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A Methodology for Multicriteria Decision-Making in Highway Asset Management

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ABSTRACT

A methodology is hereby proposed for multicriteria decision-making involving tradeoff analysis between candidate projects and optimal project selection in highway asset management under alternative scenarios of certainty, risk, and uncertainty. A set of highway asset management system goals were first identified and their relative weights were determined, and a set of performance indicators under each goal were classified. Benefits achieved under asset goals as a result of project implementation are typically measured with non-commensurable units under different goals, but need to be converted into non-dimensional units so that tradeoffs can be carried out under equal footings. Where such conversion processes involve certainty and risk, this paper develops multiattribute utility functions for each asset management program to form the basis of tradeoff analysis under certainty and risk. Due to the limitation of utility theory for situations under uncertainty, an alternative approach based on Shackle's model was introduced and corresponding models were calibrated. A case study was conducted for system-level highway project selection using information on past state highway programming candidate project selection in Indiana. Case study results were further compared with actual highway programming practice in Indiana to validate the proposed methodology for highway investment decision-making under certainty, risk, or uncertainty. High consistency matching rates were achieved for decision-making under each of the three cases. The approach could be adopted by other agencies for transportation asset management practice.

INTRODUCTION

Highway facilities constitute one of the most valuable assets in all levels of government agencies. A large amount of investments was made annually to preserve, expand, and operate these facilities that support movements of people, goods, and services. In order to enhance the ability to diagnose existing and potential problems throughout the entire highway network, and to evaluate and prioritize alternative strategies, most state transportation agencies have developed various management systems. These management systems include the Pavement Management System (PMS), Bridge Management System (BMS), Traffic Congestion Management System (CMS), and Highway Safety Management System (SMS). In addition, many states have developed Maintenance Management Systems (MMS) to aid in planning and evaluation of maintenance work on pavements and bridges. The PMS, BMS, and MMS are oriented towards the physical state of highway assets, as their primary purpose is to inventory, track, and address the condition of various components of the highway network and to assist in establishing cost-effective strategies to sustain an acceptable condition of such facilities. On the other hand, the CMS and SMS focus on the operation and performance of the transportation network. Data on system inventory and preservation, organizational integration (to implement the decision steps) and technical information (to support the decision-making process) are becoming more available. As such, integration of information generated from existing management systems for overall asset management framework for future programming becomes not only possible and but also necessary. In this paper, a methodology for multicriteria decision-making in highway asset management under situations of certainty, risk, and uncertainty, respectively, is proposed.

BACKGROUND INFORMATION

Asset Management System Goals

A goal is a general statement of a desired state or ideal function of a highway network, which reflects different perceptions of what the highway network should achieve (*1*). In general, system goals are related to the condition or usage of physical highway assets. In the current study, system goals were classified through extensive interactions with representatives from both highway agency and user groups. These goals include system preservation, agency cost, user cost, mobility, safety, and environment. System preservation aims at preserving physical asset condition at a desired level and extending asset service life to the greatest to protect public investment. With a limited budget, the agency seeks to deliver the highest levels of service with minimal cost possible. From another perspective, the highway user wishes to experience lowest vehicle operating cost while using the highway facilities. The intended purposes of providing services by a highway network are to maintain basic mobility in terms of travel time, ensure specified levels of service for traffic congestion and safety, and minimize adverse impacts to the environment.

Highway Asset Management Programs

Highway asset management programs are a set of general programs for the preservation and expansion of physical highway assets and sustaining levels of service. Asset management programs classified in Indiana cover those for bridge and pavement preservation, safety and roadside improvements, system expansion including major or new construction, management of state facilities, Intelligent Transportation Systems (ITS) installations, and miscellaneous such as multi-modal, maintenance, and studies, etc.

Highway Performance Indicators

Performance indicators are assessment measures that reflect the degree to which results of an investment decision meet system goals (*2*). As different highway asset management programs are aimed at achieving various asset management goals from different perspectives, there is a need to explore the use of different performance indicators. Performance indicators selected under various system goals for different programs are listed in Table 1.

(INSERT TABLE 1)

METHODOLOGY FOR MULTICRITERIA DECISION-MAKING IN HIGHWAY ASSET MANAGEMENT

As multiple goals are involved in a highway asset management structure including system preservation, agency cost, user cost, mobility, safety and environmental considerations, the decision-making process is multiple criteria in nature. The entire decision-making process comprises two aspects: tradeoff analysis and system optimization. Tradeoff analysis can be conducted for candidate projects within a specific program category or across difference programs. For instance, tradeoffs between a pavement maintenance project and a pavement rehabilitation project, or a pavement project versus a bridge project. Through tradeoff analysis, the economic benefits and costs of shifting funding from one program category to another and the service level possible at different program funding levels can be assessed. System optimization deals with developing a subset of most cost-effective mix projects under budget restrictions.

