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User Delay Costs and Uncertainty in the Traffic forecast for Road Projects

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Abstract

There are experimental based software packages as well as traffic simulation models that are used for analyzing life cycle cost of road projects. Among those our study was focused on currently available models to analyze the road user delay costs and to identify factors affecting road user delay costs. Sensitivity analyses were performed to identify the important factors that influence the user delay cost. Finally, prediction of future traffic demand as well as user delay cost, using the binomial lattice model, were presented to include the uncertainty of future traffic and user delay costs. The results of this study could help the highway designers with evaluating the future traffic.

KEY WORDS: Binomial lattice, future traffic demand, traffic simulations, user delay cost analysis, sensitivity analysis

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LIST OF ABBREVIATIONS

AADT	Annual average daily traffic
AASHTO	American Association of state highway and Transportation officials
AIMSUN	Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks
API	Application programming interface
BCA	Benefit cost analysis
BOT	Built Operate Transfer
Cal-B/C	California Life-Cycle Benefit/Cost Analysis Model
Caltrans	California Department of Transportation
CDF	Cumulative Distribution Function
DOS	Disc operating system
DYNASMART	Dynamic Network Assignment-Simulation Model for Advanced Road Telematics
ESAL	Equivalent single- axel
FHWA	Federal highway administration
GUI	Graphical user interface
HVR	Heavy vehicle ratios
LOS	Level of service
LCC	Life cycle cost
LCCA	Life cycle cost analysis
Mph	miles per hour
WZAC	Work Zone Related Accident Costs
MRG	Minimum Revenue Guarantee
NCHRP	National Cooperative Highway Research Program
NPV	Net Present value
NPW	Net present worth
NC	North Carolina
NJ	New Jersey
NY	New York
PPT	Public Private Partnership
SHA	State Highway Agencies

TRC	Toll Revenue Cap
TSS	Transport simulation systems
TTDC	Travel time delay costs
USA	The United States of America
VOC	Vehicle operating costs
NJDOT	New Jersey department of transportation
Vphpl	Vehicles per hour per lane
VTI	The Swedish National Road and Transport institute

LIST OF SYMBOLS

CC_i	The annual construction costs throughout the construction period
D	Downward movement in the lattice
I	number of construction day
J	The period from the first year after the completion of the project until the end of the concession period
R	real rate of return
n_k	number of years
N	Number of recurring costs
N*	The total concession length from the initial construction to the return to the government
n	Length of construction period
OCj	The annual operations, maintenance, and rehabilitation costs
P	The probability of upward movement from any node in the lattice
1-p	The probability of downward movement from any node in the lattice
PR_j	The forecasted annual traffic revenues
U	Upward movement in the lattice
Yr.	Year
Α	Expected annual growth of traffic demand
Σ	Standard deviation of the expected annual growth of traffic demand
ρ	Discount rate.

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1 Introduction

In order to keep the quality of roads and the road users' comfort, periodic maintenance or rehabilitation activities are needed throughout the useful life of the roads. The frequency of the required road works may depend on different factors such as the material quality, the traffic level, the portion of heavy vehicles and the road type. Generally, work zone activities by lowering the road capacity and consequently generating delay for road users bring costs for the society (NJDOT, 2001). In road design and planning stages, road administrations should consider the road user delay costs. This lost time for road users due to delays can be calculated by life cycle cost analysis (LCCA) tools (FHWA, Life-cycle cost analysis user manual, 1998). There are different LCCA software packages and traffic simulation models for road projects available which are developed and used in different countries such as Real Cost and Vännen. Real Cost 2.5 software is developed by Federal highway administration (FHWA) in the U.S. Vännen is developed by the Swedish National Road and Transport Research Institute (Wennström 2010) based on Aimsun microsimulation model. In this thesis the Aimsun based model was used to calculate the user delay cost for different level of traffic demand. Furthermore, a binomial lattice model has been used to predict the future traffic level.

1.1 Life Cycle Cost Analysis (LCCA)

LCCA is a process for evaluating the total economic worth of a project. It is been used as a decision support tool in order to compare two or more project alternatives. It analyzes both initial costs as well as future costs such as maintenance, rehabilitation, restoration or replacement costs and user costs. These costs are approximately discounted over the life of the project (Huvstig, 2000). LCCA applies only for comparing costs in project alternatives having equivalent benefits. For instance, project A having 2 lanes with project B having similar 2 lanes. Additionally, there are also economic analysis tools such as Benefit-Cost Analysis (BCA) in which inequivalent benefits of projects can be compared. LCCA consists of agency and user costs. However, BCA considers user benefits resulting from the other effects (e.g. noise, emission) in addition to agency and user costs. The benefits focused in BCA depend on the desired benefits of the project (i.e. shorter distance or time, reduce noise, emissions).

According to the Federal Highway Administration (FHWA, 1998), LCCA mainly focuses on the time value of money by using real rate of return. Real rate of return can be either real discount rate or nominal discount rate. It reflects the true time value of money without considering inflation or deflation premium. Net Present Value (NPV) is the discounted monetary value of expected costs. It is used to compare the value of money today to the value of the same money in the future by taking into account the real rate of return (r).

The basic Net Present Value formula as demonstrated in FHWA (1998) is shown in Equation (1).

$$\mathrm{NPV} = \mathrm{IC} + \sum_{k=1}^{N} \mathrm{RC}_k \left[\frac{1}{(1+r)^{n_k}}\right] \quad (1)$$

Where: r= real rate of return

IC = Initial Cost

RC_k = Recurring Costs

n_k = Number of Years

N = Number of Recurring Costs

Agency costs include all costs incurred directly for the agency over the life of the project. These costs are related to construction or rehabilitation of the road (FHWA, 1998).

