Incorporating Uncertainty and Risk in Transportation Investment Decision Making: Detroit River International Crossing Case Study

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Abstract

Large scale transportation projects represent major investments in construction, operation, and maintenance of facilities over an extended period. Typically, these investments are irreversible in nature and require long-term commitment by the public at large relative to utilization, maintenance, and operation. Traditional economic analysis techniques used to evaluate the feasibility of such projects are based upon the assumption of future cash flows that are deterministic in nature. In reality, many of these projects are associated with significant uncertainties and risks stemming from a lack of knowledge about future cost and benefit streams. There is not a unified methodology in the literature to address uncertainty and risk in transportation investment decision making.

The authors present a framework for addressing uncertainty and risk for large scale transportation investments involving joint participation by the public and private entity. Demand,
fare/toll, and demand responsive costs are considered in the uncertainty analysis. A bi-level programming is proposed, where the upper level constitutes the preference of the policy maker, and the lower level determines the user’s response to the policy. The uncertainty analysis provides economic feasibility of the project. A set of relaxation policies is proposed to form various Ownership, Tenure, and Governance (OTG) strategies reflecting the nature and level of participation by the public and private entity. The uncertainty analysis output serves as an input to the risk analysis. Monte Carlo Simulation is used to address risks for feasible policy options selected from uncertainty analysis. The concept of Value at Risk (VaR) is used to quantify risk. Finally, a methodology is proposed to integrate uncertainty and risk. The framework is tested on the proposed multibillion dollar international river crossing entitled as the Detroit River International Crossing (DRIC) connecting the cities of Detroit in the US with Windsor in Canada. The analysis provides insights to probable outcomes for this transportation infrastructure investment. This methodology can be used as a tool for transportation infrastructure investment decision making process.

Key words: uncertainty, bi-level programming, monte carlo simulation, value at risk, investments
1. Introduction

Transportation infrastructures are integral parts of a nation’s network connectivity. Large-scale transportation projects represent major investments in construction, operation, and maintenance of facilities over an extended period. Typically, these investments are irreversible in nature and require long-term commitment by taxpayers relative to their utilization, maintenance, and operation. Examples are mass-transit systems, freeway corridors, subways, crossings in the form of bridges and tunnels, high occupancy vehicle (HOV) lanes, and toll roads. A National Transportation Statistics report suggests that total gross transportation investment by the federal, state and local governments reached $80 billion in the US in the fiscal year 2003 (BTS 2008). Similarly expenditures in operating, maintaining and administering the nation’s transportation facilities are over $200 billion annually. Projected federal, state and local highway revenues are insufficient to meet estimates of future highway requirements (USDOT 2006). Lack of capital funds to meet the needs of the country may result in increased private participation in transportation infrastructure projects (Roth 1996). The potential of such projects to produce economic benefits has become an increasingly important factor in the investment decision making process. Some of these large investments may involve the private enterprise in the construction, operation and maintenance process along with the federal, state and local governments.

2. Problem Statement

In traditional economic analysis, future cash flows are assumed to be fully deterministic in nature. Thus, these are not designed to account for any risk and uncertainty in the assessment of
future returns. In reality, many of these infrastructure projects are associated with significant uncertainties stemming from lack of knowledge about future cost and revenue streams. The term “risk” refers to situations where the decision maker can assign mathematical probabilities to the randomness relative to future outcomes. In contrast, the term “uncertainty” refers to situations when this randomness cannot be expressed in terms of mathematical probabilities (Knight 1921).

A significant research on investment decision making under uncertainty and risk is reported in the fields of economics and financial management that includes a theoretical approach on capital investment considering the irreversibility of investment decisions and uncertainty of economic environment (Dixit and Pindyck 1994). Other relevant work on this topic includes research on decision-making process, behavioral adjustments, and actual experience of users and policy makers in an agent-based approach reflecting network management and financing policies (Zhang et al. 2008); on investment decision making for a Build Operate and Transfer (BOT) problem using a multi-objective genetic algorithm procedure and a mean-variance model for BOT scheme under demand uncertainty(Chen et al. 2003, Chen et al. 2006); on capacity expansion using demand uncertainty and simulated annealing (Sun and Turnquist 2007) and on decision making under uncertainty for highway development using real options approach (Zhao and Kockelman 2006).

The problem investigated in this research relates to a lack of unified approach in the current literature in incorporating uncertainty and risk in transportation investment decision making. This paper presents an analytic framework to explore the implications of a joint ownership of a transportation infrastructure project, with cost/revenue and demand estimates fraught with significant uncertainties. A case study is also presented to demonstrate the application of the framework.
The framework also explores various forms of joint ownership associated with the public and private enterprise. There are a number of reasons for the growing trend of private participation in public projects. These include, the scarcity of fiscal resources at the public sector level, the perception that the private sector is more efficient in managing large projects, and the advantage of jointly sharing risks and uncertainties, thereby reducing exposure levels to financial losses for both entities. Joint ownership has become increasingly popular in Europe, Australia and more recently in Asia, as it allows a part or the whole of the capital funds from private resources in exchange of future revenues (Garber and Hoel 2002, Khasnabis et al. 2010). Joint ownership is generally associated with three terms: Ownership, Tenure and Governance (OTG). An OTG strategy can be looked upon as a mechanism to plan, design, implement, operate, and maintain a project by developing various combinations of ownership, tenure, and governance procedures, where:

- The term ‘Ownership’ has embedded in it, the concept of ‘possession’ and ‘title’ related to the property in question. Depending upon the nature of the joint project, its ownership may belong to the public entity, private entity, or both during the concession period. Ownership may also change at the end of the concession period (Merna and Njiru 1998).
- ‘Tenure’ refers to the status of holding a possession of a project for a specific period, ranging from few days to a number of years. For most joint ownership projects, tenure is likely to coincide with the concession period; however, exceptions to this general rule may be encountered.
- ‘Governance’ refers to management, policy and decision making pertaining to an organization with the intent of producing desired results.
The objective of the research is to propose a framework to incorporate uncertainty and risk, and to evaluate the proposed framework with a real-world case study. The methodology proposed in the paper is designed for major transportation infrastructure projects involving public private participation. The case study is applied to an international toll bridge.