System goals classified for highway asset management are typically expressed in non-commensurable units. In order to validate the tradeoffs involving multiple, non-commensurable goals, the non-commensurable benefits under various system goals (i.e., impacts to performance indicators under system goals) resulting from implementation of a specific project need to be rescaled into a dimensionless value. Utility theory can be applied to accomplish the scaling of non-commensurable benefits.

Furthermore, the direct benefits associated with implementing a project may be governed by any of three alternative scenarios: certainty, risk, and uncertainty. The case of certainty implies that the possible project outcomes occur deterministically. However, due to the dynamic nature of a highway network, condition, environment, and usage, such an assumption may not hold true. It is therefore desirable to incorporate risk and uncertainty into the analysis to ensure that decision-making is more realistic and robust. For the sack of clarity and consistency, risk is hereby defined as the situation where the set of all possible outcomes of an action is known and the probability distribution of the outcomes is also known. The term uncertainty is defined for situation where only part or all possible outcomes of an action is known, but the probability distribution of such outcomes is not fully definable for a lack of reliable information. The paper proceeds to discuss various approaches adopted to deal with tradeoff under each of the three scenarios.

Tradeoff Analysis under Certainty and Risk

As already mentioned earlier in this paper, for situation under certainty, utility theory is applicable to scale the benefits associated with implementing a specific project in achieving various system goals into a dimensionless value. The same approach can be used for situation under risk. The only difference is to replace the utility value corresponding to the outcome resulted from the project implementation by an expected utility value. The scaling process was accomplished by developing single attribute utility functions for each of the performance indicators identified, and then synthesizing those utility functions to arrive at system-level multiattribute utility functions.

Development of System-Level Utility Functions

Since highway asset management programs were classified on the basis of their unique nature and generally serve for the purpose of different physical assets or asset usage, system-level multiattribute utility functions were developed separately for each of these programs with main steps highlighted as follows:

Step 1: Relative weights of system goals;
Step 2: Relative weights of performance indicators under each goal;
Step 3: Single attribute utility functions associated with performance indicators;

Step 4: Multiattribute utility functions for individual programs under each goal; and
Step 5: System-level multiattribute utility functions for each program.

Determining relative weights among asset management goals allowed the synthesis of a program's goal-specific multiattribute utility functions into an overall system-level multiattribute utility function. Where multiple performance indicators are involved under a program category in meeting a specific goal, relative weights of the performance indicators were established to assist in creating the goal-specific multiattribute utility function.

It is clear that for the multiple performance indicators under a specific system goal the weak independence between two single attribute utility functions and preference independence among the utility functions were generally valid. As a result, the additive form, as shown below, could be used to establish the multiple attribute utility functions under each system goal.

$$U(X_i) = \sum_{k=1}^{K_i} w_{ik} \cdot u(x_{ik}) \qquad (1)$$

where

$U(X_i)$ = Goal-specific multiattribute utility function, i = 1, 2, 3, 4, 5, and 6 for system preservation, agency cost, user cost, mobility, safety, and environment
w_{ik} = Relative weight of performance indicator k under goal i
$u(x_{ik})$ = Single attribute utility function for performance indicator k under goal i
K_i = Number of performance indicators under goal i.

The additive form was adopted for the development of goal-specific multiattribute utility functions. This approach becomes questionable when the 6 goal-specific utility functions are synthesized into a system-level multiarribute utility function for each program. This is because strong correlations typically exist between system goals. For instance, a better preserved system condition would result in reduced highway user cost, and also reduction in vehicle air pollution. In an alternative formulation, the multiplicative form was adopted for system-level multiattribute utility functions (*3*), as follows:

$$\left[c \cdot U(X_1, X_2, X_3, X_4, X_5, X_6) + 1\right] = \prod_{i=1}^{6} \left[c \cdot W_i \cdot U(X_i) + 1\right] \qquad (2)$$

where

$U(X_1, X_2, X_3, X_4, X_5, X_6)$ = System-level multiattribute utility function for a program
W_i = Relative weight of system goal i, i = 1, 2, 3, 4, 5, and 6 for system preservation, agency cost, user cost, mobility, safety, and environment
$U(X_i)$ = Goal-specific multiattribute utility function for a given program
c = Scaling constant.

Incorporation of Risk into Decision-Making Process

Performance indicators were identified and utilized to quantify benefits associated with a candidate project in terms of change in utility values before and after project implementation. Among the performance indicators, those related to geometric features, such as: lane width, clearance, are deterministic in nature, and were excluded from risk analysis. The remaining performance indicators can be classified into two groups: discrete and continuous. For discrete performance indicators (such as: bridge deck, superstructure, substructure, and wearing surface condition), the respective possible outcomes as a result of an improvement action may range from condition rating of 3 (worst) to 9 (best). The binomial distribution was considered appropriate for modeling such discrete random outcomes as a result of a given action.