User costs are those related to delay, vehicle operation, and crash due to either closing or lowering the road capacity during the rehabilitation activities.

Non vehicle operating costs are the highway user costs that are associated with lowering the capacity of a road during periods of construction, maintenance and rehabilitation.

Work zone can be classified as the work zone for road preservation such as patching, edge drainage, crack sealing, winter maintenance, pavement reconstruction and work zone for road development (upgrading, new section, widening, and realignment). In general, road works restrict the roads capacity and increase the occurrence of delays for the society due to the effect of lane closure practices.

Delays can be classified as moving or congestion delays. Moving delays are related to lowering the speed limits. Vehicles moving in a limited speed from the normal freeway speed results in moving delays or speed reduction delays. The average work zone speed is mostly estimated to be 50 km/hr compared to a free-flow speed that is 80 km/h (Chen and Schonfeld, 2003). Congestion delays (stopping delays) occur when the capacity of a work zone is less than the hourly traffic volume for a specific period of time or when the demand exceeds the capacity in a significant time period that leading to congestion or traffic queues. The traffic queue decreases only during time periods when the demand is less than the capacity (Najafi and Soares, 2001). Vehicles that are detouring because of congestion are expected to require extra travel time. Queues not only raise the risk for accidents but also increase fuel consumption, pollutants, as well as wearing of vehicles and roads due to high frequency of acceleration and braking.

The highway safety community uses crash costs instead of accident costs because highway crashes to a large extent are avoidable and described better than accident (FHWA 1998).

Generally, work zone user-costs are evaluated with respect to the travel time delay costs (TTDC), the additional vehicle operating costs (VOC), and the work zone related-accident-costs (WZAC) or crash costs. Equation (2) is used to determine work zone user costs (Najafi and Soares 2001):

$$\text{Work zone user cost} = \text{TTDC} + \text{VOC} + \text{WZAC} \tag{2}$$

Despite the above directives, most US Highway Agencies (USHAs) consider only their own costs in performing LCCA analysis (Peterson, 1985). In a 1985 survey, only three USHAs took into account the user costs, which was primarily in the form of traffic delays caused by their pavement rehabilitation activities. More surveys conducted in 1994 (FHWA 1994), indicates that 28 of the 38 USHAs used some form of LCCA. It also showed that less than half of these include user costs in their LCCA. The user costs were in the form of traffic delays due to pavement rehabilitation activities (FHWA 1998).

Some researchers examined the relative magnitude of user costs and agency costs in order to show their relative importance in the decision process of pavement investments. The results showed that user costs, especially in high capacity roads, can be significantly higher than agency costs. Hence, they should be given emphasis in pavement life-cycle cost analysis (Papagiannakis, and Delwar 2001).

Various LCCA methods are used to quantify user delay costs by using different input parameters and techniques. They also used different analysis methods to get better result. Although some LCCA methods used risk analysis or sensitivity analysis to mitigate the uncertainty, they couldn't properly address the uncertainties in future events. Thus, the need for better predictive method is needed to reduce this problem. In this study, focus is placed on the user costs related to delays and on the estimation of the user delay costs using two different traffic models. Before explaining the choice of these models, in the following section an overview is given of various types of traffic simulation models.

1.2 Traffic simulation models

A traffic simulation model is a computer program that uses mathematical model to simulate traffic systems. Since the behavior of the traffic is stochastic, the simulation model also uses random distribution for the input parameters and a number of runs of the simulation are necessary for a better result. Based on the level of details, traffic simulation models can be classified in to three.

Macrosimulation characterizes the fundamental relationship among flow, speed, and density. It takes place in section by section bases rather than focusing on individual vehicles behavior (Burghout and Wahlstedt, 2007). Macrosimulation models provide a simplified representation of reality considering all vehicles are assumed to behave in the same manner. It is applicable in Small networks to large strategic networks.

Microsimulation unlike macrosimulation model, it incorporates individual vehicles behavior, vehicles interaction with other vehicles or objects and vehicles performance. It assumes individual vehicles have different behavior. It is implemented typically from small to medium sized networks. Therefore, this model has a high level of detail information. It can accurately reproduce the actual traffic conditions on road networks. Microscopic models comprise two components: 1) an accurate road network geometry description, 2) a very detailed level of traffic behavior which takes in to consideration the behavior of vehicle drivers. It is a powerful tool and more effectively analyze the project alternatives. It has the ability to model variations in traffic volume and congestions over the peak hours and also the geometric influences. VISSIM, CORSIM, AIMSUN, and PARAMICS are some of the examples of micro-simulation model (Charypar, et al., 2008).

Mesosimulation is the combination of the above two models (Microsimulation and Macrosimulation). It simulates the individual vehicles behavior based on the microsimulation approach, but describes their activities and their interactions with other vehicles and objects based on the aggregate of macrosimulation approach. Examples of this model are DYNASMART and METROPOLIS (Charypar, et al., 2008).

1.3 Some of LCCA models

The following software packages are used in different parts of the world. However, based on the objective of the thesis and the availability, the Real Cost and AIMSUN based microsimulation model (Vännen) are chosen and used for the analysis.

