Identifying Optimal Investment Timing
of Transportation Infrastructure with Uncertainty

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May 10, 2004

I. INTRODUCTION

Every year, the immense funds have been invested in transportation infrastructure to support economic growth and enhance quality of life. These investments do not only create a new one, but also maintain the existing one to be good in the sense of both physical and functional condition. To make a better decision making in transportation infrastructure investment, various economic evaluation methods such as BC(Benefit-Cost) ratio, NPV (Net Present Value), EIRR (Economic Internal Rate of Return) have been used (Layard and Glaister, 1996; Blank and Tarquin, 1998).

The conventional evaluation process for the transportation infrastructure investment, however, does not adequately consider the timing of investments. Major investment studies typically look for performance during the life span, such as 30 years from now, which gives the result for only a build-now alternative. The optimal timing is important in some cases if a project were postponed, it would make the investment more efficient (Chu and Polzin, 1998). Another deficiency of the current transportation infrastructure investment decision procedure is that it bases on a point estimate, which is only a most likely single value. It is considered that a single most likely value is not enough for decision makers to make a proper decision. It is because it cannot tell the whole story (Hertz, 1979). At least, we should be able to know how seriously the uncertainty affects the decisions.

The objective of this study is to propose a transportation infrastructure evaluation framework which takes into account not only the optimal investment timing but also the uncertainty of benefits and costs. Monte Carlo simulation technique is utilized to capture the probability density function of evaluation index. The stochastic results from the proposed approach would give the decision maker a complete picture of all the possible outcomes for a different timing of investment. In addition, the proposed approach provides more than a table of results of a wide range of the components which are obtained from a common scenario analysis. The proposed approach is demonstrated with a transportation infrastructure project in Bangkok, Thailand.

It should be note that, although there are many studies on the improvement of infrastructure project evaluation, they are focused, if not all, on the improvement of the benefit and cost estimation. None of them has taken into account of the uncertainty to identify the optimal timing of the transportation infrastructure investment, which is the focus of this paper (Howard, 1980; Szymanski, 1991; Chu and Polzin,1998; Lam and Tam, 1998; ETA, 1999;

Nakaya, 1999; Japan Research Institute, 2000). The proposed methodology will answer not only whether the project should be implemented, but also when it should be, from the stochastic perspective. In Korea, a study was done about the risk analysis of highway investment by private sector (Lee et al., 1999). However, it does not take into account the optimal timing together with risk analysis.

This paper first defines and formulates the optimal infrastructure investment timing problem with uncertainty. The proposed methodology is then outlined and an application to an example project in Bangkok, Thailand is illustrated. Lastly, the results are discussed, followed by concluding remarks.

II. proposed METHODOLOGY

1. Problem Definition and Mathematical Formulation

The method of identifying optimal investment timing is similar to the conventional evaluation method. The difference is that the project must be evaluated over a variable project's time horizon rather than the year of construction and operation already fixed before evaluation. In the optimal time method, the construction and operation periods are flexible and they can be shifted into any year of analysis period. Therefore, the analysis period of this method must be longer than the time horizon of the conventional method. The benefit and cost for each year must be calculated for each different time alternative to start the project, as called "Time Alternative". The service life for each starting time alternative should be the same (e.g. service life being equal to 25 years) to make a fair evaluation, no matter when the project would start.

The evaluation index such as NPV, EIRR, and B/C Ratio, which composes of many kinds of uncertainties, is calculated from benefit and cost of each year. The probability density function is used to represent the uncertainty of each key variable (benefit and cost). Accordingly, the evaluation index would have distribution which provides more accurate and helpful information to planners. In this study, each key variable of each year for each alternative is assumed to have its own uncertainty as presented by the probability distribution and to be a time-dependent variable. By including the uncertainty of each stochastic variable, the expected value of NPV in the base year "*O*" when the project starts to operate at the year "*S*" would be calculated by equation (1):

$$E(NPV)_S = \int_{S}^{S+T} E(Benefit_{s,t}) \cdot e^{-rt} dt - \int_{S-U}^{S} E(Cost_{s,t}) \cdot e^{-rt} dt \qquad (1)$$

Where,

t	=	time;
S	=	starting year of operation;
T	=	operating period of the project, the period since the project starting to operate until the end of analysis period;
U	=	construction period of the project, the period since the construction beginning until the starting year;
r	=	discount rate;
e^{-rt}	=	discounting term to convert the value into base year "O", it is the same as [P|F, r, t] which is considered in the discrete function;
$E(NPV)_s$		expected value of NPV at the starting year of operation "S".

This equation is modified from the frameworks by Porter (1984), Leconte *et al.* (1987), Szymanski (1991) and Chu and Polzin (1998).

2. Conceptual Framework of the Proposed Approach

The conceptual framework to estimate NPV in the base year "O" when the project starts to operate at the year "S", NPV_s, is illustrated in <Figure 2-1>. The Monte Carlo simulation technique which performs the outstanding potential to the practical problem (Grey, 1995; Vose, 2000) is used to identify the distribution of the NPV_s. The IRR and B/C Ratio are also obtained by using the same method.

The followings illustrate the procedure which estimates the distribution of the NPV_s for each alternative using Monte Carlo simulation:

Step 1: Randomly select the input variables of the alternative "S" (i.e., $Benefit_{s,t}$ and $Cost_{s,t}$) according to their distribution.

Step 2: Calculate the $PV_{s,t}$ which is the present value of net benefit of each year by using discount rate, r.

Step 3: Sum all $PV_{s,t}$ for all t between the starting year (S-U) and the ending year (S+T) of the alternative, then, a value of NPVs is obtained.

Step 4: Repeat the procedure in Step 1 through 3 thousand times.

Step 5: Plot those thousand values of NPVs in a probability distribution diagram.

To perform Monte Carlo simulation, this study used software @RISK 4.0 which is a part of the Decision Tools Suite developed by Palisade Corporation (Palisade Corporation, 2000).