On the other hand, for the continuous performance indicators (such as: road condition, remaining service life, construction cost, rehabilitation cost, maintenance cost, average speed, detour condition, detour length, intersection delay, bridge load inventory rating, pavement skid resistance, and collision rate), their respective outcomes as a result of an improvement action are all finitely continuous, and the distribution of the possible outcomes could be symmetric or skewed. Therefore, this kind of probability distribution may be modeled as a beta distribution that accommodates a unimodal shape requirement, and allows for virtually any degree of skewness and kurtosis.

Tradeoff Analysis under Uncertainty

It has often been argued that when situation of uncertainty is encountered, it is impossible to either obtain the full range of possible outcomes of a work action, or to assign a probability distribution to the possible outcomes. As such, the weighted average values based on the utility theory thus become invalid. Shackle's model, which deals with uncertainty (*4*), was therefore considered for analysis.

Shackle's model is based on three pillars: degree of surprise function, priority function, and standardized focus gain-over-loss ratios and functions. The theory behind the degree of surprise function is that people are subject to assign higher weights to reflect their degree of surprise when the possible outcomes deviate larger and larger from the expected value. We therefore obtain an inverse bell-shaped degree of surprise function.

Given the occurrence of a set of possible outcomes, if decision-making is carried out by simultaneously considering the possible outcomes from the expectation and their respective degrees of surprise, the priority weights to be assigned correspond to different outcome /degree of surprise pairs (in fact, it is the absolute deviation from expectation/degree of surprise pairs) would be different. In general, the decision-maker will impose higher weights to larger amount of absolute deviations, in the same time he also wishes that the degrees of surprise could be minimized. For instance, at the loss from expectation side where the actual outcome could not reach the expected level, when the absolute deviation is small (i.e., positive effect is small), the degree of surprise is also low (i.e., negative effect is also low); the combined effects of the deviation/degree of surprise pair will cause a low priority weight. As we move further to the left from the expectation, the absolute deviation turns to be larger and the corresponding degree of surprise will also be higher. At the left extreme point, the deviation reaches to the maximum. However, the corresponding degree of surprise is also the highest. The combined effect of the two cancels out, resulting also a low priority weight. As such, there will be an outcome in between the expectation and the left extreme point (namely, the worst outcome) that would yield the combined highest priority weight. Similarly, at the gain from expectation side the highest priority weight could be found in between the expectation and the best outcome. Finally, a saddle-shaped priority function is established.

The two outcomes with the maximum priority values are termed as focus gain and focus loss from expectation. It should be noted that the focus gain and loss values are associated with a certain degree of surprise, representing negative reaction to uncertainty, as they fall between the expected outcome and the highest deviations from the expectation. It is therefore needed to filter out uncertainty attached from the priority indifference curves at both the gain and the loss sides on which the priority weights were equivalent to the respective maximum priorities.

The ratio of standardized gain-over-loss from expected outcome can be used to replace the utility value in the decision-making under uncertainty. The project with a larger standardized gain-over-loss ratio will have a higher likelihood to be selected. In uncertainty analysis, it is also desirable to explore the relationship between the standardized gain-over-loss ratios and range of deviations from the expected outcome for each performance indicator. A gain-over-loss ratio can therefore be determined based on the standardized focus gain-over-loss ratio function, provided with the information of a range of deviations.

APPLICATION OF PROPOSED METHODOLOGY

A series of questionnaire surveys was conducted to collect data needed for establishing the relative weights, utility functions, and standardized focus gain-over-loss functions that would assist in decision-making under certainty and risk, and uncertainty, respectively. In the process of deriving relative weights for asset management system goals as well as relative weights of multiple performance indicators under a specific goal, two decision groups were considered. The first is the highway agency group, which was represented by officials of Indiana Department of Transportation (INDOT). The second is the highway user group, which consisted of randomly selected highway users in Greater Lafayette area. In order to maintain robustness of the single attribute utility functions and the standardized focus gain-over-loss functions to be developed, in addition to considering the factor of decision group, two different approaches including the direct questioning approach and the certainty equivalency approach were also adopted (*5*). As the standard deviations of the relative weights assigned vary among the system goals and also among multiple performance indicators, the raw data concerning relative weights were further processed using Analytical Hierarchy Process (AHP) to arrive at most compromised weights by simultaneously considering the means and standard deviations (*6*). Data relevant to utility and standardized focus gain-over-loss ratio functions were first tested on the basis of Analysis of Variance (ANOVA) before being pooled together for model calibration using Ordinary Least Squares (OLS) techniques.

The results of relative weights, utility functions, as well as standardized focus gain-over-loss ratio functions are shown in Tables 2-5. It was found from the calibrated standardized focus gain-over-loss ratio functions that the standardized gain-over-loss ratio would decrease as the range of deviations became larger, which indicated that people were inclined to pose a higher weight to losses from their expectations as the deviation ranges became larger compared to gains. Even though the goodness of fit, i.e., adjusted R^2, was low for some models, the calibrated coefficients were significant at least at 5 percent level of significance as indicated by the t-statistic values.

