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# Highway Transportation Project Evaluation and Selection Incorporating Risk and Uncertainty

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## 1. Introduction

Over the past two decades, transportation agencies worldwide have developed various highway asset management systems such as pavement, bridge, maintenance, safety, and congestion management systems as analytical tools to help them make cost-effective investment decisions. In general, each management system generally performs the following tasks: i) establishing highway system goals and performance measures, ii) monitoring the performance of physical highway assets and system operations, iii) predicting performance trends over time, iv) recommending candidate projects to address system needs, v) carrying out project evaluation, vi) conducting project selection, and vii) providing feedback to refine the analysis in subsequent decision cycles (FHWA, 1987, 1991).

### 1.1 Current approaches for highway project evaluation

As one of the key tasks involved in the highway investment decision-making process, project evaluation is concerned with realistically estimating 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. 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.

### **1.2 Current approaches for highway project selection**

One of the key steps using the asset management systems for highway investment decision-making is to conduct project selection. Specifically, this process aims at selecting a subset of mixed types of highway projects from all candidate projects proposed to address the needs of a highway network to achieve maximized total benefits under budget and other constraints. Techniques for network-level project selection are classified as ranking, prioritization, and optimization. Optimization models are popular because of the inherent mathematical rigor. Over the last two decades, various optimization models have been developed to support highway project selection. Widely used optimization techniques include integer programming (Isa Al-Subhi et al., 1989; Weissmann et al., 1990; Zimmerman, 1995; Neumann, 1997), mixed integer nonlinear programming (Ouyang and S.M. Madanat, 2004), goal/compromise programming (Geoffroy and Shufon, 1992; Ravirala and Grivas, 1995), and multi-objective optimization (Teng and Tzeng, 1996; Li and Sinha, 2004).

### **1.3 Limitations of current approaches**

When applying risk-based analysis approaches for project evaluation, 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 due to lacking of pertinent information. 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.

Network-level project selection is also affected by several important factors. One of such factors is the available budget for the multi-year project selection period. In the current practice, state transportation agencies generally maintain a number of management programs to handle issues related to pavement preservation, bridge preservation, safety improvements, roadside improvements, system expansion/ new construction, Intelligent Transportation Systems (ITS), maintenance, etc. A certain level of budget is designated to each management program per year and the program-specific budget is not to be transferred across different programs for use. For instance, budget for the pavement preservation program supposedly is not used for the bridge preservation program, and vice

versa. In a multi-year project selection period, the multi-year budgets for each management program may be treated in two ways: either being treated as yearly-constrained budgets or as a cumulative budget for all years combined.

In addition to considering alternative budget constraint scenarios for each management program, the program-specific budget in each year is inherent with uncertainty. Investment decisions are usually made based on an estimated budget years ahead of the project selection period. As time passes by updated budget information would be available, project selection decisions must be updated accordingly to maintain realistic results. This is because if the actually available budgets are higher than the initially estimated budgets, additional projects might be selected. Otherwise, some of the projects selected using the initial budgets must be removed to avoid any budget violation. In either case, the question becomes what rational approach needs to be followed to ensure that the increase in total project benefits can be maximized with additional budgets, while the reduction in total project benefits could be minimized with budget cuts. Therefore, the issue of budget uncertainty needs to be explicitly addressed.

For mitigating traffic disruption at the construction stage, multiple projects within one highway segment or across multiple highway segments might be tied together for actual implementation. In some occasions, the project grouping could be extended to a freeway/major urban arterial corridor. In the project selection process, selecting any one of such projects necessitates the selection of all constituent projects in the same project group. Otherwise, all projects in the same project group would be declined. The projects grouped by highway segment or by corridor could be associated with different types of physical highway assets or system operations that would request funding from different management programs in a single year or across multiple years. In addition, some large-scale projects might have a chance to be postponed for a few years due to reasons such as right-of-way acquisition, design changes, and significant environmental impacts. As such, project selection could be carried out using segment-based, corridor-based or deferment-based project implementation approaches.

The next section introduces a new method for highway project evaluation that considers certainty, risk, and uncertainty associated with input factors for the computation. A stochastic optimization model is then introduced to explicitly consider alternative budget constraint scenarios, budget uncertainty, and project implementation approaches for network-level highway project selection. Further, a computational study is conducted to assess impacts of risk and uncertainty considerations in estimating project life-cycle benefits and on network-level project selection. Discussions and recommendations of usefulness of the proposed method and model are provided in the last section.

## **2. Proposed method for project evaluation**

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.

## **2.1 Pavement and bridge life-cycle agency 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).

## **2.2 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).

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.



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

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

### 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.

### 2.3 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.

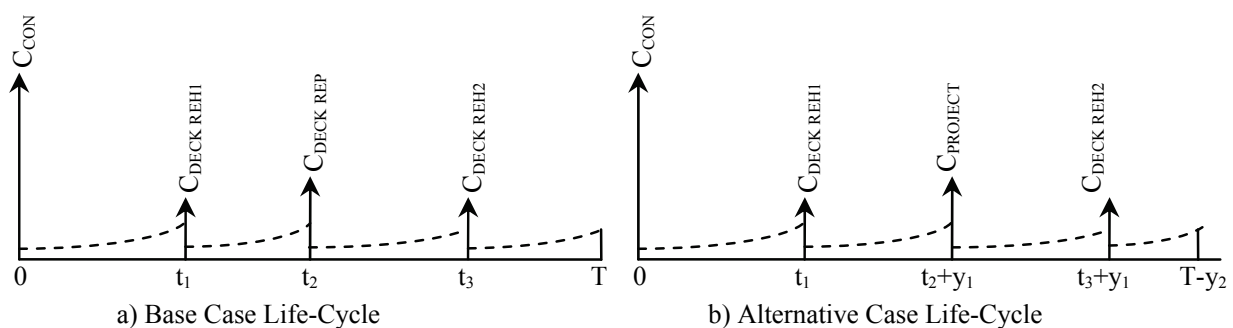


Fig. 1. Illustration of Base Case and Alternative Case Life-Cycles for the Steel-Box Beam Bridge

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. 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. 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.