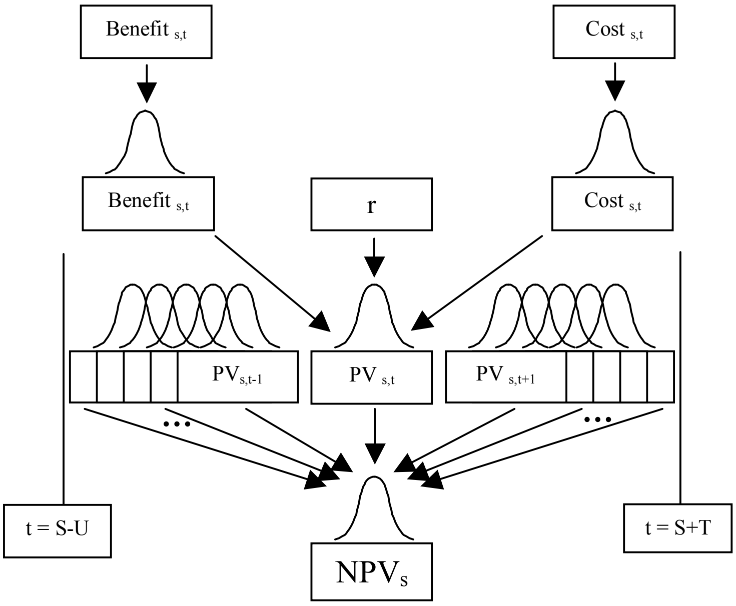


Figure 2-1. The Conceptual Framework to Identify NPV

3. Criteria for Decision Making

In this study, NPV is chosen as a project evaluation index because of its high potential for evaluation, which can give the best, actual result compared to other indices (Layard and Glaister, 1996). The NPV can also cope with the differences in the size, investment cost and returned benefit of projects for choosing the alternatives. Other familiar indices such as IRR and B/C ratio are also used as an evaluation index.

There are two criteria for choosing the optimal time "*S*" as follows:

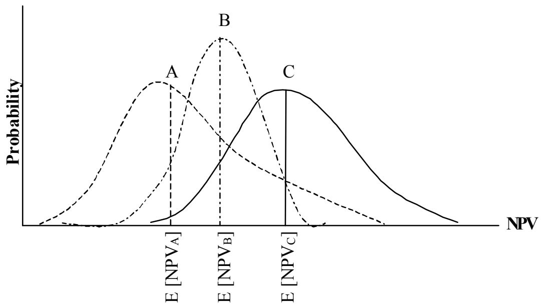
(1) Maximum E [NPV] - Using the probability density function (PDF) to choose the time "*S*" that gives the maximum of the expected NPV. The concept of this criterion is the same as the problem without uncertainty that chooses the year producing the maximum of NPV.

$$\arg\max[E(NPV_1), E(NPV_2),.....,E(NPV_S),.....,E(NPV_n)]$$

Where,

$E(NPV_S)$ = The expected value of NPV in the base year "*O*" when the project starts to operate at the year *S*.

For example, in <Figure 2-2>, the alternative C (starting at the year C) is chosen since it has the maximum expected NPV.



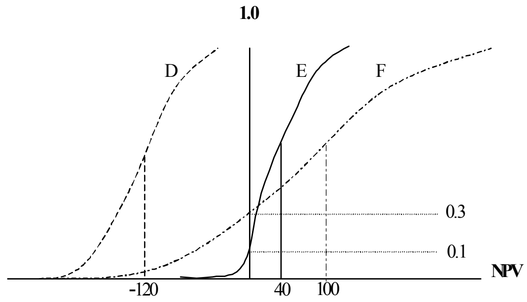


Figure 2-2. Probability Density Function Figure 2-3. Cumulative Distribution Function

(2) Maximum probability that NPV >♋. Using the cumulative distribution function (CDF) to choose the time "*S*" that gives the maximum of the probability that the NPV is greater than the minimum requirement, ♋. When ♋ is set to zero, it means that the chosen project has the highest probability to have the benefit more than the cost. The concept of this criterion could be mainly used when the supplier is risk averse. The decision-maker cannot use this criterion, unless the uncertainties are analyzed by risk analysis method, which can give the probability distribution of the result.

$$\arg\max[P(NPV_1 > \alpha), P(NPV_2 > \alpha), ..., P(NPV_S > \alpha), ..., P(NPV_n > \alpha)]$$

Where,

$P(NPV_S > \alpha)$ = The probability that the NPV of the project when starts at the year S is more than ♋

For example, if a decision-maker is risk averse, alternative E (starting at the year E) is chosen as shown in <Figure 2-3>. It is because alternative E has the highest probability that the NPV is greater than the minimum requirement, ♋ = 0, which equals to 1-0.1 = 0.9. This criterion gives the extra information to decision-maker. According to Figure 3, the ordinary decision-maker must trade-off between these two criteria, one with the higher expected NPV (100, Alternative F) and the other with the higher probability that the expected NPV is greater than the minimum requirement (0.9, Alternative E). It is important to note that the conventional method can give only one estimated value of NPV.

4. Timing Alternatives

The proposed methodology will be able to consider multiple number of alternatives for evaluating projects with the concept of optimal investment timing as outlined below:

$$
\begin{array}{cccccc}
A_{11} & A_{12} & \cdots & A_{1j} & \cdots & A_{1n} \\
A_{21} & \ddots & & \vdots & & \vdots \\
\vdots & & \ddots & \vdots & & \vdots \\
A_{i1} & \cdots & \cdots & A_{ij} & & \vdots \\
\vdots & & & & \ddots & \vdots \\
A_{m1} & \cdots & \cdots & \cdots & \cdots & A_{mn}
\end{array}
$$

Where,

A_{ij} = The i^{th} alternative from m alternatives for choosing characteristics of the project such as route selection or size of project, and the j^{th} alternative from n alternatives for optimal investment timing

That is, the conventional evaluation procedure can solve the problem only of the first column, m alternatives, since it assumes a given starting year of the project and decides only which alternative should be implemented – including do-nothing alternative. In contrast, the proposed approach will consider $m \times n$ alternatives, if it has n alternatives for choosing the best year to start operating. Not only which project should be implemented, but also when it should be would be answered. Moreover, by including the uncertainties in the evaluation procedure, it will give more information to the decision-maker.