3. A Combined Framework for Uncertainty and Risk Analysis

The proposed framework to incorporate the concept of investment decisions under uncertainty and risk is illustrated in Figure 1 and is categorized into three steps;

1. Step 1: Uncertainty Analysis
2. Step2: Risk Analysis
3. Step 3: Integration of uncertainty and risk

Step-1: Uncertainty Analysis

Uncertainty analysis is further divided into three sub-steps:

Step - 1.1: Policy Options

Step - 1.2: Bi-level Programming for uncertainty analysis

Step - 1.3: Feasibility Analysis

Step 1.1 is an examination of the investment policy options recommended by the relevant public agencies relating to new transportation projects that may represent various combinations of rights and responsibilities of public and private agencies (FHWA 2010). At one end of the spectrum, the public entity may have all the major responsibilities with the private agency playing a minor role. At the other end, the roles may be reversed. Various other combinations may form the intermediate range.
In Step 1.2, a bi-level process is proposed as for evaluation of the proposed policy options. The policy maker (upper level) is assumed to have some understanding of the road users’ likely response (lower level) to a given strategy. However, the strategy set by the policy maker can only influence (but not control) the road users’ route choice. In other words, policy options and route choice decisions can be represented as a bi-level program, where, the upper level involves the policy maker’s decision to determine the toll value, while road users are assigned to the proposed facility at the lower level. In the bi-level process, the upper level may be subdivided into three categories (1) private investor, (2) public investor, (3) road user. While the designed toll value for all the three perspectives will be different at the upper level, a user equilibrium assignment problem is addressed at the lower level with an elastic demand feature designed to consider uncertainty in travel pattern.

In Step 1.3 economic and financial feasibility of various policy options are examined. Policy regulations such as construction cost subsidy, concession period extension, etc. can be considered if necessary. The relaxations are embedded in a set of OTG strategies. The viability of the project under different strategies can be tested using a set of pre-specified criteria.

Step - 2: Risk Analysis

Three sub-steps are proposed in the risk analysis:

Step 2.1: Identification of risk variables

Step 2.2: Setting up the simulation process

Step 2.3: Estimation of Value at Risk (VaR)
FIGURE 1 Proposed Methodology for Uncertainty and Risk Analysis
In step 2.1, variables associated with different investment options are identified. For example, in transportation investments, possible risk variables are related to demand, fare, and costs. Probabilities are assigned to the risk variables in a simulation model. A number of simulation approaches and risk measures are presented in the literature (Jorion 1997). In step 2.2, various iterations of the simulation cycle are recorded. In step 2.3, the measure of risk is determined. One such measure is “Value at Risk” (VaR), that can be used to denote the maximum expected loss over a given horizon at a given confidence level for a specific policy option. This step will enable the decision maker avoid risky policy options, and focus more on those options with modest risk exposure.

**Step 3: Integration of Uncertainty and Risk**

In this step, Measures of Effectiveness (MOE) of uncertainty and risk analyses are combined. Policy options associated with least uncertainty and risk can be proposed for further consideration.

**3.1 Decision Tool for Uncertainty Analysis**

Sources of uncertainty in the transportation infrastructure investment can arise from future costs and revenues. Bulk of the cost element is from construction cost incurred before the facility is opened to traffic; other cost elements such as regular and periodic operation and maintenance costs depend on future travel demand. Revenue is directly dependent on travel demand and toll. Uncertainties related to cost and revenue are primarily generated from travel demand.

Investments in major transportation infrastructure are often complex, with a mix of public and private finance, with the respective agencies having different missions and motivations. The public sector may consist of national, state and local agencies with a social welfare perspective.
The public and private entities are interested in exploring optimal tolling strategies that may yield different solutions (Hyman and Mayhew 2008, Wong et al. 2005, Palma et al. 2006, Rouwendal and Verhoef 2006). While the public entity’s primary interest is to maximize consumer surplus\(^1\) (social welfare), the private entity is interested in maximizing profit. Since the public sector is the eventual owner and operator of the facility, it must ensure that the facility attracts users and serves the needs of the community (Yang and Meng 2000). Thus, the optimal toll must be viable to the ultimate end users. Hence, in the investment decision making process, three entities’ perspectives should be considered: (1) the private, (2) the public, and (3) the user.

**Private Investor’s Perspective**

The objective of the private investor is to maximize profit. The annual profit for demand uncertainty is the difference between benefit and cost and is presented as following (Chen and Subprasom 2007):

\[
P^n(\tau, x(\tau, \epsilon)) = B^n - C^n
\]

Where, \(P^n\) is the profit generated in year \(n\), which is a function of the demand \(x\) and toll \(\tau\). \(B^n\) and \(C^n\) are corresponding revenue and cost for year \(n\) respectively. The revenue generated is a function of uncertain demand and toll, while the cost can be presented in the form of capital and operation and maintenance cost. The revised equation 1 can be represented as:

\[
P^n(\tau, x(\tau, \epsilon)) = \sum_{a \in A} \gamma x_a^n(\tau) \tau_a^n - C_{a,c}^n - O_{a}(x_a^n)
\]

\(^1\) The additional value or benefit received over and above the expenses actually made is known as consumer surplus.
where, $\gamma$ is a parameter which converts hourly link flows to annual link flow, $x_a^n$, $\tau_a^n$, $C_a$, $O_a^n$ are the demand, toll charge, construction cost and operation and maintenance cost for year $n$ on link $a$ respectively. $N$ is the analysis period and $\bar{A}$ is a set of newly implemented links subjected to toll. The objective function for profit maximization can be formulated as:

\[
\text{max. } \sum_{n \in N} P^n(\tau, x(\tau, \epsilon))
\]

subject to: $\tau^n, x^n(\tau, \epsilon) \geq 0$

where, $x^n(\tau, \epsilon)$ is determined from the lower level program and suggests that the toll value and the volume cannot be negative.

