A SIMULATION-OPTIMIZATION APPROACH FOR ASSESSING BUILD-OPERATE-TRANSFER PROJECTS

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Abstract: In this paper, we develop a simulation-optimization framework to assess the profitability of a BOT project. An efficient network optimization solver is embedded in a stochastic simulation framework to determine the traffic volumes that will patronize the BOT links as well as the free links in a transportation network, while the stochastic simulation generates realizations of traffic forecasts and cost estimates. Using the simulation-optimization procedure, experiment is conducted to estimate the expected profit and its associated probability of making a certain desired profit. These profit forecasts and their probabilities will help the authorities or private investors to systematically evaluate BOT investment projects. A case study is used to illustrate the application of the assessment tool developed in this paper. Sensitivity analysis is also performed to examine the profit forecasts with respect to the optimal selection of the roadway capacity and toll charge of the BOT project.

Key Words: BOT projects, risk analysis, Monte Carlo simulation, uncertainty, simulation-optimization framework

1. INTRODUCTION

In the developing countries where governments are under severed financial constraints to improve the transportation infrastructure system to keep up with the fast growing economies, the Build, Operate and Transfer (BOT) approach is an attractive avenue for building new transportation infrastructures. In recent years, BOT projects have become fashionable in Southeast Asia. Some examples of BOT projects include: Taiwan's High Speed Rail (HSR) project linking Taipei to Kaoshiung, its largest harbor and second biggest city in Taiwan (Sidney, 1996); five major toll automobile tunnels in Hong Kong (Downer, J.W. *et al.*, 1992); the Superhighway project connecting the booming industrial cities of the Pearl River Delta in China (Yang and Meng, 2000); the Bangkok Second Stage Expressway in Thailand, Kepong toll road in Malaysia, and toll road Highway 1 in Vietnam (Walker, C. *et al.*, 1995).

The BOT approach is one of the public-private partnership models for transportation infrastructure development by using private funds to undertake new infrastructure facility. It involves the assembling of private investors to finance, design, build, and operate the infrastructure; in return the private investors receive revenue from toll charges for a certain number of years called a concession period. After the concession period is expired, the facility is returned back to the government. Although the BOT concept seems to be simple, there are many factors affecting the success of a BOT project. One of these factors is the selection of the roadway capacity and toll charge of the BOT links (roads). From the viewpoint of the private investors, the main concerns are cost and revenue (i.e., profit). Cost depends on the roadway capacity of the BOT links, while revenue is a function of the toll charge and the traffic volume that will patronize the BOT links. In a general transportation network, users may have a choice between choosing the BOT roads with toll charge or the free access route. This choice behavior introduces a complex inter-dependent relationship between the private investors, who decide the optimal capacity and toll charge of the BOT links to maximize profit, and the road users, who choose the routes that minimize their generalized costs. In addition, uncertainties associated with traffic forecasts and cost estimates are the great concern to the private investors, because these factors directly affect the profitability of the BOT project. The selection of roadway capacity and toll charge of the BOT links combined with the uncertain traffic forecasts and cost estimates make the investment highly uncertain and risky. Thus it can be seen that the optimal selection of capacity and toll in a BOT problem with uncertainties is quite intricate and cannot be considered solely by either risk analysis or network optimization alone. In this paper, we incorporate network optimization in a stochastic simulation framework to assess the financial feasibility of BOT projects. It extends the initial study by Chen, A. *et al.* (2001) by considering both traffic forecasts and cost estimates as random variables. Sensitivity analysis is also performed to examine the profit forecasts with respect to the optimal selection of the roadway capacity and toll charge of the BOT project.

2. A SIMULATION-OPTIMIZATION FRAMEWORK

The structure of the simulation-optimization framework for analyzing risks and financial performance of BOT projects is depicted in Figure 1. The focus is to examine the effect of traffic forecasts and cost estimates, which are generally uncertain and would vary in almost all projects, on the financial feasibility of a BOT project. According to Skamris and Bent (1996), traffic forecasts that deviated by 20 to 60 percent when compared with actual development are frequently occurred in large transportation infrastructure projects. The basic cost components of BOT project are construction cost and maintenance-operating costs. There are wide ranges of techniques for estimating construction costs. The degree of accuracy of the prediction depends on the quantity and quality of information about the BOT project (Walker, G. *et al.*, 1995). Furthermore, when the construction costs exceed original estimates, either due to economic effect or excessive design changes, it lead to cost overrun risk. The result of these inaccurate estimates can lead to an improper assessment of the project.