The Real Cost Model was developed by FHWA and released in 2002 for the purpose of providing for decision makers as a decision support tool. The model comprises some features such as graphical user interface (GUI), customized input screens, an optional user cost analysis capability, graphical display charts, risk analysis functionality and both deterministic and probabilistic computational approaches. These features make the software user friendly to be able to analyze LCC and to be used by anybody having the basic understanding of LCCA. The software calculates the life cycle cost by following five steps.

a) Establish Design Strategy Alternatives
b) Determine Activity Timing
c) Estimate Agency and User Costs
d) Compute Life-Cycle Costs
e) Analyze the Results

The two computational approaches that can be used in Real cost are:

1. Deterministic: In this approach the analysts use input values based on historical data and expertise judgment as a fixed, discrete value, which are most likely to work for every parameter. This approach is a traditional method because it is easy and can be computed manually by using hand calculator or with Microsoft excels spreadsheet. In order to address uncertainty, sensitivity analysis may be used, which is by varying one of the input variables and keeping others unchanged. With this one can determine the effect of input variables on the result. However, it cannot address variations in many inputs at the same time (FHWA, 1998).
2. Probabilistic: The main difference of probabilistic approach from deterministic is it uses Monte- Carlo simulation in order to address uncertainty and makes simultaneous changes to input parameters. Monte-Carlo simulation supports risk analysis by substituting range of values from probability distribution for any factor that has inherent uncertainty. For each range of input values probabilistic approach provides possible range of output (FHWA, 1998).

The inputs in real cost software are categorized in two groups. Those are project level input data and alternative level input data. Project level inputs consist of different panels and are entered separately as follows:

Project Details: The project detail is used to enter all the project information details such as the name of the road, project name, region, and country where the project implemented and the person who is going to analyze the cost.

Analysis Option: The analysis Option panel that helps to define the user limits which will be applied in the project alternatives analysis. This panel comprises the actual data inputs such as the analysis unit, the analysis period (years), the discount rate, the beginning of analysis period, the agency cost remaining service life value, and the user cost remaining service life value.

Traffic Data: This panel is exclusively used to evaluate work zone user costs entering project-specific traffic data. It includes the following input data:

a) AADT at the Construction Year (total for both directions): The total annual average daily traffic (AADT) for both directions is entered starting from the beginning of the analysis
b) Single Unit Trucks as Percentage of AADT (%): The percentage of the AADT that is single unit trucks (i.e., commercial trucks with two-axles and four tires or more)
c) Combination Trucks as Percentage of AADT (%): The percentage of the AADT that is combination trucks (i.e., trucks with three axles or more)
d) Annual Growth Rate of Traffic (%): The percentage by which the AADT in both directions will increase each year. The inputs which are presented in the following table are depending on the type of terrain.

Table 1. Traffic Input Values (FHWA, 1998)

Type of Terrain	Level	Rolling	Mount-ainous	Level	Rolling	Mount-ainous
Free Flow Capacity (vphpl)	1.62	1.48	1.26	2.17	1.95	1.62
Queue Dissipation Capacity (vphpl)	1.71	1.57	1.33	1.7	1.53	1.27
Maximum AADT Per Lane	40.95	37.39	31.85	53.77	48.305	40.14
Work Zone Capacity (vphpl)	1.05	960	820	1.51	1.36	1.13
Maximum Queue Length	7.0 miles if the estimated maximum queue length is longer than 7.0 miles			5.0 miles if the estimated maximum queue length is longer than 5.0 miles		

e) Speed Limit under Normal Operating Conditions (mph): This is the speed limit at the project location under normal condition as well as the anticipated speed limit for a newly built roadway.

f) Lanes Open in Each Direction under Normal Conditions: This requires the number of lanes in each direction under normal operating condition.

g) Free Flow Capacity (vphpl*):* This panel requires the number of vehicles per hour per lane under the normal operating condition. Table 1 shows typical values for standard lane and shoulder widths for various types of terrain.

h) Queue Dissipation Capacity (Vphpl): Table 1 also provides the vehicle per hour per lane capacity of each lane during queue-dissipation operating conditions. It is shown in the table in each direction for two or multiple lane highways.

i) Maximum AADT (total for both directions): The total maximum AADT for both directions can be calculated by multiplying the recommended value for AADT per lane by the total number of lanes.

j) Maximum Queue Length (miles): It is the maximum length of queue in miles or in kilometer.

k) Rural or Urban Hourly Traffic Distribution: Depending on the project location, this can be selected either “Rural” or “Urban”.

Value of User Time: This cost is categorized based on the type of the vehicles. The higher value of time is usually allocated to the heavy vehicles.

Traffic Hourly Distribution: This allows adjustment to the default values for rural and urban traffic, which are used in converting AADT to an hourly traffic distribution. The default value shows the California weekday (Monday through Friday) were generated from Caltrans traffic count data (April 2005 data by the Division of Traffic Operations) at selected highway locations and can be used for any location in the State.

Added Time and Vehicle Stopping Costs*:* Added Time and Vehicle Stopping Costs are also used to adjust the default values for added time and added cost per 1,000 stops. The default values are based upon the National Cooperative Highway Research Program (NCHRP) Study 133 (1996). These values are used to calculate user delay and vehicle costs due to speed changes that occur during work zone operations.

Alternative-Level Inputs: Agency construction cost, activity service life (years), user work zone costs ($), maintenance frequency (years), agency maintenance cost ($), and activity work zone inputs such as; work zone length (miles),work zone duration (days) work zone capacity, traffic direction, work zone speed limit, traffic hourly distribution, period of lane closure (FHWA, 1998).

Aimsun based microsimulation model (Aimsun 5.1) was developed by Transport simulation systems (TSS) to evaluate road user costs for different work zone and road types. The Swedish national road and transport research institute (VTI) modified for modeling four different types of road works such as 6-lane roads, 4- lane roads, 2+1 roads, and 2-lane roads using different types of lane closures to simulate each work zone scenarios. Lane closures can be inner or passing-lane closure, flagger control and traffic signal control. Aimsun has application programming interface (API) which helps to customize the model. A script called python is used to store special behavior of the road work. It also helps to select the data and to control the simulation. Thus, the software is able to calculate the result and simulate different work zone scenarios by using different input data such as road type, work zone type, traffic flows, heavy vehicle ratios (HVR) and some other detail inputs.

