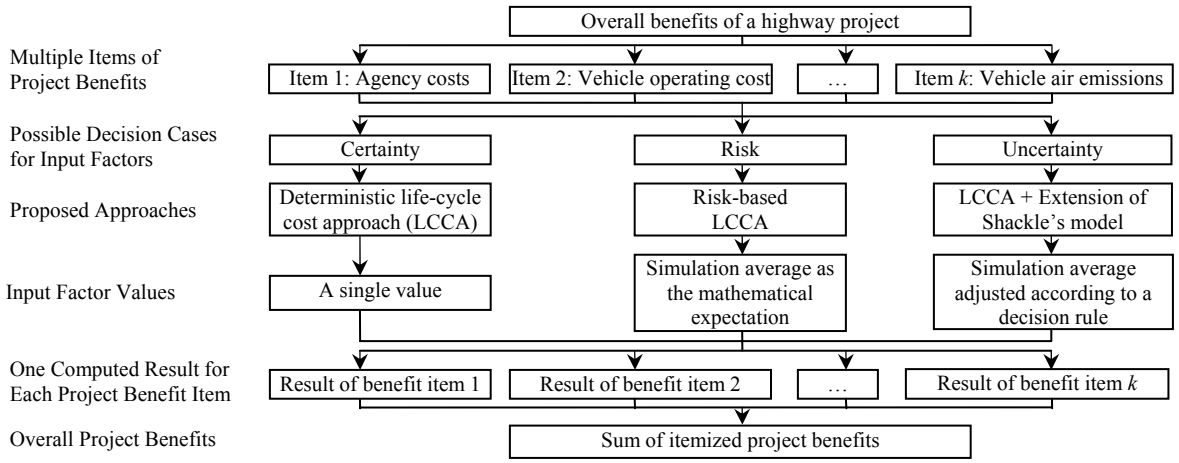

Fig. 2. A Generalized Framework for Estimating Overall Project Benefits under Certainty, Risk and Uncertainty

IMPACTS OF THE PROPOSED METHODOLOGY ON ESTIMATING PROJECT BENEFITS

Comparison of Estimated Project Benefits for Project-Level Impact Assessments

Project-level impact assessments compare project level life-cycle benefits separately estimated using the deterministic, risk-based, and the uncertainty-based project level life-cycle cost analysis approaches. For the application of deterministic project level life-cycle benefit/cost analysis, project benefits are calculated by assuming that all input factors are under certainty and each input factor has a single value. These values are directly used for the computation.

For the application of risk-based project level life-cycle benefit/cost analysis, project benefits are calculated by assuming that input factors regarding unit rates of construction, rehabilitation, and maintenance treatments, traffic growth rates, and discount rates are all under risk. The remaining input factors such as pavement or bridge service life and timing of treatments are still treated as being under certainty with single values. Monte Carlo simulations are executed to establish the grand average values of simulation outputs as mathematical expectations of input factors under risk. The single values of input factors under certainty and the grand average values of input factors under risk are used for the computation.

For the application of the uncertainty-based methodology, project benefits are calculated by assuming that the input factors regarding unit rates of construction, rehabilitation, and maintenance treatments, traffic growth rates, and discount rates are all under uncertainty or under mixed cases of risk and uncertainty. The remaining input factors are still considered under certainty with single values. For the input factor under risk, the grand average value as the mathematical expectation is established using Monte Carlo simulation outputs. For the input factor under uncertainty, the grand average value of simulation outputs is adjusted according to the preset decision rule. The single values of input factors under certainty, the grand average values of input factors under risk, and the adjusted grand average values of input factors under uncertainty are used for the computation.

Comparison of Project Selection for Network-Level Impact Assessments

In order to assess the network-level impacts of adopting different approaches for project benefit estimation, the three sets of project benefits computed using the deterministic, risk-based, and uncertainty-based approaches are separately applied to a stochastic optimization model for network-level project selection. The network-level impacts are assessed by cross comparison of the overall benefits of selected projects and consistency matching rates of project selection using the three different sets of project benefits with the actual project selection and programming practice. This section briefly discusses the stochastic optimization formulation for finding the optimal subset of highway projects from all candidate projects to achieve maximized total project level life-cycle benefits where there is stochasticity in the available budget.