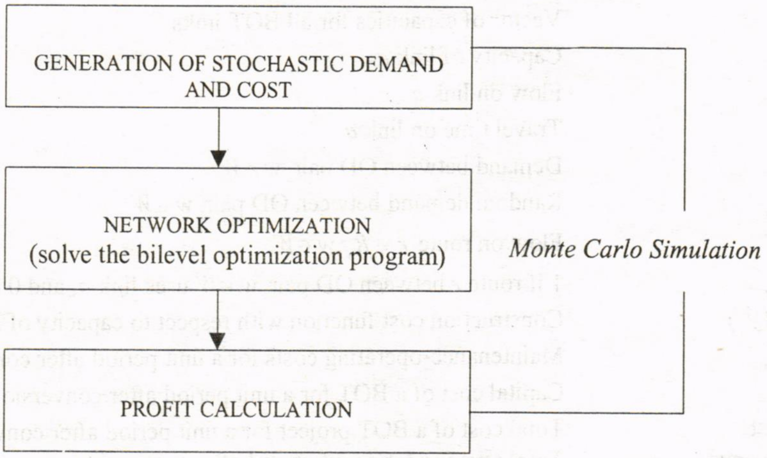


Figure 1. A Simulation-Optimization Framework

The framework in this study, therefore, assumes that the traffic forecasts and cost estimates cannot be defined precisely by a single value but are random with specific probability distribution. As a result, the financial performance measure (project profit) also becomes a random variable. In the simulation-optimization framework, random values of the uncertain traffic forecasts and costs are generated using a random variate generator. The interdependent relationship among cost, revenue, road capacity, and traffic volume can be modeled within a bi-level optimization program where the decision variables in the two-optimization programs are related to each other (Yang and Meng, 2000). For each realization of the traffic forecasts and cost estimates, the optimal selection of toll and capacity for a BOT project is determined by solving the bi-level optimization program. This yields revenue and cost of the project that are used to compute profit for each realization. A profit distribution can be constructed by repeating the process with different realizations sampled from the traffic forecast and cost estimate distributions.

2.1 Notations

For convenience, we define the following sets, variables, and parameters:

Sets

N	Set of nodes
A	Set of links
$\bar{A}$	Set of BOT links

W	Set of OD pairs
R_w	Set of routes between OD pair $w \in W$
R	Set of all routes in the network

Variables

x_a	Toll charged on BOT link a
y_a	Capacity on BOT link a
x	Vector of tolls for all BOT links
y	Vector of capacities for all BOT links
C_a	Capacity of link a,
v_a	Flow on link a
t_a	Travel time on link a
d_w	Demand between OD pair $w \in W$
D_w	Random demand between OD pair $w \in W$
f_r^w	Flow on route $r \in R_w, w \in W$
δ_{ar}^{w}	1 if route r between OD pair $w \in W$ uses link a, and 0 otherwise
$I_a(y_a)$	Construction cost function with respect to capacity of BOT links
C_{MO}	Maintenance-operating costs for a unit period after conversion
C_c	Capital cost of a BOT for a unit period after conversion
Cost	Total cost of a BOT project for a unit period after conversion
Revenue	Total revenue for a unit period after conversion
π	Profit (revenue-cost)
π^*	Desired profit.
$\phi(\pi)$	Probability density function of the financial profit
Z	Random variable generated from $N(0,1)$

Parameters

α	Parameter that transforms the capital cost of the project into unit period cost
β	Parameter that transforms toll into equivalent time value
k	Proportionality parameter
φ	Ratio of maintenance-operating costs to the capital cost
t_a^0	Free-flow travel time of link a

2.2 Project Costs

The total costs of a BOT project is comprised of construction cost and maintenance-operating costs. The total expenditure for a unit period is expressed as:

$$Cost = C_{MO} + C_C \tag{1}$$

The total investment or capital cost of the project is largely influenced by the size (number of lanes). Therefore, the unit period capital cost can be expressed as:

$$C_C = \alpha I_a(y_a) \tag{2}$$

Following the study by Yang and Meng (2000), the construction cost functions for the BOT links are also assumed to be linear:

$$I_a(y_a) = k\, t_a^0\, y_a \quad , a \in \bar{A} \tag{3}$$

Further, the maintenance-operating cost for the project is assumed to be proportional of the construction cost. Hence, it can be written as:

$$C_{MO} = \varphi\, C_C \tag{4}$$

2.3 Project Revenue

Project revenue is derived from toll charge and traffic volume patronizing the BOT links. Similar to the project cost, it is expressed as unit period revenue as follows:

$$Revenue = v_a(x,y)\, x_a \tag{5}$$

2.4 Bi-Level Program Formulation

As long as the private sector is involved in a BOT project, the fundamental objective of the investment is to maximize profit returns while keeping financial risk to a minimum. Assume a single private firm has monopoly rights from the government to construct and operate a BOT project. Under this situation, the bi-level BOT network design problem is to determine the optimal capacity-toll combination for the toll roads that maximizes profit and considers drivers' route choice behavior. Mathematically, it can be written as follows:

$$\max \pi(x,y) = \sum_{a \in \bar{A}} \{ v_a(x,y)\, x_a - [1+\varphi][\alpha I_a(y_a)] \} \tag{6}$$

subject to: $x_a \geq 0, \quad y_a \geq 0, \quad a \in \bar{A}$ (7)

where $v_a(x,y)$ is obtained by solving:

$$\min \sum_{a \in A - \bar{A}} \int_0^{v_a} t_a(w)\, dw + \sum_{a \in \bar{A}} \int_0^{v_a} \{ t_a(w, y_a) + \beta x_a \}\, dw \tag{8}$$

subject to:

$$\sum_{r \in R_w} f_r^w = d_w, \quad w \in W \tag{9}$$

$$v_a = \sum_{w \in W} \sum_{r \in R_w} f_r^w \delta_{ar}^w, \quad a \in A \tag{10}$$

$$f_r^w \geq 0, \; r \in R_w, \; w \in W \tag{11}$$

The objective of the upper-level program (6) - (7) is to maximize the difference between project revenue and project cost subject to non-negative link tolls and capacities on the BOT roads, as well as the lower-level program (8) – (11) which determines the equilibrium link flows for both the BOT links and free links. The lower-level program is a standard network equilibrium problem that can be readily solved by many efficient algorithms (Patriksson, 1994). Here we use the path-based gradient projection algorithm which has shown to outperform the state-of-the practice algorithms, such as the Frank-Wolfe and PARTAN algorithms, and at least as good as or superior to the state-of-the-art simplicial decomposition algorithms like the disaggregate simplicial decomposition (DSD) and restricted simplicial decomposition (RSD) algorithms (Chen and Lee, 1999 and Chen, A. *et al.*, 2000). Since the above upper-level program involves only a few decision variables (i.e., capacity and toll of the BOT links) with simple bounds, it can be solved efficiently using a direct search method such as the Hooke-Jeeves algorithm (Abdulaal and LeBlanc, 1979).

3. RISK ANALYSIS

Risk analysis is a methodology that considers the uncertainties relating to the key variables required for evaluating the project feasibility and determining the level of risk. The principal measure of project feasibility used in this study for decision making is profit. Thus risk is measured in terms of the chance that profit will deviate from the expected value or the standard deviation of profit.

Probability analysis is one of the several forms of risk analysis. This method relies on the random calculation of values that fall within a probability distribution. The overall result is derived by the combination of values selected for each one of the risks. The computation is repeated many times with different realizations sampled from the stochastic variables to obtain the probability distribution of the project outcome.

In the BOT project, both revenue and cost are random quantities. Since revenue and cost are random quantities, profit also becomes a random quantity. Hence, the risk assessment can be expressed as the probability of the expected profit being less than the desired profit:

$$P(\pi \le \pi^*) = \int_0^{\pi^*} \phi(\pi)\, d\pi \tag{12}$$

Using Equation (12), any desired profit can be assessed. Apart from providing a spectrum of possible values for appraisal, the standard deviation of profit (σ_π), derived from the probability density function of financial profit, provides an indication of magnitude of variation of the risk involved in a BOT investment. Such information is of vital importance to the private investors because their private firms are put at risk. The risk assessment provides the level of confidence of the profit obtained by implementing the project.

4. CASE STUDY

The simulation-optimization methodology proposed in this paper is demonstrated using the case study of an inter-city expressway in the Pearl River Delta Region of South China given in Yang and Meng (2000). The network is depicted in Figure 2 with 4 nodes, 10 links, and 12 O-D pairs. The case study involves construction of an expressway between nodes 3 and 4, leading to two new links, links 9 and 10. Because the two new links connect the same nodes in opposite directions, the same capacity and toll charge are assumed for both. Thus there are two decision variables in the problem: toll (x) and capacity (y) for the new BOT roads.