For the Real cost and Aimsun based microsimulation software packages, a similar set of data such as heavy vehicle ratios (HVR), traffic volume (AADT) and speed limit are used. However, the details of other required information may vary between the packages.

MicroBENCOST was developed by Texas department of transportation for cost-benefit analysis of highway and bridge projects. It is a disc operating system (DOS) which is not as user friendly as a Windows based models (Jiang, et al., 2010).

California Life-Cycle Benefit/Cost Analysis Model (Cal-B/C) was developed by California department of transportation for analysis of highway, railway, and transit projects such as lane addition, intersection improvements, passenger rail and light rail. It is a Microsoft excel spreadsheet based model and helps to analyze the anticipated costs and benefits (Daniel, et al., 2007).

In order to specifically analyze highway related projects the Redbook Wizard was developed by the National Cooperative Highway Research Program (NCHRP) and published by the American Association of State Highway and Transportation Officials (AASHTO) in 2010. It also uses Microsoft excel spreadsheet to analyze benefit cost analysis (Daniel, et al., 2007).

Depending on the objectives of MicroBENCOST, Cal-B/C and the Redbook software packages the input requirement may vary. The basic inputs common to all the packages are: type of highway, type of improvements and traffic volume (AADT). However, the other input parameters may differ among them. For instance, MicroBENCOST needs work zone data, number of lanes closed, number of work days, incident data. Cal-B/C needs free flow speed, accident data, ramp design speed. The Redbook also needs vehicle type, value of time, traffic growth rate and annual agency operating costs.

The anticipated outputs among the software packages are almost common. The outputs are users travel time savings, accident reduction, maintenance or rehabilitation cost savings, VOC savings, emission reduction benefits and value of time benefits.

1.4 Objectives

The main objectives of this thesis are:

- ❖ To identify the most significant factors affecting user cost
- ❖ Implementing the binomial lattice model to predict future traffic demand and user delay costs

2 Methodology

2.1 Life cycle cost analysis (LCCA) method

LCCA permits comparison between different project alternatives having similar level of service (LOS) (i.e. a range of operating conditions in a particular type of facility). However, BCA permits the application of different LOS. For instance, one project maintains existing road pavements whereas the other makes road stretches.

Real Cost LCCA passes through five different steps (FHWA, 1998). The first step is establishing design alternatives. LCCA is needed when a project is selected for improvement or reconstruction. At this time two or more mutually exclusive options have to be identified. As shown in Figure 1, the analysis period, which is the time period from the first project expenditure through the useful life of the project, should be the same for each project alternative. Furthermore, it should include at least one major rehabilitation activity. However, the frequency of maintenance or rehabilitation and the service life of each alternative may differ in order to compare the cost differences among alternatives.

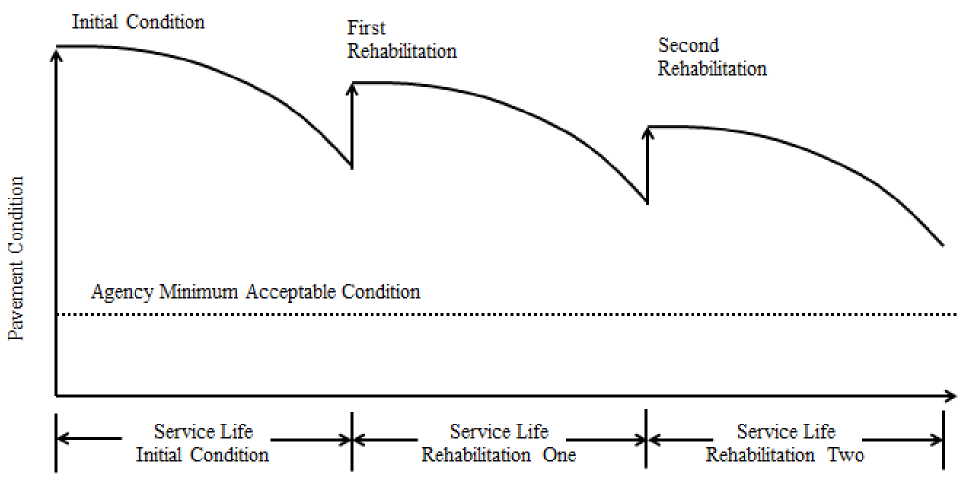

Figure 1. Example of lifetime of one design alternative

The second step is to determine the activity timing; as shown in Figure 1 a typical road pavement passes through initial construction and periodic maintenance before reaching its minimum acceptable condition throughout its life time. Pavement preservation activities may reduce the frequency of maintenance or rehabilitation activity. As the matter of fact, prevention is always better than curing. The schedule of future work depends on the rate of deterioration in addition to existing performance records which can be found from historical data and the judgment of experienced engineer. Thus, alternative maintenance and rehabilitation activities are planned according to the service life of the project.

The third step is estimating costs; basically costs considered in LCCA are agency costs and user costs. In LCCA the costs which do not bring differences between the project-alternatives should not be evaluated (i.e. land costs that are common to all alternatives are not be considered in the analysis). User costs may differ among the alternatives.

The forth step is calculating the total life cycle costs (LCCs) for each project alternative and compare the results based on the net present value (NPV). NPV is calculated for the agency and user costs by using the real rate of return as shown in Equation (1).