III. Application to an Example Project

1. Test Bed Project

Srinakkarin–Bangna–Samutprakarn Expressway in Bangkok, Thailand, is selected in this study as an illustrative example. It is a part of the Expressway and Rapid Transit Authority of Thailand's short-term master plan (ETA, 1999). It is planned to be a dual 3-lane elevated expressway of 13.8 kilometers length. The project route starts from the termination point of the second stage expressway part D, Phraram9 Road. It is built on the mid-island of the Srinakkarin Road which belongs to the Department of Highway. It goes through the south of Bangkok metropolitan area and crosses the Bangna-Trad Road and Motorway. The ending point is joining with the southern part of Outer Ring Road in Samutprakarn province. The estimated traffic of this project is 37,918 pcu (passenger car unit) per day in the year 2006, and growing up to 64,576 pcu per day in the year 2011. The construction of the project began in 1999.

2. Conventional Evaluation

From the convention evaluation, the TRAFFIC model was used to estimate PCU-KM and PCU-HRS. Then the user's benefit from the travel time saving and vehicle operating cost saving, and external benefit were estimated as called "Total Benefit". On the other hand, the investment, operating, maintenance, and environmental protection cost were estimated as called "Total Cost". Both of them were calculated for each of thirty years in analysis period as shown in <Table 3-1>, which is the case of using the toll-fee equal to 30 Bahts (ETA, 1999). It is used as basic source data in this study.

3. Alternatives

From the methodology presented earlier, the conventional evaluation method gave only one alternative which is A1. It is the built-now alternative. The methodology developed here will have ten alternatives to choose the optimal timing of investment. Each of ten alternatives is different in the sense of timing, not in the sense of choosing characteristics of the project. <Table 3-2> shows the ten alternatives.

4. Assumptions for the Application

1) General Assumptions

This study considers ten alternatives of different investment timing and there is no characteristic alternative such as route selection or size of project (i.e., m = 1 and n = 10). Each alternative is different in the starting year of operation (S). The starting time of construction (S-U) of the first alternative (A1) is the year of 1999, and the end of analysis period ($S+T$) of it is the year of 2028. The construction periods of all alternatives are assumed to be four years. The second alternative (A2) means the starting time of construction (S-U) is the year of 2000, and the end of analysis period ($S+T$) is the year of 2029, and so on. Thus, the last time alternative (A10) implies the project alternative starting in 2008 and ending in 2037 as shown in <Table 3-2>.

Table 3-1. Source Data and Results of the Conventional Evaluation (ETA, 1999)

Year	Cost						Benefit				Net Benefit
	Investment	Operating	Maintenance	Environment	Oper.(Envi)	**Total**	VOC-saving	VOT-saving	External	**Total**	
1999	698.97					698.97				0.00	(698.97)
2000	3,892.22			0.28		3,892.50				0.00	(3,892.50)
2001	4,607.15			0.02		4,607.17				0.00	(4,607.17)
2002	3,195.68			0.09		3,195.77				0.00	(3,195.77)
2003		24.52			0.78	25.30	130.66	345.93	(3.50)	473.09	447.79
2004		25.20			0.78	25.98	1,601.88	1,719.97	175.14	3,496.99	3,471.01
2005		25.89			0.78	26.67	3,073.09	3,094.00	353.78	6,520.87	6,494.20
2006		26.58				26.58	4,544.30	4,468.03	532.42	9,544.75	9,518.17
2007		27.40				27.40	4,886.10	4,858.33	567.58	10,312.01	10,284.61
2008		28.25				28.25	5,253.60	5,282.73	605.07	11,141.40	11,113.15
2009		29.12	233.09			262.21	5,648.75	5,744.20	645.03	12,037.98	11,775.77
2010		30.02				30.02	6,073.62	6,245.98	687.64	13,007.24	12,977.22
2011		30.95				30.95	6,530.44	6,791.60	733.05	14,055.09	14,024.14
2012		31.54				31.54	7,204.39	7,490.43	808.88	15,503.70	15,472.16
2013		32.14				32.14	7,947.88	8,261.16	892.56	17,101.60	17,069.46
2014		32.76				32.76	8,768.11	9,111.21	984.88	18,864.20	18,831.44
2015		33.39				33.39	9,672.98	10,048.72	1,086.76	20,808.46	20,775.07
2016		34.03	233.09			267.12	10,671.23	11,082.70	1,199.18	22,953.11	22,685.99
2017		34.46				34.46	10,771.80	11,207.78	1,208.69	23,188.27	23,153.81
2018		34.91				34.91	10,873.31	11,334.28	1,218.27	23,425.86	23,390.95
201		35.35				35.35	10,975.78	11,462.21	1,227.92	23,665.91	23,630.56

9											
2020		35.81				35.81	11,079.22	11,591.57	1,237.65	23,908.44	23,872.63
2021		36.27				36.27	11,183.63	11,722.40	1,247.46	24,153.49	24,117.22
2022		36.78				36.78	11,525.30	12,181.48	1,276.57	24,983.35	24,946.57
2023		37.25	233.09			270.34	11,877.41	12,658.52	1,306.36	25,842.29	25,571.95
2024		37.73				37.73	12,240.28	13,154.26	1,336.84	26,731.38	26,693.65
2025		38.21				38.21	12,614.23	13,669.40	1,368.04	27,651.67	27,613.46
2026		38.90				38.90	12,999.61	14,204.72	1,399.96	28,604.29	28,565.39
2027		39.40				39.40	13,396.76	14,761.00	1,432.63	29,590.39	29,550.99
2028	(5,110.37)	39.91				(5,070.46)	13,806.05	15,339.07	1,466.06	30,611.18	35,681.64

NPV = 61,822.03 Million Baht *PV (Benefit)= 61,822.03 Million Baht*
EIRR = 35.82% *PV (Cost) =9,126.65 Million Baht*
B/C Ratio= 6.77