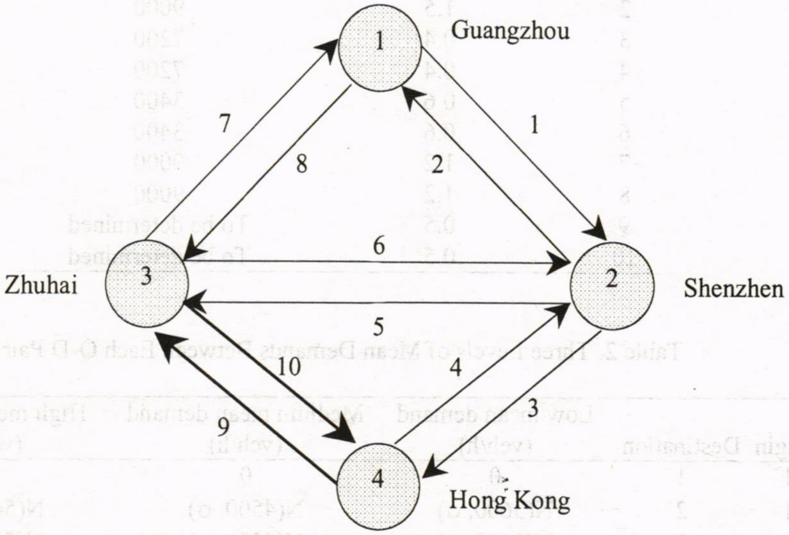


Figure 2. Pearl River Delta Regional Network

The link travel time function used in the traffic assignment problem is the standard Bureau of Public Road (BPR) function given below:

$$t_a(v_a) = t_a^0\left\{1.0+0.15\left(\frac{v_a}{c_a}\right)^4\right\}, a \in A \cup \bar{A} \tag{13}$$

The basic inputs of the link travel time function is presented in Table 1. To simulate the uncertainty of the traffic forecasts, a normal distribution is used to model traffic forecasts of the OD demand. Three levels of mean demand are specified for each OD pair, as given in Table 2. Basically, the low and high mean OD demand is varied ±20% from the medium mean OD demand. For each level of mean OD demand, three levels of standard deviation (σ) of the OD demand is specified to reflect the relative accuracy of the OD demand estimates as follows: (1) $\sigma = 1.5(d_w/3)$ for low accuracy demand estimates, (2) $\sigma = 1.0(d_w/3)$ for medium accuracy demand estimates, and (3) $\sigma = 0.5(d_w/3)$ for high accuracy demand estimates. These three accuracy levels of traffic forecasts can also be interpreted as high-risk scenario, moderate-risk scenario, and low-risk scenario, respectively, for each level of mean OD demand. Given that both the mean and standard deviation of OD demands are defined for a total of nine combinations (3 means x 3 standard deviations), random samples for each OD pair can be generated according to a standard normal distribution as follows:

$$D_w = d_w \pm Z\sigma \tag{14}$$

Table 1. Input Data for the Link Travel Time Function

Link no.	Free-flow travel time (h)	Link capacity (veh/h)
1	1.5	9000
2	1.5	9000
3	0.4	7200
4	0.4	7200
5	0.6	3400
6	0.6	3400
7	1.2	9000
8	1.2	9000
9	0.5	To be determined
10	0.5	To be determined

Table 2. Three Levels of Mean Demands Between Each O-D Pair

Origin	Destination	Low mean demand (veh/h)	Medium mean demand (veh/h)	High mean demand (veh/h)
1	1	0	0	0
1	2	N(3600, σ)	N(4500, σ)	N(5400, σ)
1	3	N(3600, σ)	N(4500, σ)	N(5400, σ)
1	4	N(2400, σ)	N(3000, σ)	N(3600, σ)
2	1	N(3600, σ)	N(4500, σ)	N(5400, σ)
2	2	0	0	0
2	3	N(1200, σ)	N(1500, σ)	N(1800, σ)
2	4	N(2400, σ)	N(3000, σ)	N(3600, σ)
3	1	N(3600, σ)	N(4500, σ)	N(5400, σ)
3	2	N(1200, σ)	N(1500, σ)	N(1800, σ)
3	3	0	0	0
3	4	N(2400, σ)	N(3000, σ)	N(3600, σ)
4	1	N(2400, σ)	N(3000, σ)	N(3600, σ)
4	2	N(2400, σ)	N(3000, σ)	N(3600, σ)
4	3	N(2400, σ)	N(3000, σ)	N(3600, σ)
4	4	0	0	0

σ is the standard deviation of the OD estimate which reflects the relative accuracy of the traffic forecast.