#### **2.4 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.

## 2.5 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  $\alpha$  and  $\beta$ , with density function given by

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

where the  $\Gamma$ -functions serve to normalize the distribution so that the area under the density function from L to H is exactly one.

The mean and variance of the Beta distribution are given as

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

### 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).

## 2.6 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  $\langle x_{SFL}, X_{(E)}, x_{SFG} \rangle$  for each input factor under uncertainty. More details of Shackle’s model are in Ford and Ghose (1998), Young (2001), Li and Sinha (2004, 2006), and Li and Madanu (2009).

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 be 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 be used as standardized focus gain value  $x_{SFG}$  for the input factor under uncertainty.

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

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

where

$N_r$  = Number of simulation outputs in the  $r^{\text{th}}$  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  $x_{\text{SFL}}$  and the standardized focus gain value  $x_{\text{SFG}}$  thus refers to number of simulation outputs in the  $r^{\text{th}}$  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  $\langle x_{\text{SFL}}, X_{(E)}, x_{\text{SFG}} \rangle$  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  $\Delta X$  and if higher outcome values are preferred, the decision rule is set as

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

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

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

If the standardized focus loss  $x_{\text{SFL}}$  from the expected outcome  $X_{(E)}$  does not exceed  $\Delta X$ , 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  $x_{\text{SFL}}$  from the expected outcome  $X_{(E)}$  exceeds  $\Delta X$ , a penalty is applied to derive a unique value for the input factor. Different tolerance levels  $\Delta X$ 's may be used for different input factors under uncertainty.

## 2.7 A generalized framework for project evaluation under certainty, risk, and uncertainty

Figure 2 shows a generalized framework for project evaluation under *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.

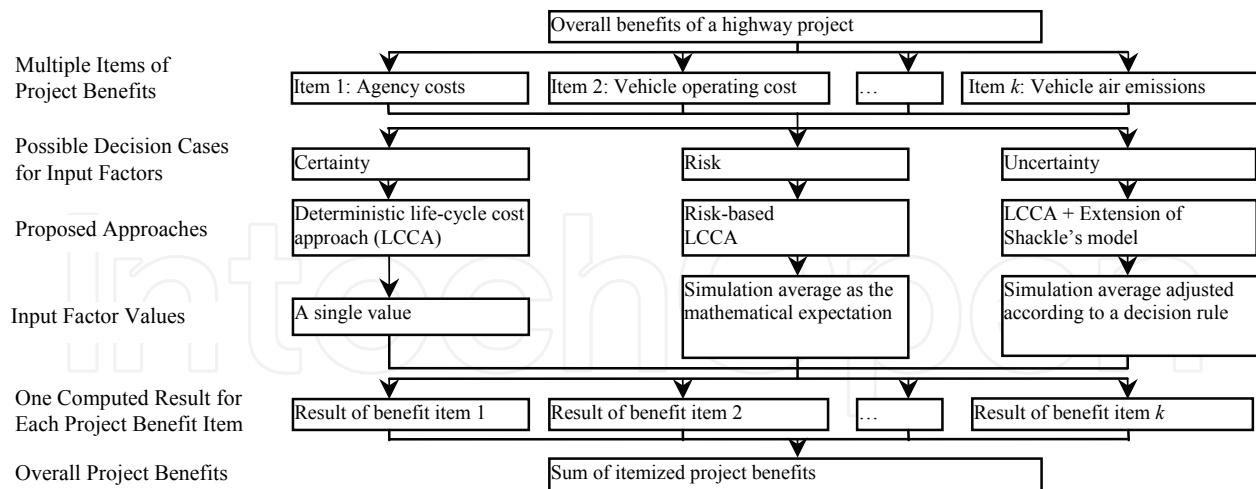


Fig. 2. A Generalized Framework for Project Evaluation under Certainty, Risk, and Uncertainty

### 3. Proposed model for project selection

This section begins with a basic deterministic optimization formulation for network-level project selection subject to the constraints of available budgets and integrality of decision variables under yearly-constrained and cumulative budget scenarios, respectively. It then introduces a stochastic model augmented from the basic model by incorporating budget uncertainty using recourse functions. The stochastic model is further enhanced to incorporate options of using segment-based, corridor-based, and deferment-based project implementation approaches for project selection.

#### 3.1 A basic optimization model

In general, optimization models for project selection can be formulated as the 0/1 integer multi-choice multidimensional Knapsack problem (MCMDKP). Multi-choice corresponds to multiple categories of budgets designated for different management programs to address the needs of physical highway assets and system operations. While multi-dimension refers to a multi-year analysis period (Martello and Toth, 1990). The objective is to select a subset from all economically feasible candidate projects to achieve maximized total benefits under various constraints. The 0/1 value of a decision variable implies rejection or selection of a proposed project.

Denote:

- $x_i$  = Decision variable for project  $i, i = 1, 2, \dots, N$
- $a_i$  = Benefits of project  $i, i = 1, 2, \dots, N$
- $c_{ikt}$  = Costs of project  $i$  using budget from management program  $k$  in year  $t$
- $X$  = Decision vector for all decision variables,  $X = [x_1, x_2, \dots, x_N]^T$
- $A$  = Vector of benefits of  $N$  projects,  $A = [a_1, a_2, \dots, a_N]^T$
- $C_{kt}$  = Vector of costs of  $N$  projects using budget from management program  $k$  in year  $t$ ,  
 $C_{kt} = [c_{1kt}, c_{2kt}, \dots, c_{Nkt}]^T$
- $i = 1, 2, \dots, N$

$k = 1, 2, \dots, K$

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

Note: The superscript "T" of the vector refers to the transpose of the vector.

A basic deterministic optimization model as a MCMDKP formulation under the yearly-constrained budget scenario is given below:

$$\text{Maximize } A^T \cdot X \quad (8)$$

$$\text{Subject to } C_{kt}^T \cdot X \leq B_{kt} \quad (9)$$

$X$  is a decision vector with 0/1 integer decision variables.

As Equation (8), the objective function of the model essentially helps select a subset from all candidate projects to achieve maximized total benefits. Equation (9) lists budget constraints by management program and by analysis year. The 0/1 integrality constraints for the decision variables in the decision vector are used for rejection or selection of individual projects. For the cumulative budget scenario, budget constraints by analysis year are reduced to a single period constraint. Only the budget constraints by management program

are retained. The notations  $B_{kt}$  is replaced by  $\sum_{t=1}^M B_{kt}$ , accordingly.