Table 3-2. Ten Alternatives

t	Year	Alternatives									
		A1	A2	A3	A4	A5	A6	A7	A8	A9	A10
1	1999	C									
2	2000	C	C								
3	2001	C	C	C							
4	2002	C	C	C	C						
5	2003	B & C	C	C	C	C					
6	2004	B & C	B & C	C	C	C	C				
7	2005	B & C	B & C	B & C	C	C	C	C			
8	2006	B & C	B & C	B & C	B & C	C	C	C	C		
9	2007	B & C	B & C	B & C	B & C	B & C	C	C	C	C	
10	2008	B & C	B & C	B & C	B & C	B & C	B & C	C	C	C	C
11	2009	B & C	B & C	B & C	B & C	B & C	B & C	B & C	C	C	C
12	2010	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	C	C
13	2011	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	C
14	2012	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
15	2013	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
16	2014	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
17	2015	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
18	2016	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
19	2017	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
20	2018	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
21	2019	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
22	2020	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
23	2021	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
24	2022	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
25	2023	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
26	2024	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
27	2025	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
28	2026	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
29	2027	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
30	2028	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
31	2029		B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
32	2030			B & C	B & C	B & C	B & C	B & C	B & C	B & C	B & C
33	2031				B & C	B & C	B & C	B & C	B & C	B & C	B & C
34	2032					B & C	B & C	B & C	B & C	B & C	B & C
35	2033						B & C	B & C	B & C	B & C	B & C
36	2034							B & C	B & C	B & C	B & C
37	2035								B & C	B & C	B & C
38	2036									B & C	B & C
39	2037										B & C

All prices are based on the constant "Baht" (Thai currency) in the year of 1998, which is the base year (i.e. year '0') of the project evaluation in this study. Discount rate is assumed as 12%, which is most commonly assumed value in Thailand (ETA, 1999). The estimated salvage value of each alternative is defined in Equation 2 (ETA, 1999).

$$\text{Salvage Value} = \frac{\text{Remaining live of the project Investment cost}}{\text{Project total live}} \qquad (2)$$

In this study, the project's total life is assumed to be 50 years. Therefore, the remaining life of the project is 24 years because this study assumes operation period as 26 years.

2) Key Variables

Key variable is defined as the factor that has the effect on the output. Since the output is defined as the NPV (also IRR and BC ratio), the key variables in this study are defined as benefit and cost of each alternative. If one wants to consider every small component of the key variable that goes into a detailed estimate, the approach will be impractical. In this sense, only main items that are totally independent are probabilistically modeled. With this approach, the possibility that some correlations of uncertainties (uncertainties at the intersection among those sub-items) are omitted or double-counted will decrease (Touran and Bolster, 1994). This integrated approach would assess the key variables (i.e., benefit and cost) consistently and completely with the assumption that there is no correlation among these key variables. In other words, benefit does not depend on cost since the actual cost that is lower or higher than the estimated cost has no effect on benefit and vice versa.

Since this study bases on the data from the feasibility study which using the conventional project evaluation method, the estimated values of benefit and cost exist only for the A1 alternative. Accordingly, in this study the estimated value must be assumed for other alternatives starting later. There are estimated benefits for 30 years (i.e., until year 2028) in the feasibility study (ETA, 1999). The trend line is used to estimate the benefit until the year 39 (year 2037), which is the last year of evaluation as shown in <Figure 3-1>.

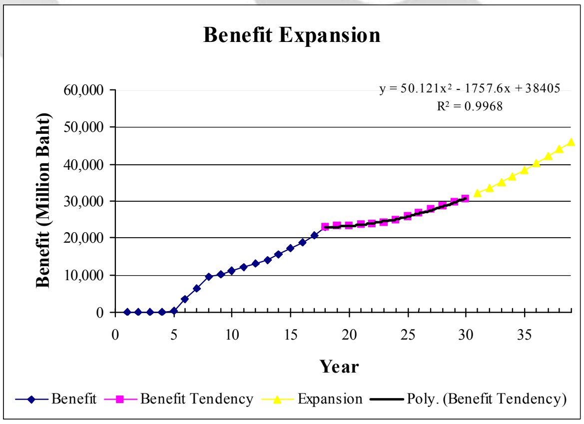


Figure 3-1. Benefit Expansion

The estimated benefit of each year is assumed to be the same across all alternatives. For example, the benefit of the year 2007 is 20,808.46 Million Baht for all alternatives. It is because traffic demands for the target project for all alternatives in the same year would be the same no matter when the project started. On the other hand, the estimated cost of the first year for all of the alternatives is assumed to be the same. It is important to note that these estimated values of benefit and cost can be more realistically captured by repeating the conventional feasibility study for the different starting years.

3) Statistical Distribution of Key Variables

The statistical distribution of benefit and cost of each year is estimated by combining experts' opinion. The PERT distribution is used to model an expert's opinion because it requires only three parameters (i.e., minimum, most likely, maximum). Five experts, two from consulting companies, two from universities, one from central government in Thailand, were interviewed in order to estimate these three parameters of cost and benefit in the year of 2004, 2009, 2014, 2019, 2024, 2029, 2034, and 2039 as shown in <Figure 3-2>. These three parameter values of other years were estimated by extrapolating those values of the years estimated by interview.

Each value is defined as the actual value divided by the estimated value. For example, 1.10 means that the actual value would be 10% higher than the estimated value. This value has similar role as the error. Accordingly, the word "Error" is used to shortly call the distribution in this study. Therefore, the error represents the uncertainty in estimated key variables (i.e., Benefit and Cost) and it also includes the mistake or something that the conventional estimation method cannot cope.

After five experts were interviewed, their opinions were combined. For this, a discrete ($\{x_i\}$,$\{p_i\}$) distribution is used where the $\{x_i\}$ are expert opinions and the $\{p_i\}$ are weights given to each opinion according to the emphasis one wishes to place on them (Vose, 2000). In this study, equal weight was assigned to all experts. The statistical distributions of cost and benefit represent the total uncertainty of them. They were multiplied by estimated values to obtain the total value of cost and benefit. All alternatives were assumed to have the same distribution of cost and benefit in the same year.