Whenever a negative value is generated, the OD demand is reset to a lower bound of 10 units. To simulate the uncertainty of cost estimates, which are governed by the proportionality parameter k given in Equation (3), a triangular distribution is used to generate random cost estimates. The values of k were altered within the range 0.5x10^6 to 1.3x10^6 HK$/(h·veh/h), with the most likely value (mode) being 1.2x10^6 HK$/(h·veh/h).

The concession period of this project is assumed to be 30 years. To facilitate the analysis, the 30-year concession period is converted into a unit period (see equation 2). This conversion is similar to an annual worth such as the equivalent uniform annual cost (EUAC) that is used in engineering economic analysis (White, J.A. *et al.*, 1998). Hence, the BOT feasibility analysis in terms of profit (revenue - cost) is converted into a unit period value. Other parameters used in this study are taken from Yang and Meng (2000).

$$\alpha = 3.4 \times 10^{-5}(1/h) \text{ and } \beta = 1/120(h/HK\$)$$

To obtain a high degree of accuracy, we use 60,000 samples to generate the results for this study.

4.1 Scenario I: Stochastic OD Demands with Deterministic Costs

Scenario I considers the source of uncertainty arised solely from the OD demands. The costs are deterministic (i.e., k is fixed at the mean value of $1.0\text{x}10^6$ HK\$/(h·veh/h)). Mean and standard deviation (shown in parenthesis) of profit, optimal toll, and optimal capacity for the 9 combinations of OD demand uncertainty are shown in Table 3. The matrix is constructed with mean OD demand as row entries and standard deviation of OD demand as column entries both in ascending order. For any given row (i.e., constant OD demand with different standard deviation levels or accuracy demand estimate levels), the mean profit remains relatively the same with a slight increase due to truncation error (i.e., negative values of OD demand are reset with a minimum of value of 10 veh/h). However, the standard deviation of profit increases significantly as the accuracy of traffic forecasts deteriorates. This implies that low accuracy of demand estimates can lead to a higher risk for the BOT investment. This can be assessed graphically by the profit profile depicted in Figure 3(a) with the corresponding optimal distributions of toll (HK\$) and capacity (veh/h) given in Figures 3(c) and 3(e), respectively, for the medium demand level. Similarly, for any given column (i.e., constant standard deviation of OD demand with different OD demand levels), it seems that the larger the OD demand, the higher the mean profit and standard deviation of profit. Albeit higher mean profit, the risk is also greater due to larger variations of profit. An illustration of the profit profile, optimal distributions of toll (HK\$) and capacity (veh/h) for the medium standard deviation of demand is provided Figures 3(b), 3(d), and 3(e), respectively.

4.2 Scenario II: Stochastic OD Demands with Stochastic Costs

Scenario II considers the uncertainty for OD demands and cost estimates. Similar to scenario I, Table 4 shows the mean and standard deviation (shown in parenthesis) of profit, optimal toll, and optimal capacity for the same 9 combinations; Figures 4(a), 4(c), and 4(e) depict the profit profile, optimal distributions of toll (HK\$) and capacity (veh/h) for the case of constant OD demand with different standard deviation levels or accuracy demand estimate levels; and Figures 4(b), 4(d), and 4(e) depict the profit profile, optimal distributions of toll and capacity for the case of constant standard deviation of OD demand with different OD demand levels.

Comparing the results of scenario I with scenario II, it is found that the overall outputs of mean profit, optimal toll, and optimal capacity from both scenarios are quite similar. In some cases, especially low demand level and low level of standard deviation, the uncertainty of cost estimates can contribute significantly to the increase of standard deviation of profit that would lead to a higher risk. Thus it is necessary to account for both demand and cost uncertainties when assessing the financial feasibility of a BOT investment.