Consider a state transportation agency that carries out highway network-level project selection over a future project implementation period of t_Ω years. The agency makes first round of investment decisions many years prior to project implementation using an estimated budget for all years. With time elapsing, updated budget information on the first few years of the multi-year project selection and programming period becomes available that motivates the agency to refine the investment decisions. In each refined decision-making process, the annual budget for the first few years that can be accurately determined is treated as a deterministic value, while the budget for the remaining years without accurate information is still handled as a stochastic budget.

Stochastic Optimization Model for Network-Level Project Selection

Assuming that the multi-year budget is refined Ω times and each time an increasing number of years with accurate budget information from the first year is obtained, Ω-decision stages are therefore involved. Without loss of generality, a discrete probability distribution of budget possibilities can be assumed for each year where no accurate budget information is available. The stochastic model with Ω-stage budget recourses can be formulated as a deterministic equivalent program that combines first stage decisions using the initial budget estimate with expected values of recourse functions for the remaining (Ω -1) stages (Birge and Louveaux, 1997).

Denote:

x_i = Decision variable of contract i, $i = 1, 2,\ldots, N$ ($x_i = 0/1$)

a_i = Benefits of contract i, $i = 1, 2, \ldots, N$

c_{ikt} = Cost of contract i using budget from highway asset management program k in year t

$X_L(p)$ = Decision vector using budget $B_{kt}^L(p)$ in stage L, $X_L(p)= [x_1, x_2,\ldots, x_N]$

A = Vector of benefits of N contracts, $A = [a_1, a_2,\ldots, a_N]$

C_{kt} = Vector of costs of N contracts using budget from program category k in year t,

$C_{kt} = [c_{1kt}, c_{2kt},\ldots, c_{Nkt}]$

ξ_L = Randomness associated with budget and decision space comprised of all possible combinations in the values of decision variables in stage L

$Q(X_L(p), \xi_L)$ = Recourse function in stage L

$E_{\xi_L}[Q(X_L(p), \xi_L)]$ = Mathematical expectation of the recourse function in stage L

$B_{kt}^L(p)$ = The pth possibility of budget for program category k in year t in stage L

$p(B_{kt}^L(p))$ = Probability of having budget scenario $B_{kt}^L(p)$ occur in stage L

$E(B_{kt}^L)$ = Expected budget in stage L, where $E(B_{kt}^L) = \sum_{p=1}^{p_L}\left[P\left(B_{kt}^L(p)\right)\cdot B_{kt}^L(p)\right]$

p = $1, 2,\ldots, p_L$, where $p_L = s_L.s_{L+1}\ldots.s_\Omega$

L = $1, 2,\ldots, \Omega$

i = $1, 2,\ldots, N$

k = $1, 2,\ldots, K$ for different highway asset management programs, which typically include bridge preservation, pavement preservation, safety improvements, roadside improvements, system expansion, state park highway facilities, ITS installations, and maintenance programs

t = $1, 2,\ldots, M$.

The stochastic model with Ω-stage budget recourses formulated as a Multi-Choice Multidimensional Knapsack Problem (MCMDKP) is shown below:

Maximize $A^T.X_1 + \sum_{\omega=2}^{\Omega} E_{\xi_\omega}\left[Q_\omega\left(X_\omega(p), \xi_\omega\right)\right]$ (8)

Stage 1

Subject to $C_{kt}^T.X_1 \leq E(B^1_{kt})$ (9)

X_1 is a decision vector with 0/1 integer elements.

Stage 2

$E_{\xi_2}[Q_2(X_2(p), \xi_2)] = \max \{ A^T.X_2(p) \mid B^2_{kt}(p) = E(B^2_{kt}) \}$ (10)

Subject to $C_{kt}^T.X_2(p) \leq B^2_{kt}(p)$ (11)

$X_1 + X_2(p) \leq 1$ (12)

X_1 and $X_2(p)$ are decision vectors with 0/1 integer elements.

...

Stage L

$E_{\xi_L}[Q_L(X_L(p), \xi_L)] = \max \{ A^T.X_L(p) \mid B^L_{kt}(p) = E(B^L_{kt}) \}$ (13)

Subject to $C_{kt}^T.X_L(p) \leq B_{kt}^L(p)$ (14)

$X_1 + X_2(p) + \ldots + X_L(p) \leq 1$ (15)

$X_1, X_2(p), \ldots, X_L(p)$ are decision vectors with 0/1 integer elements.