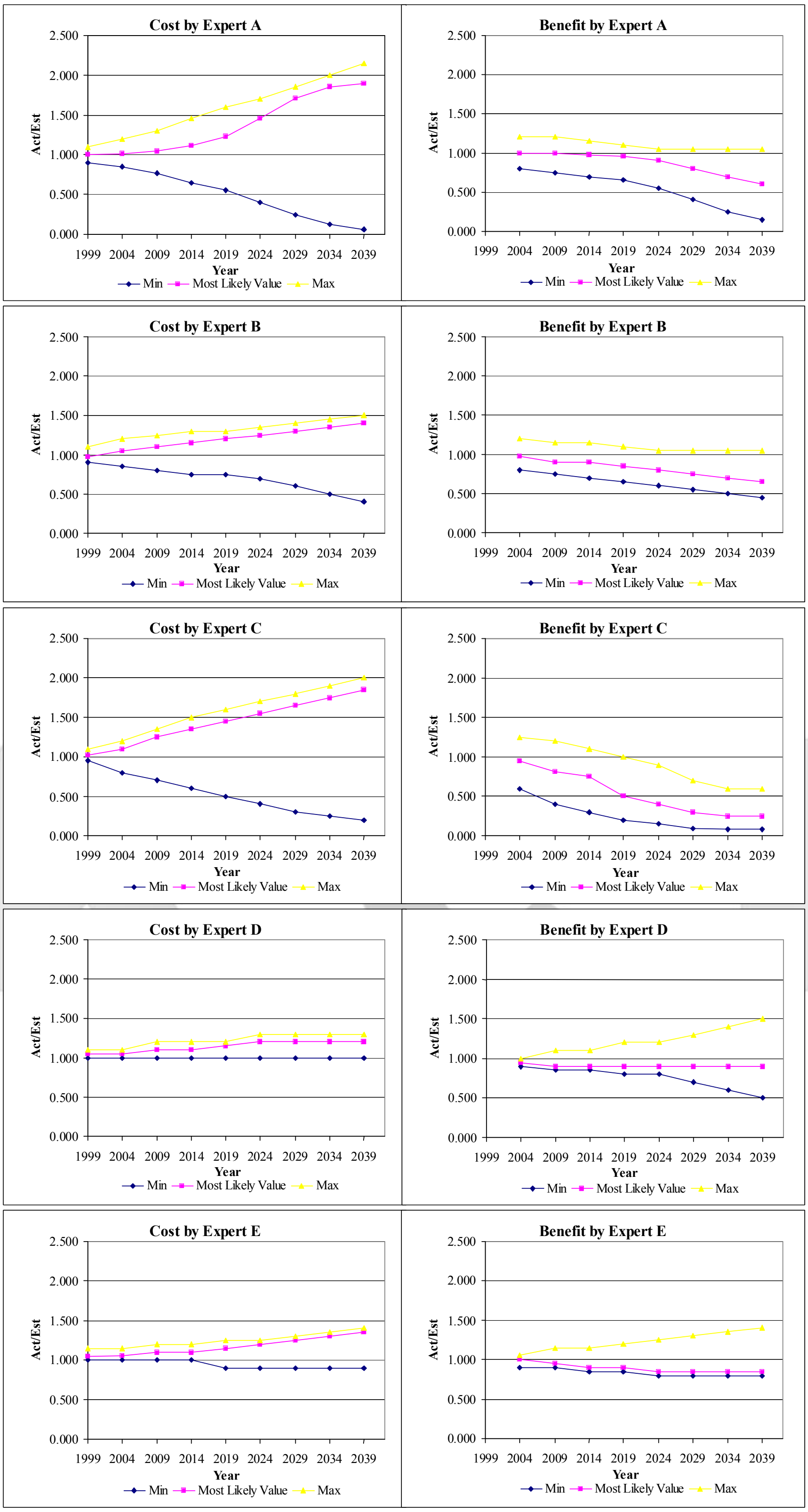


Figure 3-2. Interview Data from Five Experts

4) Monte Carlo Simulation

This study utilizes Monte Carlo simulation technique. For each iteration, the error term of cost and benefit from each expert in each year are randomly picked up considering its distribution. These values from five experts are combined to estimate the total error. It is then multiplied with the estimated value to obtain the trial value of cost and benefit. Consequently, the trial value of benefit is subtracted by the trial value of cost in the same year in order to estimate net benefit of that year. <Table 3-3> shows the first iteration of A2. The procedure is repeated one thousand times and every time the values of the NPV, EIRR, B/C are computed. At the end, the results are apparent in term of probability density function (PDF). The results can then be converted into a cumulative distribution function (CDF) so that the planner can use it for choosing the best alternatives.

IV. Analysis of Results

<Table 4-1> shows the central tendency and variability of NPV, EIRR, and B/C Ratio for the ten alternatives. <Figure 4-1> shows the CDF (cumulative density function) of NPV of the ten alternatives, and <Figure 4-2> shows the 5^{th} percentile, mean, and 95^{th} percentiles of NPV of the ten alternatives. It may be seen that, when the expected value of NPV is used as an evaluation index, A2 is the best option. It implies that this project should be started to construct in the year 2000 and be operated from the year 2004.

When evaluating the ten alternatives in terms of the distribution of NPV, A2 is again chosen as the best one. It is because other alternatives are stochastically dominated by A2 (i.e. not only 1^{st} order but also 2^{nd} order) (see Vose (2000) for details). That is, whatever '♋' is chosen, A2 is the best one. In summary, it was found that A2 is the best alternative not only by the first criterion (i.e. Maximum E[NPV]) but also the second one (Maximum probability that NPV >♋).

As shown in <Figure 4-3>, A2 will provide the average NPV of 47,430.41 Million Baht, and it is 95% confident that this alternative will give NPV more than 30,464.68 Million Baht. If EIRR is considered, this alternative will provide 39.86% on average. It has only five percent of chance that this project will give the EIRR lower than 35.54%. If B/C Ratio is considered, its expected value is of 6.65. The project will give B/C Ratio more than 4.62 with 95% confidence.