Table 3. Output for Scenario I (profit in HK$, toll in HK$, and capacity in veh/h)

Profit

STDEV	Low	Medium	High
MEAN			
Low	40832 (6810)	40425 (15743)	41939 (28986)
Medium	68579 (13255)	76053 (34568)	91649 (65794)
High	129685 (34961)	154074 (81085)	192848 (136223)

Toll

STDEV	Low	Medium	High
MEAN			
Low	44.14 (1.91)	45.15 (2.85)	47.38 (8.23)
Medium	48.89 (4.00)	52.38 (9.22)	59.13 (17.27)
High	65.15 (9.82)	69.41 (17.23)	76.35 (20.62)

Capacity

STDEV	Low	Medium	High
MEAN			
Low	1971 (310.60)	1179 (584.92)	1671 (646.93)
Medium	2136 (352.03)	1988 (483.72)	1898 (601.43)
High	2042 (201.66)	2122 (433.99)	2262 (720.84)

Table 4. Output for Scenario II (profit in HK$, toll in HK$, and capacity in veh/h)

Profit

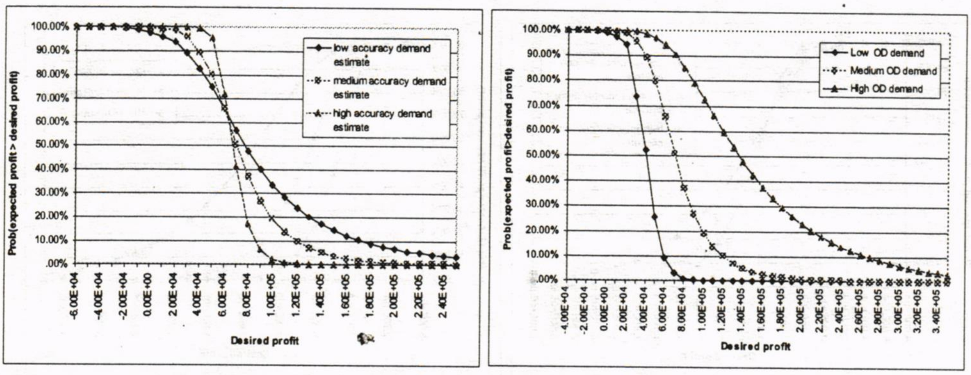
STDEV	Low	Medium	High
MEAN			
Low	42601 (25212)	42706 (28257)	44152 (37237)
Medium	72236 (31369)	79111 (43626)	94508 (71490)
High	132595 (44357)	156829 (85791)	196708 (140873)

Toll

STDEV	Low	Medium	High
MEAN			
Low	44.70 (2.24)	43.89 (3.63)	48.16 (8.98)
Medium	50.99 (6.18)	53.54 (10.27)	59.78 (17.50)
High	65.19 (11.88)	69.39 (17.42)	76.35 (20.65)

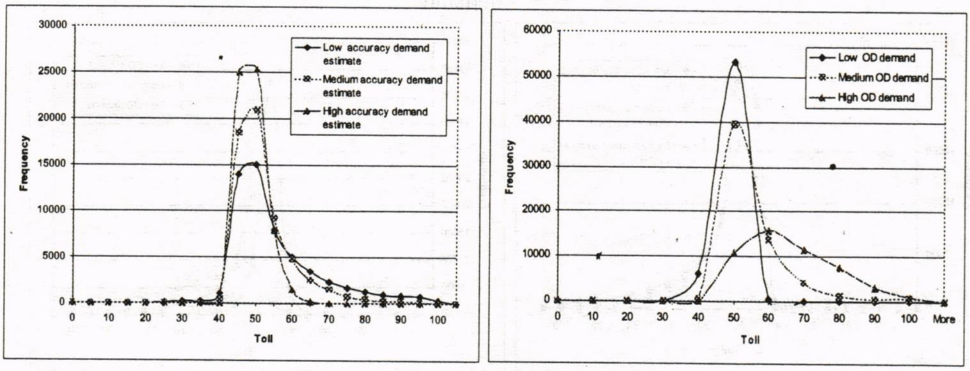
Capacity

STDEV	Low	Medium	High
MEAN			
Low	1804 (555.178)	1670 (664.52)	1603 (718.03)
Medium	2028 (758.45)	1941 (752.21)	1900 (788.35)
High	2153 (724.49)	2188 (695.82)	2311 (860.42)