### 3.2 A stochastic model incorporating budget uncertainty

This section first discusses the proposed method for addressing the budget uncertainty issue and then introduces a stochastic model extended from the basic optimization model to handle budget uncertainty using recourse functions.

#### Treatments of Budget Uncertainty

As Figure 3, consider a multi-year project selection period of  $t_\Omega$  years. The transportation agency makes first round of investment decisions many years ahead of the project implementation period using estimated budgets for all years. With time elapsing, updated budget information on the first few years of the multi-year project selection period would become available that motivates the agency to refine the investment decisions. In each refined decision-making process, the annual budget for each management program for the first few years that can be accurately determined is treated as a deterministic value, while the budgets for the remaining years without accurate information are still processed as stochastic budgets.

Assuming that the multi-year budgets are refined  $\Omega$  times and each time an increasing number of years with accurate budget information from the first analysis year onward is obtained. Hence,  $\Omega$ -decision stages are involved. Without loss of generality, we assume a discrete probability distribution of budget possibilities for each year where no accurate budget estimates are available. For the first stage decisions, the multi-program, multi-year budget matrix is comprised of the expected budgets for all years that can be best estimated at the time of decision-making. For the second stage decisions, accurate information on budgets for years 0 to  $t_1$  is known and the budgets are treated as deterministic, and there are  $(p_2=s_2, s_3, \dots, s_{(L-1)}, s_L, s_{(L+1)}, \dots, s_\Omega)$  possible budget combinations for the remaining years from  $t_1+1$  to  $t_\Omega$ . For the generic stage  $L$  decisions, budgets up to year  $t_{(L-1)}$  are deterministic and there are  $(p_L=s_L, s_{L+1}, \dots, s_\Omega)$  possible combinations for years  $t_{(L-1)}+1$  to  $t_\Omega$ . The final stage has deterministic budgets up to year  $t_{(\Omega-1)}$  and  $p_\Omega=s_\Omega$  budget possibilities from year  $t_{(\Omega-1)}+1$  to  $t_\Omega$ .



Year	1 to $t_1$	$t_1+1$ to $t_2$	...	$t_{(L-2)}+1$ to $t_{(L-1)}$	$t_{(L-1)}+1$ to $t_L$	$t_L+1$ to $t_{(L+1)}$	...	$t_{(Q-1)}+1$ to $t_Q$
Budget	1 possibility	$s_2$ possibilities	...	$s_{(L-1)}$ possibilities	$s_L$ possibilities	$s_{(L+1)}$ possibilities	...	$s_Q$ possibilities

Stage 1:	Deterministic (initially estimated budget)							
Stage 2:	Deterministic	Stochastic						
...	...							
Stage L-1:	Deterministic	Stochastic						
Stage L:	Deterministic				Stochastic			
Stage L+1:	Deterministic					Stochastic		
...	...							
Stage $\Omega$ :	Deterministic							Stochastic

Fig. 3. Budget Attributes in an  $\Omega$ -Stage Recourse Project Selection Process

**A Stochastic Optimization Model Using Budget Recourse Functions**

The stochastic model with  $\Omega$ -stage budget recourses is formulated as a deterministic equivalent program that combines first stage decisions using the initially estimated budgets with expected values of recourse functions for the remaining ( $\Omega - 1$ ) stages (Birge and Louveaux, 1997, Li *et al.*, 2010).

Denote:

- $x_i$  = Decision variable for project  $i, i = 1, 2, \dots, N$
- $a_i$  = Benefits of project  $i, i = 1, 2, \dots, N$
- $c_{ikt}$  = Costs of project  $i$  using budgets from management program  $k$  in year  $t$
- $\xi_L$  = Randomness associated with budgets in stage  $L$  and decision space
- $X_L(p)$  = Decision vector using budget  $B_{kt}^L(p)$  in stage  $L, X_L(p) = [x_1, x_2, \dots, x_N]^T$
- $A$  = Vector of benefits of  $N$  projects,  $A = [a_1, a_2, \dots, a_N]^T$
- $C_{kt}$  = Vector of costs of  $N$  projects using budget from management program  $k$  in year  $t,$   
 $C_{kt} = [c_{1kt}, c_{2kt}, \dots, c_{Nkt}]^T$
- $Q(X_L(p), \xi_L)$  = Recourse function in stage  $L$
- $E_{\xi_2}[Q(X_L(p), \xi_L)]$  = Mathematical expectation of the recourse function in stage  $L$
- $B_{kt}^L(p)$  = The  $p^{th}$  possibility of budget for management program  $k$  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  $E(B_{kt}^L) = \sum_{p=1}^{p_L} [P(B_{kt}^L(p)) \cdot B_{kt}^L(p)]$
- $p$  =  $1, 2, \dots, p_L,$  where  $p_L = s_L \cdot s_{L+1} \cdot \dots \cdot s_\Omega$
- $L$  =  $1, 2, \dots, \Omega$
- $i$  =  $1, 2, \dots, N$
- $k$  =  $1, 2, \dots, K$
- $t$  =  $1, 2, \dots, M.$

The stochastic model with  $\Omega$ -stage budget recourses under yearly-constrained budgets is as

$$\text{Maximize} \quad A^T \cdot X_1 + \sum_{\omega=2}^{\Omega} E_{\xi_\omega} [Q_\omega(X_\omega(p), \xi_\omega)] \tag{10}$$