**Public Investor’s Perspective**

The proposed framework is based on the premise that the primary objective of the public entity is to maximize consumer surplus, typically measured as the additional monetary revalue over and above the price paid (Wohl and Hendrickson 1984). There are other social benefits such as improved traffic flow, environmental benefits, higher safety etc., that may be derived from major infrastructure projects. The public sector appears to be increasingly interested in revenue maximization decisions with transportation assets (Johnson 2007). These are not incorporated in the proposed framework and the classical approach of maximization of consumer surplus was used at the only public benefit. The consumer surplus can be mathematically represented as,

\[
\phi_{rs}^n = \int q_{rs}^{n-1}(\omega) d\omega - q_{rs}^n \pi_{rs}^n
\]
where, \( \phi_{rs}^n \) is the consumes surplus for the O-D pair \( r-s \) for the year \( n \), \( q_{rs}^n \) is the demand between O-D pair \( r-s \) for year \( n \), \( q_{rs}^{-1}(\omega) \) is the inverse demand function for the Origin-Destination (O-D) pair \( r-s \), and \( \pi^n_\alpha \) is the minimum travel cost between the O-D pair \( r-s \). The first term of the equation 5 represents the user willingness to pay to travel from \( r-s \) and the second term is the amount user actually paid (or minimum travel cost to travel from \( r-s \)). The consumer surplus is a measure from the public entity perspective used in a number of studies in transport network design (Ukkusuri and Patil 2009, Chen and Subprasom 2007, Yang and Meng 2000, Zhang and Ge 2004, Zhang and Kumaraswamy 2001, Zhao and Kockelman 2006).

Consumer surplus for an O-D pair \( r-s \) for an improved case is given by (Ukkusuri and Patil 2009):

The consumer surplus for the total network can be represented as:

\[
\sum_{rs} \phi_{rs}^n = \sum_{rs} \int_{\vartheta}^{q_{rs}^n} q_{rs}^{-1}(\omega) d\omega - \sum_{rs} q_{rs}^n \pi^n_\alpha
\]

(6)

The annual consumer surplus in monetary terms can be represented as:

\[
\sum_{rs} \phi_{rs}^n = \frac{\gamma}{\theta} \left[ \sum_{rs} \int_{\vartheta}^{q_{rs}^n} q_{rs}^{-1}(\omega) d\omega - \sum_{rs} q_{rs}^n \pi^n_\alpha \right]
\]

(7)

where, \( \theta \) is a parameter which converts time value to monetary terms, \( \gamma \) is the parameter that converts hourly to annual demand. The savings in consumer surplus can be defined as the difference between the consumer surplus and the cost of the project (Chen and Subprasom 2007, Yang and Meng 2000). This can be represented as:
\[ \psi^n(\tau, x(\tau, \varepsilon)) = \varphi^n - C^n \]  \hspace{1cm} (8)

where, \( \psi^n \) is the savings in consumer surplus. A higher consumer surplus is better for the public investor. The public entity perceives the user benefit equivalent to a value which travelers expect to receive from making trips as measured by the gross amount paid by the travelers in making a trip. The objective function for consumer surplus maximization can be formulated as:

\[
\max \sum_a \psi^n(\tau, x(\tau, \varepsilon)) \hspace{1cm} (9)
\]

subject to: \( \tau, x(\tau, \varepsilon) \geq 0 \hspace{1cm} (10) \)

where, \( x(\tau, \varepsilon) \) is determined from the lower level program.

**Road User’s Perspective**

If the implementation of project only benefits a small section of travelers in the study area, then the distribution will not be called as equitable. Theil’s index, one of the commonly used measures of inequality distribution, was used in this study because of its flexible structure (Theil 1967). Theil’s index, in its simplest form, can be estimated as (Theil 1967):

\[
T^n_b = \sum_r \left( \frac{\sum_s q^n_{rs}}{q^n} \right) \left( \frac{\sum_s \phi^n_{rs}}{\phi^n} \right) \ln \left( \frac{\sum_s \phi^n_{rs}}{\phi^n} \right) \hspace{1cm} (11)
\]

where, \( q^n_{rs} \) is the travel demand of OD pair \( r-s \) in the \( n^{th} \) year, \( q^n \) is the total demand (i.e. \( \sum_r \sum_s q^n_{rs} \)) for the whole network, \( \phi^n_{rs} \) is the consumer surplus improvement for OD pair \( r-s \) in the
nth year, \( \phi^n \) is the total consumer surplus improvement (i.e. \( \sum_r \sum_s \phi^n_{rs} \)). If every zone has same benefit then the Theil’s index is zero (perfect equality), and if the benefit is concentrated at one (perfect inequality) zone then the Theil’s index is \( \ln q^n \). The lower the Theil’s index, the more equitable is the project.

The objective function for user inequality (between groups) minimization can be formulated as:

\[
\min \sum_n T^n_b (\tau, x(\tau, \epsilon))
\]

subject to: \( \tau, x(\tau, \epsilon) \geq 0 \)

where, \( x(\tau, \epsilon) \) is determined from the lower level program.

While the upper level program determines the toll for various perspectives considered, the lower level determines the route choice of users for a designed toll value subjected to uncertain demand. The lower level problem is a user equilibrium traffic assignment with elastic demand (Sheffi 1985).

\[
\min_{x(\tau, \epsilon), A} \sum_{a \in (A-3)} \int_0^{x_a} t_u(w) dw + \sum_{a \in A} \int_0^{x_a} (t_u(w) + \theta \tau) dw - \sum_{rs} q^{rs}_w(w) dw
\]

subject to:

\[
\sum_k f^{rs}_k = q^{rs}_w
\]

\[
f^{rs}_k \geq 0
\]
\[ q_{rs} \geq 0 \quad \text{(16)} \]

\[ x_a = \sum_{r} \sum_{s} \sum_{k} f_{k}^{rs} \delta_{a,k} \quad \text{(17)} \]

\[ \delta_{a,k}^{rs} = \begin{cases} 1 & \text{if link } a \text{ is on path } k \text{ between O-D } r-s \\ 0 & \text{Otherwise} \end{cases} \quad \text{(18)} \]

The objective function in expression 13 minimizes the travel time of the network till equilibrium is achieved. The first two terms are the link performance function of all non-tolled and tolled links in the network respectively. The third term is the inverse demand function associated with the OD pair \( r-s \), which is a decreasing function of the OD travel times. Expression 14 is a flow conservation constraint to ensure that flow on all paths connecting each OD pair has to equal the trip rate. Expression 15 and 16 are non-negativity constraints to ensure that the flow cannot be negative. The definitional relationship of link flow from path flows is presented in expression 17 and 18. The minimization problem in expression 13 consists of toll value \( \tau \) which is a function of a set of link flows \( (x_a(\tau, r)) \) and a set of OD demands \( (q_{rs}(\tau, r)) \). Flow in lower level is a function of toll in the upper level (recall three policy perspectives specified in upper level).