In the last step, the results of LCCA will be analyzed and interpreted. Many analysts do not emphasis user costs. Consequently, the comparison between project alternatives is often made between agency costs. However, it is suggested to include the user costs in the analysis (FHWA, 1998).

2.2 Aimsun-based microsimulation model

This model uses microscopic simulation approach for calculating the user cost. The model uses different input data such as road type, work-zone type, traffic flows and heavy vehicle ratios (HVR). These are divided in to two categories i.e. road properties and traffic properties**.**

a. Road properties include the road type, the road geometry, the speed limit and area type. However, these can have insignificant effect on the result compare to traffic properties.
b. Traffic properties are traffic flow, heavy vehicle ratio, variation of traffic distribution and deployment time.

Traffic flow is the interaction between the vehicle and the road based on the flow capacity. If the flow is above the road's capacity there will be congestion. During work-zone the delay starts to grow due to the limit of the passing lane. However, hourly traffic distribution can control the flow level by distributing the flow for each hour.

Heavy vehicle ratios: In comparison with cars, heavy vehicles travel with a lower speed. More cars drive fast to overpass heavy vehicles and prone to congestion near to work zone area. Since heavy vehicle ratios greatly affect the delay, it's important to use various HVRs in the simulation.

Variations of traffic distribution: The weekday and weekend variation of traffic volumes and hourly distributions needs to be considered. The traffic flow depends on the condition of the road and different hours of the day. According to (Wennström 2010) the hourly traffic distribution is used in the simulation to account for average condition. It is classified as midday hours (9-16), peak hours (7-9, 16-18) and night hours (0-7, 18-24) and get 5%, 12% and 1% of the daily flow respectively.

Deployment time: The traffic flow during the midday hours and night hours is comparatively lower than the peak hours.

2.3 Binomial lattice approach

This approach is used to evaluate future traffic as well as road user delay costs for three different types of roads. In this thesis the time step is assumed to be one month. The user cost is calculated for a rehabilitation activity at the 15^{th} year. For the given AADT values 1000 number of iterations is carried out. The first value of AADT ($AADT_0$) in the binomial lattice tree is the most likely AADT value in the first year after the completion of the project. The anticipated AADT value at the beginning of the 15^{th} year or 180^{th} month after the completion of the project is evaluated using binomial lattice formulation. The binomial lattice model is addressed in detail in the next section.

3 Binomial lattice model

A binomial lattice model is used to estimate traffic prediction uncertainties. Different researchers explained the binomial lattice model as a simple discrete time approach to characterize uncertainty about future traffic in highway projects (Ho and Liu, 2002; Garvin and Cheah, 2004, and Hull, 2008). It was observed that the variation between actual traffic and forecast ranged between 20 to 40 % for most examined projects (Lemp, 2009). This traffic uncertainty leads to traffic revenue risk, which is a main source of financial risk and one of the most significant risks in built operate transfer (BOT) contracts.

Public-private partnership (PPP) is a partnership between government and private sector in a way that the private party provides a public project by contributing financial, technical and other supports and the government may provide a capital subsidy or encourage the private investment by incorporating traffic revenue risk mitigation mechanisms. There are two types of risk sharing mechanisms: 1) Minimum Revenue Guarantee (MRG) is a common risk mitigation strategy in which the government guarantees a minimum income of the project 2) Toll Revenue Cap (TRC) for sharing the surplus revenue beyond the anticipated threshold. In different countries mostly government chooses MRG and TRC to mitigate traffic revenue risk (Kashani, 2012).

Net present value (NPV) is a traditional method in order to evaluate BOT road projects (Cheah and Garvin 2009). The selection of discount rate is up to the concessionaire interest in NPV analysis. The discount rate reveals the rate of return that the stakeholders expect from investing in the toll road project. NPV can be expressed as follows:

$$\mathrm{NPV} = -\sum_{i=0}^{n} \frac{\mathrm{CC}_i}{(1+\rho)^i} + \sum_{j=n+1}^{N} \frac{(\mathrm{PR}_j + \mathrm{OC}_i)}{(1+\rho)^j} \quad (3)$$

where,

n is the length of construction period (yr)

N is the total concession length (yr) from the initial construction to the return to the government

CC_i (i=1, 2... n) is the annual construction costs throughout the construction period from beginning to end

OC_j (j=n+1, n+2…N) are the annual operations, maintenance, and rehabilitation costs from the first year after the completion of the project until the end of the concession period

PR_j (j=n+1, n+2… N) is the forecasted annual traffic revenues from the first year after the completion of the project until the end of the concession period

ρ is the real rate of return (discount rate)

Even though NPV has merits in providing clear and consistent decision criteria, it has some drawbacks regarding future traffic uncertainty and cannot be used to establish an appropriate MRG and TRC minimum level.

Since inappropriate choice of MRG and TRC can lead to improper allocation of risks between the stakeholders and can cause huge unexpected costs to the government or the concessionaire, the real option theory is recommended for evaluating BOT projects. The real option model has been implemented by using a binomial lattice framework. A binomial decision tree uses a market-based option pricing approach which is known as risk-neutral probabilities to approximate the risk associated with traffic uncertainty in the project over time. There are several important characteristics that make it more useful than NPV models. It is a financial model to evaluate investments in highway projects under future traffic uncertainty. The real option analysis also helps the concessionaires to price MRG and TRC as well as to compare their financial risk profile and give chance to reduce the loss of the investment by conducting probabilistic life cycle cost and revenue analysis (Cheah and Garvin, 2009).

