A Framework for Optimal Highway Capacity Expansion Decision-Making

A thesis submitted in partial fulfillment of

the requirements for the degree of

Master of Science

in

Transportation Engineering

Submitted By

Muhammad Asif Khan
(NUST – 2012 – 60953 - MSCEE – 15112 – F)

National Institute of Transportation (NIT)
School of Civil and Environmental Engineering (SCEE)
National University of Sciences & Technology (NUST)
Sector H-12, Islamabad, Pakistan
(2015)

Certified that the contents and form of thesis titled "A Framework for Optimal Highway Capacity Expansion Decision-Making" submitted by Muhammad Asif Khan have been found satisfactory for the requirement of the degree.

Supervisor: ______________________________

Associate Professor (Dr. Anwaar Ahmed, PhD)

Dedicated to my Parents Sakeena and Sher Khan,

and my Grandfather Ghulam Mustafa.

ACKNOWLEDGMENTS

I am thankful to Almighty Allah for blessing me with the patience and strength to complete my research. I wish to express my sincere gratitude to my advisor, Dr. Anwaar Ahmed for contributing his valuable ideas, inspiring guidance and encouragement that made it possible to complete my research work. My profound gratitude is also extended to other members of advisory committee, Dr. S. Muhammad Jamil, Dr. Muhammad Bilal Khurshid and Dr. Arshad Hussain for their support and guidance throughout my research.

I am also grateful to the academic staff of the National Institute of Transportation for their cooperation and support during my postgraduate studies. In the end, I would like to thank my parents, sister, uncle and my grandparents for their support and prayers that have always played a vital role in my life.

TABLE OF CONTENTS

Page

LIST OF TABLES

APPENDIX TABLE

LIST OF FIGURES

LIST OF ACRONYMS

FHWA	Federal Highway Administration
GASB	Governmental Accounting Standards Board
ESP	Economic Survey of Pakistan
SMITE	Spreadsheet Model for Induced Travel Estimation
OLS	Ordinary Least Squares
TTI	Texas Transportation Institute
NPTS	National Personal Transportation Study
MSAs	Metropolitan Statistical Areas
AR1	Autoregressive Structure of the first Order
TCAD	Travis Central Appraisal District
OECD	Organization for Economic Cooperation and Development
ECMT	Europeans Conference of Ministers of Transport
ITS	Intelligent Transportation System
ARC	Atlanta Regional Commission
BEA	Bureau of Economic Analysis
REIS	Regional Economic Information System
TRB	Transportation Research Board
SHRP	Strategic Highway Research Program
GDP	Gross Domestic Product
QCEW	Quarterly Census of Employment and Wages
NMDP	Nested Markov Decision Process
ANOVA	Analysis of Variance

BPR	Bureau of Public Roads
FWC	Future Worth of Cost
ADT	Average Daily Traffic
NSC	National Safety Council
PWD	Public Works Department
ROW	Right of Way
NHA	National Highway Authority
VOC	Vehicle Operating Cost
CPI	Consumer/Construction Price Index
VMT	Vehicle Miles Travelled

Abstract

Transportation facilities besides providing mobility and accessibility for people and goods also play an important role in economic vitality and global competitiveness of any nation. The involvement of enormous investments in highway development necessitates the exigency of economic analysis and modeling techniques before any decision could be implemented. In Pakistan highway expansion and/or construction decisions are mostly politically influenced and are implemented without any detailed engineering economic analysis techniques. Present study developed a comprehensive framework for determining optimal time for highway capacity expansion based on detailed engineering economic analysis duly incorporating user and agency cost components. The development of framework was based upon the annualized widening costs (agency lane addition cost and workzone user delay cost) and excessive user costs for do-nothing scenario (excessive travel delay cost, excessive VOC and excessive crash cost) for each analysis year within highway life cycle. The breakeven point between two cost categories was determined as the optimal time for highway capacity expansion intervention. A segment of Islamabad Highway from Airport Chowk to the intersection of Islamabad Highway with Grand Trunk road was selected for case study. The case study results revealed an ADT ranging from 34430 to 37600 as optimal for initiating widening intervention of 4-lanes to 8-lanes divided highway. Furthermore, sensitivity analysis was conducted to evaluate the magnitude and direction of influence of varying weights of agency to user cost, annual traffic growth rate and annual interest rate on optimal time range for highway capacity expansion. The proposed framework provides a comprehensive insight about highway capacity expansion decision making and it is anticipated that study results if applied by national highway agencies shall result in saving huge amount of needless agency expenditures and excessive user costs.

CHAPTER 1. INTRODUCTION

1.1 Background

Due to huge amount of investment involved in highway development and preservation process, highway agencies seek to optimize the available funds in order to preserve the highway assets cost-effectively and also to ensure better operational liability (FHWA, 1999; GASB, 1999). The present transportation environment is facing problem of rapid growth in commercial and personal travel demand besides higher travelers expectations. Despite of universal recognition of the importance of long-lasting transportation system development, highway agencies around the globe are striving to provide such robust transportation system due to economic, environmental and social impacts (SHRP, 2009).

Conventionally, the assessment of transportation systems is intended to evaluate the economic efficiency of proposed alternatives through their monetary benefits and costs comparison. Detailed knowledge of agency and user cost estimates for each of the possible alternatives is an important input for reliable or good decision making at any stage of transportation system development process (Sinha and Labi, 2007). Due to ever increasing travel demand highway construction/reconstruction and up gradation is a major investment decision at most of the highway agencies. A detailed analysis is required by highway agencies before implementing any decision regarding highway development, operation, expansion and rehabilitation due to huge amount of investment involved in this process (Zhao et al., 2004).

Highway capacity expansion can take form of widening of existing highway, construction of new road, or providing new access control points to up-grade highway to access controlled freeway (Handy and Boarnet, 2014). A number of studies from past have highlighted the importance of optimal highway decision making (Mamlouk and Zaniewski, 2001; Abaza, 2002; Peshkin et al., 2004; Hang and Hastak, 2007; Marasteanu et al., 2008; Khurshid et al., 2010) however there are limited studies that have specifically addressed the issue of optimal highway capacity expansion decision making. Capacity expansion decisions are more sensitive to traffic growth rates than maintenance and rehabilitation treatments decisions unless there is a major contribution of trucks in the traffic stream. Opportunities to expand the highway increases for higher traffic growth rate scenarios, as more traffic lanes will be needed to meet increased travel demand (Yang, 2012). Adding lane(s) to an existing highway (within available right of way) is linked with huge amount of agency cost (cost of lane addition) and user cost (safety, workzone user delay cost, discomfort and inconvenience). Too early expansion of highway facility would result in extra agency cost due to underutilized capacity and too late expansion would result in excessive user costs due to travel time delays. In between these two extremes, there exists a certain optimal facility expansion timing that can result in optimal trade-off between both agency and user costs (Sinha et al., 2011).

Pakistan is a developing country having a population of over 180 million and total road network of approximately 260,000 km that serve about 11 million vehicles of all types (ESP, 2012). There is huge investment involved in the both preservation of existing roads and capacity expansions or construction of new roads in Pakistan e.g. from 2005 to 2010 Rs 248 billion were estimated to be incurred by highway agencies to preserve existing road length of 14,100 km and 7000 km new road construction (Pakistan Infrastructure Report, 2005-2010). In Pakistan vehicle growth rate is much higher as compared to road infrastructure. In last one decade vehicle population almost doubled however, there was just 0.38% growth in road infrastructure (Khan, B. A., 2013). Rapid growth in vehicle population and comparatively slow growth in road infrastructure in Pakistan has result in excessive delay cost. Also highway construction or expansion decisions in Pakistan are mostly influenced politically and are not made on the basis of detailed engineering economic analysis. Non-optimal decisions result in either too early or too late expansion of highways in Pakistan and accentuate the importance of new efforts to provide framework for optimal highway expansion decision making based on detailed engineering economic analysis.

1.2 Problem Statement

The expansion of existing highway in order to meet ever increasing travel demand require huge amount of investment from highway agencies. Therefore highway agencies always seek to solve the congestion problem through some operational strategies and they never want to expand the highway. On the other hand highway users urge highway agencies to expand the highway because users always want comfortable, safe and free flowing travel conditions in order to avoid travel time delays and other congestion related costs.

An expansion intervention that is applied too early means that highway facility is expanded when its operational performance is satisfactory and would result in premature facility expansion. This would eventually result in smaller user benefits and premature needless agency expenditure. On the other hand an expansion intervention that is applied too late means that highway is expended when its performance is below than required. So in this case agency conserves funds even though highway users experience worse operational condition, leading to excessive user costs in the longer run due to travel time delays. In between these two extremes there exist a certain highway expansion intervention time that would result in optimal trade-off between both agency and user costs, which need to be established in analysis.

1.3 Research Objectives

As highway system development involves huge irreversible investments, therefore it must be based on rigorous research efforts so that optimal decisions are made. Due to economic crises, Pakistan's highway agencies are facing acute shortage of funding, there is highly important for highway agencies to make optimal highway expansion decisions. In order to address this issue of optimal decision making regarding highway expansion, the objectives set fourth for present study are:

- To synthesize the state of the art and practice on highway capacity expansion decision making at national and international level.
- To develop a generalized framework for optimal highway capacity expansion decision making.
- To demonstrate the applicability of the developed framework for a typical urban highway expansion project.

1.4 Overview of the Study Approach

For successful attainment of research objectives, a detailed methodology is developed and following research tasks were identified in the study:

- A comprehensive literature review of past research efforts regarding highway capacity expansion decision making.
- Development of the framework to predict optimal time for highway capacity expansion.
- Collection and collation of data
- Demonstration of the developed framework through its application to a typical urban highway expansion project.
- Sensitivity analysis to assess the impact of different factors on optimal highway capacity expansion intervention time.
- At the end summary of the research findings, recommendations and directions for the future possible research are presented.

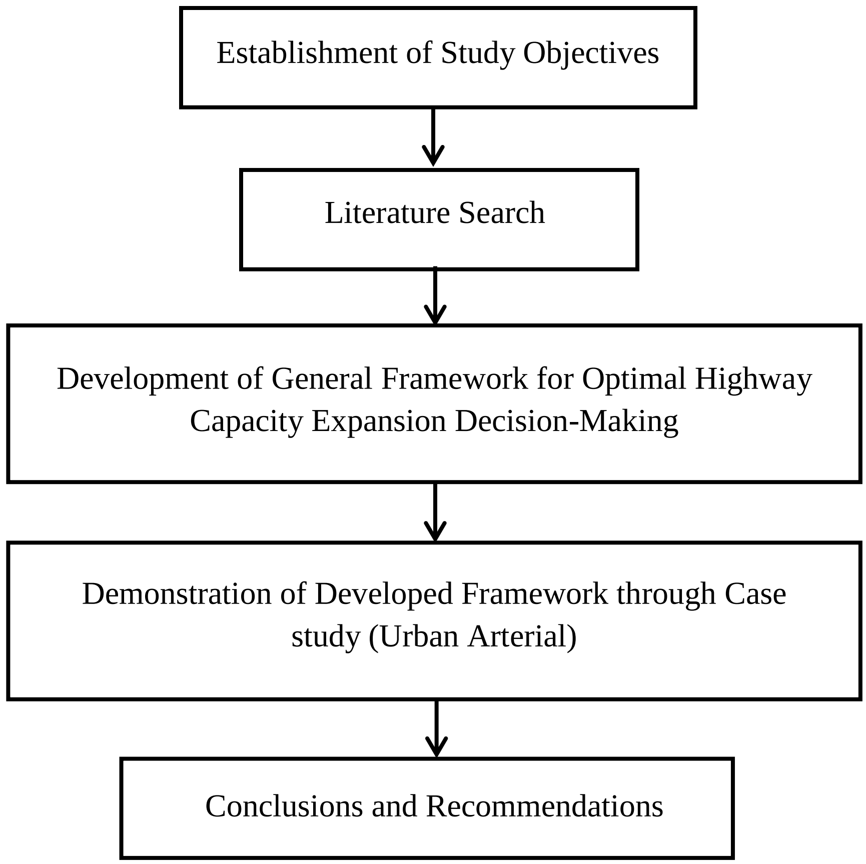

Figure 1 Overview of Study Approach

1.5 Organization of the Thesis

In this thesis chapter 1 provides a background for the need to develop a framework for optimal highway capacity expansion decision making followed by problem statement and objectives of the study. Chapter 2 presents the detailed literature review which include past research efforts on highway capacity expansion decision making, highway capacity expansion after impacts and factors affecting highway capacity expansion decision making. Chapter 3 provides the study framework for optimal highway capacity expansion intervention time. Case study for developed framework for a typical urban highway is demonstrated in chapter 4. Sensitivity analysis to assess the impact of different factors on optimal highway capacity expansion intervention is also discussed in chapter 4. Research summary, conclusions, recommendations and possible directions for the future research are presented in chapter 5.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

This chapter summarizes several studies related to highway capacity expansion decision making and highway capacity expansion after impacts. The literature review covers studies related to optimal decision making in highway development, and importance of comprehensive economic evaluation in transportation decision making between different alternatives. The discussion also covers different methodologies to estimate induced travel impact after highway capacity expansion, effects of highway capacity expansion on urban growth and travel demand.