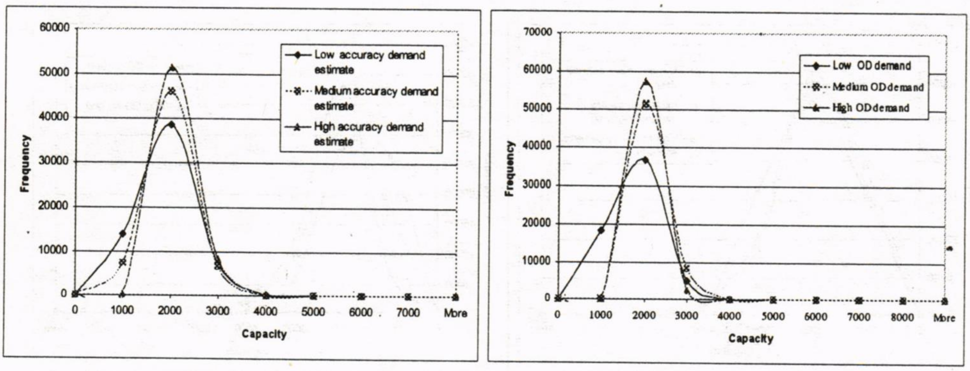
(a) Profit profile for a medium demand with three levels of standard deviation

(b) Profit profile for a medium level of standard deviation with three levels of demand



(c) Optimal toll distribution for a medium demand with three levels of standard deviation

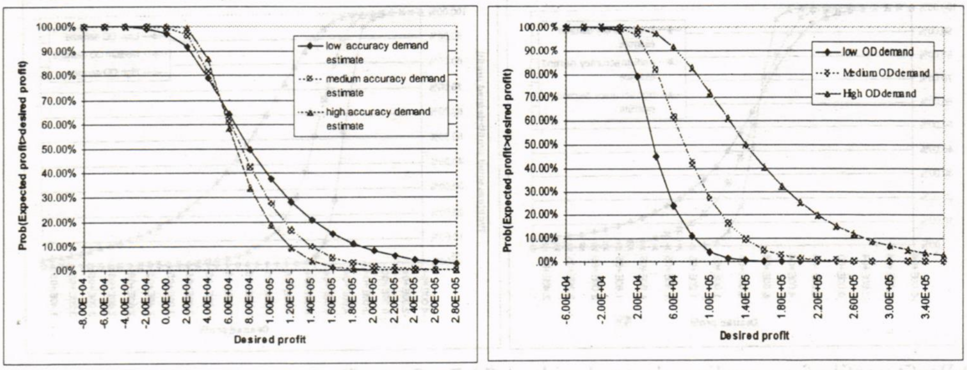
(d) Optimal toll distribution for a medium level of standard deviation with three levels of demand



(e) Optimal capacity distribution for a medium demand with three levels of standard deviation

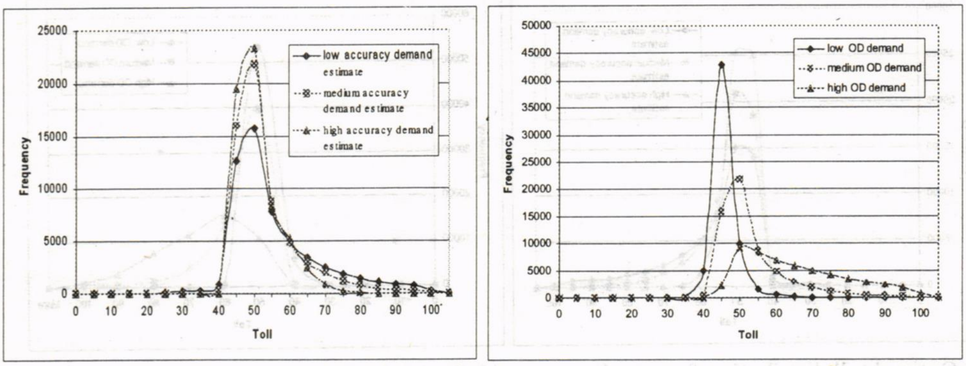
(f) Optimal capacity distribution for a medium level of standard deviation with three levels of demand

Figure 3. Risk Analysis for Scenario I.



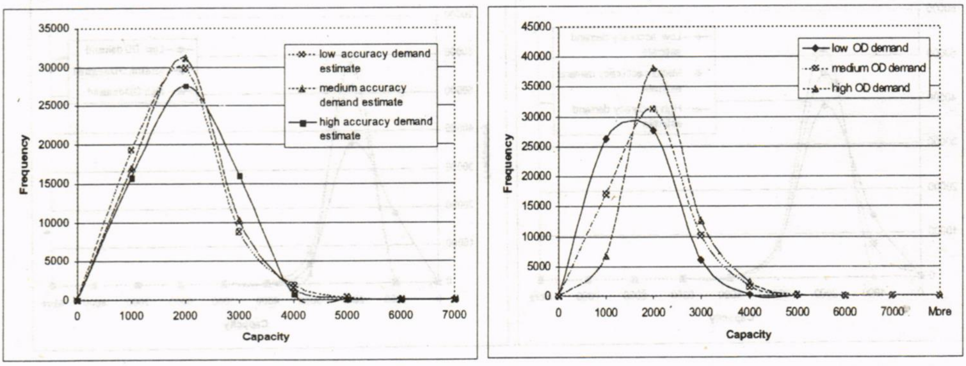
(a) Profit profile for a medium demand with three levels of standard deviation