(INSERT TABLE 2)

(INSERT TABLE 3)

(INSERT TABLE 4)

At this stage, the scaling constant *c* needs to be determined to finalize the exact form of the system-level utility functions. To do this, the special case where $U(X_i) = 1$ for all 6 goals was considered. As a result, Equation (2) simplifies to $\left[c + 1\right] = \prod_{i=1}^{6} \left[c \cdot W_i + 1\right]$. Assuming equal weights between the agency and user decision groups, and substituting the relative weights established for system goals, a *c* value of -0.3352 was obtained. Hence, the system-level multiattribute utility function for each program is in the following specification

$$U(X_1, X_2, X_3, X_4, X_5, X_6) = \left(\frac{1}{-0.3352}\right) \cdot \left\{\prod_{i=1}^{6}\left[1 - 0.3352 \cdot W_i \cdot U(X_i)\right] - 1\right\} \quad (3)$$

(INSERT TABLE 5)

In the presence of uncertainty, the general form of the system-level utility functions for various highway asset management programs still holds. However, single attribute utility functions for the relevant performance indicators would be replaced by the standardized focus gain-over-loss functions.

APPLICATION OF CALIBRATED MODELS FOR HIGHWAY INVESTMENT DECISION-MAKING UNDER CERTAINTY, RISK, AND UNCERTAINTY

It is intended that the calibrated system-level utility functions and focus gain-over-loss ratio functions developed on the basis of utility theory and Shackle's model be used for state-level highway investment decisions in Indiana. It is therefore desirable to implement the calibrated models for real world decision-making problems to further validate the proposed methodology. Using information of candidate projects for state highway programming purposes in Indiana, a case study by applying the calibrated models for project selection was carried out. To facilitate data integrity and retrieval from the INDOT database, a programming horizon for 1998-2001 was selected. One reason for using a past programming period for the case study is that programming decisions for all relevant projects was made and the decision outcomes could then be used to validate the output based on the calibrated models.

System Optimization Formulation

Decision Variable

The decision that needs to be made for project selection is a binary choice process: 1 for selecting the project; 0, otherwise. As projects are implemented by construction contract, the decision process becomes one of selecting an entire contract that may contain single or multiple projects or eliminating it in whole. Correspondingly, the decision variables are denoted as below:

$$Y_i = \begin{cases} 1, \text{ if contract } i \text{ is selected} \\ 0, \text{ otherwise} \end{cases} \tag{4}$$

Objective Function

The objective is to maximize focus gain-over-loss ratio values by selecting a subset from the candidate contract list. Factors that affect the selection of a specific contract include number of projects under the contract, program category to which the underlying projects belong, and year of implementation of the designated projects. The system objective function is formulated as follows:

$$\text{Maximize } \sum_{i=1}^{N} \left\{ \left[\left(\sum_{j=1}^{N_i} \left(a_{ijkt} * k_{ij} \right) \right) / N_i \right] * Y_i \right\} \tag{5}$$

where

a_{ijkt} = Weighted total standardized gain-over-loss ratios associated with all performance indicators for project *j* under contract *i* that belongs to program category *k* and to be implemented in fiscal year *t*

k_{ij} = Scaling multiplier for project *j* under contract *i*, $k_{ij} = \left(\frac{\text{Traffic}_{ij} * \text{Length}_{ij}}{\text{Cost}_{ij}} \right)$

Traffic_{ij} = Traffic volume that project *j* under contract *i* can serve during its service life

Length_{ij} = Length of project *j* under contract *i*

Cost_{ij} = Cost of project *j* under contract *i*

N_i = Number of projects under contract *i*
N = Number of candidate contracts
M = Number of years for analysis
i = Contract *i*, *i* = 1, 2, …N
j = Project *j* under contract *i*, *j* = 1, 2, …N_i
k = Program category *k*, *k* = 1, 2, 3, 4, 5, 6, 7, and 8 for bridge preservation, pavement preservation, safety improvements, roadside improvements, expansion, state facilities, ITS installations, and miscellaneous, respectively
t = Fiscal year *t*, *t* = 1, 2, …, M.

Constraints

The constraints that need to be considered are budgets by category in each fiscal year period. Also, the decision variables only take zero-one integer values. The budget constraints are formulated in following:

$$\sum_{i=1}^{N}\left[\left(\sum_{j=1}^{N_i} c_{ijkt}\right) * Y_i\right] \le B_{kt} \tag{6}$$

Y_i = 0/1 integers.

where
c_{ijkt} = Cost of project *j* under contract *i* that uses money from budget category *k* in year *t*
B_{kt} = Budget for program category *k* in fiscal year *t*
k = Program category *k*, *k* = 1, 2, 3, 4, 5, 6, 7, 8 for the 8 budgetary categories
t = Fiscal year *t*, *t* = 1, 2, …, M.