The literature review revealed that highway capacity expansion results in peak narrowing, and benefits of capacity expansion would be overstated if induced travel impact is not considered. Capacity expansion with express toll net-work provides better congestion relief with maximum revenues estimated. The researchers have found that systematic institutionalization of collaborative decision making, comprehensive economic evaluation, and fundamental reform for congestion pricing at federal and local level are necessary for the development of efficient and sustainable highway system. For shorter planning period construction costs have been found out to be the major impact factors while delay cost is more significant factor for longer planning period. Lastly the literature review illustrates major factors related to highway capacity expansion decision making that includes design traffic volume, design level of service, economic impact, environmental impact, and social and political considerations.

2.2 Highway Capacity Expansion - Summary of Past Research Efforts

Decorla-Souza and Cohen (1998) developed a methodology to estimate the induced travel demand due to metropolitan highway capacity expansion at the sketch planning level. The authors also described sources of induced travel and its estimation at facility, corridor and region wide levels. The developed methodology at the sketch planning level was demonstrated through a hypothetical corridor example for low, moderate and high levels of initial congestion. Induced travel was estimated for moderate (-0.5) and extreme (-1.0) travel demand elasticity scenarios and it was found out that initial level of congestion has a significant positive effect on induced travel. The authors concluded from the study results that capacity expansion releases the congestion efficiently even if there is significant induced travel impact.

Decorla-Souza and Cohen (1999) developed a model (Spreadsheet Model for Induced Travel Estimation (SMITE)) to estimate induced travel demand due to highway capacity expansion. Authors carried out economic analyses for highway capacity expansion decision in an urban setting using developed model. The results suggested that capacity expansion could be warranted even when magnitude of induced travel is high due to larger reductions in delays.

Zhang et al., (2000) analyzed the effect of highway capacity expansion on peak narrowing using ordinary least squares (OLS) technique. The temporal redistribution of travel from off-peak times to peak times due to roadway capacity enhancement is defined as peak narrowing (Zhang et al., 2000). Data related to roadway capacity were obtained from Texas Transportation Institute (TTI) mobility study, and the National Personal Transportation Study (NPTS) survey data in disaggregate form were used for empirical analysis. Model-1 accounted for only morning commuters while model-2 accounted for both morning and non-morning commuters. The dependent variable used in the analysis was “departure time for work from the peak time for all workers in all Metropolitan Statistical Areas (MSAs) in US”. Lane-mile per capita was the key independent variable along with demographic, time and two dummy variables. Model results revealed statistically significant negative association between capacity expansion and peak narrowing. Thus with increased highway capacity, home to work departure time get closer to peak travel time.

Poole and Orski (2000) studies the concept of high occupancy toll (HOT) lanes to solve urban highway congestion in a better way. Authors justified the economic and political feasibility of converting high occupancy vehicle (HOV) lanes to HOT lanes. Using data from past projects authors concluded that HOT lanes provide better level of service and efficient capacity to handle urban highway congestion problems than HOV lanes.

Noland and Cowart (2000) studies the issue of induced travel demands resulting from increased Vehicle Miles Traveled (VMT) due to highway capacity expansion. Authors developed two stage least squares regression models with VMT per capita as dependent variable. Cross-sectional time series data of metropolitan areas obtained from TTI was used for model estimation. Lane-miles per capita of freeway and arterial, fuel cost, real per capita income and population density were used as independent variables. Per capita income and lane miles were found to be significantly positively associated with VMT per capita while population density showed significant negative association with VMT per capita. Fuel cost showed inverse but insignificant relationship with VMT per capita. It was concluded from models outputs that one lane mile addition to highway capacity would result in approximately 15% of annual VMT growth. Study concluded that benefits of highway expansion would be overstated if induced travel impacts are not considered.

Litman (2001) studied the importance of comprehensive economic evaluation techniques in transportation for planning and optimal decision making between different alternatives. Study described planning process, framework for evaluating different alternatives and types of economic analysis techniques. Economic analysis techniques include cost-effectiveness analysis, benefit-cost and net benefit analysis, life cycle cost analysis and multiple accounts evaluation. Study also described importance of normalized measurement units for alternative comparison, general steps involved in the comprehensive economic evaluation, important issues to be considered in economic evaluation performance, uncertainty in the estimation of benefits and costs and economic evaluation perspective. The author used hypothetical travel demand management examples to recognize all the above mentioned techniques and issues.

Corvero (2001) introduced hypothesized near-term and longer-term path models between supply, demand, benefit and activity development to analyze the effects of road expansion on urban growth and travel demand. These hypothesized path models were empirically tested through log linear functional form specification. Road improvement data and land-use additions data were taken from California department of transportation (Caltrans) and US. Census Bureau respectively for 24 California freeway projects across 15 years (1980-1994). The variables included in the analysis were (1) lane-mile proportion (2) vehicle mile travelled proportion, (3) employment density (4) population density (5) operating speed (6) black population proportion (7) Hispanic population proportion (8) building activity and (9) personal income. For near-term path analysis two models were tested by using operating speed and induced travel as dependent variables. For longer-term path analysis five models were tested by taking operating speed, induced travel, induced growth, building activity and induced investment as dependent variables. It was revealed from near-term model outputs that highway capacity increment result in higher operating speeds and induced travel demand elasticity of 0.24 was estimated. The outputs of long-term model showed that it takes about 5 to 6 years for activity development and VMT growth to respond to addition of lane miles and further 2 years to influence freeway investment feeds back due to VMT growth. Long-term path models accounted for 55% association between freeway expansion and VMT growth. For long-term model induced travel demand elasticity of 0.637 was obtained, which was higher than near-term model (0.24).

Siethoff and Kockelman (2002) studied the effect of construction and completion time of freeway expansion, distance of corridor to parcel land, corner location and land use on the property valuation. Authors estimated three separate models (autoregressive structure of the first order (AR1)) using improvement value, land value and total value as dependent variables. Square feet of improvement, age of improvement, land uses, land area, time trend, number of years since right of way (ROW) acquisition, construction start and construction completion, distance from facility, corner with signal indicator and corner without signal indicator were used as independent variables. Parcel-level land and improvement value data over an 18 year period (1982-1999) for the US 183 corridor in northwest Austin, Texas were taken from Travis Central Appraisal District (TCAD) records (TCAD, 2000). US 183 corridor used for the analysis expanded almost 200% from its initial capacity from 1992 to 1998. Model results revealed that timing of freeway expansion, proximity of corridor to the parcel land, corner location, size of property and land use have positive and significant association with property valuation. The study also suggested that early ROW acquisition action taken by highway agencies would result in efficient investment savings.

Zhao et al., (2004) developed a multistage stochastic model and solution algorithm based on Monte Carlo simulation and least squares regression for optimal decision making in highway development, expansion, operation and rehabilitation. Real options based approach had been incorporated in the model that accounts for three uncertainties i.e. traffic demand, land price and highway deterioration as well as their interdependence. The developed model and solution algorithm were demonstrated through numerical examples.

Polus and Pollatschek, (2004) developed a criteria for addition of lanes to rural two lane highways. Authors used delay equations and specifically developed simulation software i.e. Two-Lane-Sim to assess the delay and flow of vehicles on two lane rural roads. The accumulated delay over an analysis period of 20 years for unit length (1 km) was deducted to show its monetary value. This monetary value of delay cost was then compared to unit length (1 km) construction cost of adding two lanes. The average daily traffic volumes at the points when these two costs become equal were determined as threshold for widening of highway. The authors estimated range of benchmark two-way traffic volumes between 9000 to 12000 vehicles/day for roadway construction cost of US$300,000/km/lane for the year 2003.

Rodier (2004) developed regional land use and travel demand models based on the number of case studies. These models were integrated to induced travel model in order to represent induced travel effects due to expanded highway capacity. Land use, trip distribution, mode choice and traffic assignment were taken as induced travel model components. Sensitivity analysis was conducted by turning on and off model components to assess the contribution of each model component in induce travel demand model. The results indicated that benefits and negative environmental impacts of highway expansion project would be overstated and understated respectively without the representation of induced travel in travel demand and land use models.

Yu and Lo (2005) presented a time dependent construction social costs (COSCO) model in order to quantify the social costs i.e. traffic, environmental and business during the construction phase of highway project. The authors developed the COSCO model based on several assumptions through the integration of traffic, environmental and business impact costs by taking COSCO as dependent variable. Real data of highway expansion project from Hsinchu County in Taiwan were used for the demonstration of the integrated COSCO model. The authors also discussed the importance and potential applications of COSCO model. The results of COSCO model using field data revealed that social costs during construction were about 5.52 times more than construction costs. However, study followed to incorporate psychological, visual, aesthetic, accident, and water waste costs.

Organization for economic cooperation and development (OECD) and European conference of ministers of transport (ECMT) addressed the issue of urban traffic congestion in the report “Managing Urban Traffic Congestion – 2007”. The report addressed some general concepts about congestion i.e. congestion definition, congestion measurement and congestion categorization. The study also addressed congestion impacts, provided conceptual frameworks to assess the congestion impacts and suggested efficient congestion management strategies. The key findings of the report were to putts forward research based, policy oriented recommendations to effectively manage urban traffic congestion.

Williams-Derry (2007) from the Sightline Institute roughly estimated the change in green-house gas emissions due to highway expansion using spread sheet model. The study results revealed that over short time period (5 to 10 years) expansion of highway would result in lower green-house gas emissions, and green-house gas emissions would be higher over the long period due to induced traffic.

Gillen (2007) studied use of Intelligent Transportation System (ITS) technology and road pricing schemes for congestion management. The author classified the road pricing schemes into three broad categories: (1) facility based schemes (2) area based schemes and (3) network based schemes. Each scheme had three objectives: (1) to increase the efficiency of congested facilities (2) environmental impacts reduction and (3) revenue generation. This study also discussed ITS classification, ITS components and analysis of ITS application framework for congestion management. The study findings suggested that it is necessary to implement ITS technologies in road pricing schemes due to complexity of toll collection systems to manage the congestion efficiently.

Lewis (2008) proposed various options for solving the America's traffic congestion problem through a nationwide reform. Fundamental reform were proposed for congestion pricing at federal and local level in a sense that congestion mirror real economic costs and revenue generated from congestion pricing can be used later for capacity expansion. Reforms were necessary for the development of an effective, efficient and sustainable highway system.

Fields et al., (2009) analyzed the problem of severe congestion through capacity expansion using Atlanta State case study. Authors modeled additional lane-miles needed for Atlanta from 2005 to 2030 to relief congestion using Atlanta regional commission (ARC) data. Authors identified and analyzed four innovative capacity expansion project types which include: (1) express toll net-work (2) north-south tunnel (3) Lakewood tunnel and freeway extension and (4) toll truck way system from Atlanta. It was concluded from the analysis that capacity expansion with express toll net-work provided better congestion relief with maximum revenue generation.

A recent SHRP study (SHRP, 2009) proposed a systems-based performance measurement collaborative decision making framework for highway capacity enhancement. The proposed framework emphasized on use of different performance measurements that can be used by department of transportation (DOTs) to address the frequently faced problems in highway expansion projects.

Jiwattanakulpaisarn et al., (2009) analyzed the effect of highway capacity expansion on economic productivity of private sector in US. Private sector output data, labour input data, private capital stock data, roadway lane-miles data and population data were obtained from Bureau of Economic Analysis (BEA), Regional Economic Information System (REIS) of BEA, BEA national stock estimates, Highway Statistic series published by US Federal Highway Administration (FHWA) and REIS respectively for 48 US states from 1984 to 2005 and were used for the analysis purpose. Authors used first order distributed lag (ARDL) model in the dynamic specification for estimating the changes in states economic productivity due to highway infrastructure improvement. Private sector output was taken as dependent variable and private capital stock, private labour input and a variable "g" to capture the effect of highway improvement were used as independent variables. It was revealed from the model outputs that all variables are positively and significantly associated with private sector output in long run but in short run analysis the effect of highway improvement was found insignificant. The analysis was also performed by disaggregating the data of road networks by types and it was revealed that lane-mile addition to interstates would result in more economic productivity than other types of road networks. Authors concluded from the estimates that roadway capacity increment takes about decade to respond to private sector output and productivity benefits are insignificant.