**Demand Elasticity and Uncertainty**

Addition of new links or improvement of the road network will reduce the travel cost between origin and destination. This improvement can result in increasing demand between the corresponding OD pairs. An exponential demand function can be used to estimate the annual demand (Sheffi 1985).
\[ q^n_{rs} = q^n_{rs} \exp\left(-\lambda \pi^n_{rs}\right) \]  

(19)

Where, \( q^n_{rs} \) is the random potential demand between \( r-s \), \( \pi^n_{rs} \) is the minimum travel cost between \( r-s \) which includes the designed toll value, \( \lambda \) is a positive constant, and \( q^n_{rs} \) is the realized travel demand for year \( n \) between the OD pair \( r-s \).

Uncertainty in travel demand is incorporated through a random sampling approach with a predefined mean and variance. Random numbers are generated with predefined probability distribution function (i.e. normal distribution). This is performed exogenously from the lower level traffic assignment (Chen and Subprasom 2007)

\[ \tilde{q}^n_{rs} = \bar{q}^n_{rs} + z\sigma^n_{rs} \]  

(20)

Where, \( \bar{q}^n_{rs} \), \( \sigma^n_{rs} \) are the mean and standard deviation of random potential demand for OD pair \( r-s \), and \( z \) is a random variable generated from normal distribution with mean zero and unity variance. The link travel time used in the lower level traffic assignment problem is the Bureau of Public Roads function, denoted as (Sheffi 1985):

\[ t^n_a\left(x^n_a\right) = t^0_a \left(1 + 0.15 \left(\frac{x^n_a}{G_a}\right)^4\right) \]  

(21)

where, \( t^0_a \) and \( G_a \) is the free flow travel time and capacity for link \( a \).
3.2 Decision Tool for Risk Analysis

Risk is often defined as the probability of occurrence of an undesirable outcome (Jorion 1997). Risk analysis consists of simulating the various inputs over the life of the project and finding the present value. This process is repeated number of times using Monte Carlo Simulation (MCS) to incorporate risks from multiple sources, both on revenues and costs. The Measure of Effectiveness (MOE) thus obtained reflects the effect of risk.

In the proposed risk analysis, the simulation model employs pre-defined realizations of toll, and traffic volume to analyze the effect of indecisive inputs on the output of the modeled system. Risk can be quantified and measured in different ways (Mun 2006). Value at Risk (VaR) is one such that can be defined as the maximum expected loss over a target horizon, with a given level of confidence (Jorion 1997). VaR describes the quantile of the projected distributions of gains and losses over the target horizon. If $\alpha$ is the selected confidence level, VaR corresponds to the $(1-\alpha)$ lower tail level. For example for 90 percent confidence level, VaR should be such that it exceeds 10 percent of the total number of observations in the distribution.

4. Case Study

A proposed international bridge between the city of Detroit in the US and the city of Windsor in Canada is selected as the case study. Surface trade between Southwestern Ontario and Southeastern Michigan exceeded 200 billion in 2004 and is expected to increase by twofold by the year 2030(MDOT 2003). 70 percent of trade movement between the US and Canada is by trucks. Approximately 28 percent of surface trading is by trucks for the crossings between Southeast Michigan and Southwest Ontario(MDOT 2008). Majority of the trade is for the crossings in the Detroit River area, connecting the city of Detroit in the US and the city of
Windsor in Canada. This large trade volume has a significant positive effect on the local, regional and national economies through cross-border employment opportunities.

The Central Business Districts (CBDs) of the cities of Detroit and Windsor are currently connected by four crossings: (1) The Ambassador Bridge (AB), (2) The Detroit Windsor Tunnel (DWT), (3) a Rail Tunnel (RT), and (4) The Detroit Windsor Truck Ferry (DWTF). Both AB and DWT are across the Detroit river, built during the late 1920s. AB is a privately owned four-lane suspension structure, while DWT is a two-lane facility with height restriction, jointly owned by the two cities and operated by a private corporation. The Blue Water Bridge (BWB) across the St. Clair River (100 km north of Detroit) that connects Port Huron in the USA with Sarnia in Canada. BWB is a six lane arch structure built in 1938 and renovated in 1999; and is jointly owned by the two cities. The RT and DWTF, both constructed under the Detroit River, carry cargo between two cities.

The Canada–US–Ontario–Michigan Transportation Partnership Study (Partnership Study) attempted to develop long-term strategies to provide safe and efficient movement for people and goods between Michigan and Ontario (MDOT 2008). Even though the current capacities of the Ambassador Bridge and the Detroit-Windsor tunnel adequately serve the traffic needs during most hours, on specific days during peak periods, the systems operates at full capacity. Considering long-term traffic growth and the overall importance of the Detroit River crossings on the regional economy, the need for a third crossing seems immensely justified. As a result of number of studies initiated in early 2000’s and currently nearing completion, the Michigan Department of Transportation (MDOT), and the Ontario Ministry of Transportation have identified a bridge known as X-10(B) as the most preferred alternative to built in the
vicinity of the Ambassador Bridge (MDOT 2008). The alternative has been referred to as the Detroit River International Crossing (DRIC) in the case study (Figure 2).

5. Results

Two alternative bridge structures are proposed for X-10(B); (1) a suspension bridge, or (2) a cable-stay bridge. The preliminary cost estimates of the bridges along with associated infrastructures are $1809 million and $1814 million respectively. In the case study, it is assumed that a suspension bridge will be built. The cost components, are shown in Table 1. The planning for the bridge was started in 2004. A part of the planning/design/construction engineering cost is already incurred. The construction is expected to be complete in 2014, and the bridge will be open to traffic in 2015. The cost elements shown in Table 1 are only for the US part of the bridge. By the same token, all the toll revenue compiled to assess the benefits reflects the fare collected at the Detroit end of the bridge.