Budget Scenarios

As a practical matter, budget available for program categories including bridge preservation, pavement preservation, safety improvements, roadside improvements, expansion, state facilities, ITS installations, and miscellaneous are not transferable across each other. For instance, budget for pavement program is not supposed to be used for bridge program, and vice versa. However, within each program category, budget constraints for multi-year project selection process could be imposed in two ways: either being constrained year-by-year or only by a cumulative budget for all years in a given analysis period. For the year-by-year budget scenario, it might be possible that there would be a small amount leftover from preceding year that is not sufficient to select any single contract. The surplus could then be carried over to the next year so as to make full utilization of available funding. For the cumulative budget scenario, no carry over is necessary, as it is just similar to single year decision process. As such, system optimization was conducted separately under yearly budget with carryover (budget scenario 1) and one cumulative budget (budget scenario 2).

Proposed Algorithm

The underlying optimization formulation can be categorized into the multi-choice multidimensional knapsack problems (MCMDKP). Multi-choice lies in the fact that multiple categories of budget were classified corresponding to the 8 program categories, and multiple analysis periods were involved. The MCMDKP problems are regarded as NP-hard implying no guarantee of polynomial time algorithms (*7*). To ensure an optimal solution with minimum computational time efforts, a heuristic algorithm based on the concept of Lagrangian relaxation was developed with main steps highlighted as follows:

Part I: Main Steps prior to Budget Carryover from Year to Year

Step 0: Add all contracts and sort their benefits in descending order
Step 1: Initialize Lagrangian multipliers and normalize contract cost and budget
Step 2: Determine the least total cost constraint for each budget category for all years
Step 3: Compute increase of Lagrangian Multipliers based on benefit-over-cost (B/C) ratio
Step 4: Remove contract with smallest B/C one at a time, repeat until no budget violation
Step 5: Improve solution by adding removed contract, stop if no improvement

Part II: Main Steps for Budget Carryover by Program Category for Each Year

Step 1: Hold solution from Part I for the first year
Step 2: Increase budget for the second year, re-optimize starting from the second year
Repeat the process for each year until the last time period.

It should be noted that for budget scenario 2 (i.e., one cumulative budget for each budget category), only Part I of the algorithm is needed.

CASE STUDY RESULTS

Comparison of Results based on Two Budget Scenarios

The case study results are shown in Figures 1 and 2. For all three situations of certainty, risk, and uncertainty, the cumulative budget scenario yielded a higher number of contracts selected and slightly better system benefits. These results are not unexpected. The cumulative budget scenario does not have the year-by-year budget constraints as those added on for the yearly budget with carryover, which allows for project selection being conducted in a more flexible and holistic manner, leading to an improved global optimality. As seen in Figure 2, the total benefits for cases under risk and uncertainty for the two budget scenarios were consistently higher than those for decision-making under certainty. This finding indicates that highway investment decision-making could be biased if only the situation under certainty is considered. Consistent results were achieved for decision-making under risk and uncertainty.

(INSERT FIGURE 1)

(INSERT FIGURE 2)

Comparison of Results with INDOT Programming Practice

Further comparisons were made for the results generated from the use of the calibrated models for cases under certainty, risk, and uncertainty with INDOT actual programming practice. The measure of consistency used is the percentage of contracts both selected by the calibrated models and actually athhorized by INDOT. The cross comparison results are listed in Table 6. The matching percentage for all three decision situations was quite reasonable. For either the yearly budget with carryover scenario or cumulative budget scenario, the matching rates for the three decision cases in each year of the given analysis period are quite similar. However, the overall matching rate for the cumulative budget scenario is slightly higher, which is attributable to fewer constraints in the optimization process. In general, for all decision cases, the consistency matching rates are at minimum 85 percent and 90 percent respectively for yearly budget with carryover scenario and cumulative budget scenario for 1998-2001.

(INSERT TABLE 6)

CONCLUSIONS

Highway asset management is a systematic process that focuses on the preservation, upgrade, and operation of physical assets in the most cost-effective manner. This paper provided a methodology that enables highway investment decision-making under cases of certainty, risk, and uncertainty. For the cases of certainty and risk, utility theory was adopted, while for cases of uncertainty an alternative approach based on Shackle's model was employed. The proposed model was calibrated using data collected from a series of questionnaire surveys. The calibrated models were then utilized in a case study for system-level project selection using information of INDOT programming projects in the past time period. The results were further compared with INDOT actual programming practice. The findings reveal that highway decision-making should not only based on the cases of certainty, which may considerably skew the benefits that could be resulted from project implementation. The findings also demonstrate that the proposed methodology provided reliable results and it could indeed be used by state transportation agencies for asset management practice.