Transportation Research Board (TRB) and Strategic Highway Research Program (SHRP), (2009) prepared a comprehensive report that covered collaborative decision making framework in order to support decision making within existing laws and regulations. Twenty three case studies ranging from simple bridge reconstruction to a full corridor-wide planning program of successful collaborative decision making have been discussed. The report also discussed the project success factors and barriers that agencies frequently face. The research findings highlighted that systematic institutionalization of collaborative decision making is essential for delivering necessary capacity due to increased environmental and community integration.

Bai et al., (2010) presented a methodology to optimize the number of lanes construction on an urban arterial by establishing an objective function of minimum total cost i.e. lane construction cost, appended cost and delay cost. The results using case study from Huaibei city of China suggested that decision maker should consider both indirect user delay cost and direct capital construction costs over the entire analysis period for each alternative.

Kandil et al., (2010) investigated optimal user and agency costs trade-off decision as a function of starting time and length of construction workzones. Authors developed a multi objective optimization model using both agency and user cost calculation parameters in order to get optimal trade-off between agency and user costs. Multi objective genetic algorithm was utilized to obtain optimum trade-off between agency and user costs as a function of starting time and length of workzone. The algorithm was applied to an artificial four lane highway problem in which one lane in one of two directions was closed. It was revealed that workzone length of 0.35 km and starting time of 08:00 AM would result in minimum agency and user costs. It was also highlighted that there are many other such optimal decision points based on starting time and length of workzone using developed model and algorithm.

Sinha et al., (2011) carried out a theoretical study that investigated highway up-gradation decision making for three different alternatives (do nothing, addition of lanes to existing highway and construction of new expressway) on the basis of benchmark traffic volume. Using historical traffic volume data from state of Indiana (USA) it was revealed that, an average benchmark traffic volume for 4-lanes major arterials to be widened to 6-lanes or upgraded to expressway have a range between 18,000 to 20,000 vehicles/day.

Jian Lu et al., (2011) developed a real options valuation model to determine likelihood distribution of optimal highway expansion timing using least squares monto-carlo simulation technique. The authors also incorporated the traffic demand uncertainty in the model. The developed model was applied to real highway expansion project (4-lanes to 6-lanes) in China using analysis period from 2000 to 2020. The results suggested that likelihood of highway expansion was higher from 2008 to 2014 and decreases from

2014 onwards due to less highway remaining life cycle. The sensitivity analysis for traffic growth rate of 5% and 15% was carried out and revealed that increase in traffic demand volatility would result in earlier highway expansion.

Kahn and Levinson (2011) discussed the America's highway infrastructure priorities based on economic policy using data from Hamilton project. For efficient and systematic highway investment decisions and to manage the congestion efficiently three major recommendations of the study are: (1) funds are allocated to all major programs by state department of transportation and primarily dedicated to improve the existing highway infrastructure (2) funding should be dedicated to new construction or expansion actions based on the user costs and (3) there should be some performance standards or thresholds for each project and subsides should be rewarded to only those projects that meet performance standards.

Michael and Levinson (2012) analyzed the effect of highway expansion on industry level earnings and local employment level. Authors developed OLS regression models (natural log linear specification) for industry level earnings and local employment level by taking earnings in a given industry in county "i" at time "t" and total private sector employment in city "i" at time "t" as dependent variables respectively. Real GDP at time "t", state level earnings in a given industry at time "t", population in county "i" at time "t" and county indicator variable were used as explanatory variables for industry level earning model. Population in county "i" at time "t", real per capita income in city "i" at time "t" and highway indicator variable were used as explanatory variables for local employment level model. Case studies included in the analysis were: (1) expansion of Minnesota TH 371 (2) expansion of US 71 (3) Minnesota TH 23 and (4) expansion of US highway 53. The data for industrial level earnings from 1991 to 2009 were obtained from Bureau of Economic Analysis (BEA) and local employment level data from 2000 to 2011 were obtained from Quarterly Census of Employment and Wages (QCEW). It was concluded from the model outputs that there was no significant impact of highway expansion on earnings and employment. The authors suggested that user benefits (travel time savings, safety benefits etc.) should be evaluated as core justification for highway expansion.

Yang (2012) proposed a methodology using nested Markov decision process (NMDP) to obtain the joint optimal pavement maintenance and capacity enhancement decisions. The author considered agency, user delay and vehicle operating cost to demonstrate the applicability of developed framework for a hypothetical road segment. For simplicity the author did not consider the workzone user delay cost.

Vidya et al., (2012) studied the impact of highway expansion workzones on vehicle speed variation. Authors analyzed the speed variation in advance warning, transition area, activity area, and terminal area. Four stages of construction were considered: (1) stage-1 only shoulder extension with original two lanes open for traffic (2) stage-2 new lane construction with some part of original lane restricted to traffic (3) stage-3 second new lane construction with first new lane open and (4) stage-4 adjacent original lane restricted and all four lanes open. Real spot speed data for Thanjavur to Trichy highway (56.44 km) which was expanded from two lanes to four lanes were used to analyze the speed variation. Analysis of variance (ANOVA) tests were conducted to check the speed variation between advance warning zone and termination area. It was concluded from ANOVA test results that there is significant variation in mean speed between advance warning and termination area during stage-2 and stage-3 construction.

2.3 Factors affecting highway capacity expansion decision making

The decision to expand highway is influenced by many factors such as traffic volume, level of service and social, political, economic, and environmental factors (Sinha and Labi, 2007). All the possible factors that may affect highway expansion decision making are discussed in ensuing paragraphs.

2.3.1 Design Traffic Volume

Design traffic is an important factor that can affect highway expansion decision making. Design traffic volume is average daily traffic (ADT) projected to some future design year most often 20 years (TRB, 2000). If the traffic volume of a particular highway section approaches its design traffic volume before its design life completion its expansion should be warranted in order to meet design traffic volume in future. Every country has its own design traffic volume threshold based on no of lanes and road functional class set by their respective highway agencies. So when ever actual traffic volume exceeds threshold volume its expansion should be warranted. For example China has traffic volume threshold of 55,000veh/day for four lane freeway (Sinha et al., 2011).

2.3.2 Design level of service

Design level of service is another important factor that could affect the highway expansion decision similar to design traffic volume. Actually design level of service also depends upon traffic volume. Level of service is defined as qualitative measure of performance of highway in terms of speed, freedom to maneuver, comfort and convenience (TRB, 2000). Design level of service of a particular highway section is the minimum level of service it is designed for. When the actual level of service of a highway section becomes worse than its design level of service its expansion is warranted. Different countries uses their own design level of service symbols and set out their own design level of service threshold measures for different highway functional class. Threshold measures are defined as speed, maximum density, average speed, maximum volume to capacity (v/c) ratio and maximum service flow rate (Sinha et al., 2011).

2.3.3 Economic impact

Detailed economic analysis is necessary for highway expansion decision making. Economic analyses involve the conversion of all costs (agency and user) into monetary terms and assess the efficiency of each alternative from monetary stand point thus help in decision making (Sinha and Labi, 2007). There are various measures or criteria to evaluate economic efficiency of each alternative such as present worth of costs, equivalent uniform annual cost, equivalent uniform annual return, net present value, internal rate of return and benefit-cost ratio. By applying a suitable criteria to each alternative the best alternative can be selected (Sinha et al., 2011).

2.3.4 Environmental impact

Environmental impacts also affect the highway expansion decision making as highway expansion may involve additional right of way (ROW) acquisition and degradation of natural environment. Highway expansion may also affect the ecosystem due to destruction of wetlands and woodlands and community due to air and noise pollution and visual impacts. So it is important to check the environmental feasibility of the highway expansion project before its execution. If highway expansion is environmentally not feasible it should not be warranted even if design traffic volume or other factors warrant the expansion (Sinha et al., 2011).

2.3.5 Social and political considerations

Social and political considerations also affect highway expansion decision making. Social impacts refer to relocation of homes, businesses, recreational areas etc. due to additional ROW acquisition (FHWA, 1982). This relocation results in stresses generated in familiar neighbor hoods. Highway expansion could also disturb the social pattern of community due to separation of homes, businesses, schools and recreational areas (Sinha and Labi, 2007). Political considerations in addition with social impacts also affect the highway expansion decision making. Competition between different political parties, their power distribution in specific areas, party personal benefits and poverty alleviation also affect the highway expansion decision making (Sinha et al., 2011).

2.3.6 Other factors

Other factors that could affect highway expansion decision making include v/c ratio, travel time delay, and land use. Travel time delay and v/c ratio often matters when a highway section is facing severe congestion problems. Travel time delay and v/c ratio also depends upon traffic volume.

2.4 Chapter Summary and Conclusions

The detailed review of the literature and state of the art and practice regarding highway capacity expansion decision making, travel demand management through highway capacity expansion and highway capacity expansion after impacts revealed important aspects that provided information and guidance for the development of framework for highway capacity expansion decision making. The overall body of literature is characterized by the lack of comprehensive, performance-based framework for highway capacity expansion decision making.

Literature review showed that highway expansion should be warranted even if magnitude of induced travel is significant due to larger reductions in delays. Research findings indicate that highway capacity expansion results in reductions in travel delays, peak narrowing, and efficient congestion management. Systematically institutionalization of collaborative decision making, comprehensive economic evaluation, implementation of ITS technologies, and fundamental reform in congestion pricing are necessary for the development of efficient and sustainable highway system. Also past research has shown that user benefits (travel time savings, vehicle operating cost savings, and safety savings) are valuated as core justification for highway capacity expansion decision making. The major factors affecting highway capacity expansion decision making included: (1) design traffic volume (2) design level of service (3) economic impact (4) environmental impact and (5) social and political considerations. Highway expansion project should be economically, environmentally and socially feasible for its successful execution.

CHAPTER 3. STUDY FRAMEWORK

3.1 Introduction

In this chapter a framework is developed that can be used to determine an optimal time for highway capacity expansion in order to achieve optimal trade-off between both agency and user costs. In this thesis, the development of framework to determine optimal time for highway capacity expansion is based upon annualized agency and user costs estimation. To determine optimal time for highway capacity expansion the developed study framework include: basic framework information, estimation of total highway widening costs, estimation of total excessive user costs for do-nothing, determination of optimal time for highway capacity expansion based upon break-even point analysis, and mathematical formulation of the objective function followed by sensitivity analysis. Basic framework information includes definition of alternatives and assumptions made in the development of framework. The total widening costs comprise agency lane addition cost and workzone user delay cost, and total excessive user costs for do-nothing include excessive travel delay cost, excessive vehicle operating costs (VOC) and excessive crash cost.

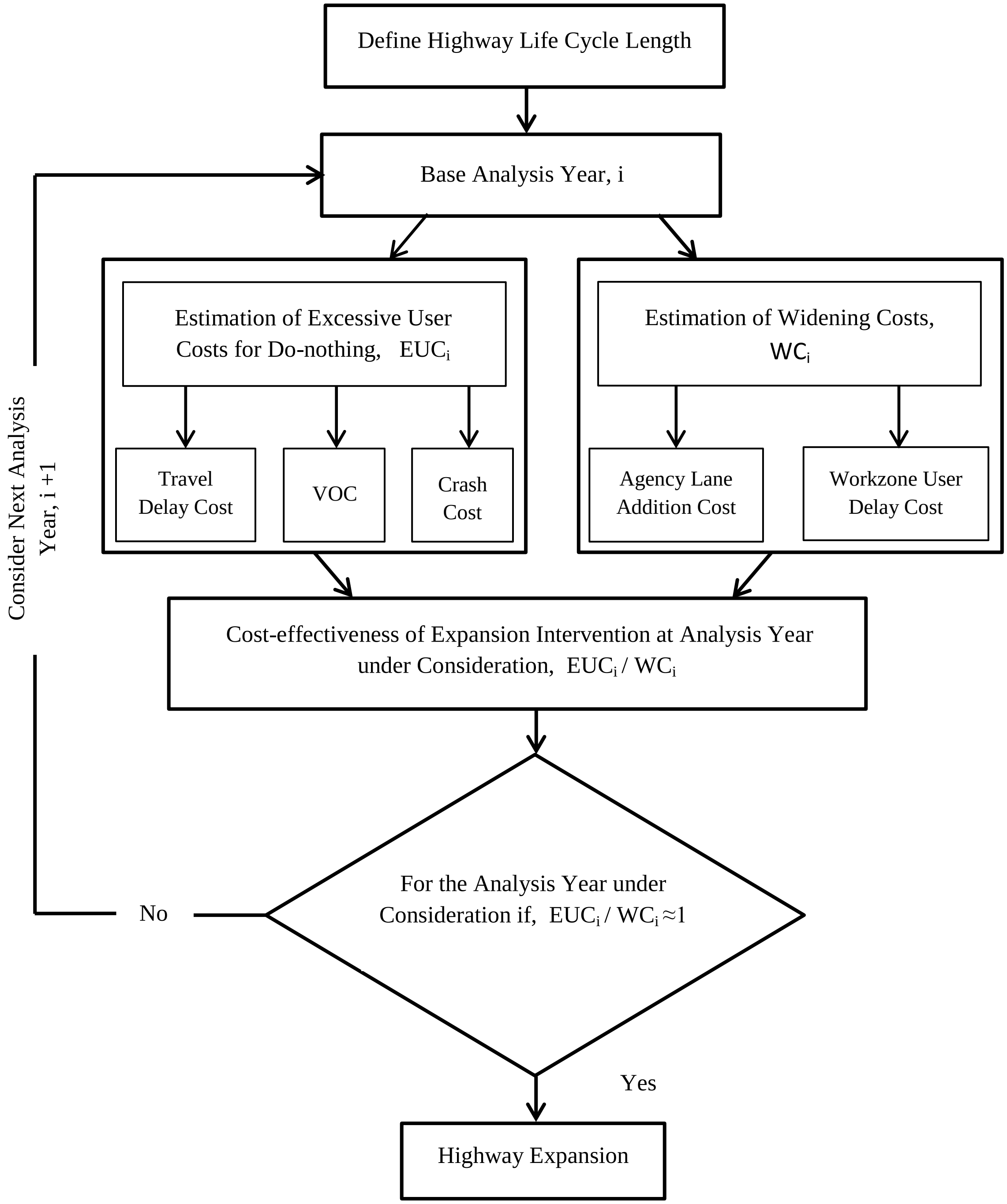

Figure 2 Analytical Framework for Optimal Highway Capacity Expansion Timing

3.2 Basic Framework Information

The proposed framework incorporates widening costs (agency lane addition cost and workzone user delay cost) and excessive user costs (travel time delay, vehicle operating and crash cost) for existing highway. These two costs i.e. widening costs and excessive user costs for existing highway were compared for each analysis year over the complete highway life cycle in order to find an optimal time for highway capacity expansion intervention. Two alternatives were selected and defined for the proposed framework:

Widening: Widening alternative is defined as adding lane(s) to an existing highway during its design life or analysis period in order to increase its physical capacity and to achieve better level of service. Widening does not change the class or type of highway facility and there is no change associated with access control rather it only accounts for user benefits in terms of speed, safety, comfort and convenience.

Do-nothing: Do-nothing alternative is defined as no action of expansion or widening is applied to highway during its life cycle or analysis period.

3.2.2 Assumptions made in the development of framework

For simplicity following assumptions are made for development of proposed framework.

- The analysis period or service life of highway facility is assumed to be 20 years.
- The highway facility is assumed to be widened or expanded only once within its service life and decision makers needs to find that specific point in time when it should be expanded.
- Traffic split on the lanes is assumed to be similar in proportion e.g. if existing highway with two lanes and contain ADT per lane of 10,000 vehicles/day is expanded to four lanes then after widening the ADT per lane would be 5000 vehicles/day.

3.3 Widening Costs Estimation

Widening or expansion of highway facility includes the two direct costs: (1) agency lane addition cost and (2) workzone user delay cost due to construction activity. Workzone user delay costs include the travel time cost and fuel consumption cost due to travel time delay. In this section we discuss the detailed methodology to compute widening costs.

3.3.1 Agency Lane Addition Cost Estimation

Agency costs in highway investment comprise all those costs that are directly incurred by highway agencies. These costs typically include project planning costs, preliminary design costs, ROW acquisition costs, initial construction costs, and future routine maintenance and rehabilitation costs etc. (Walls and Smith, 1998). In case of widening of highway only lane addition cost is considered. Using historical cost data on agency lane addition cost, base year agency lane addition cost can be estimated as follows:

$$C_{BY} = C_{RY} \times \frac{CPI_{BY}}{CPI_{RY}} \qquad (3.1)$$

Where C_{BY} is cost of intervention in the base year, C_{RY} is cost of intervention in the reference year, CPI_{BY} and CPI_{RY} are the construction price indexes for the base year and reference year respectively. Base year cost of agency lane addition intervention for one lane-km can be shifted to any analysis year within highway service life using time value of money concept as follows:

$$FWC_{\_LAC_n} = LAC_{BY} \times (1+r)^n \qquad (3.2)$$

Where FWC is future worth of cost, LAC_n is the lane addition cost for any future analysis year, LAC_{BY} is lane addition cost for base year, r is the real discount rate, and n is the analysis year.

3.3.2 Workzone User Delay Cost Estimation for Widening

Highway workzone is defined as an area or segment of highway in which maintenance and rehabilitation activities are carried out which affect the flow and operational characteristics of vehicles passing through that segment (HCM, 2000; MUTCD, 2009). Workzone activities result into operational costs due to travel time delay, and detouring of vehicles etc. Due to short duration of workzone activities, the operational cost reduction due to improvement of facility over its longer service life would outweighs the operational costs due to workzone activities (Sinha and Labi, 2007). Traffic impact costs due to workzone activities include fuel consumption cost, and travel time cost due to travel time delay and detouring costs of vehicles (Yu and Lo, 2005). In the proposed framework fuel consumption and travel time costs due to travel time delay are considered for widening alternative. Total workzone user cost due to travel time delay is given as follows:

$$WZ(UC) = \sum_{i=1}^{k} \left(V_i^{TT} + V_i^{FCC}\right) \times ADT_{EC} \times P_i^V \times TD \times WZ_D \tag{3.3}$$

Where WZ(UC) represent total workzone user delay cost per lane-km, k is the number of vehicle types, V_i^{TT} is the value of travel time for type i vehicle, V_i^{FCC} is the unit fuel consumption cost value for type i vehicle, ADT_{EC} is per lane average daily traffic for existing condition, P_i^V is the percentage of type i vehicles and TD is the travel time delay in hours, WZ_D is duration of workzone in days required to construct per lane-km roadway section.

a. Travel Time Delay (T) Estimation:

There are various methods for travel time estimation e.g. COMSIS Corporation method (COMSIS et all., 1995), direct field measurements of travel time (Roess et al., 2004) and using BPR function of Highway Capacity Manual (TRB, 2000). In this study Travel time delay is estimated using BPR function of Highway Capacity Manual (TRB, 2000). So expression for “T” can be written as:

$$TD = \sum_{d=1}^{24} P_0 \times \left\{1 + y \times \left(\frac{ADT_{EC} \times F_i^h}{C}\right)^z\right\} - P_0 \quad (3.4)$$

Where P_0 is the link travel time at free flow link speed, F_i^h is the percentage of vehicles in ith hour during a day, C is the per lane hourly design capacity of highway, and “y” and “z” are BPR parameters.

b. Workzone Duration (WZ_D) Estimation:

Workzone duration can be estimated using workzone duration model as a function of project cost, project type and contract type (Irfan et al., 2010). Also workzone duration may be assumed to be fixed percentage of the contract duration (Lamptey et al., 2005).

c. Workzone User Delay Cost per km Estimation for Widening:

Equation 3.3 can be used to estimate total workzone user delay cost due to highway construction of one lane-km. A number of preliminary calculations are made that are followed in a sequence and are explained herein. Per day per lane-km travel time delay in hours is estimated using Equation 3.4. Then Equation 3.3 is used to estimate per lane-km annual workzone user delay cost for widening using unit travel time and fuel consumption cost values.

Future workzone cost (FWC) due to user delay for widening, in analysis year “n” can be written as:

$$FWC_{\_WZ(UC)_n} = WZ(UC)_{BY} \times \{(1+g)^{z+1} \times (1+r)\}^n \quad (3.5)$$

Where g is the annual traffic growth rate and $WZ(UC)_{BY}$ is annual workzone user delay cost for the base year.

3.4 Excessive User Costs Estimation for Do-nothing

User costs contribute a significant part of overall transportation costs and depend upon highway physical and operational condition (Lamptey et al., 2005). In this study excessive travel delay cost, vehicle operating cost (VOC) and crash cost for do-nothing are computed for each successive analysis year within existing pavement life cycle. Separate excessive annual costs for do-nothing for both weekdays and weekends were computed due to change in travel pattern and hence traffic volume. These excessive user costs for do-nothing are converted to constant dollars using Consumer Price Index (CPI).

3.4.1 Excessive Travel Delay Cost Estimation for Do-nothing

Travel delay cost depends on highway capacity enhancement actions and can be represented as a function of travel speed and traffic demand. Travel delay cost is related to additional travel time that highway users spent on highway section compared to free flow travel time (Yang, 2012). Travel time cost mainly depends upon two components i.e. amount of travel time and value of travel time (VTPI, 2005). Travel delay time is defined as difference between actual travel time and travel time under free flow condition (Sinha et al., 2011). As discussed in section 3.2.2 traffic split on the lanes is assumed to be similar in proportion, so travel delay cost per lane-km for do-nothing would be greater than travel delay cost per lane-km for widening due to higher ADT per lane. Excessive travel delay cost per lane-km for do-nothing is the difference between travel delay cost per lane-km for do-nothing and widening alternative. Total annual travel delay cost is given as follows:

$$TDC(Total) = \sum_{i=1}^{K} V_i^{TT} \times P_i^{V} \times TD \times (260ADT_{WD} + 105ADT_{WND}) \qquad (3.6)$$

Where TDC is the annual travel delay cost per lane-km, ADT_{WD} and ADT_{WND} represents per lane average daily traffic on weekday and weekend respectively (260 and 105 represents annual weekdays and weekends respectively), and rest of the terms are same as defined previously.

a. Travel Time Delay (T) Estimation:

Travel time delay can be calculated using BPR function of Highway Capacity Manual (TRB, 2000). So expression for travel time delay can be written as:

$$TD = \sum_{d=1}^{24} P_0 \times \left\{1 + y \times \left(\frac{ADT \times F_i^h}{C}\right)^z\right\} - P_0 \quad (3.7)$$

Where ADT is per lane average daily traffic, C is the per lane hourly design capacity, and rest of the terms are defined previously.

b. Excessive Travel Delay Cost Estimation for Do-nothing:

Equation 3.6 is basically used to compute total annual excessive travel delay cost per lane-km for do-nothing. A number of preliminary calculations are made that are explained herein. Using Equation 3.7 first of all per day per lane-km travel time delay in hours is computed for both do-nothing and widening alternatives. After calculating total travel time delay in hour's Equation 3.6 is used to compute annual travel delay cost per lane-km for both alternatives. Excessive annual travel delay cost per lane-km for do-nothing is estimated as follows:

$$ETDC_{DN} = TDC_{DN} - TDC_W \quad (3.8)$$

Where $ETDC_{DN}$ is excessive annual travel delay cost for do-nothing, TCD_{DN} and TDC_W are the annual travel delay costs for do-nothing and widening alternatives respectively. This annual excessive travel delay cost per lane-km for do-nothing estimated for base year ($ETDC_{BY}$) can be shifted to any future analysis year "n" using equation as follows:

$$FWC_{-ETDC_n} = ETDC_{BY} \times \{(1+g)^{z+1} \times (1+r)\}^n \quad (3.9)$$

3.4.2 <u>Excessive Vehicle Operating Cost Estimation for Do-nothing</u>

VOC referred to those vehicle costs that varies with vehicle use and depends upon vehicle type, vehicle condition and highway physical and operational condition. VOC include fuel consumption, tires, maintenance and repairs, and shipping inventory costs etc. VOC components that are largely due to operational deficiencies of highway facility include fuel consumption and shipping inventory costs due to travel time delay (Sinha and Labi, 2007). In this study we considered fuel consumption and shipping inventory costs for VOC analysis as our analysis focused mainly on operational deficiencies of highway facility.

a. Excessive Fuel Consumption Cost Estimation for Do-nothing

Fuel consumption cost depends upon unit price of fuel and efficiency of fuel. Fuel efficiency depends upon vehicle class, vehicle condition and speed (AASHTO, 2003). Widening alternative would result in lower per lane-km fuel consumption cost than do-nothing alternative due to less ADT per lane and hence higher operating speed. Annual fuel consumption cost is given by the following expression:

$$FUC = \sum_{i=1}^{K} V_i^{FCC} \times P_i^V \times TD \times (260ADT_{WD} + 105ADT_{WND}) \tag{3.10}$$

Where FUC is the total annual fuel consumption cost, V_i^{FCC} is the unit monetary value of fuel consumption cost, and rests of terms are same as defined previously. The expression can be used to estimate annual fuel consumption cost for both alternatives by substituting the value of "TD" from Equation 3.7 in 3.10.

$$FUC = \sum_{i=1}^{K} V_i^{FCC} \times P_i^V \times \left\{ \sum_{j=1}^{24} \frac{L}{S_0} \times y \times \left(\frac{ADT \times F_i^h}{C} \right)^z \right\} \times (260ADT_{WD} + 105ADT_{WND}) \tag{3.11}$$

b. Excessive Fuel Consumption Cost Estimation for Do-nothing:

Using Equation 3.11 annual fuel consumption cost per lane-km is estimated for both do-nothing and widening alternatives. Annual excessive fuel consumption cost per lane-km for do-nothing is estimated by subtracting total annual fuel consumption cost per lane-km of widening from do-nothing alternative and is expressed as follows:

$$EFUC_{DN} = FUC_{DN} - FUC_W \tag{3.12}$$

Where $EFUC_{DN}$ is total annual excessive fuel consumption cost for do-nothing, FUC_{DN} and FUC_W are the total annual fuel consumption cost for do-nothing and widening alternatives respectively. Annual excessive fuel consumption cost per lane-km for do-nothing can be estimated for any future analysis year "n" using equation as follows:

$$FWC_{\_EFUC_n} = EFUC_{BY} \times \{(1+g)^{z+1} \times (1+r)\}^n \tag{3.13}$$

c. Excessive Shipping Inventory Cost Estimation for Do-nothing

Shipping inventory cost is associated with commercial vehicles during freight transportation. Inventory cost of cargo per vehicle kilometer traveled should be used to compute unit user cost associated with cargo carrying commercial vehicles. The VOC components that significantly affect the shipping inventory cost are delay and cargo value. Also interest rate has a direct relationship with shipping inventory cost (AASHTO, 2003). Widening alternative would result in higher operating speed of commercial traffic due to less ADT per lane and hence resulting in lower shipping inventory cost than that for do-nothing. Total shipping inventory cost for commercial vehicles due to delay is given as:

$$SIC = 100 \times \left(\frac{r}{365 \times 24}\right) \times ADT_C \times TD_C \times CV \times (365) \tag{3.14}$$

Where SIC is the total annual shipping inventory cost, ADT_C is average number of commercial vehicles per day per lane, TD_C is travel time delay for commercial vehicles, r is the interest rate, and CV represents cargo value.

d. Travel Time Delay (T_C) Estimation for commercial vehicles:

Travel time delay for commercial vehicles is calculated by using BPR function of Highway Capacity Manual (TRB, 2000). So expression for travel time delay estimation is as follows:

$$T_C = \sum_{j=1}^{24} P_0 \times y \times \left(\frac{ADT_C \times F_i^h}{C} \right)^z \tag{3.15}$$

e. Excessive Shipping Inventory Cost Estimation for Do-nothing:

Annual shipping inventory cost per lane-km for commercial vehicles is estimated for both alternatives using Equation 3.14. Travel time delay per day for commercial vehicles is estimated using Equation 3.15. Annual excessive shipping inventory cost per lane-km for do-nothing is estimated using expression as follows:

$$ESIC_{DN} = SIC_{DN} - SIC_W \tag{3.16}$$

Where $ESIC_{DN}$ is the total annual excessive shipping inventory cost for do-nothing, SIC_{DN} and SIC_W are the annual shipping inventory cost for do-nothing and widening alternatives respectively. Expression for estimating annual excessive shipping inventory cost for do-nothing for any future analysis year is given as:

$$FWC_{\_ESIC_n} = ESIC_{BY} \times \{(1+g)^{z+1} \times (1+r)\}^n \tag{3.17}$$

3.4.3 Excessive Crash Cost Estimation for Do-nothing

Crash cost is also one of the major components of user cost and its value depends upon average unit crash cost and crash rate (Lamptey et al., 2005). Unit crash cost depends on crash severity (fatality, injury and property damage) with fatality having the highest unit crash cost and property damage having the lowest (National Safety Council, 2001). Crash rate have the inverse relationship with highway physical and operational condition and also depends upon highway geometry, and traffic conflicts etc. (Sinha and Labi, 2007). In this study for highway expansion scenario, crash rate decreases with widening of highway due to operational improvements. Harkey et al., (2004) recommended crash reduction factors for addition of lanes to existing highway. Total annual crash cost for do-nothing alternative is given as follows:

$$CC = \sum_{x=1}^{s} V_R^{CC} \times C_R \times (260ADT_{WD} + 105ADT_{WND}) \times 1.6 \times 10^{-8} \tag{3.18}$$

Where CC is total annual crash cost for do-nothing, s is number of crash types by severity, V_R^{CC} is unit crash cost for type R crashes, C_R is crash rate for type R crashes in crash count per 100 million vehicle kilometers traveled.

a. Excessive Crash Cost per km Estimation for Do-nothing:

Equation 3.18 is used to estimate total annual cash cost per lane-km for do-nothing. Annual crash costs per lane-km for individual crash types are added up to obtain total annual crash cost per lane-km for do-nothing. Total annual excessive crash cost per lane-km for do-nothing is estimated by multiplying annual crash cost per lane-km for do-nothing with crash reduction factor due to widening.

For simplicity lets denote base year annual excessive crash cost per lane-km for do-nothing as ECC_{BY} than annual excessive crash cost per lane-km for do-nothing scenario for any future analysis year "n" can be written as:

$$FWC_{-ECC_n} = ECC_{BY} \times \{(1+g) \times (1+r)\}^n \tag{3.19}$$

3.5 <u>Optimal Time for Highway Capacity Expansion Intervention</u>

In the proposed framework total widening costs (agency lane addition cost and workzone user delay cost) and total excessive user costs for do-nothing (excessive travel delay cost, excessive VOC and excessive crash cost) are estimated for each analysis year within highway life cycle. These total widening costs and excessive user costs for do-nothing are represented as a function of ADT corresponding to each analysis year. The reason to express these costs as a function of ADT of the analysis year is because ever increasing ADT is the only dominant factor that warrants highway capacity expansion. Amalgamated total highway widening cost (lane addition cost and workzone user delay cost) and amalgamated total excessive user costs (excessive travel delay cost, VOC and crash cost) for do-nothing scenarios are plotted against analysis year (highway life cycle) on the same graph. The breakeven point between two cost categories is determined as the optimal time for highway capacity expansion intervention.

3.6 Mathematical formulation of the objective function

The objective of the study is to develop a methodology that would help decision makers to determine optimal time for highway capacity expansion in order to achieve optimal trade-off between agency and user costs. An objective function is developed in this section that takes into account total excessive user costs for do-nothing and total widening costs. It is sought to determine the point in time when total excessive user costs for do-nothing becomes equal to total widening costs, thus ratio between total excessive user costs for do-nothing and total widening costs approximately equal to one is the threshold value of the objective function. Thus the overall objective function is as follows:

$$Z = \left\{\frac{(TEUC_{DN})}{(R_W \times ALAC_W + WUC_W)}\right\} \approx 1 \tag{3.20}$$

Where Z is objective function, $TEUC_{DN}$ is the total excessive user cost for do-nothing, R_W is relative weight of agency to user cost, $ALAC_W$ and WUC_W are the agency lane addition cost and workzone user delay cost respectively for widening alternative. A low value of Z would result in extra agency cost (too early expansion) and value too greater than one would result in excessive user cost.

3.8 Chapter Summary and Conclusions

This chapter presented the framework for determining the optimal time for highway capacity expansion. Two alternatives i.e. do-nothing and widening were defined in proposed framework and for simplicity assumptions were made in the development of the framework. Annualized agency and user costs estimation have been used as a basic case scenario to develop the proposed framework. Detailed formulations have been developed in order to compute total widening costs (agency lane addition cost and workzone user delay cost) and total excessive user costs (excessive travel delay cost, excessive VOC and excessive crash cost) for do-nothing. After computing total costs for both alternatives break-even point analysis was used to determine optimal time for highway capacity expansion.

CHAPTER 4. DEMONSTRATION OF STUDY FRAMEWORK THROUGH CASE-STUDY

4.1 Case study Basic Information

A dramatic increase in vehicle growth has been observed in urban areas of Pakistan in last few years resulting in an increased travel demand. Existing highways in most of the urban areas of Pakistan are not capable of providing reliable level of service due to rapid motorization and relatively slow growth in highway infrastructure (ESP, 2012). In this study a portion of major arterial "Islamabad Highway" (divided highway with 2-lanes each sides) connecting twin cities of Rawalpindi and Islamabad is selected to demonstrate the applicability of proposed framework. A 12.5 km long segment of Islamabad highway from Airport Chowk to the intersection of Islamabad Highway with Grand Trunk Road is considered for case study. Due to rapid urbanization and development of new housing units e.g. Bahria town, Pakistan town, Public Works Department (PWD) town, Korang town etc. alongside the highway an increase in traffic volume has been observed. The highway which was initially constructed in year 1967 underwent a major rehabilitation work in year 2003. Highway has wide grass median (18ft to 20ft) and inner and outer shoulders on both sides with estimated free flow speed of 70 km/hr.

The proposed methodology (Figure 1) can be applied for any number of lane(s) additions. Case study addition of two lanes on each side (up gradation from 4-lanes divided highway to 8-lanes divided highway) is demonstrated. The case study results were used to identify the optimal highway expansion intervention time and to quantify the excessive user costs that are incurred due to non-optimal decisions.

4.2 Data

Data required to demonstrate the proposed framework comprised basic project data, agency cost data and user cost data. Basic project data include maintenance history of highway facility, hourly design capacity of roadway section, right of way acquisition

(ROW), and design speed of roadway section. Agency cost data include unit lane addition cost.

In order to estimate user costs for both alternatives data needed include (1) average annual daily traffic along with annual growth rates, (2) percentage of each type of vehicle on the highway facility, (3) twenty four hour traffic distribution, (4) unit travel time cost for each type of vehicle, (5) unit fuel consumption cost for each type of vehicle, (6) crash rate for each type of crashes, and (7) unit crash cost for each type of crashes.

4.3 Case Study - Widening Costs Estimation

As discussed in the previous section that widening of highway section resulted in two types of direct costs: (1) Agency lane(s) addition cost and (2) Workzone user delay cost. We will estimate these two types of costs separately in the following subsections.

4.3.1 Case Study - Agency Lane Addition Cost Estimation

Initial lane addition cost was estimated for the base year (2003 constant $) and all future analysis years (2003-2022). Lane addition cost per lane-km for base year (2003 constant $) was estimated to be $0.22 million (NHA annual maintenance plan, 2003). Future year lane addition costs were estimated using 4% real discount rate. Figure 3 shows the relationship between initial lane addition cost and analysis year.

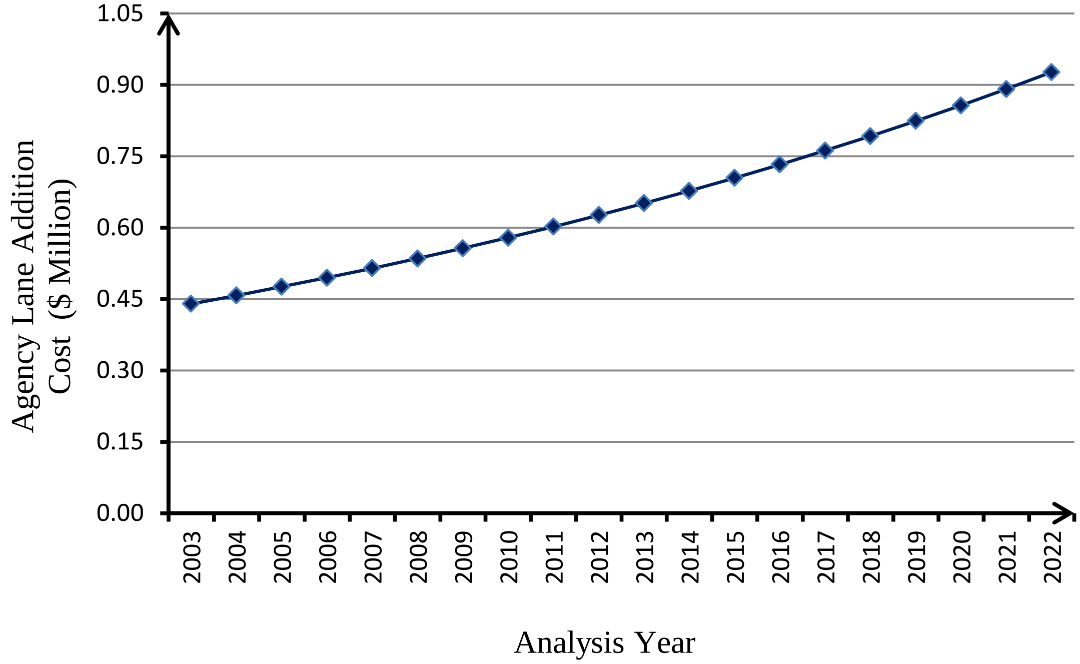

Figure 3 Variation of Initial Lane Addition Cost during Highway Life Cycle

4.2.2. Case Study - Workzone User Delay Cost Estimation

During widening highway users suffer from travel time delay and excessive fuel consumption costs due to workzone activity. Workzone duration, unit travel time and unit fuel consumption cost values data are needed to estimate workzone user delay cost. Following Lamptey et al., (2005) this study assumed workzone duration as 65% of the contract duration. Historical contract duration data for different highway construction projects was obtained from National Highway Authority (NHA) pavement management section (NHA, 2012) and is shown in Table 1. Average workzone duration per lane-km addition is estimated to be 10 days. ADT data for this highway section obtained from NHA and is given in Table 2.