...

Stage Ω

$E_{\xi_\Omega}[Q_\Omega(X_\Omega(p), \xi_\Omega)] = \max \{ A^T.X_\Omega(p) \mid B^\Omega_{kt}(p) = E(B^\Omega_{kt}) \}$ (16)

Subject to $C_{kt}^T.X_\Omega(p) \leq B_{kt}^\Omega(p)$ (17)

$X_1 + X_2(p) + \ldots + X_L(p) + \ldots + X_\Omega(p) \leq 1$ (18)

$X_1, X_2(p), \ldots, X_L(p), \ldots, X_\Omega(p)$ are decision vectors with 0/1 integer elements.

In the objective function as Equation (8), the first term is for the overall project benefits in the first stage decisions using the initial budget estimate and the second term is for the expected value of overall project

benefits for the remaining (Ω-1) stages with budget recourse decisions. Equations (9), (11), (14), and (17) are budget constraints for the optimization model. The constraints are imposed by highway asset management program *k* and by project implementation year *t* for the multi-year project implementation period. Equations (10), (13), and (16) compute the expected values of maximized total project benefits under budget constraints at stages 2, *L*, and Ω, respectively. At each stage, the budget used for the computation is determined by selecting a possible budget that maintains the least amount of deviations from the expected budget for that stage. For instance, the stage *L* budget for the computation is chosen from all possible budgets $B^L_{kt}(1)$, $B^L_{kt}(2)$, …, $B^L_{kt}(p_L)$ such that $\sum_{k=1}^{K}\sum_{t=1}^{M}\left[B^L_{kt}(p)-E\left(B^L_{kt}\right)\right]^2$ is minimized. Equations (12), (15), and (18) ensure that each highway project can be selected at most once in the multi-stage recourse decision process.

In the above optimization model, budget constraints are imposed by highway asset management program *k* and by year *t* for the multi-year project implementation period. In current practices, available budgets for different highway asset management programs such as pavement preservation program and bridge preservation program are not transferable across programs. For each asset management program, the yearly constrained multi-year budgets in the optimization model can however be treated as a cumulative budget for all years combined. For the option of cumulative budget constraints, the notations $B_{kt}^L(p)$, $p(B_{kt}^L(p))$, and $E(B_{kt}^L)$ in Equations (9), (11), (14), and (17) are replaced by $\sum_{t=1}^{M}B^L_{kt}(p)$, $p(\sum_{t=1}^{M}B^L_{kt}(p))$, and $E(\sum_{t=1}^{M}B^L_{kt})$, where $E(\sum_{t=1}^{M}B^L_{kt}) = \sum_{p=1}^{p_L}[p(\sum_{t=1}^{M}B^L_{kt}(p)).\sum_{t=1}^{M}B^L_{kt}(p)]$ (L = 1, 2,…, Ω). In this study, the optimization model is applied using the yearly constrained budget scenario and the cumulative budget scenario, respectively.

Model Solution

For the purpose of the present paper, the solution algorithm developed based on the LaGrangian relaxation technique was implemented using a customized computer code.

CASE STUDY

A case study was conducted to examine the impacts of using deterministic, risk-based, and uncertainty-based project level life-cycle cost analysis approaches on computing the benefits of individual highway projects. The computed project benefits were used to assess the network-level impacts of adopting different project level life-cycle cost analysis approaches on project selection results.

Data Sources

Data Collection and Processing for Highway Project Benefit Estimation

For assessing the project-level impacts of using deterministic, risk-based, and uncertainty based project level life-cycle cost analysis approaches for project benefit estimation, historical data on the Indiana state highways for period 1990-2006 were collected to establish the base case life-cycle activity profiles and annual user cost profiles for different types of pavements and bridges. The data items collected mainly included project type and size; unit rates of construction, rehabilitation, and maintenance treatments; unite rates of vehicle operating costs, travel time, crashes, and air emissions; traffic volume and growth rates; discount rates, etc. Table 2 presents Beta parameters for those factors on the basis of historical data.