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Table 1 Performance Indicators for Various Highway Asset Management Programs

Program Category	Asset Management Goal					
	Preservation	Agency Cost	User Cost	Mobility	Safety	Environment
Bridge Preservation	Structure condition Wearing surface condition Remaining service life	Construction Rehabilitation Maintenance	Detour condition Travel speed	Travel speed Detour length	Load inventory Deck width Vertical clearance Horizontal clearance	Travel speed
Historical Bridges	Structure condition Wear surface condition Remaining service life Historical bridge age Historical bridge length	Construction Rehabilitation Maintenance	Detour condition Travel speed	Travel speed Detour length	Load Inventory Deck width Vertical clearance Horizontal clearance	Travel speed
Pavement Preservation	Road condition	Construction Rehabilitation Maintenance	Road condition Travel speed	Travel speed	Travel speed Skid resistance Lane width Shoulder width	Travel speed
Intersection Improvements	Road condition	Construction Rehabilitation Maintenance	-	Intersect delay	Collision rate	-
Railroad Crossing Improvements	Road condition Remaining service life	Construction Rehabilitation Maintenance	-	-	RR cross adequacy Collision rate	-
Safety	Remaining service life	Construction Maintenance	-	-	Sight distance Luminance	-
Traffic Signals	Remaining service life	Construction Maintenance	-	Intersect delay	Travel speed Collision rate	-
Enhancements	-	-	-	-	Collision rate	-
Roadside Improvements	-	Construction Maintenance	Travel speed	Travel speed	Travel speed	Travel speed
Weigh Station/ Rest Area	Remaining service life	Construction Maintenance	-	-	Collision rate	-
Small Structures/ Drainages	Remaining service life	Construction Maintenance	-	-	-	-
Expansion	Roads: Road condition Remaining service life Bridges: Structure condition Wear surface condition Remain life	Construction Construction	Road condition Travel speed Detour condition Travel speed	Travel speed Travel speed Detour length	Travel speed Skid resistance Lane width Shoulder width Load inventory Deck width Vertical clearance Horizontal clearance	Travel speed Travel speed
DNR Facilities/ Forest Highways/ State Facilities	Roads: Road condition Remaining service life Bridges: Structure condition Wear surface condition Remaining service life	Construction Rehabilitation Maintenance Construction Rehabilitation Maintenance	Road condition Travel speed Detour condition Travel speed	Travel speed Travel speed Detour length	Travel speed Skid resistance Lane width Load inventory Deck width Vertical clearance Horizontal clearance	Travel speed Travel speed
Bridge Inspection	-	-	-	-	Collision rate	-
ITS Projects	Remaining service life	Procurement Maintenance	Travel speed	Travel speed	Collision rate	Travel speed
CMAQ Projects	-	Construction Maintenance	Travel speed	Travel speed	Travel speed	Travel speed
Maintenance	Road condition Remaining service life	Maintenance	Road condition	-	Skid resistance	-
Multi-modal	Remaining service life	Construction Maintenance	Travel speed	Travel speed	Collision rate	Travel speed

Table 2 Relative Weights of Highway Asset Management System Goals

Asset Management Goal	Agency Group	User Group
a. System Preservation	0.2259	0.1857
b. Agency Cost	0.1922	0.1625
c. Highway User Cost	0.1776	0.1795
d. Mobility	0.2112	0.1956
e. Safety	0.2319	0.2294
f. Environment	0.1715	0.1911

Table 3 Relative Weights for Performance Indicators under Individual System Goals

System Goal	Program	Performance Indicator	Agency Group	User Group
System Preservation	Bridge Preservation	Structural condition	0.3971	0.4162
		Wearing surface condition	0.2679	0.3401
		Remaining service life	0.3349	0.2437
	Historical Bridge Preservation	Structural condition	0.2372	0.2483
		Wearing surface condition	0.1652	0.1788
		Remaining service life	0.2012	0.1954
		Historical bridge age	0.2252	0.2384
		Historical bridge length	0.1712	0.1391
	Pavement Preservation	Road condition	0.5000	0.5000
		Remaining service life	0.5000	0.5000
Agency Cost	Bridge Preservation	Construction cost	0.3535	0.3769
		Rehabilitation cost	0.3581	0.3015
		Maintenance cost	0.2884	0.3216
	Pavement Preservation	Construction cost	0.3519	0.3547
		Rehabilitation cost	0.3565	0.3153
		Maintenance cost	0.2917	0.3300
	ITS Improvements	Procurement cost	0.7083	0.6700
		Maintenance cost	0.2917	0.3300
User Cost	Bridge Preservation	Detour condition	0.4609	0.4748
		Travel speed	0.5391	0.5252
	Pavement Preservation	Road condition	0.5000	0.4662
		Travel speed	0.5000	0.5338
Mobility	Bridge Preservation	Detour length	0.4965	0.5133
		Travel speed	0.5035	0.4867
Safety	Bridge Preservation	Load inventory rating	0.1935	0.2327
		Clear deck width	0.2143	0.2170
		Vertical clearance-over	0.1905	0.1950
		Vertical clearance-under	0.2054	0.1698
		Horizontal clearance	0.1964	0.1855
	Pavement Preservation	Travel speed	0.2720	0.2698
		Skid resistance	0.2605	0.2619
		Lane width	0.2567	0.2619
		Shoulder width	0.2107	0.2063
	Railroad-Crossing Improvements	Railroad crossing adequacy	0.5267	0.4863
		Collision rate	0.4733	0.5137
	Safety	Sight distance	0.3709	0.3397
		Luminance	0.2958	0.3014
		Collision rate	0.3333	0.3589
	Traffic Signal Improvements	Travel speed	0.4589	0.4604
		Collision rate	0.5411	0.5396
	DNR/ Forest highways/ State facilities	Travel speed	0.3447	0.3400
		Skid resistance	0.3301	0.3300
		Lane width	0.3252	0.3300