Table 3-3. The First Iteration of A2

	Year	Cost								Benefit						
		Estimated	Err1	Err2	Err3	Err4	Err5	Total Err	Trial Value	Estimated	Err1	Err2	Err3	Err4	Err5	Total Err
1	1999															
2	2000	698.97	0.992	0.961	1.029	1.082	1.082	0.961	671.80							
3	2001	3,892.50	0.993	1.021	1.039	1.082	1.083	0.993	3,865.95							
4	2002	4,607.17	0.994	0.974	1.049	1.082	1.085	0.974	4,487.71							
5	2003	3,195.77	0.995	0.981	1.058	1.082	1.086	0.981	3,134.06							
6	2004	25.30	0.995	0.987	1.068	1.082	1.088	0.987	24.98	3,496.99	1.094	1.072	1.127	0.980	1.021	0.980
7	2005	25.98	0.998	0.991	1.091	1.098	1.098	0.991	25.76	6,520.87	1.093	1.058	1.109	0.985	1.023	0.985
8	2006	26.67	1.000	0.995	1.114	1.114	1.109	0.995	26.55	9,544.75	1.093	1.043	1.091	0.989	1.024	0.989
9	2007	26.58	1.002	1.000	1.137	1.131	1.120	1.000	26.57	10,312.01	1.092	1.029	1.073	0.993	1.024	0.993
10	2008	27.40	1.005	1.004	1.160	1.147	1.130	1.004	27.50	11,141.40	1.092	1.015	1.055	0.997	1.023	0.997
11	2009	28.25	1.007	1.008	1.183	1.163	1.140	1.007	28.45	12,037.98	1.091	1.001	1.037	1.001	1.021	1.001
12	2010	262.21	1.015	1.012	1.199	1.163	1.140	1.012	265.44	13,007.24	1.085	1.002	1.022	1.001	1.015	1.001
13	2011	30.02	1.022	1.017	1.214	1.163	1.140	1.017	30.52	14,055.09	1.079	1.002	1.006	1.001	1.008	1.001
14	2012	30.95	1.030	1.021	1.230	1.163	1.140	1.021	31.61	15,503.70	1.073	1.003	0.990	1.001	1.001	0.990
15	2013	31.54	1.037	1.025	1.245	1.163	1.140	1.025	32.34	17,101.60	1.067	1.003	0.975	1.001	0.994	0.975
16	2014	32.14	1.045	1.030	1.260	1.163	1.140	1.030	33.10	18,864.20	1.061	1.004	0.959	1.001	0.988	0.959
17	2015	32.76	1.059	1.038	1.275	1.168	1.151	1.038	33.99	20,808.46	1.053	0.994	0.923	1.012	0.991	0.923
18	2016	33.39	1.073	1.045	1.289	1.173	1.161	1.045	34.91	22,953.11	1.046	0.984	0.886	1.023	0.994	0.886
19	2017	267.12	1.088	1.053	1.304	1.178	1.172	1.053	281.37	23,188.27	1.039	0.974	0.849	1.034	0.997	0.849
20	2018	34.46	1.102	1.062	1.318	1.182	1.181	1.062	36.58	23,425.86	1.032	0.964	0.810	1.045	1.000	0.810
21	2019	34.91	1.117	1.070	1.332	1.185	1.191	1.070	37.34	23,665.91	1.025	0.954	0.772	1.056	1.004	0.772
22	2020	35.35	1.146	1.074	1.347	1.202	1.197	1.074	37.98	23,908.44	1.015	0.944	0.750	1.056	1.000	0.750
23	2021	35.81	1.176	1.079	1.361	1.219	1.202	1.079	38.64	24,153.49	1.005	0.934	0.729	1.056	0.996	0.729
24	2022	36.27	1.206	1.083	1.375	1.235	1.207	1.083	39.30	24,983.35	0.995	0.924	0.708	1.056	0.993	0.708
25	2023	36.78	1.237	1.088	1.390	1.252	1.212	1.088	40.02	25,842.29	0.985	0.914	0.686	1.056	0.989	0.686
26	2024	270.34	1.267	1.093	1.404	1.268	1.217	1.093	295.49	26,731.38	0.975	0.904	0.666	1.056	0.985	0.666
27	2025	37.73	1.304	1.095	1.419	1.268	1.227	1.095	41.30	27,651.67	0.965	0.898	0.635	1.068	0.988	0.635
28	2026	38.21	1.340	1.097	1.433	1.268	1.237	1.097	41.92	28,604.29	0.954	0.891	0.605	1.081	0.991	0.605
29	2027	38.90	1.376	1.099	1.448	1.268	1.246	1.099	42.75	29,590.39	0.944	0.885	0.574	1.093	0.995	0.574
30	2028	39.40	1.413	1.101	1.462	1.268	1.256	1.101	43.38	30,611.18	0.933	0.879	0.544	1.106	0.998	0.544
31	2029	(5,796.66)	1.160	1.059	0.791	1.025	1.039	1.025	(5,939.14)	32,085.68	0.923	0.872	0.514	1.118	1.001	0.514
32	2030															
33	2031															
34	2032															
35	2033															
36	2034															
37	2035															
38	2036															
39	2037															

PV(Benefit)	*55,426.44*	*Million Baht*
PV(Cost)	*7,977.78*	*Million Baht*
NPV	*47,448.66*	*Million Baht*
EIRR	*41.95%*	
B/C Ratio	*6.95*	