Stage 1

$$\text{Subject to} \quad C_{kt}^T \cdot X_1 \leq E(B_{kt}^L) \tag{11}$$

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

Stage 2

$$E_{\xi_2}[Q_2(X_2(p), \xi_2)] = \max \{ A^T \cdot X_2(p) \mid B_{kt}^2(p) = E(B_{kt}^2) \} \quad (12)$$

$$\text{Subject to } C_{kt}^T \cdot X_2(p) \leq B_{kt}^2(p) \quad (13)$$

$$X_1 + X_2(p) \leq 1 \quad (14)$$

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

Stage L

$$E_{\xi_L}[Q_L(X_L(p), \xi_L)] = \max \{ A^T \cdot X_L(p) \mid B_{kt}^L(p) = E(B_{kt}^L) \} \quad (15)$$

$$\text{Subject to } C_{kt}^T \cdot X_L(p) \leq B_{kt}^L(p) \quad (16)$$

$$X_1 + X_2(p) + \dots + X_L(p) \leq 1 \quad (17)$$

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

Stage  $\Omega$

$$E_{\xi_\Omega}[Q_\Omega(X_\Omega(p), \xi_\Omega)] = \max \{ A^T \cdot X_\Omega(p) \mid B_{kt}^\Omega(p) = E(B_{kt}^\Omega) \} \quad (18)$$

$$\text{Subject to } C_{kt}^T \cdot X_\Omega(p) \leq B_{kt}^\Omega(p) \quad (19)$$

$$X_1 + X_2(p) + \dots + X_L(p) + \dots + X_\Omega(p) \leq 1 \quad (20)$$

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

In the objective function as Equation (10), the first term is for total project benefits in the first stage decisions using initially estimated budgets and the second term is for the expected value of total project benefits for the remaining ( $\Omega - 1$ )-stage recourse decisions. Equations (11), (13), (16), and (19) are employed to hold budget constraints by management program and by project implementation year for the investment decisions at each stage. Equations (12), (15), and (18) compute the expected values of optimal project benefits that use one possible budget closest to the budget updated following the preceding decision stage. Equations (14), (17), and (20) ensure that one highway project is selected at most once in the multi-stage decision process.

For the cumulative budget constraint scenario, budget constraints by management program are still maintained. The notations  $B_{kt}^L(p)$ ,  $p(B_{kt}^L(p))$ , and  $E(B_{kt}^L)$  are replaced by  $\sum_{t=1}^M B_{kt}^L(p)$ ,  $p(\sum_{t=1}^M B_{kt}^L(p))$ , and  $E(\sum_{t=1}^M B_{kt}^L)$ , where  $E(\sum_{t=1}^M B_{kt}^L) = \sum_{p=1}^{p_L} [p(\sum_{t=1}^M B_{kt}^L(p)) \cdot \sum_{t=1}^M B_{kt}^L(p)]$  ( $L = 1, 2, \dots, \Omega$ ), respectively.

### The Enhanced Stochastic Model using Alternative Project Implementation Approaches

This section first discusses alternative project implementation approaches, including jointly implementing candidate projects by highway segment, by freeway/ major urban arterial corridor or deferring the implementation of some large-scale projects. The basic stochastic model presented in the previous section is enhanced to accommodate alternative project implementation approaches for project selection.

*Segment-Based Project Implementation Approach.* As discussed in the problem statement section, multiple projects within one highway segment or across multiple highway segments might be tied together for actual implementation to reduce traffic disruption at the construction stage. The first step for applying this approach is to identify the list of highway segments in the highway network to be considered for segment-based project implementation. Next, all projects within one highway segment or across multiple highway segments are tied together to form one "project group" and they are either all rejected or selected for implementation. For example, if three projects  $(i+1)$ ,  $(i+2)$ , and  $(i+3)$  belong to one "project group"  $S_g$ , the respective 0/1 decision variables  $x_{(i+1)}$ ,  $x_{(i+2)}$ , and  $x_{(i+3)}$  are replaced by one 0/1 decision variable  $x_{S_g}$ . For those isolated projects that do not belong to any of the identified "project groups", they are still treated as stand-alone projects that are designated with unique 0/1 decision variables.

Suppose that  $g$  "project groups" are identified from  $N$  candidate projects as

$1, 2, \dots, i$  ( $i$  isolated projects),

$i+1, i+2, \dots, i+n_1$  ( $n_1$  projects in "project group"  $S_1$ ),

$i+n_1+1, i+n_1+2, \dots, i+n_1+n_2$  ( $n_2$  projects in "project group"  $S_2$ ),

$i+n_1+n_2+1, i+n_1+n_2+2, \dots, i+n_1+n_2+n_3$  ( $n_3$  projects in "project group"  $S_3$ ),

...

$i+n_1+n_2+\dots+n_{g-2}+1, i+n_1+n_2+\dots+n_{g-2}+2, \dots, i+n_1+n_2+\dots+n_{g-2}+n_{g-1}$  ( $n_{g-1}$  projects in "project group"  $S_{g-1}$ ),  $i+n_1+n_2+\dots+n_{g-2}+n_{g-1}+1, i+n_1+n_2+\dots+n_{g-2}+n_{g-1}+2, \dots, N$  ( $N-i-n_{g-1}$  projects in "project group"  $S_g$ ).

The decision vector in stage  $L$  decisions  $X_L(p) = [x_1, x_2, \dots, x_i, \dots, x_N]^T$  in the stochastic model is thus replaced by  $X_L(p) = [x_1, x_2, \dots, x_i, x_{S_1}, x_{S_2}, x_{S_3}, \dots, x_{S_{g-1}}, x_{S_g}]^T$  ( $L = 1, 2, \dots, \Omega$ ). This implies that the basic stochastic model could still be used, but size of the decision vector  $X_L(p)$  is reduced from having  $N$  decision variables to  $(i+g)$  decision variables. Each decision variable still takes a 0/1 integer value representing the rejection or selection of an isolated project or multiple projects in a segment-based "project group". The benefits of all constituent projects of each segment-based "project group" are directly added together to establish the overall benefits of the "project group".

*Corridor-Based Project Implementation Approach.* As an extension of segment-based project implementation approach, the tie-ins of multiple projects within one or more highway segments could be further expanded to a freeway or an urban arterial corridor. First, the list of corridors in the network to be considered for corridor-based project selection is identified. Then, all candidate projects in the same corridor that are grouped by segment are further grouped into one corridor-based "grand project group". In the project selection process, all constituent projects in the same "grand project group" are either all rejected or selected for implementation. For those isolated projects that do not belong to any of the identified

segment-based “project groups” or corridor-based “grand project groups”, they are still treated as stand-alone projects with unique decision variables assigned.