Table 1 Contract Duration of Different Highway Construction Projects

Sr. No	Project	Nature of Project	Province	Lanes	Project Length (KM)	Contract Duration (Days)
1	Islamabad - Peshawar Motorway (M-1) (N)	Construction	Punjab	4	154	6878
2	Takht Bhai - Shergarh - Dargai Section	Construction	KPK	4	30	1706
3	D.I. Khan-Zam Tower-Mughal Kot (N-50)	Construction	KPK	4	124	5296
4	Darra Adam Khel - Badha Bher (ICB-3)	Construction	KPK	4	24	2074
5	Zahir Pir-TMP, Section-1 (N)	Construction	Punjab	4	45	4748
6	Pleri-Gabd Section	Construction	Balochistan	4	34.6	3530
7	Khuzdar-Shahdadkot sec-4 (Package-5)	Construction	Balochistan	4	55.77	5114
8	Multan - Muzaffargarh (ICB-2)	Construction	Punjab	4	36.2	1216
9	Package-I: Gharo-Mirpur Sakro Road	Construction	Sindh	4	24	2498
10	Package-II: Mirpur Sakro-Garhho Road	Construction	Sindh	4	30	2374

Table 2 Traffic Count Data for Islamabad Highway

Sr. No	Time (Hours) From	To	Motorcycle	Car/Jeep	Hiace	Buses	Trucks	Trailor	Total	Percentage
1	7	8	351	886	229	35	60	5	1561	5.74%
2	8	9	449	1047	217	14	41	2	1818	6.69%
3	9	10	443	714	188	17	106	6	1468	5.41%
4	10	11	324	749	236	16	126	5	1451	5.34%
5	11	12	285	758	237	17	113	4	1409	5.18%
6	12	1	282	773	225	20	128	6	1428	5.26%
7	1	2	273	617	223	18	85	9	1216	4.47%
8	2	3	312	707	255	25	98	14	1397	5.14%
9	3	4	348	702	252	23	99	8	1423	5.24%
10	4	5	342	875	238	62	115	13	1631	6.00%
11	5	6	423	964	227	41	143	10	1797	6.61%
12	6	7	446	971	219	25	122	16	1784	6.56%
13	7	8	251	636	152	23	137	18	1197	4.40%
14	8	9	244	727	152	11	158	23	1294	4.76%
15	9	10	236	506	100	19	137	32	998	3.67%
16	10	11	185	491	88	14	158	29	936	3.44%
17	11	12	143	444	63	10	171	32	831	3.06%
18	12	1	96	333	53	11	185	38	679	2.50%
19	1	2	60	201	47	8	182	35	499	1.84%
20	2	3	35	150	36	7	158	28	386	1.42%
21	3	4	27	125	27	4	125	31	308	1.13%
22	4	5	29	170	29	5	104	22	336	1.24%
23	5	6	55	348	49	11	75	13	538	1.98%
24	6	7	125	507	72	23	59	8	794	2.92%
Total Traffic			5812	14402	3614	457	2885	405	27180	
%age of Total Traffic			21.38%	52.99%	13.30%	1.68%	10.62%	1.49%		

Unit travel time cost values for each vehicle class were obtained from Gwilliam, (1997) by taking average unit travel time cost values estimates of South East Asian countries. Unit travel time cost values for each vehicle class were converted to constant dollars (2003 constant $) using Consumer Price Index (CPI) values for Pakistan given in appendix A. Fuel consumption (litters) per hour of delay for each vehicle class were obtained from AASHTO, (2003). Unit fuel consumption cost (2003 constant $) were computed by multiplying corresponding vehicle class fuel (litters) consumption due to per hour delay with per litter fuel price (Detail Appendix D).

The BPR parameter values were obtained from Highway Capacity Manual (TRB, 2000). The values of these parameters depend on highway class and difference between free flow speed and speed at capacity. For this case study “a” and “b” have the values of 1.0 and 5.0 respectively for the estimation of workzone user delay cost.

Total workzone user delay cost estimated for two lanes-km addition (2003 constant $) is $0.025 million. Using 3% traffic growth rate and real discount rate of 4% workzone user delay cost was estimated over the entire analysis period. Figure 4 shows the relationship between workzone user delay cost for widening and analysis year.

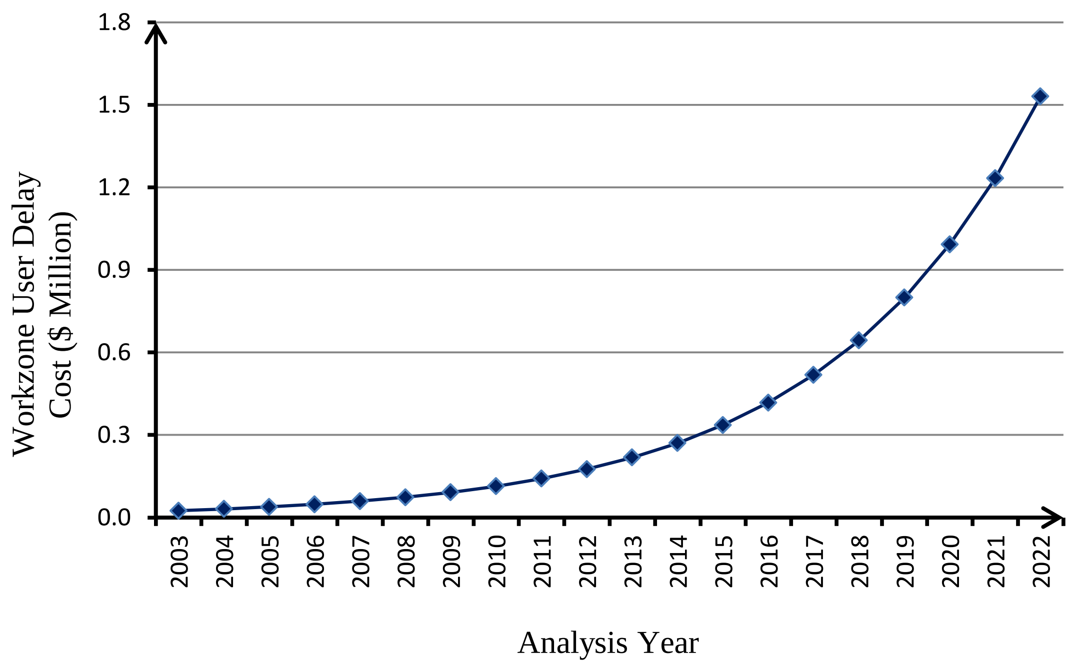

Figure 4 Variation of Workzone User Delay Cost for Widening during Highway Life Cycle

4.4 Case Study - Excessive User Cost Estimation for Do-nothing

Excessive travel delay cost, vehicle operating cost and crash cost for do-nothing scenario were computed for each successive analysis year within pavement life cycle. Different past studies have suggested weekend traffic as certain percentage of week day traffic. O'Fallon and Sullivan (2003) found weekend traffic as 73% of the weekday traffic. Similarly in another study weekend traffic volume was estimated to be approximately 70% of the weekday traffic volume (TTI, 2005). For this case study weekend traffic volume is assumed to be 70% of the weekday traffic volume.

4.4.1 Case Study - Excessive Travel Delay Cost Estimation for Do-nothing

Excessive travel delay cost for do-nothing is estimated by taking the difference between travel delay costs for do-nothing and widening. The same values of unit travel time cost (V_i^{TT}) in constant dollars (2003 constant $) for each vehicle class estimated for workzone user delay cost are used to estimate excessive travel delay cost for do-nothing. For the proposed case study the BPR parameters "a" and "b" have the values of 0.74 and 5.0 respectively for the excessive travel delay cost estimation.

Annual excessive travel delay cost for do-nothing at weekdays and weekends were estimated for the year 2003 (base year) and are given in Table 3. Excessive travel delay cost for the future years were estimated using 3% annual traffic growth rate and 4% real discount rate. Figure 5 represents the relationship between excessive travel delay cost for do-nothing and analysis year.

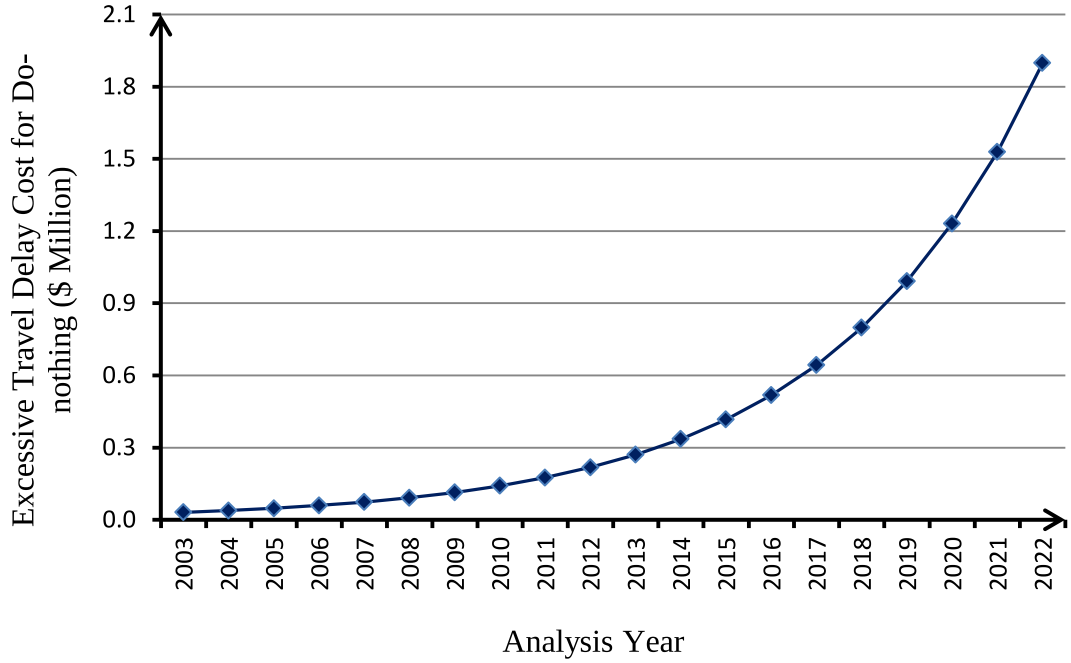

Figure 5 Variation of Excessive Travel Delay Cost for Do-nothing during Highway Life Cycle

4.4.2 Case Study - Excessive Vehicle Operating Cost Estimation for Do-nothing

Excessive vehicle operating cost for do-nothing is estimated in this subsection using case study data. Only fuel consumption cost due to travel time delay is considered for excessive vehicle operating cost for do-nothing due to non-availability of data for shipping inventory cost estimation. Annual excessive fuel consumption cost per km for do-nothing at weekdays and weekends in constant dollars (2003 constant $) for two lanes additions were estimated and are given in Table 3. Total annual excessive fuel consumption cost for the future analysis years is estimated using traffic growth rate (3%) and time value of money (4%) and is shown in Figure 6.