5.1 Travel Demand Uncertainty

Travel demand data for the study area in the form of OD matrices for the study area are obtained from MDOT for the years 2015, 2025, and 2035. There are a total of 960 Traffic Analysis Zones (TAZ) in the Detroit (US) side of the border and 527 TAZs in the Windsor (Canada) side of the border. Including 23 external TAZs, the study area consists of a total of 1510 TAZs. The analysis period for the case study is considered as 35 years (2015-2050). The OD matrices for
FIGURE 2 Network of Study Area (Mishra 2009)
the years 2045, projected by considering the growth trends from each TAZ. A coefficient of variation\(^3\) of 0.15 is considered to incorporate variance in travel demand. The potential\(^4\) OD matrix was not available. The base and horizon year projected OD matrices were increased by ten percent to obtain the potential OD. The standard deviation of the OD matrix is obtained from the coefficient of variation and the expected demand of the OD matrix.

**Solution Approach for Demand Uncertainty**

A Monte Carlo Simulation (MCS) procedure was used to simulate the OD matrix. The potential OD matrix (expected demand matrix) and the variance OD matrix served as the input to the MCS. The OD matrices were subjected to 200 realizations and each realization was recorded (Equation 20). From the distribution of OD matrix, the median matrix was chosen for further analysis. However, one can use any percentile from the distributed OD matrix. This procedure was followed for all the horizon years. The resulting OD matrix from MCS incorporates the variation and resulting uncertainties in travel demand, which is used in the elastic traffic assignment procedure.

The proposed traffic assignment model is calibrated for the base year 2004. Actual toll values for cars and trucks for the year 2004 are utilized to determine the assigned volume on the existing river crossings in the network. The proposed elastic traffic assignment model and the potential OD matrix for the year 2004 are utilized to

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\(^3\)The coefficient of variation (COV) is the ratio of the standard deviation and the mean. For this research a COV of 0.15 is assumed by observing the variation in demand over time for ten years.

\(^4\) The potential OD matrix contains the maximum possible trips that can be made if the travelers are not sensitive to the user cost. In elastic traffic assignment the potential OD matrix is used to test the sensitivity of demand with respect to the user cost (both travel time and travel cost).
determine the assigned volume for cars and trucks. The observed car and truck volumes are obtained from MDOT (MDOT 2003). The close correspondence between the assigned and observed volumes at the respective crossings demonstrates the calibration of the model. Results of the calibration are not presented in the paper for the sake of brevity. The details of calibration of the model are discussed in the project report(Khasnabis and Mishra 2009).

TABLE 1 Cost Components for DRIC (MDOT 2008)

<table>
<thead>
<tr>
<th>Investment Type</th>
<th>Cost (Million $)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Construction Costs</strong></td>
<td></td>
</tr>
<tr>
<td>DetroitRiverBridge (U.S. Cost Only)</td>
<td>399</td>
</tr>
<tr>
<td>Toll and InspectionPlaza</td>
<td>57</td>
</tr>
<tr>
<td>Interchange and Local Roadways</td>
<td>190</td>
</tr>
<tr>
<td>Enhancements</td>
<td>21</td>
</tr>
<tr>
<td>Utilities</td>
<td>157</td>
</tr>
<tr>
<td>Management Reserve (5%)</td>
<td>40</td>
</tr>
<tr>
<td><strong>Planning/Design/Construction Engineering</strong></td>
<td></td>
</tr>
<tr>
<td>Final Design and Permits (10%)</td>
<td>80</td>
</tr>
<tr>
<td>Construction Engineering (10%)</td>
<td>80</td>
</tr>
<tr>
<td>Initial planning, design and other costs</td>
<td>173</td>
</tr>
<tr>
<td><strong>Property Acquisition/Remediation</strong></td>
<td></td>
</tr>
<tr>
<td>Property Acquisition</td>
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<tr>
<td>Remediation</td>
<td>17</td>
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<tr>
<td>Inflation ROW</td>
<td>35</td>
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<tr>
<td>GSAPlaza Costs</td>
<td>200</td>
</tr>
<tr>
<td>Grand Total Cost</td>
<td>1,814</td>
</tr>
</tbody>
</table>

5.2 Single Entity Perspective Decision Making Under Uncertainty

For a viable transportation investment, the interest of three decision making entities (public, private, and user) should be satisfied. The objectives of the three entities from investment viewpoint are different, as discussed earlier. Three entity objectives are used at the upper level and ridership is determined at the lower level. The bi-level process is solved in TransCAD (Caliper 2008). A GISDK script is written to solve the bi-level
model in TransCAD. The output of the upper level (toll value and the entity-specific objective function) served as the input to the lower level (ridership estimation). The bi-level process can be viewed as a non-linear problem reflecting the nature of the objective functions at the upper and the lower level. The elastic traffic assignment problem is solved by user equilibrium method using Frank Wolfe Algorithm (Sheffi 1985).

5.3 Base Case
The base case scenario refers to exclusive entity participation. Results of the base case are presented for the three entities for different horizon years in Table 2. For private entity, the objective is profit maximization with the assumption that the total cost (capital, operation and maintenance cost) will be borne by the private entity. Revenue is considered as a surrogate for profit in this paper. As explained earlier, the profit maximization is solved by the bi-level process. Toll values are set at the upper level and ridership is determined at the lower level. For example, in the profit maximization strategy, toll values of $2 per car and $14 per truck resulted in an annual revenue\(^5\) of $68.54 million in the year 2015. The toll values are obtained in an iterative manner with directional search\(^6\) to obtain the optimum value of the objective function for profit maximization, consumer surplus maximization and inequality minimization. For the same toll values the consumer surplus and Theil’s index are estimated to be $346.07 million and 0.86 respectively for the year 2015.

When the objective of the public entity is considered, the optimal toll is $0.5 per car and $4.33 per truck (year 2015, second row, Table 2) that resulted in an optimal

\(^5\) Revenue is defined as the monetary benefit obtained by the toll/fee collection only.

\(^6\) Directional search is a technique for finding the optimal value of a unimodal function by successively narrowing from the possible range of values.
consumer surplus of $730.36 million, which is higher than the estimated consumer surplus for profit maximization. The consumer surplus allows more travelers\(^7\) to use the facility in lowering the difference between willingness to pay and what the travelers actually pay. The revenue and Theil’s index for toll value of $0.5 for cars and $4.33 for trucks are estimated to be $25.78 million and 0.79 respectively.