Table 2. Input Values of Factors for Risk and Uncertainty-Based Project Benefit Analysis

Input Factors (1)		Mean (2)	Standard Deviation (3)	Beta Distribution Parameters			
				L (4)	H (5)	α (6)	β (7)
Flexible Pavement Cost (1990, $/lane-mile)	Construction	1,353,537	694,614	588,385	3,165,840	2.49	4.50
	Rehabilitation	155,287	509,879	29,147	1,119,863	2.56	4.50
	Resurfacing	52,938	19,689	26,364	101,602	2.56	4.50
	Routine maintenance	138	499	4	2,186	2.27	4.50
Rigid Pavement Cost (1990, $/lane-mile)	Construction	1,334,841	763,709	674,299	2,947,173	2.25	4.50
	Rehabilitation	383,704	242,260	57,952	2,052,896	2.41	4.50
	Routine maintenance	323	204	4	1,981	3.10	4.50
All Pavement Cost (1990, $/lane-mile)	Preventive maintenance	4,120	6,544	186	21,999	2.56	4.50
Concrete Bridge Cost (1990, $/ft^2)	Deck	62	42	0.1	387	2.39	4.50
	Superstructure	110	82	0.2	372	2.39	4.50
	Substructure	115	92	0.1	372	2.39	4.50
Steel Bridge Cost (1990, $/ft^2)	Deck	86	59	0.4	734	2.17	4.50
	Superstructure	171	75	0.4	734	2.17	4.50
	Substructure	206	99	0.4	734	2.17	4.50
Annual Routine Maintenance Growth		3%	1%	1%	5%	4.50	4.50
Annual Traffic Growth		2%	1%	1%	3%	4.50	4.50
Discount Rate		4%	1%	3%	5%	4.50	4.50

Furthermore, eleven-year data on 7,380 candidate projects (grouped into 5,068 contracts) proposed for Indiana state highway programming during 1996-2006 were collected for applying the deterministic, risk-based, and uncertainty based project level life-cycle cost analysis approaches for project benefit estimation. For each pavement or bridge project, base case and alternative case life-cycle activity profiles and annual user cost profiles were established. As described in the proposed methodology, the agency benefits and user benefits associated with reduction in vehicle operating costs, shortening of travel time, decrease in vehicle crashes, and cutback of vehicle air emissions for each project were separately estimated by comparing the respective base case and alternative case life-cycle profiles. For the application of the deterministic life-cycle cost analysis approach, the single values of all input factors were utilized for estimating the project level life-cycle benefits.

For the application of the risk-based life-cycle cost analysis approach, Beta distribution parameter values for the input factors regarding unit rates of construction, rehabilitation, and maintenance treatments; traffic growth rates; and discount rates were applied in 10 simulation runs, each with 1,000 iterations using the @RISK software, Version 4.5 (Palisade, 2007). The Latin Hypercube stratified sampling technique was used in the simulations to reach faster convergence. The grand average of simulation runs for each risk factor was adopted for computing the mathematical expectations of agency benefits and user benefits.

When conducting risk-based analysis, it was found that project benefits related to decrease in agency costs, reduction in vehicle operating costs, and cutback of vehicle air emissions were not very sensitive to the variations of simulation outputs of the input factors under risk. However, travel time and vehicle crash reductions varied considerably with the simulation outputs of the factors. For this reason, the project user benefits concerning travel time and vehicle crash reductions were further estimated using the uncertainty-based analysis approach. Specifically, the grand average values of simulation runs for unit rates of construction, rehabilitation, and maintenance treatments, traffic growth rates, and discount rates were adjusted according to the preset decision rules as the proposed methodology for uncertainty-based analysis.

The adjusted values were used to compute the benefits of travel time and vehicle crash reductions under uncertainty.

Data Collection and Processing for Network-Level Highway Project Selection

The three sets of project level life-cycle benefits estimated for the 7,380 candidate projects were used to assess the network-level impacts of using deterministic, risk-based, and uncertainty-based project level life-cycle cost analysis approaches for estimating project benefits on project selection results.

Additional data on available budgets by highway asset management program and by project implementation year for period 1996-2006 were collected. The annual average budget was approximately 700 million dollars with 4 percent increment per year. The initially estimated budget for the project implementation period was found to have being updated three times by the Indiana Department of Transportation (DOT). This provided 4-stage budget recourses in the application of the stochastic optimization model for project section. The budget adjustments were mainly made on pavement preservation, bridge preservation, system expansion, and maintenance programs, with changes varying from -32 percent to +60 percent.