Traffic study for all major BOT projects can be carried out in stochastic manner to treat future traffic demand forecasts. The traffic study assumes AADT projections as pessimistic, most likely, and optimistic forecasts. Suppose $AADT_j$ where, j= n+1,n+2,…,N are the most likely forecasts of AADT from (n+1) which is the first year after the project is completed until (N) the end of concession lifetime. The expected annual growth rate of AADT (α) is computed based on Equation 4 (Luenberger, 1998).

$$\alpha = \frac{1}{N-(n+1)} ln\left[\frac{AADT_N}{AADT_{n+1}}\right] \tag{4}$$

In order to evaluate the future traffic level the annual traffic volatility (σ) should also be involved in the calculations. The annual volatility of AADT is the standard deviation of the expected annual growth rate of AADT. It shows how much variation exists in the expected annual growth of the traffic demand. Since volatility of traffic demand is the source of uncertainty for project revenue, the private sectors should give emphasis to mitigate the risk. However, the choice of volatility is not always easy since it is highly exposed to uncertainty.

There are three sources indicated by different authors to determine σ in toll road projects: 1) historical traffic demand data which has been applicable to similar toll road project in the region (Irwin, 2003), 2) the annual volatility of regional gross domestic product (Banister, 2005) and 3) the expertise opinion to estimate the annual volatility of the traffic demand

(Brandao and Saraiva, 2008). The concessionaire uses one of the aforementioned methods to make an appropriate estimate. In order to reduce or to account for the uncertainty regarding the inappropriate estimation of σ, sensitivity analysis should also be carried out.

In the binomial lattice model usually a one month time step or a shorter period is considered to make it more powerful to characterize dynamic uncertainty regarding future traffic demands. In Figure 2 the $AADT_0$ is equal to the most likely AADT value in the first year operation stage of the investment after the project is completed. The AADT value for the coming month would be one of the two multiples of $AADT_0$, i.e., either $u \times AADT_0$ with probability p or $d \times AADT_0$ with probability 1-p (Hull, 2008).

The upward movement multiple can be expressed by:

$$u = e^{\sigma\sqrt{\Delta t}} \tag{5}$$

The downward movement can also be expressed by:

$$d = \frac{1}{u} \tag{6}$$

where, both u and d are positive values. The probability of upward movement from any node in the lattice can be determined by:

$$p = \frac{e^{\sigma\sqrt{\Delta t}} - d}{u - d} \tag{7}$$

1-*p* is then the probability of downward movement from any node.

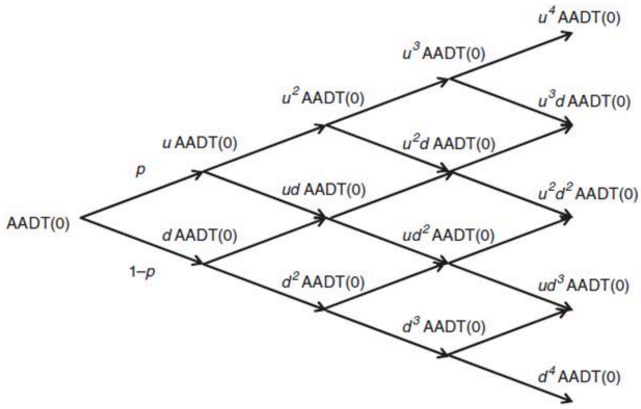

Figure 2. Binomial lattice model to characterize traffic uncertainly (Ashuri, et al., 2012)

The above binomial distribution tree is used to generate random binomial parameters over the project life time. A series of continues random up and downside movements are along the sample path on the binomial lattice tree. The Monte Carlo simulation algorithm is then applied for binomial random variables in order to generate a significant number of random AADT paths along the binomial lattice.

This is a powerful feature of the proposed model for characterizing uncertainty about future traffic demands and paves the way to determine revenue streams for concessionaire. $AADT_0$ is the initial AADT at the beginning of the n+1 year which is the AADT value of the root node in the model. The expected value of AADT at the beginning of n+2 year, n+3 year,…(N) year are summarized in the binomial lattice node of 12^{th} month, 24^{th} month,…12x(N-(n+1)) month, respectively. Any node in month m= 12, 24…12x(N-(n+1)) from root node can be reached upside movements by $0 \leq k \leq 1$ and downward movement by $0 \leq 1\text{-}k \leq 1$ along the binomial lattice. The AADT at the beginning of the m^{th} month becomes $AADT_0 \text{ x } u^k d^{1\text{-}k}$ (Hull, 2008).

$$\binom{m}{k} p^k \left(1-p\right)^{1-k} \tag{8}$$

4 Results and Discussion

4.1 Factors that affect the delay costs

In this study, sensitivity analysis is carried out to identify the most important factors affecting the road user delay costs. The analysis is carried out using the Real Cost software. All the input parameters are checked out to identify the influential inputs.

The following values are assumed to be constant in the calculations:

1. 1000 AADT in both directions
2. 10 % HVR
3. Value of time: $91 per hour for passenger cars, $ 578 per hour for single unit trucks, $578 per hour for combination trucks
4. 1km work-zone length
5. 1day work zone duration
6. 50km/h work zone speed

By changing one of the above input variables and keeping the other input variables constant, the impact of each variable is assessed in Figure 3.