Suppose that  $N$  candidate projects are classified as  $1, 2, \dots, i$  isolated projects and  $S_1, S_2, S_3, S_4, \dots, S_{g-2}, S_{g-1}, S_g$  segment-based “project groups”. The corresponding decision vector in stage  $L$  decisions is  $X_L(p) = [x_1, x_2, \dots, x_i, x_{S_1}, x_{S_2}, x_{S_3}, x_{S_4}, \dots, x_{S_{g-2}}, x_{S_{g-1}}, x_{S_g}]^T$  ( $L = 1, 2, \dots, \Omega$ ).

Further assume that all projects in “project groups”  $S_2$  and  $S_3$  are in one freeway corridor and all projects in “project groups”  $S_{g-1}$  and  $S_g$  are in one urban arterial corridor. This creates two corridor-based “grand project groups” for possible implementation: “grand project group”  $C_1$  that combines “project groups”  $S_2$  and  $S_3$ ; and “grand project group”  $C_2$  that joins “project groups”  $S_{g-1}$  and  $S_g$ . Hence, the decision vector in stage  $L$  decisions  $X_L(p) = [x_1, x_2, \dots, x_i, x_{S_1}, x_{S_2}, x_{S_3}, x_{S_4}, \dots, x_{S_{g-2}}, x_{S_{g-1}}, x_{S_g}]^T$  in the stochastic model that uses segment-based project implementation approach for project selection is further reduced to  $X_L(p) = [x_1, x_2, \dots, x_i, x_{S_1}, x_{C_1}, x_{S_4}, \dots, x_{S_{g-2}}, x_{C_2}]^T$  ( $L = 1, 2, \dots, \Omega$ ).

This implies that the enhanced stochastic model incorporating segment-based project implementation approach can still be used for the stochastic model utilizing corridor-based project implementation approach. However, the size of the decision vector  $X_L(p)$  is reduced from having  $(i+g)$  decision variables to  $(i+g-2)$  decision variables. Each decision variable still takes a 0/1 integer value representing the rejection/ selection of an isolated project, multiple projects in a segment-based “project group” or multiple projects in a corridor-based “grand project group”. The benefits of all constituent projects of each corridor-based “grand project group” are directly added together to obtain the overall benefits of the “grand project group”.

*Deferment-Based Project Implementation Approach.* As discussed in the problem statement section, some large-scale projects may have a high risk of being deferred for a few years due to various reasons. In this study, the proposed deferment-based project implementation approach considers a fixed number of years of delays in implementing large-scale projects with project costs exceeding a threshold value.

In the application of the deferment-based project implementation approach, the basic stochastic model essentially remains unchanged and the decision vector in stage  $L$  decisions  $X_L(p) = [x_1, x_2, \dots, x_N]^T$  in the stochastic model is kept the same. For projects involving deferred implementation, the project benefits and costs are adjusted according to the number of years of deferment. In the project selection process, the deferred projects would compete for funding with other unaffected projects in the newly designated implementation years using the adjusted project benefits and costs.

### 3.3 Model solution algorithm

This section first presents a theorem of Lagrange multipliers and briefly discusses the essential part of the proposed heuristic algorithm extended from the heuristic of Volgenant and Zoon (1990), which uses two Lagrange multipliers, on how (suboptimal) values for multiple Lagrange multipliers can be determined. It then discusses the improvement of the upper bound for the optimum of the proposed model.

#### Theorem of the Lagrange multipliers

The stage  $L$  optimization can be reformulated as

$$\text{Objective} \quad \text{maximize } z(X_L) = A^T X_L \quad (21)$$

Subject to  $C_{kt}^T \cdot X_L \leq B_{kt}^L$  (22)

where  $X_L$  is stage  $L$  decision vector with zero/one integer elements for rejecting or selecting individual projects.

Given non-negative, real Lagrange multipliers  $\lambda_{kt}$ , the Lagrange relaxation of (21),  $z_{LR}(\lambda_{kt})$ , can be written as

Objective  $z_{LR}(\lambda_{kt}) = \text{maximize } A^T \cdot X_L + \sum_{k=1}^K \sum_{t=1}^M [\lambda_{kt} \cdot (B_{kt}^L - C_{kt}^T \cdot X_L)]$   
 $= \text{maximize } \left( A^T - \sum_{k=1}^K \sum_{t=1}^M (\lambda_{kt} \cdot C_{kt}^T) \right) X_L + \sum_{k=1}^K \sum_{t=1}^M (\lambda_{kt} \cdot B_{kt}^L)$  (23)

Subject to  $X_L$  with zero/one integer elements.

Because  $\sum_{k=1}^K \sum_{t=1}^M (\lambda_{kt} \cdot B_{kt}^L)$  in (23) is a constant, optimization can just be concentrated on the first term, namely, maximizing

$$\left( A^T - \sum_{k=1}^K \sum_{t=1}^M (\lambda_{kt} \cdot C_{kt}^T) \right) X_L \cdot \tag{24}$$

The solution to (24) is  $X_L^*$ , where

$$X_L^* = \begin{cases} 1, & \text{if } \left( A^T - \sum_{k=1}^K \sum_{t=1}^M (\lambda_{kt} \cdot C_{kt}^T) \right) > 0 \\ 0, & \text{otherwise} \end{cases} \tag{25}$$

Then,  $X_L^*$  maximizes  $z(Y_L) = A^T \cdot X_L$ , subject to  $X_L$  with zero/one integer elements.

In order to obtain optimal solution by maximizing  $z(X_L) = A^T \cdot X_L$ , only subject to  $X_L$  with zero/one integer elements, the following condition needs to be satisfied

$$\sum_{k=1}^K \sum_{t=1}^M [\lambda_{kt} \cdot (B_{kt}^L - C_{kt}^T \cdot X_L)] = 0 \tag{26}$$

In this regard, stage  $L$  optimization operations need to focus on determining Lagrange multipliers  $\lambda_{kt}$  such that i)  $X_L^*$  obtained in (25) is feasible to the original model, i.e.,  $C_{kt}^T \cdot X_L \leq B_{kt}^L$  is valid, and ii) condition (26) is satisfied to maintain optimality to the original model as Equations (21) and (22).