Summary of Estimated Project Level Life-Cycle Benefits

Table 3 lists project level life-cycle benefits of some pavement and bridge projects. On average, the present worth amounts of project level life-cycle benefits estimated using deterministic, risk-based, and uncertainty-based analysis approaches for the 7,380 projects are 4.18, 7.14, and 6.64 million dollars per project (in 1990 constant dollars), respectively. The average benefit-to-cost ratios are 3.24, 5.54, and 5.16, correspondingly. The significant difference between the project benefits estimated using the deterministic analysis approach and risk-based analysis approach is mainly attributable to large standard deviations of input factors considered for probabilistic risk assessments. The comparable results of project benefits computed using the risk-based analysis approach and uncertainty-based analysis approach are intuitive. This is because the grand average of simulation outputs for each input factor under uncertainty is adjusted only if the deviation between the grand average as the expected outcome and standardized focus loss value

exceeds the preset threshold level. The input factor values for risk-based and uncertainty-based analyses will be identical if no adjustment is made.

Table 3. Project Level Life-Cycle Benefits of Some Pavement and Bridge Projects Computed Using Deterministic, Risk-Based, and Uncertainty-Based Analysis Approaches (1990 Constant Dollars)

Contract No. (1)	Let Year (2)	Lanes (3)	Length (Miles) (4)	AADT (5)	Work Type (6)	Project Cost (7)	Project Benefits Estimated under Certainty (8)	Risk (9)	Uncertainty (10)
12021	2000	4	0.11	69,200	Bridge widening	2,291,000	6,959,434	11,703,264	11,703,264
12040	2000	4	0.50	32,630	Pavement resurfacing	4,620,000	4,776,319	6,927,669	6,365,844
12077	2000	2	2.06	3,170	Pavement resurfacing	3,000,000	9,436,804	15,545,501	15,545,501
12158	1999	2	3.70	16,770	Added travel lanes	750,000	3,036,253	5,405,621	4,806,134
20694	1996	2	1.34	3,420	Flexible pave. replace	51,000	43,704	131,989	131,989
21743	1996	4	0.40	25,310	Pavement rehabilitation	696,000	1,271,574	1,878,375	1,878,375
21749	1998	2	13.63	4,190	Pavement resurfacing	11,573,000	38,024,319	63,943,225	63,943,225
21825	1996	4	2.53	11,150	Pavement rehabilitation	151,000	504,574	1,033,274	1,505,738
21931	1996	4	0.78	2,664	Rigid pavement replace	196,000	705,235	736,046	736,046
21944	1996	2	9.46	1,100	Pavement rehabilitation	131,000	239,334	353,545	353,545
22026	1996	2	0.15	8,291	Bridge widening	108,000	267,380	299,746	254,516
22032	1996	4	6.30	12,274	Pavement resurfacing	754,000	1,743,188	2,753,259	2,559,337
22044	1996	2	1.10	13,994	Pavement resurfacing	2,757,000	6,169,067	6,773,242	5,702,627
22119	1998	4	0.10	27,700	Pavement rehabilitation	264,000	445,933	658,734	658,734
22264	1996	2	1.13	7,843	Pavement resurfacing	1,226,000	3,566,566	7,164,611	6,450,209
…	…	…	…	…	…	…	…	…	…

Comparisons of Project Selection Results

Comparison of Total Benefits of Selected Projects

Figure 3 illustrates the total benefits of projects selected using the optimization model based on three sets of estimated project benefits (deterministic, risk-based, and uncertainty-based), two types of budgets (deterministic and stochastic), and two budget constraint scenarios (yearly constrained and cumulative). Regardless of budget types and budget constraint scenarios, the total benefits of selected projects are the lowest for project benefits estimated using the deterministic analysis approach and are the highest for project benefits computed using the risk-based analysis approach.

Despite approaches used for computing project benefits and types of budgets used in the optimization model, the project selection using the cumulative budget scenario generally yielded higher total benefits. The results are not unexpected. The cumulative budget scenario does not have year-by-year budget

restrictions as those added to the yearly constrained budget scenario. This entails more flexibility to the optimization model in conducting project selection, leading to increases in the total project benefits.