Table 4-1. Simulation Outputs of 10 Alternatives

	A1			A2			A3			A4			A5		
	NPV	**EIRR**	**B/C Ratio**	**NPV**	**EIRR**	**B/C Ratio**	**NPV**	**EIRR**	**B/C Ratio**	**NPV**	**EIRR**	**B/C Ratio**	**NPV**	**EIRR**	**B / C Ratio**
Minimum	12,358.64	0.2243	2.2971	15,590.89	0.2654	2.7167	15,405.14	0.2986	2.9864	16,082.71	0.3311	3.3542	12002.39	0.3069328	2.923895
Mean	46,034.02	0.3417	5.9089	47,430.41	0.3986	6.6486	47,354.92	0.4505	7.3005	45,903.23	0.4899	7.8181	43529.44	0.5088346	8.182926
Maximum	60,688.57	0.3974	8.1797	62,860.31	0.4729	9.2567	61,464.86	0.5294	9.9634	59,680.66	0.5912	10.9831	56900.04	0.6113188	11.85293
S.D.	7,579.75	0.0206	0.8485	7,712.26	0.0258	0.9779	7,632.25	0.0314	1.0899	7,493.40	0.0357	1.2047	7523.829	4.10E-02	1.363094
Variance	5.75E+07	4.23E-04	7.20E-01	5.95E+07	6.67E-04	9.56E-01	5.83E+07	9.89E-04	1.19E+00	5.62E+07	1.27E-03	1.45E+00	5.66E+07	1.68E-03	1.858026
Skewness	-1.1650	-1.0453	-0.8924	-1.1660	-0.8788	-0.8474	-1.2495	-0.8332	-0.8728	-1.2213	-0.7600	-0.8159	-1.265137	-0.9521247	-0.8483486
Kurtosis	4.8919	5.6869	4.4303	4.8870	5.6642	4.3923	5.0950	5.0558	4.3665	4.8794	4.7415	4.1896	4.963689	5.419147	4.229636
Mode	47,783.25	0.3437	6.0557	49,050.94	0.3900	6.6166	49,427.86	0.4600	8.0092	49,251.70	0.5016	7.6976	47268.91	0.5106295	8.61075
5th Perc.	30,237.63	0.3041	4.2041	30,464.68	0.3554	4.6219	31,378.88	0.3976	5.1772	29,570.11	0.4272	5.3209	27446.95	0.4402581	5.381233
95th Perc.	56,098.55	0.3698	7.0609	57,685.96	0.4366	8.0132	57,355.42	0.4960	8.8506	55,538.88	0.5431	9.5414	52743.48	0.566844	10.03309

	A6			A7			A8			A9			A10		
	NPV	**EIRR**	**B/C Ratio**	**NPV**	**EIRR**	**B/C Ratio**	**NPV**	**EIRR**	**B/C Ratio**	**NPV**	**EIRR**	**B/C Ratio**	**NPV**	**EIRR**	**B / C Ratio**
Minimum	12,899.81	0.3311	3.2623	10,523.88	0.3274	3.1363	8,367.69	0.3053	2.7834	7,746.87	0.3177	2.8638	6962.132	0.3369381	3.032895
Mean	40,863.35	0.5276	8.5100	38,556.10	0.5486	8.8871	36,324.93	0.5707	9.2429	33,940.95	0.5942	9.5862	31938.6	0.6220247	9.996564
Maximum	54,645.92	0.6620	12.8156	53,836.17	0.6815	13.2173	49,697.84	0.7101	14.6946	46,812.64	0.7500	15.1731	45524.59	0.8045475	16.14442
S.D.	7,552.81	0.0448	1.5168	7,269.58	0.0495	1.6405	6,998.50	0.0535	1.7730	7,030.62	0.0597	1.9731	6496.138	6.30E-02	2.092931
Variance	5.70E+07	2.01E-03	2.30E+00	5.28E+07	2.45E-03	2.69E+00	4.90E+07	2.86E-03	3.14E+00	4.94E+07	3.57E-03	3.89E+00	4.22E+07	3.97E-03	4.380362
Skewness	-1.2494	-0.8906	-0.8056	-1.3494	-1.1828	-0.8868	-1.2801	-1.0044	-0.7192	-1.3067	-1.1177	-0.7068	-1.214884	-0.854773	-0.5149902
Kurtosis	4.5523	4.9816	3.9403	5.1538	5.9424	4.2167	4.9797	5.6252	4.0315	4.8379	5.9426	3.9818	4.648698	5.404249	3.749468
Mode	44,349.17	0.5089	8.9224	40,738.68	0.5730	9.0173	37,911.07	0.5849	9.2948	36,267.33	0.6060	10.7308	36106.9	0.6301543	9.726519
5th Perc.	24,114.59	0.4440	5.3234	22,760.34	0.4657	5.6779	21,364.62	0.4772	5.6497	18,731.52	0.4867	5.6341	17506.16	0.5121909	5.902032

95th Perc.	50,195.13	0.5926	10.6587	47,449.99	0.6148	11.0607	45,177.36	0.6491	11.8636	42,445.46	0.6815	12.4199	40156.73	0.7153429	13.16089

Figure 4-1. Cumulative Distribution of NPV of 10 Alternatives

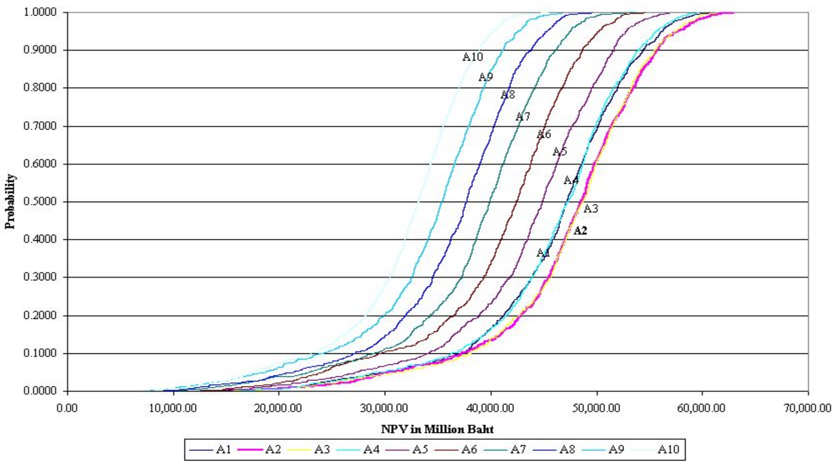
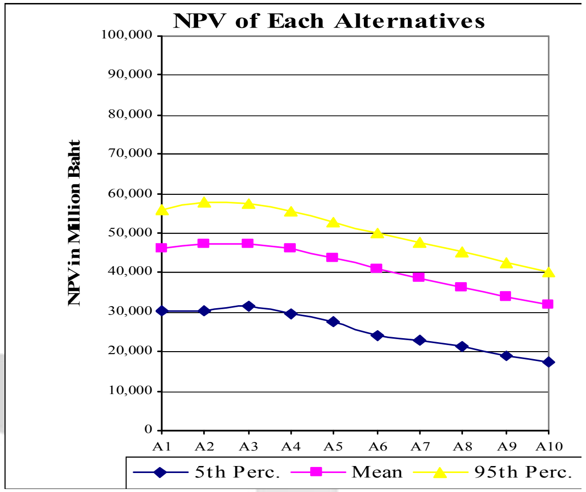