**The Heuristic Algorithm**

At the recourse decision stage  $L$ , the heuristic initializes the Lagrange multiplier values to zero and all variables to the value one so that Equation (25) is satisfied. In general this solution is not feasible, because constraints of the proposed model as Equation (22) are violated. In each of the iterations, the constraint that has the largest ratio of the remaining total benefits and costs is first determined. Then the corresponding multiplier value is increased as much as necessary to violate Equation (25) for just one variable, the variable will be reset to zero. This step is repeated until the solution has become feasible. An improvement step ‘polishes’ the solution obtained.



Denote  $X_L^*$  is the optimal decision vector at stage  $L$ ,  $s(X'_{(L-1)})$  is the set of projects selected at stage  $L-1$ ,  $s(X'_L)$  is the set of projects selected at stage  $L$ ,  $S(X'_L)$  is the set of projects selected at stage  $L-1$  so that each of these projects has at least uses budget from year 1 to  $t_{(L-1)}$ , where budget at stage  $L$  remains the same as that at stage  $L-1$  for period from year 1 to  $t_{(L-1)}$ , which means that project  $i \in s(X'_{(L-1)})$  and  $c_{ikt} > 0$  for any  $k$  and at least one  $t$  ( $t = 1, 2 \dots t_{(L-1)}$ ) and  $S(X'_L) \subseteq s(X'_{(L-1)})$ , and  $S(X''_L)$  is the set of projects not selected at stage  $L-1$ , or selected projects that do not use budget between year 1 and year  $t_{(L-1)}$  (complement of  $S(X'_L)$ ). In full, the heuristic has the following steps:

*Step 0 (initialize and normalize)*

- For stage 1, set  $X_0^* = \{0, 0, \dots, 0\}$  (No project selected at stage 0). Hence,  $s(X'_0) = S(X'_1) = \phi$ .
- For stage  $L$ , use budget  $B_{kt}^L = B_{kt}^L(p)$  for computation such that  $\Delta B^L(p) = \min \left\{ \sum_{k=1}^K \sum_{t=1}^M [B_{kt}^L(p) - E(B_{kt}^L)]^2 \right\}$  and perform the following calculations for project  $i \in S(X'_L)$ : i) sort the projects by benefits ( $A_i$ ) in descending order, set  $\lambda_{kt} = 0$  for all  $k, t$  and  $x_i = 1$ ; ii) normalize cost and budget matrices by setting  $c'_{ikt} = \frac{c_{ikt}}{B_{kt}^L}$  for all  $k, t$  and  $B_{kt}^L = 1$  for all  $k, t$ ; and iii) compare sum of normalized costs with normalized budgets  $C_{kt} = \sum_{i=1}^N c'_{ikt}$ . If  $C_{kt} \leq 1$  for all  $k, t$ , go to Step 4. Otherwise, go to Step 1.

*Step 1 (determine the most violated constraint  $k, t$ )*

Set  $C'_{kt} = \text{maximum } \{C_{kt}\}$  for all  $k, t$

*Step 2 (compute the increase of Lagrange multiplier value  $\lambda_{kt}$ )*

$$\theta_i = \begin{cases} \frac{A_i - \sum_{k=1}^K \sum_{t=1}^M (\lambda_{kt} \cdot c'_{ikt})}{\sum_{k=1}^K \sum_{t=1}^M (c'_{ikt} \cdot \frac{C_{kt}}{C'_{kt}})}, c_{ikt} > 0 & \text{for all project } i \in S(X'_L) \\ \infty, & \text{otherwise} \end{cases}$$

Select project  $i \in S(X'_L)$  that has the minimum  $\theta_i$  and let  $\theta'_i = \min\{\theta_1, \theta_2, \dots, \theta_i, \dots\}$

*Step 3 (increase  $\lambda_{kt}$  by  $\theta'_i \cdot (C_{kt}/C'_{kt})$  and reset  $x_i$  the value zero)*

Let  $\lambda_{kt} = \lambda_{kt} + \left( \theta'_i \cdot \frac{C_{kt}}{C'_{kt}} \right)$  and  $C_{kt} = C_{kt} - c'_{ikt}$  for all  $k, t$ ;

Reset  $x_i = 0$  for project  $i \in S(X'_L)$  and shift project  $i$  from  $S(X'_L)$  to  $S(X''_L)$

If  $C_{kt} \leq 1$  for all  $k, t$ , go to Step 4. Otherwise, go to Step 1.

*Step 4 (improve the solution)*

For the feasible solution obtained in Step 3, check whether the projects with zero-variable values can have the value one without violating the constraints  $C_{kt} \leq 1$ . When this is the case, choose the project with highest benefits and add it to the selected project list. Repeat this step until no project with zero-variable value can be found and stop. Update the set of projects selected at stage  $L$ ,  $s(X'_L) = \{i \mid \text{for all } x_i = 1\}$ , and this establishes an improved solution.

Step 5 (further improved solution with budget carryover)

In each year of the multiyear project implementation period, a small amount of budget might be left after project selection. Such amount could be carried over to the immediate following year one year at a time to repeat Steps 1 to 4 to further improve the solution. Update the set of projects selected at stage  $L$ ,  $s(X'_L) = \{i \mid \text{for all } x_i = 1\}$ , and this finds an improved solution with budget carryover.

If  $L = \Omega$ , stop.  $X^*_L$  is final. Otherwise, repeat Steps 1-5.

The budget categories  $K$  and project implementation years  $M$  are much smaller than number of projects  $N$ . Practically, 3 budget possibilities for each year may be considered to represent low, medium, and high budget levels. This gives possible budget combinations for stages 1, 2, 3, ..., and  $\Omega$  to be  $p_1=1, p_2=3^{M-1}, p_3=3^{M-2}, \dots$  with stage 2 having the highest possible combinations. At each stage, the computational complexity for executing Steps 1-4 is  $O(MN^2)$  and the extended Step 5 for budget carryover require  $M$  iterations. The  $\Omega$ -stage recurses need at most  $M$  iterations. Thus, the computing time of the heuristic is  $O(M^3N^2)$ .