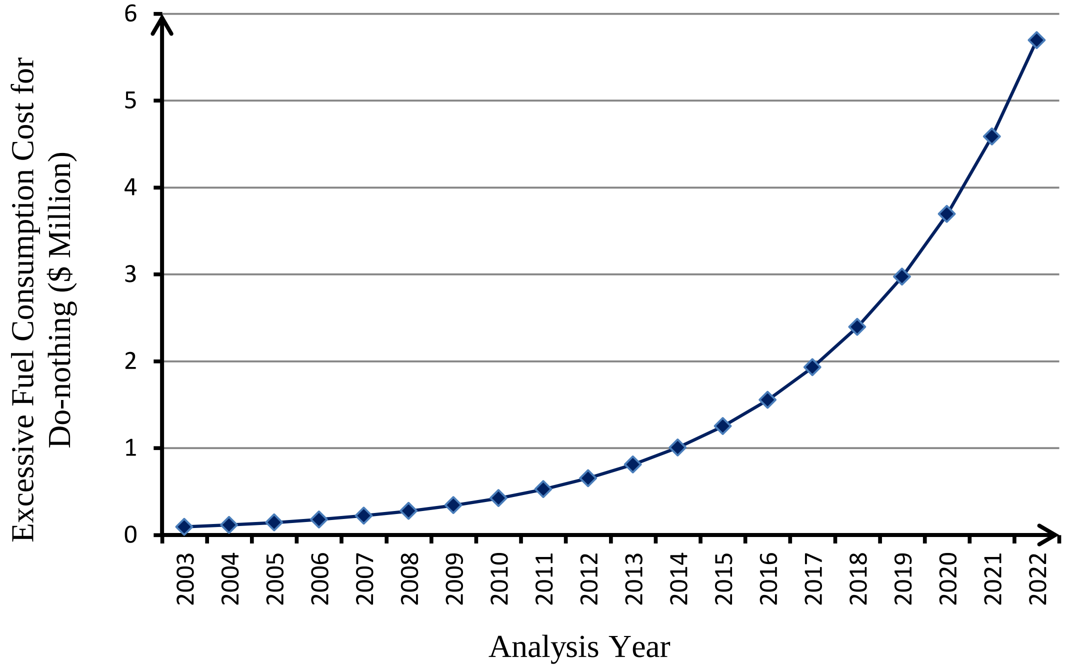

Figure 6 Variation of Excessive Fuel Consumption Cost for Do-nothing during Highway Life Cycle

Table 3 Annual Excessive User Costs for Do-nothing $Million (2003 Constant $)

Type of User Cost	Annual Cost at Weekdays ($ Million)	Annual Cost at Weekends ($ Million)	Total Annual Cost ($ Million)
Excessive Travel Delay Cost	0.029	0.0015	0.031
Excessive Fuel Consumption Cost	0.089	0.0043	0.093
Excessive Crash Cost	0.03	0.009	0.039

4.4.3 Case Study - Excessive Crash Cost Estimation for Do-nothing

Excessive crash cost for do-nothing or crash cost savings due to widening is estimated by multiplying crash cost for do-nothing with crash reduction factor of 0.46 for two lanes addition (Harkey et al., 2004). Unit crash cost values for fatality, injury and property damage are taken from NSC, (2001). An average value of incapacitating, injury evident and injury possible is taken as unit crash cost value for injury. These unit crash cost values for each crash type are multiplied with the ratio of GDP of Pakistan to US to obtain unit crash cost values for Pakistan. US to Pakistan GDP ratio of 70, 20 and 5 is estimated for fatality, injury and property damage respectively. Then these unit crash cost values of each crash type are converted to constant dollars (2003 constant $) using Consumer Price Index (CPI) values for Pakistan.

In this study due to non-availability of crash rate data for Pakistan, crash rates per 100 million VMT for each type of crashes are estimated from FHWA, (1998). Total annual excessive crash costs were estimated for the year 2003 and are enlisted in Table 3. Excessive crash cost for the future analysis year is estimated using 3% annual traffic growth rate and time value of money (4%) concept (illustrated Figure 7).

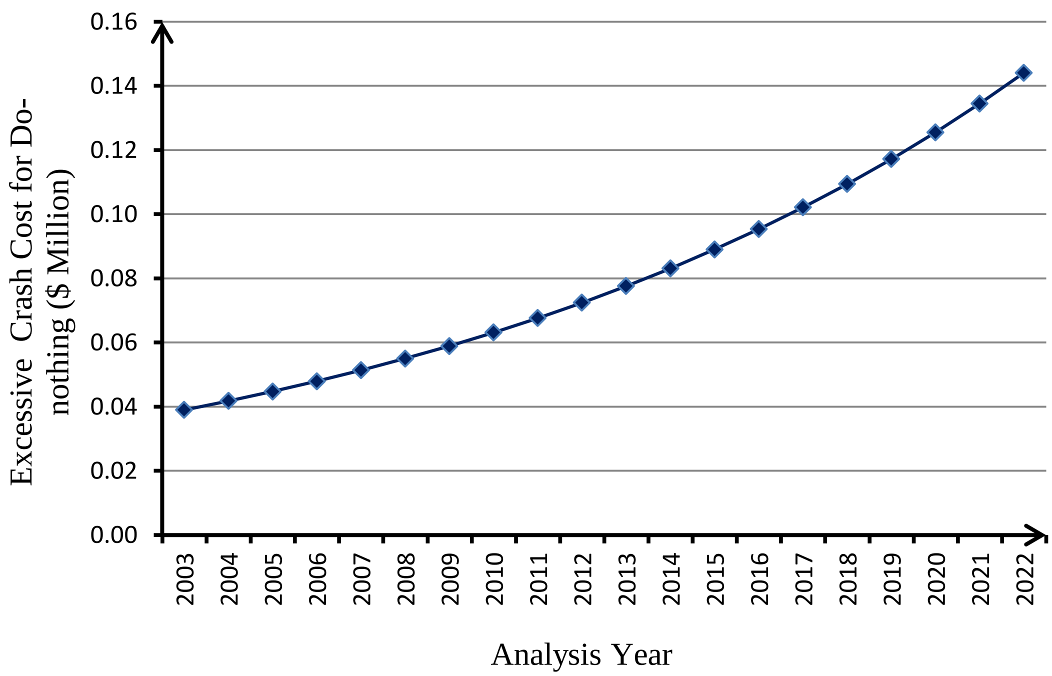

Figure 7 Variation of Excessive Crash Cost for Do-nothing during Highway Life Cycle

4.5 Optimal Time for the Case Study Highway Capacity Expansion

Figure 8 represents the relationship between amalgamated widening costs and amalgamated excessive user costs for do-nothing. In initial years highway is having relatively less traffic and therefore relatively lower user costs. Also, there is gradual increase is widening cost, however the user delay cost increases at very fast rate around year 2014. Expansion of highway before 2011 shall not bring major benefit to agency due to comparatively low excessive user cost (low travel demand), hence too early to add lane(s) to highway. From 2014 onwards if physical capacity of the highway is not enhanced, excessive user costs starts to increase at very fast rate, hence resulting in too late widening of highway. Thus the time period from 2011 to 2014 (between solid black lines) is the favored time for highway capacity expansion from existing 4-lanes to 8-lanes divided highway for the given case study and would result in optimal trade-off between agency and user costs.

As discussed in the previously that ADT or traffic volume is the most dominant factor that warrants highway capacity expansion. The methodology presented in present study can also be used by highway agencies to identify desirable range of traffic volume which warrant capacity addition for optimal decision making. For the highway section under consideration ADT ranging from 34430 to 37600 was found optimal for expansion from 4-lanes to 8-lanes divided highway.

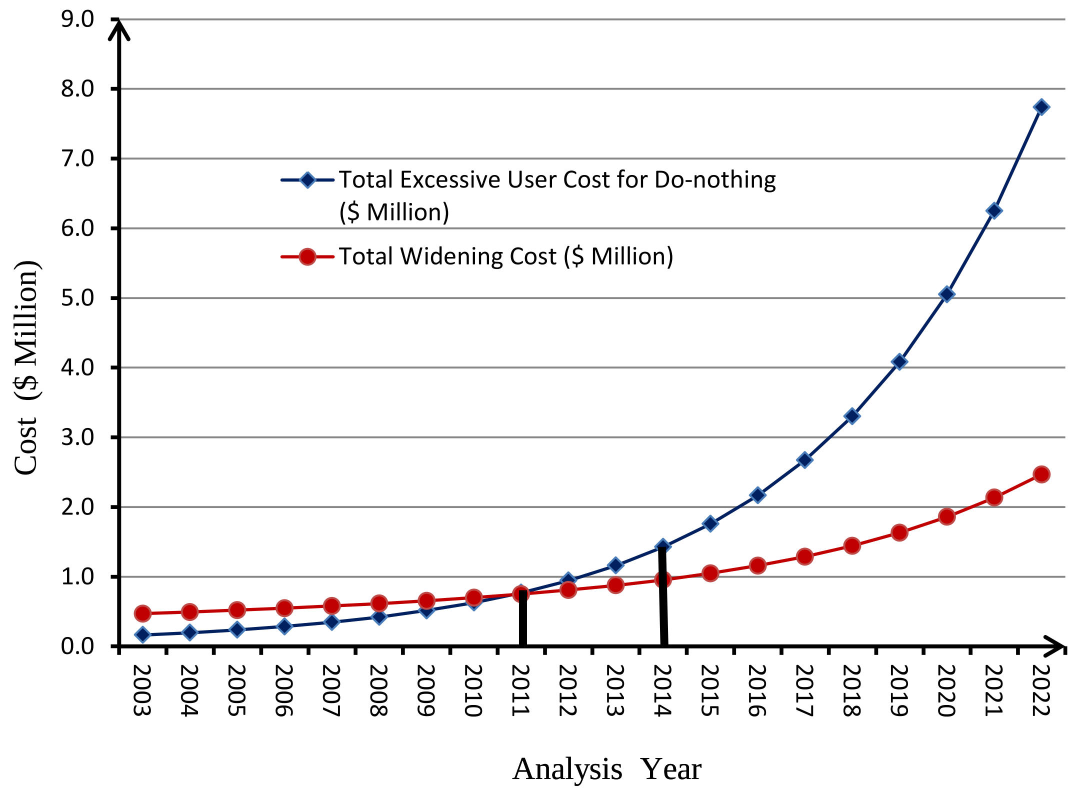

Figure 8 Optimal Time Range for Highway Capacity Expansion (Lane(s) Addition)

4.6 Sensitivity Analysis

Sensitivity analysis is a technique widely used by decision makers to check the robustness of optimal solution with different parameters and to identify the variables that are sensitive to optimal solution. Sensitivity analysis can be used to check the fitness of model results while making decisions (Saltelli et al., 2000). Sensitivity analysis is one of the most important and concerned areas in optimization. Sensitivity analysis is conducted to assess the changes in optimal value of the objective function due to changes in the input parameters as well as their validity ranges (Kavitha and Pandian, 2012). There are three broad categories of sensitivity analysis methods i.e. mathematical, statistical and graphical (Frey and Patel, 2002). Graphical method analyzes the sensitivity of different variables to optimal solution through graphs and charts. In this study graphical method of sensitivity analysis has been used to demonstrate the sensitivity of optimal time for highway expansion intervention with factors like different agency to user cost relative weights, time value of money (annual interest rate) and annual traffic growth rates.

Figures 9, 10 and 11 show the sensitivity of agency to user cost relative weight, annual traffic growth rate and annual interest rate with optimal highway expansion intervention time range respectively.

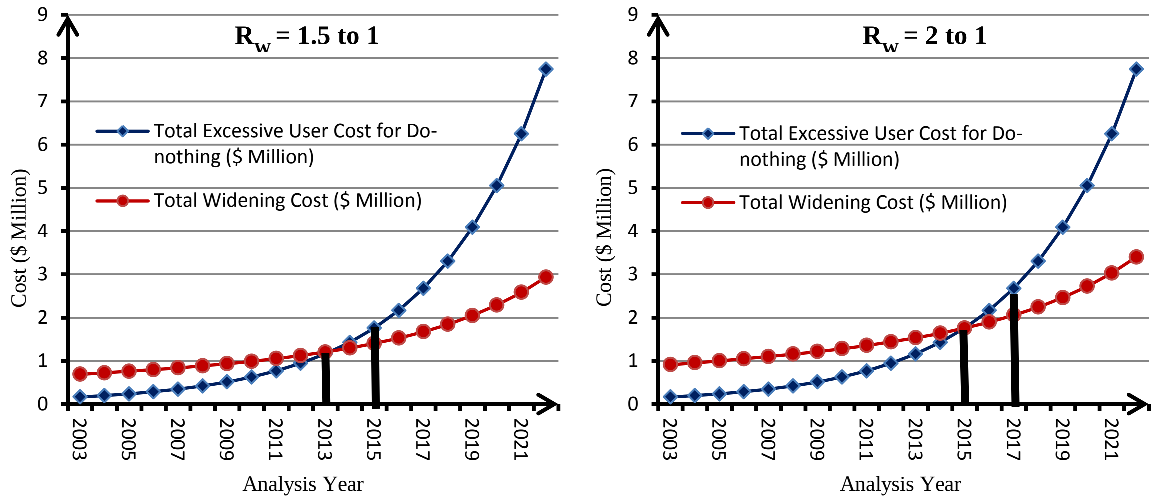

Figure 9 Variation of Optimal Highway Lane(s) Addition w.r.t Relative Weights of Agency to User Cost

Equivalent agency to user cost weight (1$ agency cost equivalent to 1$ user cost) was used in most past research (Darter et al., 1985; Peterson, 1985; Peshkin et al., 2004; Lamptey et al., 2004; Khurshid et al., 2010). However, literature reveal that instead of direct summation of these two costs by considering them equivalent, agency costs should be given more weightage as these are directly incurred by highway agencies while user costs are not as physically visible (Walls and Smith, 1998; FHWA, 2002; Lamptey, 2004; Labi and Sinha, 2005). Therefore a fraction of user to agency cost during alternative projects evaluation should be used (Lamptey, 2004). It is evident (Figure 9) that increase in agency to user cost relative weight would result in shifting of optimal tradeoff point to later years i.e. shifting optimal time range two years and four years later for agency to user cost relative weight of 1.5 and 2 respectively. This finding is quite intuitive as with increase in relative agency cost would lead the highway agencies to expand the highway later.