Similarly, when the objective of the users is considered (year 2015, third row, Table 2) the optimal toll values obtained are $0.25 per car and $1.04 per truck, resulting in a Theil’s index of 0.70 (minimum of the three Theil’s index values) for the year 2015. For the toll value of $0.25 per car and $1.04 per truck the corresponding revenue and consumer surplus are estimated at $7.41 and $258.62 million respectively.

Three distinct toll values are obtained for three different entities, each of which represents the optimum values for the three objective functions defined in equations 3, 9, and 12. The highest toll value resulted for profit maximization and the least toll value for Theil’s Index, thereby demonstrating that the objectives of the private investor and the users are satisfied. Additionally, the toll value for the public entity perspective is lower than that for the private perspective for all the years. Similar trends are observed for the other horizon years during the analysis period presented in Table 2. Increased travel demand in future years resulted in higher toll values, higher revenue and higher consumer surplus in succeeding years. The same is generally true in Theil’s Index, although there are some exceptions. The Theil’s Index is considered as a minimization function and based on the distribution of trips among the TAZs in the study area.

\(^7\) It should be noted that more travelers using the facility does not necessarily increase the revenue, because revenue is the product of toll value and the corresponding ridership.
5.4 Ownership, Tenure and Governance Strategies

The authors’ initial work on the concept of OTG scenarios was presented at the World Conference on Transport Research at the University of California, Berkeley in 2007.

---

<table>
<thead>
<tr>
<th>Year</th>
<th>Car Toll ($)</th>
<th>Truck Toll ($)</th>
<th>Annual Revenue (Million $)</th>
<th>Annual Consumer Surplus (Million $)</th>
<th>Theil’s Inequality Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Private Perspective</td>
<td>2⁸</td>
<td>14⁹</td>
<td>68.54¹⁰</td>
<td>346.07</td>
</tr>
<tr>
<td></td>
<td>Public Perspective</td>
<td>0.5¹¹</td>
<td>4.33¹²</td>
<td>25.78</td>
<td>730.36¹³</td>
</tr>
<tr>
<td></td>
<td>User Perspective</td>
<td>0.25¹⁴</td>
<td>1.04¹⁵</td>
<td>7.412</td>
<td>258.62</td>
</tr>
<tr>
<td>2025</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Private Perspective</td>
<td>3</td>
<td>15</td>
<td>118.22</td>
<td>550.98</td>
</tr>
<tr>
<td></td>
<td>Public Perspective</td>
<td>0.78</td>
<td>5.28</td>
<td>43.65</td>
<td>1091.91</td>
</tr>
<tr>
<td></td>
<td>User Perspective</td>
<td>0.52</td>
<td>2.06</td>
<td>19.53</td>
<td>352.60</td>
</tr>
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<td>2035</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Private Perspective</td>
<td>4.5</td>
<td>19</td>
<td>199.30</td>
<td>681.45</td>
</tr>
<tr>
<td></td>
<td>Public Perspective</td>
<td>1.28</td>
<td>6.75</td>
<td>73.70</td>
<td>1343.04</td>
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<tr>
<td></td>
<td>User Perspective</td>
<td>0.86</td>
<td>3.35</td>
<td>40.02</td>
<td>464.08</td>
</tr>
<tr>
<td>2045</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Private Perspective</td>
<td>6.00</td>
<td>21.00</td>
<td>281.95</td>
<td>802.24</td>
</tr>
<tr>
<td></td>
<td>Public Perspective</td>
<td>1.75</td>
<td>7.41</td>
<td>105.42</td>
<td>1594.95</td>
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<tr>
<td></td>
<td>User Perspective</td>
<td>1.26</td>
<td>4.52</td>
<td>68.13</td>
<td>565.78</td>
</tr>
<tr>
<td>2050</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Private Perspective</td>
<td>8.73</td>
<td>22.25</td>
<td>330.63</td>
<td>936.19</td>
</tr>
<tr>
<td></td>
<td>Public Perspective</td>
<td>1.93</td>
<td>7.82</td>
<td>125.19</td>
<td>1664.37</td>
</tr>
<tr>
<td></td>
<td>User Perspective</td>
<td>1.60</td>
<td>5.70</td>
<td>96.22</td>
<td>685.32</td>
</tr>
</tbody>
</table>

---

²⁸ Represents the Optimal value of car toll from the Private Perspective
⁹ Represents the Optimal value of truck toll from the Private Perspective
¹⁰ Represents the maximum value of Revenue from the Private Perspective
¹¹ Represents the Optimal value of car toll from the Public Perspective
¹² Represents the Optimal value of truck toll from the Public Perspective
¹³ Represents the maximum value of Consumer Surplus from the Public Perspective
¹⁴ Represents the Optimal value of car toll from the User Perspective
¹⁵ Represents the Optimal value of truck toll from the User Perspective
¹⁶ Represents the minimum value of Theil’s value from the User Perspective
Though single entity participation in large transportation projects is important, their involvement with other entities is likely to increase the overall viability of the project. Ownership, Tenure and Governance (OTG) are the three principal components of a joint ownership.

A number of OTG strategies are considered to represent varying levels and types of public-private participation in the DRIC project. The strategies vary in the degree of participation by the public and the private entity. Five types of OTG strategies are considered:

1. OTG-1: Exclusive Private Participation

2. OTG-2: Major Private Participation

3. OTG-3: Moderate Private Participation

4. OTG-4: Major Public Participation

5. OTG-5: Exclusive Public Participation

The transition from OTG-1 to OTG-5 is marked by decreasing levels of private and increasing levels of public participation. A number of relaxation policies are also considered to encourage joint ownership in DRIC. The significance of each OTG strategy is explained in the project report (Khasnabis and Mishra 2009). The feasibility of OTG strategies are determined by considering the analysis period till 2050.
For OTG-1, the total capital cost is borne by the private entity. The objective of the strategy is profit maximization. After construction of the facility, the private entity is authorized to collect toll, operates and maintains the facility throughout the concession period. The eventual owner of the facility is the public entity, even though the private entity is responsible for all the expenditures and toll collection during concession period.