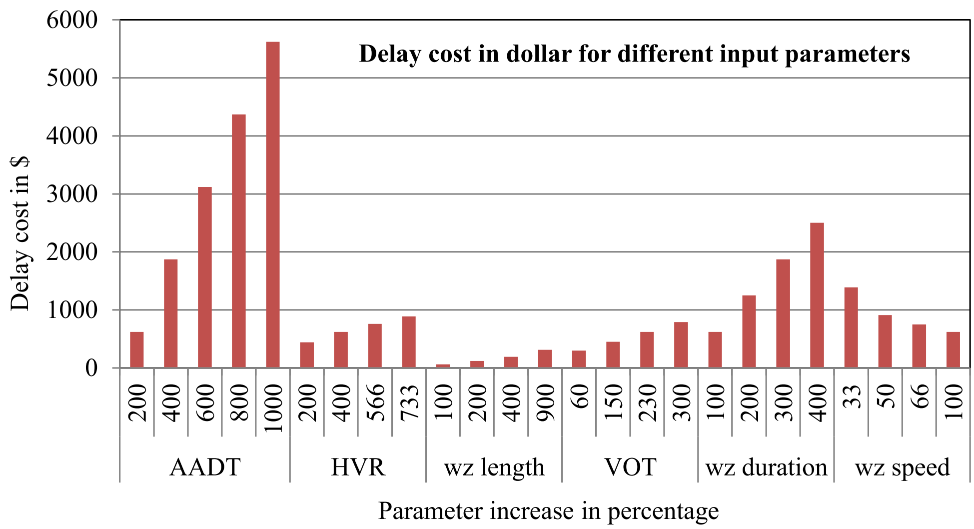

Figure 3. Sensitivity analysis on Delay Cost

It is important to note that the increase of values for each input parameters is according to the limit and behavior of the inputs. For instance, work zone speed limit varied from 30 to 60 km/h or from 33 % to 100% of the initial value to see the changes on the result while AADT varied from 1000 to 9000 (200-1000%). To make them all comparable, the result is presented based on the increase in percentage as shown in figure 3.

The increase of AADT values from 200 % to 1000 % increased the delay cost linearly high compared to all the parameters. The number of work days on the road, work zone speed limit, HVR, value of time for vehicles, and work zone length also significantly affected the delay cost respectively. However, the increase in percentage of work zone speed limit decreased the delay cost as shown in the figure.

The decrease of the speed limit and the increase of all the mentioned inputs increases the delay cost. However, the vales in the figure are in order to show their influence on the outcome and to compare one another.

In fact, the demand of the highway users is always increasing i.e. AADT values increase year by year. As it can be observed in the analysis the impact of traffic demand had a significant effect on user delay costs. By understanding the major influential factors on road user delay costs, the road traffic engineers can minimize the effect of future traffic flows and other factors on road users.

4.2 Predicting uncertainty in traffic

LCCA tools can predict future traffic demands based on traditional NPV methods. However, they couldn't appropriately predict future traffic. Thus, better risk analysis method is implemented to address the future uncertainties.

In order to estimate the traffic demand uncertainties the binomial lattice model was used. The amount of delay was calculated with the Vännen software which is based on AIMSUN traffic microsimulation model (Wennström, 2010). Figure 4 shows the estimated total delay hour and cost respectively as a function of AADT.

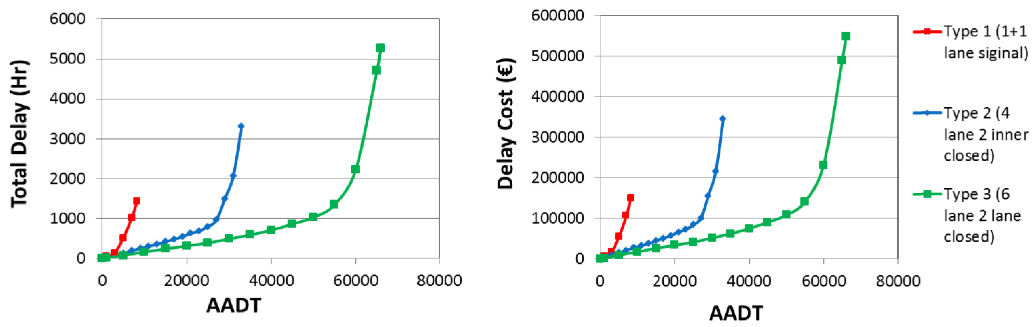

Figure 4. Estimated Delay hour and Cost using *AIMSUN*

The delay cost can be predicted from the fitting Equations (7-8) which are based on Figure 4.

Type 1 (1+1 lane closed with signal) - $R^2 = 0.999$

$$Delay\_Cost = 0.0024AADT^2 - 1.5073AADT + 1485.8 \quad (9)$$

Type 2 (4 lane 2 inner closed) - $R^2 = 0.9989$

$$Delay\_Cost = 3E-21AADT^6 - 2E-16AADT^5 + 5E-12AADT^4 - ... \\ -6E-08AADT^3 + 0.0003AADT^2 + 2.4353AADT + 21.288 \quad (10)$$

Type 3 (6 lane 2 inner closed) - $R^2 = 0.9994$

$$Delay\_Cost = 2E-22AADT^6 - 3E-17AADT^5 + 2E-12AADT^4 - ... \\ -5E-08AADT^3 + 0.0006AADT^2 - 0.9039AADT + 1168 \quad (11)$$

The delay cost distribution was calculated by using Matlab code (Appendix 1) for rehabilitation at the 15th year. In the analysis, 2, 4 and 6 lanes in both directions have been considered and traffic at the year zero was taken as 2000, 7000, and 10000 respectively for each cases. The annual volatility or standard deviation and annual growth rate were considered 0.1 and 0.04 respectively for all cases.