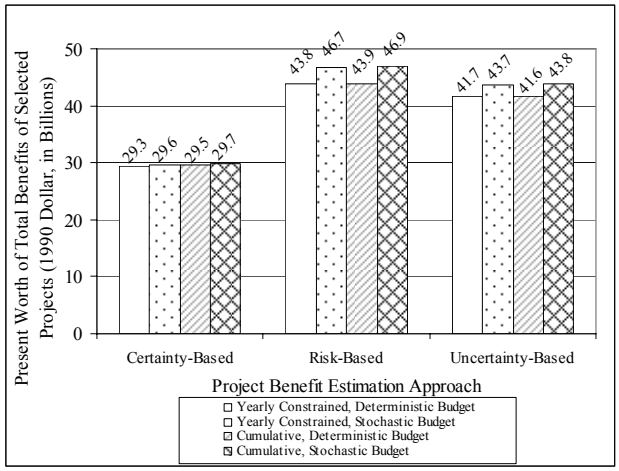

Fig. 3. Comparison of Total Benefits of Selected Projects Using Deterministic and Stochastic Budgets under Yearly Constrained and Cumulative Budget Scenarios (1996-2006)

Comparison of Number of Selected Contracts

Table 4 presents the comparison of contracts selected using the three sets of project benefits, two types of budgets, and two budget constraint scenarios. The matching rates were established in reference to the contracts being authorized by the Indiana DOT. One match is counted if a contract is both selected in the optimization model application and also authorized by the Indiana DOT.

For the deterministic budget, the average matching rates for the three sets of estimated project benefits and two budget constraint scenarios are 81-95 percent. Irrespective of using project benefits estimated by the deterministic, risk-based or uncertainty-based life-cycle cost analysis approach, the use of cumulative budget constraint scenario in the optimization model for project selection resulted in the selection of a higher number of contracts and with a higher matching rate. The net increases in the matching rates for the cumulative budget scenario as opposed to the yearly constrained budget scenario are 1 percent for deterministic project benefits, 7 percent for risk-based project benefits, and 5 percent for uncertainty-based project benefits, respectively. The relative increases in the matching rates resulted from the use of the cumulative budget scenario versus the yearly constrained budget scenario are 1%/94% = 1.1 percent for

deterministic based project benefits, 7%/81% = 9 percent for risk-based project benefits, and 5%/83% = 6 percent for uncertainty-based project benefits, correspondingly.

Table 4. Summary of Consistency in Contract Selection Results under Different Extents of Risk and Uncertainty Considerations

Year	No. of Contracts	Indiana DOT Authorized	Yearly Constrained Budget						Cumulative Budget						All Methods Matched with Indiana DOT	
			Deterministic			Stochastic			Deterministic			Stochastic				
			M_D	M_R	M_U	M_D	M_R	M_U	M_D	M_R	M_U	M_D	M_R	M_U	No.	%
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)	(16)	(17)
1996	464	443	433	390	388	437	390	394	439	411	414	439	412	415	319	72%
1997	412	358	387	338	344	386	336	343	390	370	372	390	369	374	250	70%
1998	429	275	408	351	363	409	353	361	413	375	377	414	377	377	187	68%
1999	411	323	376	322	333	381	322	332	388	352	352	388	351	352	203	63%
2000	610	578	576	506	516	579	504	514	582	544	544	586	546	546	416	72%
2001	418	412	395	348	358	396	343	356	393	363	363	393	360	366	289	70%
2002	422	421	399	343	343	398	339	343	402	373	373	406	373	377	291	69%
2003	469	461	437	373	381	440	371	375	444	413	414	446	413	418	315	68%
2004	649	648	608	519	531	615	521	528	612	578	580	613	578	581	463	71%
2005	408	406	380	337	339	384	337	340	387	355	359	389	357	364	282	69%
2006	376	375	355	302	307	353	303	303	357	333	336	359	334	338	259	69%
Total	5,068	4,700	4,754	3,871	4,203	4,778	3,896	4,189	4,807	4,625	4,484	4,823	4,660	4,508		
Total Match with Indiana DOT			4,400	3,828	3,889	4,421	3,817	3,877	4,451	4,129	4,145	4,466	4,131	4,168	3,274	
% Match with Indiana DOT			94%	81%	83%	94%	81%	82%	95%	88%	88%	95%	88%	89%		70%

Note: M_D, M_R, and M_U - Project benefits estimated using deterministic based, risk-based, and uncertainty-based analysis approaches, respectively.