The cumulative cash flow and IRR are the two MOEs plotted in Figure 3. The negative cost elements for 2004-2014 represent the planning and construction of the facility. When the facility is opened to traffic, the cumulative negative value of cash flow decreases, as the toll charges are collected and the break even period occurs in the year 2034. The Internal Rate of Return (IRR)\textsuperscript{17} for OTG-1 strategy is 4.61% over the 35 years of concession period. The Minimum Attractive Rate of Return (MARR)\textsuperscript{18} was assumed to be 6%. The IRR being lower than the MARR lends the project economically infeasible for the strategy (OTG-1) tested.

\textsuperscript{17} IRR provides an estimate of the return or yield of the investment, given a set of expenditure and revenue data along with their expected dates over the life of the project. IRR is defined as the interest rate at which the Net Present Worth (or Net Annual Worth or Net Future Worth) of the investment is equal to zero.

\textsuperscript{18} MARR is the rate of return below which the investment proposal is to be deemed unacceptable.
FIGURE 3 Cumulative Cash Flow and IRR: Exclusive Private Participation (OTG-1)

(Note: There is no IRR value till the end of 2025 as the cost is much higher than the benefit received. The IRR at the end of 2030 is -1.82)

*Other OTG’s*

A complete description of the four other OTG’s is provided in the project report (Khasnabis and Mishra 2009). Essentially, the transition from OTG-1 to OTG-4 is marked by higher levels of subsidy to the private entity either by reduced cost, or by extension of the concession period. These relaxation policies adopted to encourage private participation will obviously reflect on higher financial responsibility for the public sector. OTG-5, represents a completely public undertaking, encompassing all financial, management, operational and maintenance responsibilities.
### TABLE 3 OTG Strategies, Relaxation Policies and IRR’s

<table>
<thead>
<tr>
<th>OTG Strategy</th>
<th>Explanation</th>
<th>Relaxation Policy</th>
<th>Entity Objective</th>
<th>IRR (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTG-1</td>
<td>Exclusive Private Participation</td>
<td>No Relaxation</td>
<td>Profit Maximization</td>
<td>4.61</td>
</tr>
</tbody>
</table>
| OTG-2        | Major Private Participation | 1. Toll Plaza Cost Subsidy  
2. Toll Plaza, Interchange, and Inspection Plaza Cost Subsidy  
3. Construction Cost Subsidy | Profit Maximization | 5.14  
5.89  
5.84 |
| OTG-3        | Moderate Private Participation | 1. Construction Cost Subsidy  
2. Concession Period Extension  
6.01  
7.20 |
| OTG-4        | Major Public Participation | 1. Partly Construction Cost by Private Entity  
2. Operation and Maintenance Cost –Public Entity  
3. Construction Cost Subsidy-Public Entity | Consumer Surplus Maximization | 22.97*  
3.69**  
3.95** |
| OTG-5        | Exclusive Public Participation | No Relaxation | Consumer Surplus Max. | 3.51** |

Note: *: Private entity is only responsible for a part of the construction cost and receives all the benefits throughout the concession period. Lesser investment and higher return for the private entity has resulted in relatively larger IRR. This OTG strategy is considered as an attractive option for the private entity. **: IRR for the public entity (the remainder of the IRR are for the private entity).
Synthesis of Results for OTG Strategies

The objective of OTG strategy analysis is to formulate a series of joint ownership scenarios for the public and private entities for large scale investments. Results of this analysis are presented in Table 3, and can be summarized as follows:

- For exclusive private participation (OTG-1), the project is not financially viable. Further, varying degree of relaxation are proposed in (OTG-2 and OTG-3) to encourage private participation. All relaxation policies in OTG-3 resulted in financially viable solutions for the project.

- For major and exclusive public participation (OTG-4and OTG-5), the project is not financially viable, with the assumed levels of charges needed for the maximization of consumer surplus.

- In summary, OTG strategies representing joint ownership scenarios provided financial viability for the project analyzed. Table 3 also shows that for OTG strategies 2, 3, and 4, there are a number of sub-strategies considered in the analysis.

5.5 Risk Analysis

The OTG strategies are further considered in the risk analysis. Feasible options from the relaxation polices are subjected to risk analysis. Toll values for the horizon years were determined from the uncertainty analysis. The upper and lower limit of the toll values are set using an assumed coefficient of variation of ten percent. MCS technique was used to
obtain the simulated cumulative cash flow for design years. The random values are
instrumental in developing ridership estimates
resulting from elastic traffic assignment, and the corresponding operation and
maintenance cost. For each random toll value, and the appropriate ridership, operation
and maintenance cost changes, the IRR value is estimated. 10,000 such iterations are
performed, and the corresponding IRR’s are recorded. The distribution of all realizations
of IRR is plotted in Figure 4.

*Procedure for Obtaining VaR*

VaR is measured in absolute and relative terms. Absolute VaR is defined as the maximum
expected loss at a given level of confidence. Relative VaR is defined as the difference
between mean and the absolute VaR. Figure 4 shows the mean value of IRR on the X-
axis, the frequency on primary Y-axis, and the probabilities on secondary Y-axis for the
OTG-3, concession period extension. The 5th and the 50th percentile IRR of the
distribution are 5.99 percent 6.04 percent respectively. The VaR for OTG-3 concession
period extension is 5.99 percent at 95 percent level of confidence. In other words, the
maximum expected loss for five percent of the times in IRR can not be lower than 5.99
percent. The 95th percentile relative VaR is the difference between the 50th percentile
(mean) IRR and 5th percentile IRR (or VaR at 95th percentile), i.e. 6.04-5.99 = 0.05
percent. The 95th percentile relative VaR suggests that the maximum loss in IRR at 95th
percentile level of confidence can not exceed 0.05 percent for the OTG-3 concession
period extension strategy. Similarly, the 90th percentile VaR can be determined. The
95th and 90th percentile absolute and relative VaR for all the strategies are presented in
Table 4.
6. Integration of Uncertainty and Risk