3.4 Improvements of the upper bound

Let  $X_L^s$  be the solution obtained in Step 3 of the above algorithm, we could substitute this solution to Equation (23). Then, an upper bound for the objective function  $z^U$  is given by

$$z^U = A^T \cdot X_L^s + \sum_{k=1}^K \sum_{t=1}^M [\lambda_{kt} \cdot (B_{kt} - C_{kt}^T \cdot X_L^s)] \tag{27}$$

The upper bound depends on the non-violated budget constraints with positive Lagrange multipliers. At the beginning of each iteration, suppose that more than one non-violated constraints have positive Lagrange multipliers. Denote  $I^s$  be the index of the constraint with the largest value of  $\lambda_{kt} \cdot (B_{kt} - C_{kt}^T \cdot X_L^s)$ . The question is then whether the value of Lagrange multiplier  $\lambda_{kt(I^s)}$  can be chosen smaller so that the influence of constraint  $I^s$  in the computation of the upper bound for the objective function is reduced. Obviously, there is no influence if the multiplier value is set to zero. However, if a smaller value of  $\lambda_{kt(I^s)}$  is used, some other Lagrange multiplier value must be increased in order to satisfy the condition in Equation (18). In the proposed algorithm, we have heuristically chosen the multiplier  $\lambda_{kt(i')}$  that is associated with the selected project maintaining the least extent of loss in "benefit-to-cost" ratio if removed, where the index  $i'$  is determined by  $\theta'_{i'} = \min\{\theta_1, \theta_2, \dots, \theta_i, \dots\}$  in Step 2. In the execution of the proposed algorithm, only the decision variable  $x_i$  with the value one is set to zero, i.e., a project selected previously is removed in the current iteration. For the two non-violated constraints with positive multipliers  $\lambda_{kt(I^s)}$  and  $\lambda_{kt(i')}$ , the tradeoffs of decreasing  $\lambda_{kt(I^s)}$  and increasing  $\lambda_{kt(i')}$  satisfy the following conditions:

$$b_i - \sum_{k=1}^K \sum_{t=1}^M (\lambda_{kt} \cdot c_{ikt}) + \alpha_1 \cdot c_{ikt(I^s)} \cdot \left(\frac{C_{kt}}{C'_{kt}}\right) - \alpha_2 \cdot c_{ikt(i')} \cdot \left(\frac{C_{kt}}{C_{kt}}\right) \leq 0, \text{ for all } x_i = 0 \tag{28}$$

$$b_i - \sum_{k=1}^K \sum_{t=1}^M (\lambda_{kt} \cdot c_{ikt}) + \alpha_1 \cdot c_{ikt(I^s)} \cdot \left(\frac{C_{kt}}{C'_{kt}}\right) - \alpha_2 \cdot c_{ikt(i')} \cdot \left(\frac{C_{kt}}{C_{kt}}\right) \geq 0, \text{ for all } x_i = 1 \tag{29}$$

where  $\alpha_1$  and  $\alpha_2$  are respective changes in the values of  $\lambda_{kt(I^s)}$  and  $\lambda_{kt(i')}$ .

For a specific project  $i$  with  $x_i = 1$ , the decision variable  $x_i$  will be changed from one to zero only when Equation (29) holds with equality. For the purpose of determining  $(\alpha_1, \alpha_2)$  pair,

two conditions must be satisfied: i)  $\alpha_1$  is maximal; and ii) Equation (29) holds with equality. Having obtained the values of  $\alpha_1$  and  $\alpha_2$ , a project  $i$  with  $x_i = 1$  that satisfies the equality condition is removed by setting its decision variable  $x_i$  to zero. The values of  $\alpha_1$  and  $\alpha_2$  can be determined by the following procedure:

The inequalities in (28) and (29) define the lower and upper boundaries of the feasible region for  $(\alpha_1, \alpha_2)$  pair. The lower bound function  $f_L(\alpha_1)$  and upper bound function  $f_U(\alpha_1)$  for  $\alpha_1$ , can be defined as

$$f_L(\alpha_1) = \max \left\{ \left[ b_i - \sum_{k=1}^K \sum_{t=1}^M (\lambda_{kt} \cdot c_{ikt}) + \alpha_1 \cdot c_{ikt(I^S)} \cdot \left( \frac{C_{kt}}{C_{kt}'} \right) \right] / \sum_{k=1}^K \sum_{t=1}^M c_{ikt} \cdot \left( \frac{C_{kt}}{C_{kt}'} \right) \right\}, \text{ for all } x_i = 0 \quad (30)$$

$$f_U(\alpha_1) = \min \left\{ \left[ b_i - \sum_{k=1}^K \sum_{t=1}^M (\lambda_{kt} \cdot c_{ikt}) + \alpha_1 \cdot c_{ikt(I^S)} \cdot \left( \frac{C_{kt}}{C_{kt}'} \right) \right] / \sum_{k=1}^K \sum_{t=1}^M c_{ikt} \cdot \left( \frac{C_{kt}}{C_{kt}'} \right) \right\}, \text{ for all } x_i = 1 \quad (31)$$

This is identical to determine the  $\alpha_1$  value such that the function  $g(\alpha_1) = f_U(\alpha_1) - f_L(\alpha_1)$  reaches zero value. The function is continuous and piecewise linear that requires a computational complexity of  $O(N)$ , where  $N$  is total number of projects. A numerical method that combines the secant and bisection methods for the computation of zero of the function  $g(\alpha_1)$  can be found in Bus and Dekker (1975).

#### 4. Impacts of the proposed method and model on project evaluation and selection

##### 4.1 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.

## 4.2 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  $t_0$  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.

## 5. A computational study

A computational study is 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 are used to assess the network-level impacts of adopting different project level life-cycle cost analysis approaches on project selection results.

### 5.1 Data sources

#### Data collection and processing for highway project evaluation

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; unit rates of vehicle operating costs, travel time, crashes, and air emissions; traffic volume and growth rates; discount rates, etc. Table 2 presents Beta distribution parameters established for those factors on the basis of historical data.

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

Input Factors		Mean	Standard Deviation	Beta Distribution Parameters			
				L	H	$\alpha$	$\beta$
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 <sup>2</sup> )	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 <sup>2</sup> )	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

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

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 selection. 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.

### Optimization Model Solution

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

## 5.2 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

Contract No.	Let Year	Lane s	Length (Miles)	AADT	Work Type	Project Cost	Project Benefits Estimated under		
							Certainty	Risk	Uncertainty
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
...	...	...	...	...	...	...	...	...	...