For the stochastic budget, the average matching rates for the three sets of estimated project benefits and two budget constraint scenarios also range from 81-95 percent. The use of cumulative budget constraint scenario in the optimization model for project selection resulted in the selection of a higher number of contracts and with a higher matching rate. The increases in the matching rates for the cumulative budget scenario as opposed to the yearly constrained budget scenario are 1 percent for deterministic based project benefits, 7 percent for risk-based project benefits, and 7 percent for uncertainty-based project benefits, respectively. The relative increases in the matching rates are 1%/94% = 1.1 percent, 7%/81% = 9 percent, and 7%/82% = 8.5 percent, correspondingly.

Irrespective of budget types and budget constraint scenarios, the use of project benefits estimated by the deterministic life-cycle cost analysis approach for project selection produced a higher percentage of

matching rate as compared to matching rates established for project benefits estimated by risk-based and uncertainty-based analysis approaches. The matching rates for project benefits estimated using the uncertainty-based analysis approach are slightly higher than those of the project benefits computed by the risk-based analysis approach. In particular, increases in the matching rates are 2 percent for yearly constrained deterministic budget, 2 percent for yearly constrained stochastic budget, 0 percent for cumulative deterministic budget, and 1 percent for cumulative stochastic budget, respectively. The relative increases in the matching rates are 2%/81% = 2.5 percent, 2%/81% = 2.5 percent, 0%/82% = 0 percent, and 1%/88% = 1.1 percent, accordingly.

Without regard to using different approaches for project benefit estimation and employing different types of budgets and budget constraint scenarios in the optimization model for project selection, the average matching rate between projects selected using the optimization model and actually authorized by the Indiana DOT for the eleven-year analysis period is 70 percent. After removing this portion of matching rate invariant to approaches used for project benefit analysis and types of budgets and budget constraint scenarios used in the optimization model for project selection, the relative increases in the matching rates of project selection resulted from the use of uncertainty-based analysis approach versus the risk-based analysis approach for project benefit estimation are 2%/(81%-70%) = 18 percent for yearly constrained deterministic budget, 2%/(81%-70%) = 18 percent for yearly constrained stochastic budget, 0%/(82%-70%) = 0 percent for cumulative deterministic budget, and 1%/(88%-70%) = 9 percent for cumulative stochastic budget, accordingly.

SUMMARY AND CONCLUSION

This paper proposed a new methodology for highway project level life-cycle benefit/cost analysis that handles certainty, risk, and uncertainty inherited with input factors for the computation. A case study was conducted to assess the impacts of risk and uncertainty considerations in estimating project level life-cycle benefits and on the results of network-level project selection.

The case study results revealed that using project level life-cycle benefits estimated by the proposed uncertainty-base analysis approach yielded a higher percentage of matching rate with the actual programming practice of the Indiana DOT as compared to the matching rate of using the project benefits computed by the risk-based analysis approach. The relative increase in matching rate with uncertainty considerations is up to 2.5 percent. After removing the portion of matching rate invariant to approaches used for project benefit estimation and types of budgets and budget constraint scenarios considered in the optimization model for project selection, the relative increase in the matching rate is as high as 18 percent. The difference is quite significant. The proposed methodology offers a means for transportation agencies to explicitly address uncertainty issues in project level life-cycle benefit/cost analysis that would enhance the existing risk-based life-cycle cost analysis approach.

RECOMMENDATIONS

Application of the proposed methodology requires collecting a large amount of data. This may limit the methodology application primarily to state and large-scale local transportation agencies that maintain sufficient historical data on highway system preservation, expansion, operations, and expenditures. In addition, the customized Beta distribution parameters need to be updated over time to reflect changes in the values of input factors for the analysis. Moreover, the equally assigned weights for project level life-cycle agency benefits and user benefits may be adjusted to assess the impact of such changes on the estimation of project benefits and on the results of network-level project selection.

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