The output in the proposed binomial lattice model was the cumulative distribution function of the traffic uncertainty for rehabilitation at the 15th year, which is presented in Figure 5 below:

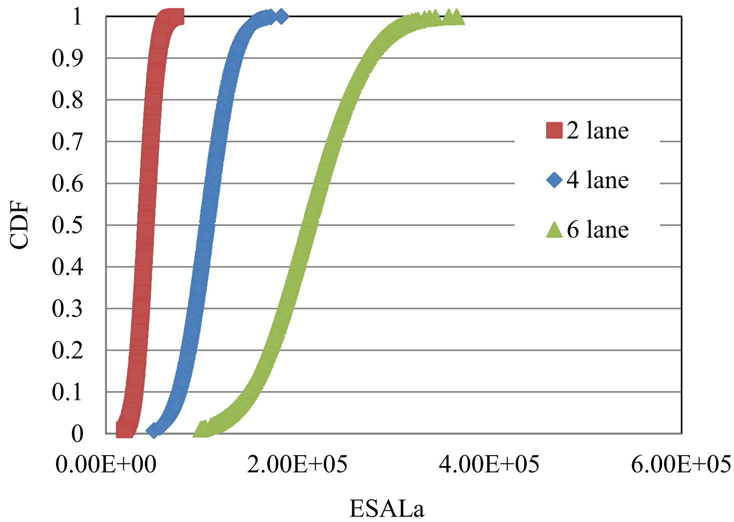

Figure 5. Commulative distribution function (CDF) and Traffic demand

From the above equation 7-9, the delay cost was estimated using the chosen AADT for 1000 binomial iteration in order to correlate the delay cost uncertainty corresponding to the traffic demand. Figure 6 described the delay cost uncertainty of the estimated traffic demand over 15 years or 180 months according to the binomial lattice estimation.

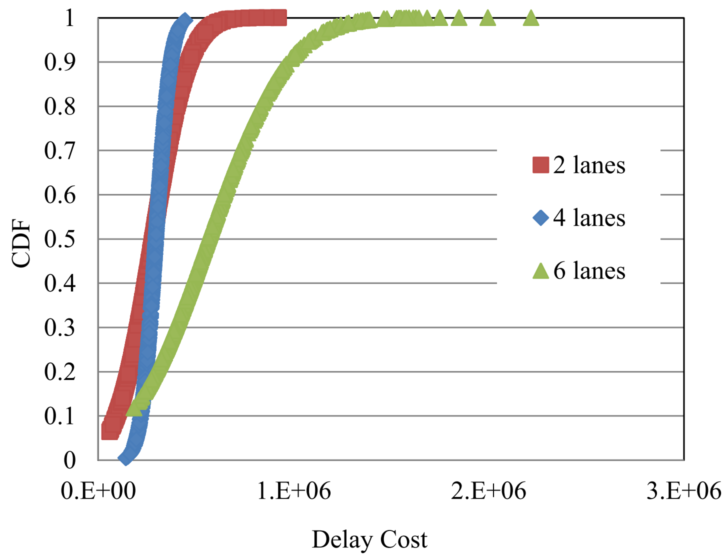

Figure 6. Commulative distribution function and Traffic delay cost

5 Conclusions

LCCA has been an economic analysis tool in order to choose the most cost effective design alternative. The costs considered in LCC studies are agency and road user costs. However, this study was set out to explore only on road user costs specifically on road user delay costs. Different LCCA models have been developed and used to quantify user delay costs in different countries; however, the risk related to future events could not be well addressed. This study has sought to identify the important factors which have significant effect on road user delay costs. Furthermore, the study implemented a binomial lattice method to assess the uncertainties regarding the user costs.

The important factors affecting the road user delay cost were included in the sensitivity analysis. Some of the detailed inputs which had insignificant effect on the result have been ignored. The most important factors influencing the outcome in the analysis were traffic demand (AADT), number of work days on the road and work zone speed limit. However, AADT was shown to be the most influential factor.

In the literature review it was observed that LCCA models evaluated the user delay cost based on an initial AADT value and a growth factor regarding traffic. However, the uncertainty regarding the future traffic has not been addressed.

By implementing the binomial lattice method this thesis addressed the effect of traffic volatility in the calculation of the user delay cost. Incorporating the traffic volatility in the delay cost calculations enables a better prediction of future traffic. This can help the road engineers with a better risk analysis regarding the road structure design. Furthermore, it can improve the assessment of uncertainties in the LCC studies.

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Appendix

```
% Created by Iman Mirzadeh
% AADT prediction based on binomial lattice model
% Version 2013.06.26
%% Inputs
clear all
AADT0=2000; %Traffic at the year zero
sigma=.1; %annual volatility
alfa=.04; %annual growth rate
dt=1;     %time step (month)
Rt=180;   %Rehabilitation time (month)
n=1000;   %number of iteration
tt=Rt/12;
%% parameters:
u=exp(sigma*(dt)^.5);
d=exp(-sigma*(dt)^.5);
p=(exp(alfa*dt)-d)/(u-d); %Probability

%%
for j=1:n
BB=1;i=0;
for m=12:12:Rt
  g= binornd(1,p);
  i=1+i;

if g==1
B=u;
else
B=d;
end

BB=B*BB;
A(i)=AADT0*BB;
end
ESAL(j)=A*ones(1,i)';
ADT(j,:)=A;
for ii=1:tt
    costy(ii)=0.0024*(ADT(j,ii))^2-1.5073*(ADT(j,ii))+1485.8;
end
cost(j)=costy*ones(1,ii)';
end

X=cost;
[muhat,sigmahat]=normfit(X);  % Mean & Standard deviation

Y = cdf('norm',X,muhat,sigmahat);
plot(X,Y,'.')
xlabel('Delay Cost')
ylabel('CDF')

for i=1:tt
    ADDT(i)=mean(ADT(:,i));
end
```

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