Figure 4-2. The 5th Perc., Mean, and 95th Perc. of 10 Alternatives



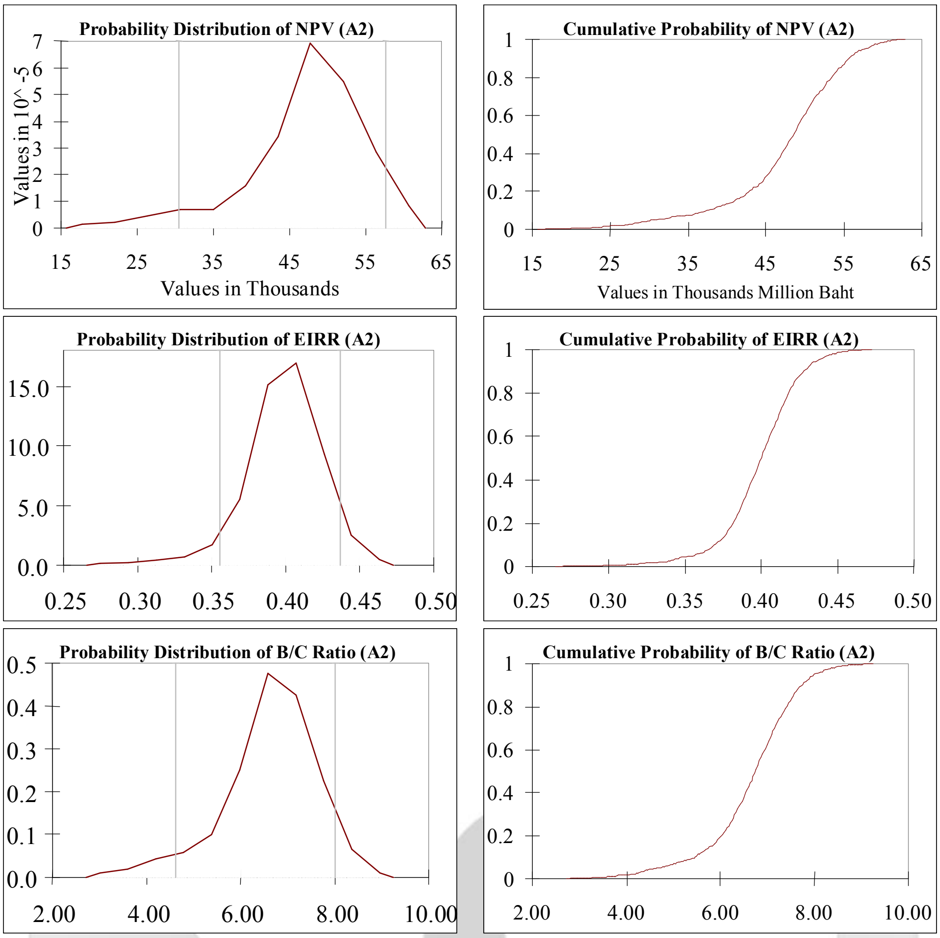


Figure 4-3. Evaluation Indices' PDF and CDF of the Best Alternative (A2)

V. concluDing remarks

Motivated from a number of deficiencies of the conventional transportation project evaluation method, this study proposed a new evaluation framework which takes into account not only the optimal investment timing but also the uncertainty of benefits and costs. The proposed methodology helps decision makers perform more scientific and systematic evaluation for the transportation infrastructure project. The scope of evaluation was expanded to consider the built-later alternative. The quantitative risk analysis was applied through Monte Carlo simulation technique to estimate uncertainty. It provided an evaluation index with probability distribution which is more valuable than only a single-point estimate. The proposed methodology was applied to a feasibility study of expressway project in Bangkok, Thailand. It was found that the proposed framework could provide more valuable information for the project evaluation than the conventional one. It is expected that the proposed methodology can be applied for different entities (i.e., public or private sector) and different type of evaluation (economic or financial analysis).

In this study, the benefit and cost were expanded to the later year since there is no data available. For the further study, this assumption can be alleviated if the benefit and cost are re-estimated for built-later alternatives. Post evaluation should also be established. The actual benefit and cost of transportation infrastructure investments should be collected into a database for comparison with the estimated values. Although they may not be directly used to identify the probability distributions of benefit and cost of a project due to low transferability, they can provide valuable information in the context of uncertainty estimation in project evaluation. In addition, more sophisticated estimation of benefit and cost by breaking down sub-items would be valuable.

초 록

불확실성을 고려한 교통시설의 적정 투자시기 결정에 관한 연구

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일반적으로 교통분야의 사회간접자본시설투자에 대한 경제성 평가는 투자 시기 및 평가지표의 불확실성에 대한 고려를 하지 않고 있다. 이러한 단점을 보완하고자 그 동안 세계적으로 교통분야 사회간접자본시설의 적정 투자시기와 평가지표의 불확실성에 대한 개별적인 연구들이 진행되어왔다. 그러나 두 가지 측면을 동시에 고려한 연구는 없었다. 이에 본 연구는 평가지표의 불확실성과 적정 투자시기를 동시에 고려할 수 있는 평가 틀을 제시하였다. 본 논문에서는 교통시설공급으로 발행하는 편익과 비용을 확률변수로 취급하고 이들에 대한 불확실성을 전문가 집단의 판단을 바탕으로 추정하였다. 추정된 각 년도의 비용과 편익으로부터 평가지표 (예: 순현재가치 (NPV))의 확률밀도 함수를 추정하기 위해 Monte Carlo 시뮬레이션을 사용하였다. 제시된 방법론은 태국 방콕의 도시고속도로에 대한 경제성 평가에 적용되었다. 적용결과, 본 연구에서 제시된 방법론은 보편적으로 사용되는 경제성평가 기법보다 의사결정자에게 보다 많은 유용한 정보를 제공할 수 있는 것으로 판명되었다.

Keywords: Economic Evaluation, Monte Carlo Simulation, Net Present Value, Transportation Infrastructure Investment, Uncertainty

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