Uncertainty and risk are addressed individually in the earlier sections of this chapter. The implications of both uncertainty and risk are important from investment viewpoint. An approach is to integrate uncertainty and risk for exploring different options for the DRIC project is presented in this section, with IRR serving as the MOE for uncertainty analysis, VaR for the risk analysis.
<table>
<thead>
<tr>
<th>OTG Strategy</th>
<th>Relaxation Policy</th>
<th>Mean IRR (%)</th>
<th>95% VaR (%)</th>
<th>90% VaR (%)</th>
<th>95% Relative VaR (%)</th>
<th>90% Relative VaR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTG-1</td>
<td>No Relaxation</td>
<td>4.66</td>
<td>4.58</td>
<td>4.59</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>OTG-2</td>
<td>1. Toll Plaza Cost Subsidy</td>
<td>5.19</td>
<td>5.10</td>
<td>5.11</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>2. Toll Plaza, Interchange, and Inspection Plaza Cost Subsidy</td>
<td>5.95</td>
<td>5.86</td>
<td>5.88</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>3. Construction Cost Subsidy</td>
<td>5.90</td>
<td>5.81</td>
<td>5.83</td>
<td>0.08</td>
<td>0.07</td>
</tr>
<tr>
<td>OTG3</td>
<td>1. Construction Cost Subsidy</td>
<td>6.19</td>
<td>6.10</td>
<td>6.12</td>
<td>0.09</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>2. Concession Period Extension</td>
<td>6.04</td>
<td>5.99</td>
<td>6.00</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td></td>
<td>3. Construction Cost Subsidy and Concession Period Extension</td>
<td>7.24</td>
<td>7.18</td>
<td>7.19</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>OTG-4</td>
<td>1. Partly Construction Cost by Private Entity</td>
<td>23.66</td>
<td>23.19</td>
<td>23.27</td>
<td>0.46</td>
<td>0.39</td>
</tr>
<tr>
<td></td>
<td>2. Operation and Maintenance Cost</td>
<td>3.83</td>
<td>3.74</td>
<td>3.76</td>
<td>0.09</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>3. Public Entity</td>
<td>4.10</td>
<td>4.01</td>
<td>4.02</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>OTG-5</td>
<td>No Relaxation</td>
<td>3.65</td>
<td>3.55</td>
<td>3.59</td>
<td>0.10</td>
<td>0.07</td>
</tr>
</tbody>
</table>
The MOE’s are presented in Figure 5(a) and 5(b) to demonstrate both uncertainty and risk on the OTG strategies. on the X-axis and Y-axis respectively.

A favorable OTG strategy is the one with higher IRR (higher than the MARR of six percent in this case) and lower relative VaR. Table 3 shows that four OTG strategies
resulted in IRR’s of greater than six percent. The highest IRR (22.97%) resulted for the OTG-4 strategy for the private entity with construction cost subsidy. For the same OTG strategy, the relative VaR is also the highest (0.46%, at 95 percent level of confidence), which makes the OTG strategy vulnerable to future risks (also shown in Figure 5(a)). From the remaining feasible strategies, the combination of construction cost subsidy and concession period extension (OTG-3) resulted in an IRR of 7.24% and a relative VaR is 0.06% at 95 percent level of confidence. However, all the OTG-3 strategies appear to be feasible with higher IRRs and lower relative VaR (Figure 5(b)).

7. Conclusions

The primary objective of this study is to develop a framework for large scale transportation infrastructure investment decisions that incorporates the concept of uncertainties and risks; and apply the framework on a real world case-study to augment the decision making process. The entities often involved in, or affected by, large-scale infrastructure investment decision are enlisted as: private, public, and users each with different set of objectives and expectations; profit maximization, consumer surplus maximization and inequality minimization, respectively. A procedure for single entity uncertainty analysis is presented as a bi-level process. The upper level constitutes the preference of the policy maker, and the lower level determines the user’s response to the policy. The output of uncertainty analysis is designed to serve as input to risk analysis. IRR and VaR are considered as the MOE’s for uncertainty and risk analysis respectively and determined using MCS technique. The objective of each entity, when subjected to uncertainty, is considered in assessing the optimal demand and toll estimates.
Typically, economic analysis of infrastructure projects are based upon the assumption of deterministic cash flows using the premise that all future costs and revenues are fully “known”. In reality, there are significant uncertainties stemming from the lack of knowledge about the future cash flow streams. The picture is further complicated by the fact that transportation projects are typically long-term in nature, and that “the longer the project, the higher the uncertainty”. The proposed framework is an attempt by the authors to address the effect of uncertainty and risk on transportation investment decisions.

Uncertainty analysis can be used to determine the optimal value of the entity-specific objective function (profit maximization or welfare maximization or inequality minimization) in a joint ownership project, in the face of variable travel demand, toll, operation and maintenance costs. With no prior information on demand, toll, and cost, a deterministic analysis can result into misleading conclusions, whereas uncertainty analysis determines the optimal results from each entity perspective. Further, risk analysis considers inputs from uncertainty analysis to further determine the maximum expected loss at a given level of confidence.

If the single entity uncertainty analysis does not result in feasible solutions, relaxation policies are proposed. Relaxation policies may include extension of the concession period and financial support from the other entities involved in the decision making process, leading to the formulation of a set of OTG strategies. A set of joint OTG scenarios are created considering the multi entity operation of the transportation facilities. For some OTG strategies, relaxation policies are proposed to ensure feasibility of the
project. The IRR is considered as the measure of feasibility for uncertainty analysis. Similarly, the VaR is recommended as a measure of risk.

A methodology for integrating uncertainty and risk is proposed. It is observed that projects producing higher IRR may also be associated with higher VaR. The integration of uncertainty and risk allows the decision maker to choose from a set of alternative investment strategies of a project to minimize uncertainty and risk subject to the IRR meeting the MARR criterion. The concept of integrating uncertainties and risks demonstrated the need to consider not only the return on the investment (IRR) in the decision making process, but also the risk factor (VaR). The final decision should be based upon the joint consideration of both factors.

The framework is applied to study the investment decision making of DRIC connecting two countries US, and Canada; a project in the planning stage for over ten years. Results of the case study indicate that the framework presented is viable; however additional research is needed to integrate the perspectives of all the entities into a multi-objective framework. The case study presented clearly demonstrates that a strategy considered economically viable under deterministic scenario, may not be so when risk factors are incorporated in the analysis. As another future task, the effect of changes in the toll structure of the competing bridges on DRIC can be incorporated into the uncertainty and risk analysis framework. The proposed procedure may be used by transportation and financing professionals involved in infrastructure investment decisions. Such professionals include: engineers/planners/economists, investment and cost analysts involved both in private and public financing of infrastructure projects.
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