(b) Profit profile for a medium level of standard deviation with three levels of demand



(c) Optimal toll distribution for a medium demand with three levels of standard deviation

(d) Optimal toll distribution for a medium level of standard deviation with three levels of demand



(e) Optimal capacity distribution for a medium demand with three levels of standard deviation

(f) Optimal capacity distribution for a medium level of standard deviation with three levels of demand

Figure 4. Risk Analysis for Scenario II

4.3 Sensitivity Analysis

Sensitivity analysis is performed to examine the profit forecasts with respect to the optimal selection of capacity and toll for the BOT project. In Figure 5, we use a spider plot to show the effect of individual decision variable (i.e., optimal capacity and optimal toll) on the profit. Each decision variable is varied one at a time from –50% to +50% of its optimal value while keeping all other decision variables fixed at their optimal values. Then simulation is performed to examine the effect of such deviation from the optimal value on profit. As can be seen in Figure 5, the greater the deviation from the optimal value of the decision variable, the larger the decrease in profit for that variable will cover. Between the two decision variables, it seems that toll is more sensitive to profit than capacity.

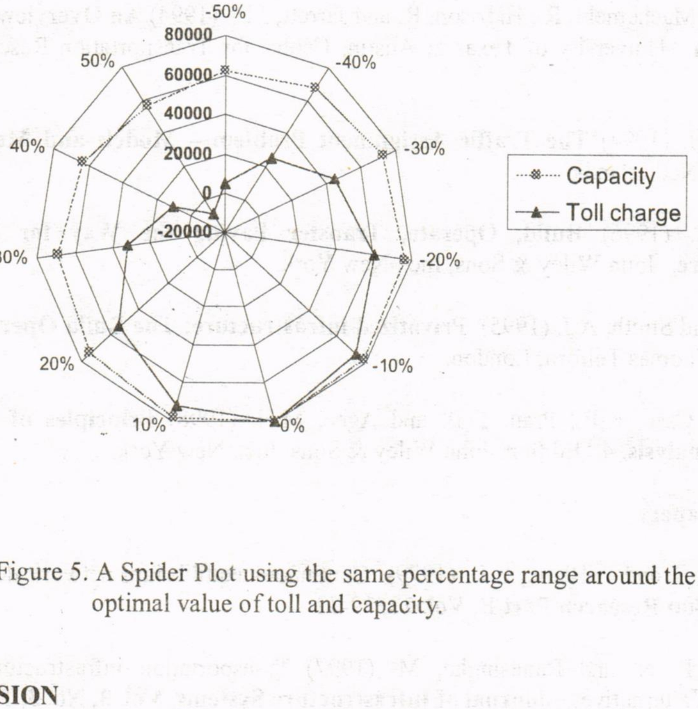


Figure 5. A Spider Plot using the same percentage range around the optimal value of toll and capacity.

5. CONCLUSION

This study has presented a simulation-optimization framework as an assessment tool to evaluate the feasibility of a BOT project. It extends the initial study by Chen, A. *et al.* (2001) by including both traffic forecasts and cost estimates as random variables. Using the profit profile constructed by the simulation-optimization assessment tool, it can evaluate quantitatively the feasibility of BOT project for any desired level of profit. In addition, the standard deviation of profit provides an indication of the risk involved in a BOT investment (i.e., a larger standard deviation of profit implies that there is a higher risk associated with the investment).

The case study shows that risk comes from the variability of traffic forecasts. Uncertainty in the cost estimates can further magnify the risk involved. Thus it is necessary to account for both demand and cost uncertainties when assessing the financial feasibility of a BOT investment. In addition, sensitivity analysis shows that toll is more sensitive to profit than capacity when it deviates from its optimal value.

In summary, the proposed simulation-optimization framework is a useful assessment tool to analyze the risk involved in a BOT project. The framework can be further refined to consider different financial options for BOT projects such as public-private partnership, guarantor to share risk, and private sector with donor funds from government (Seneviratne and Ranasinghe, 1997), and to identify the effects of financial risk under each option.

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