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)

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.

### 5.3 Comparisons of project selection results

#### Comparison of Total Benefits of Selected Projects

Figure 4 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),

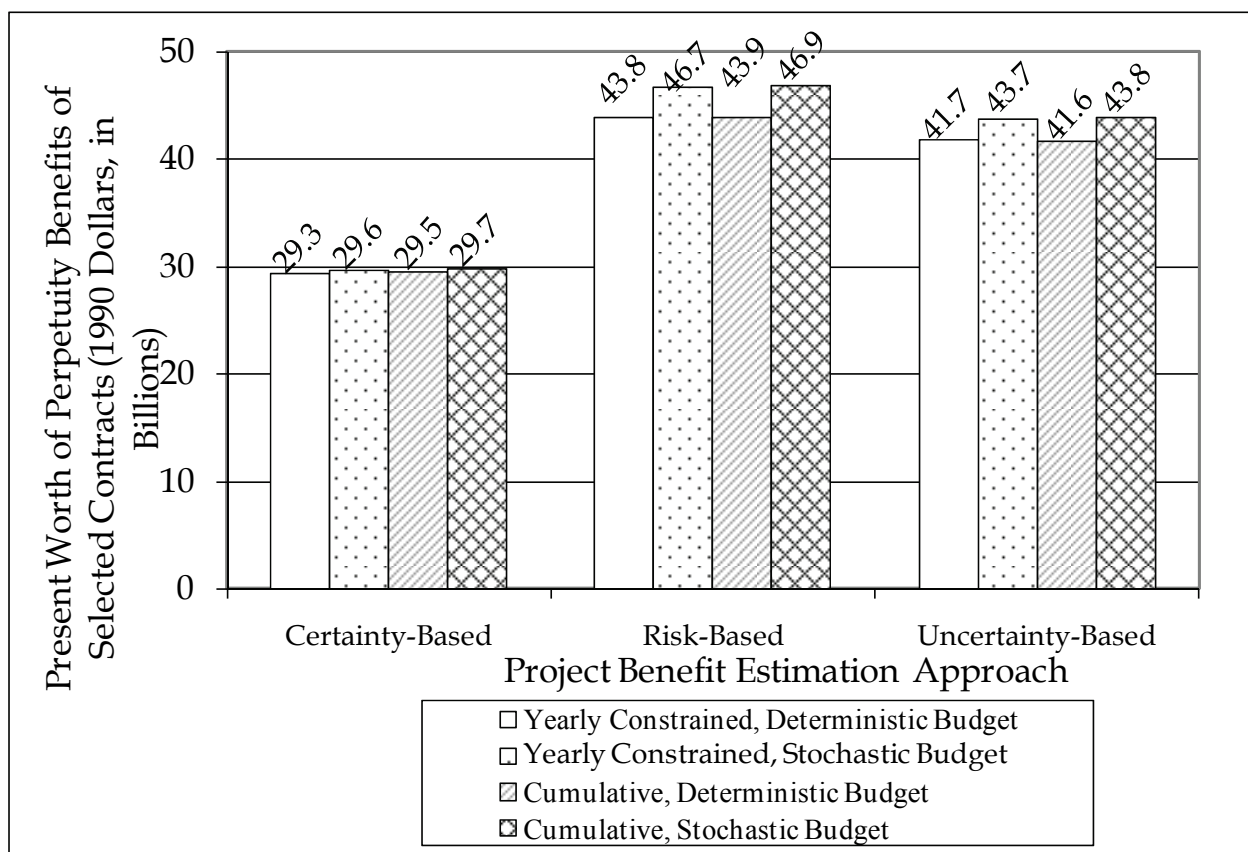


Fig. 4. Comparison of Total Benefits of Selected Projects Using Deterministic and Stochastic Budgets under Yearly Constrained and Cumulative Budget Scenarios (1996-2006)

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.

**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.

Year	No. of Contracts	Indiana DOT Authorized	Yearly Constrained Budget						Cumulative Budget						All Methods Matched with Indiana DOT	
			Deterministic			Stochastic			Deterministic			Stochastic			No.	%
			M <sub>D</sub>	M <sub>R</sub>	M <sub>U</sub>	M <sub>D</sub>	M <sub>R</sub>	M <sub>U</sub>	M <sub>D</sub>	M <sub>R</sub>	M <sub>U</sub>	M <sub>D</sub>	M <sub>R</sub>	M <sub>U</sub>		
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<sub>D</sub>, M<sub>R</sub>, and M<sub>U</sub> - Project benefits estimated using deterministic based, risk-based, and uncertainty-based analysis approaches, respectively.

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

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.

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.

## 6. Summary, conclusion, and recommendations

A new method is introduced for highway project evaluation that handles certainty, risk, and uncertainty inherited with input factors for the computation. Also, a stochastic model is proposed for project selection that rigorously addresses issues of alternative budget constraint scenario, budget uncertainty, and project implementation approach considerations. A computational study is 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 computational study results have 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 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.

Application of the proposed method and model requires collecting a large amount of data. This may limit the method and model application primarily to large-scale 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 estimated project benefits and on the results of network-level project selection.

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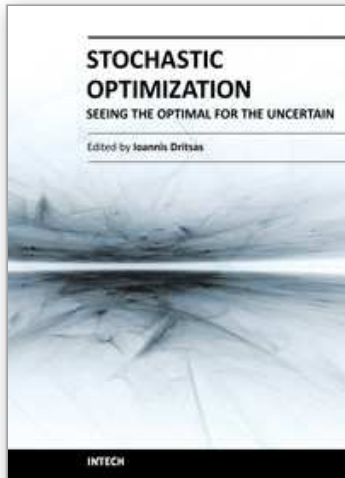
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Stochastic Optimization Algorithms have become essential tools in solving a wide range of difficult and critical optimization problems. Such methods are able to find the optimum solution of a problem with uncertain elements or to algorithmically incorporate uncertainty to solve a deterministic problem. They even succeed in "fighting uncertainty with uncertainty". This book discusses theoretical aspects of many such algorithms and covers their application in various scientific fields.

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