Table 4 Utility Functions for Performance Indicators under Individual System Goals

System Goal	Performance Indicator	Unit	Utility Function
System Preservation	Bridge structure condition	rating	$1 - e^{-0.0249x2}$
	Bridge wear surface condition	rating	$1 - e^{-0.025x2}$
	Historical bridge age	year	$1 - e^{-0.0144(x-80)}$
	Historical bridge length	feet	$1 - e^{-0.0112(x-40)}$
	Road condition	IRI, inch/mile	$e^{-0.000044x2}$
	Remain service life	year	$1 - e^{-0.0195x2}$
Agency Cost	Construction Rehabilitation Maintenance	\$/unit/year	$[1-(x-\mu)/3\sigma]/2$
User Cost	Travel speed	mph	$1 - e^{-0.0486(x-15)}$ $1 - e^{-0.0778(75-x)}$
Mobility	Travel speed	mph	$1 - e^{-0.0005x2}$
	Detour length	mile	$e^{-0.2145x}$
	Intersection delay	min/vehicle	$[e^{-0.0982x} + e^{-0.1772x}]/2$
Safety	Load inventory	ton	$1 - e^{-0.0404x2}$
	Deck width	feet	$1 - e^{-8.5113[(x-10)/12]}$ $1 - e^{-59.2952[(13.5-x)/12]}$
	Vertical clearance-over	feet	$1 - e^{-8.2612[(x-20)/25]}$
	Vertical clearance-under	feet	$1 - e^{-8.2672[(x-16)/20]}$
	Horizontal clearance	feet	$1 - e^{-8.2278[(x-48)/60]}$
	Travel speed	mph	$e^{-0.0004x2}$
	Skid resistance	skid number	$1 - e^{-0.0437(x-10)}$
	Lane width	feet	$1 - e^{-8.2827[(x-10)/12]}$ $1 - e^{-59.6314[(13.5-x)/12]}$
	Shoulder width	feet	$1 - e^{-2.4343x2}$
	Railroad crossing	number	$1 - e^{-0.6963x}$
	Sight distance	meter	$1 - e^{-4.5181[(x-150)/250]}$
	Luminance	watt	$1 - e^{-4.6399[(x-240)/400]}$
Environment	Travel speed for SO_2	mph	$1 - e^{-0.0478(x-15)}$ $1 - e^{-0.0816(75-x)}$
	Travel speed for NMHC	mph	$1 - e^{-0.0338x}$
	Travel speed for CO	mph	$1 - e^{-0.0618x}$ $1 - e^{-0.0609(65-x)}$
	Travel speed for NO_X	mph	$1 - e^{-0.0949x}$ $1 - e^{-0.0366(65-x)}$

Table 5 Calibrated Standardized Gain-over-Loss Ratio Functions for Individual Performance Indicators

Goal	Performance Indicator	SGLR = $\alpha_0 + \alpha_1$ Range of Deviation				Adj. R^2
		α_0	(*t*-statistic)	α_1	(*t*-statistic)	
System Preservation	Pavement condition	1.1785	(46.55)	-0.7683	(-9.42)	0.91
	Remaining service life	1.0380	(72.61)	-0.0759	(-4.12)	0.64
Agency Cost	Construction cost	1.0382	(106.66)	-0.1847	(-5.89)	0.79
	Rehabilitation cost	1.0398	(106.12)	-0.2647	(-8.38)	0.89
	Maintenance cost	1.0132	(216.41)	-0.1538	(-0.19)	0.92
User Cost	Average travel speed	1.1535	(58.04)	-0.2331	(-9.10)	0.90
Mobility	Detour length	1.0251	(64.62)	-0.2070	(-7.68)	0.87
Air Pollution	Intersection delay time	1.1414	(38.17)	-0.1572	(-3.45)	0.55
Safety	Average travel speed	1.1248	(56.36)	-0.1330	(-8.05)	0.88
	Bridge load inventory	1.0924	(69.61)	-0.1791	(-7.08)	0.85
	Pavement skid resistance	1.0834	(76.77)	-0.1887	(-8.30)	0.88
	Vehicle collision rate	1.0750	(88.34)	-0.1526	(-7.78)	0.87

Table 6 Number of Contracts Proposed by INDOT, Both Authorized by INDOT and Selected by the Proposed Methodology (1998-2001)

Fiscal Year	Contracts Proposed by INDOT	Contracts Programmed by INDOT	Same Contracts Selected by Proposed Methodology				
			Case	Scenario 1	% Match	Scenario 2	% Match
1998	429	152	Certainty	139	91%	142	93%
			Risk	143	94%	142	93%
			Uncertainty	142	93%	142	93%
1999	412	323	Certainty	292	90%	305	94%
			Risk	293	91%	306	95%
			Uncertainty	292	90%	302	93%
2000	611	583	Certainty	496	85%	524	90%
			Risk	496	85%	530	91%
			Uncertainty	497	85%	535	92%
2001	418	414	Certainty	413	100%	397	96%
			Risk	413	100%	395	95%
			Uncertainty	413	100%	397	96%

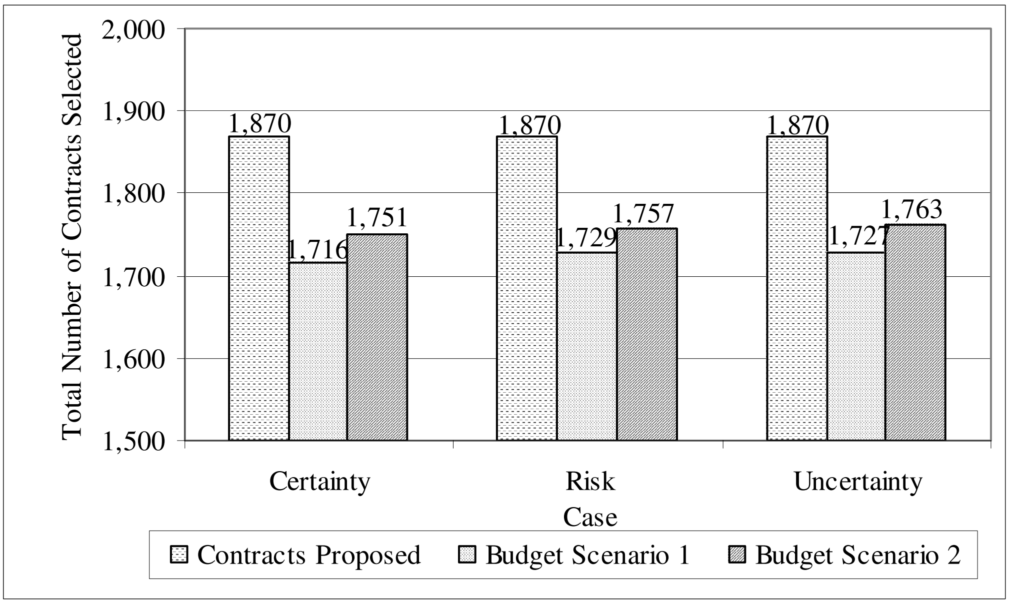

Figure 1 Number of contracts proposed by INDOT and selected by yearly budget with carryover and cumulative budget scenarios under certainty, risk, and uncertainty (1998-2001).

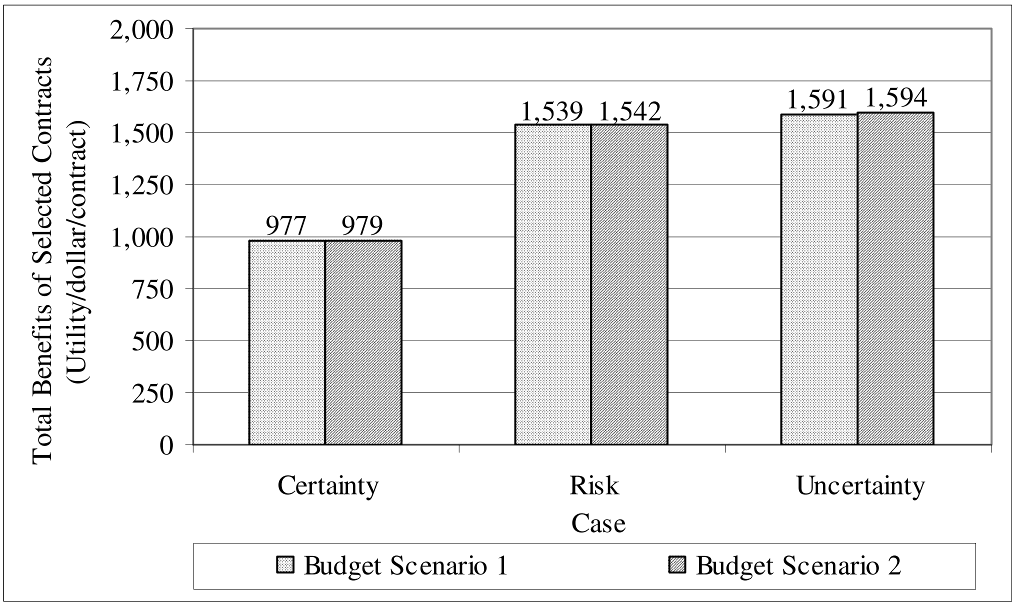

Figure 2 benefits of selected contracts by yearly budget with carryover and cumulative budget scenarios under certainty, risk, and uncertainty (1998-2001).