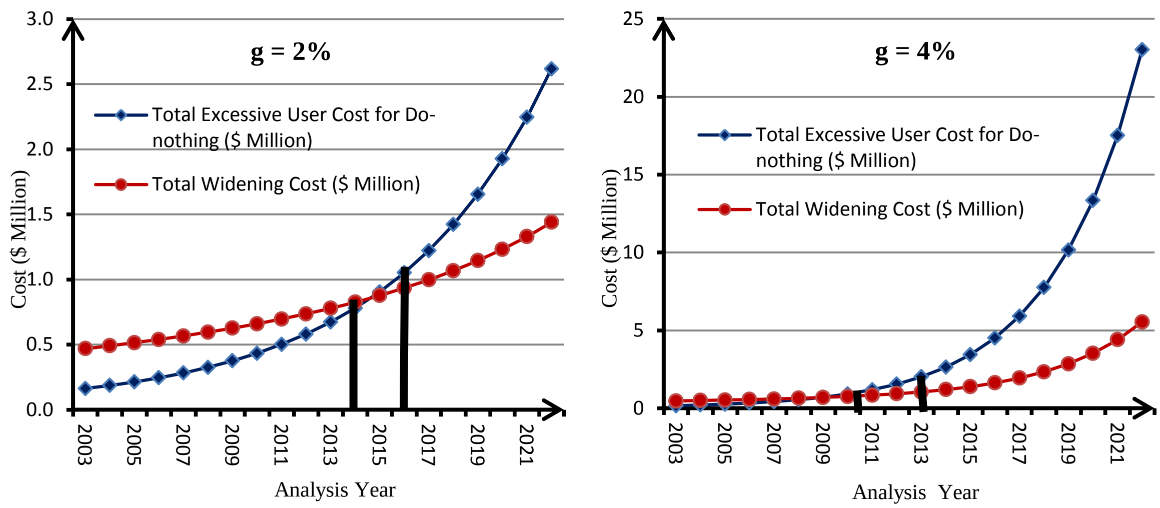

Figure 10 Variation of Optimal Highway Lane(s) Addition w.r.t Annual Traffic Growth Rate

The impact of traffic growth rate was also investigated in this paper (Figure 10). It was revealed that with increase in annual traffic demand, the motivation to optimally expand the highway by agency shifts to earlier years. The finding is also intuitive; highway capacity expansion is sensitive to traffic growth rate, as more traffic lanes will be required to meet the increased travel demand (Yang, 2012). Also Jian Lu et al., (2011) conducted sensitivity analysis of likelihood distribution of highway expansion with different traffic demand volatility scenarios, concluding that increase in annual traffic demand volatility would result in earlier highway expansion.

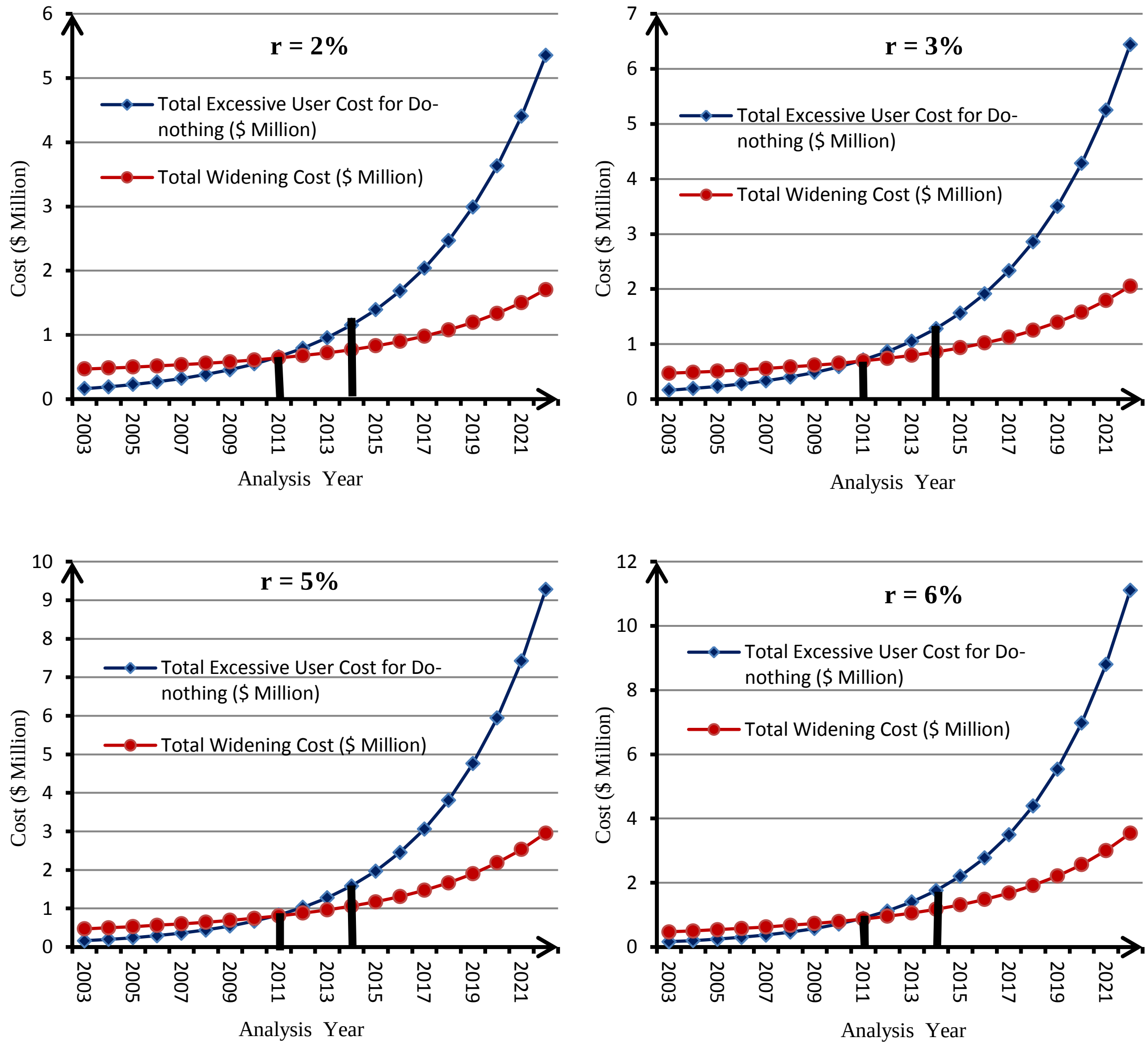

Figure 11 Variation of Optimal Highway Lane(s) Addition w.r.t Annual Interest Rate

Investments in highway life cycle cost analysis are usually estimated for base year and real discount rates are used for future years investments estimation (Lamptey et al., 2004). FHWA, (1998) suggested use of constant dollars along with real discount rates for conducting highway life cycle cost analysis and recommends 3% to 5% real discount rate range during analysis. It was observed (Figure 11) that there is almost no change in optimal highway expansion intervention timing due to change in interest rate as interest rate will affect both agency and user cost components. Although interest rate has more impact on excess user costs due to more individual components, but this effect is neutralized due to high initial lane(s) addition cost, hence desirable time range of highway lane(s) addition remains unchanged.

4.7 Chapter Summary and Conclusions

This chapter presented demonstration of the framework developed for determining optimal highway capacity expansion (lane(s) addition) intervention time through a case study application. The case study selected for the demonstration of the proposed framework was a segment of Islamabad Highway from Airport Chowk to the intersection of Islamabad highway with GT road. The chapter began with the basic case study information; data required, total widening costs estimation followed by total excessive user costs estimation for do-nothing, optimal time for case study highway capacity expansion intervention and at the end sensitivity analysis was performed in order to check the robustness of optimal highway expansion intervention time to agency to user cost relative weights, annual traffic growth rate and annual interest rate. Agency lane addition cost and workzone user delay cost were estimated in the total widening costs estimation section. Excessive travel delay, fuel consumption and crash cost were estimated in the total excessive user costs estimation for do-nothing section. Optimal time predicted for capacity expansion was found to occur between 2011 to 2014 based on annualized widening costs and excessive user costs for do-nothing estimation. Bench mark traffic volume have a range of 34430 vehicles/day to 37600 vehicles/day for the optimal widening of proposed highway section from initial 4-lanes divided highway to 8-lanes divided highway. The sensitivity analysis results revealed that interest rate have almost no impact on optimal highway expansion timing while increase in annual traffic demand volatility would result in earlier optimal highway expansion and by increasing the agency to user cost relative weight would result in later optimal highway expansion intervention.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Synopsis of the Research

This research focused on the development of a comprehensive framework for highway capacity expansion (lane(s) addition) decision making. The study began with an extensive literature review that covers state of the art and practice regarding highway capacity expansion decision making, travel demand management through highway capacity expansion and after impacts of highway capacity expansion. The literature review highlighted the gaps in current practice and also provided guidance for the development of the proposed framework. The literature review also illustrates factors affecting highway capacity expansion decision making.

A general framework for determining optimal highway capacity expansion intervention time was then presented. Annualized widening costs and excessive user costs estimation for do-nothing was used as a basic case scenario for the development of the proposed framework and an objective function based on estimated costs was then formulated. Detailed formulations were developed for estimating both widening costs and excessive user costs for do-nothing and break-even point analysis method was used for determining optimal highway capacity expansion intervention time. The demonstration of the proposed framework was then carried out using data from a major urban arterial. At the end to assess the magnitude and direction of influence of varying agency to user cost relative weights, annual traffic growth rate and annual interest rate on optimal highway expansion intervention time, sensitivity analysis was carried out.

5.2 Research Findings

A thorough review of the literature focused on the development of framework for highway capacity expansion decision making revealed that highway capacity expansion resulted in better traffic safety, larger reductions in delays and better congestion management. The general body of the literature is characterized by the lack of an established methodology for determining optimal highway capacity expansion intervention time. Researchers also suggested that user benefits in terms of travel time savings, vehicle operating cost savings, and safety savings are valuated as core justification for highway capacity expansion decision making. Design traffic volume, design level of service, economic impact, environmental impact, and social and political considerations were found to be major factors affecting highway capacity expansion decision making.

With this background of the abovementioned lack of the proposed methodology, this study presented a comprehensive framework for determining optimal highway expansion intervention time. The framework was based upon the annualized widening costs (agency lane addition cost and workzone user delay cost) estimation and excessive user costs (excessive travel delay cost, excessive VOC and excessive crash cost) for do-nothing estimation. The case study results revealed that 2011 to 2014 was found as optimal time for its expansion (Initial 4-lanes to 8-lanes divided highway) based on annualized widening costs and excessive user costs for do-nothing estimation. The case study results also revealed an ADT ranging from 34430 to 37600 as optimal for initiating widening intervention of 4-lanes to 8-lanes divided highway. Bench mark traffic volume is specific to the case study traffic mix and underlying assumptions and should not be used as standard. At the end the sensitivity analysis results revealed that annual interest rate have no impact on optimal highway expansion decision while increase in annual traffic growth rate and agency to user cost relative weight would result in earlier and later optimal highway expansion intervention respectively.

5.3 Recommendations and Directions for Future Research

The proposed framework can be applied to any multilane divided highway to find the optimal time for its capacity expansion. The optimal highway expansion intervention time predicted by the proposed methodology should be considered only for planning purposes and decision-support. The actual on-ground decision should be based upon detailed feasibility study of the project. A comprehensive study for estimation of unit travel time cost, unit VOC, and unit crash cost for Pakistan is recommended. There is need to establish traffic volume ranges for different highway functional classes at national level using methodology developed in present research effort. Research should be carried out to create stochastic processes in order to characterize the uncertainty about future annual traffic demand volatility. Research should also be conducted to contain other uncertainty sources such as time value of money, construction costs variation, and agency to user costs relative weights. Also future research efforts should incorporate environmental, social, and community costs during analysis.

References

AASHTO (2003). "A Manual of User Benefit Analysis for Highways, 2nd Edition American Association of State Highway and Transportation Officials, Washington, D.C.

Abaza, K. A. (2002). "Optimum Flexible Pavement Life Cycle Analysis Model". ASCE Journal of Transportation Engineering. ASCE. Vol. 128, pp. 542-549.

Bai, H., Chen, J., and Xie, Z. (2010). "A Multiple Attributive Decision Making Method for the no of Lanes based on Delay Cost". International Conference of Chinese Transportation Professionals (ICCTP) 2010: pp.125-131.

COMSIS Corporation, Scientific Applications International Corporation, Garman Associates (1995). Development of diurnal traffic distribution and daily, peak and off-peak vehicle speed estimation procedures for air quality planning, Work Order B-94-06, Federal Highway Administration, U.S. Department of Transportation, Washington, DC.

Corvero, R. (2001). "Road expansion, urban growth, and induced travel: A path analysis."

Darter, M. I., Smith, R .E., and Shahin, M. Y. (1985). "Use of Life Cycle Cost Analysis as the Basis for determining the Cost Effectiveness of Maintenance and Rehabilitation Treatments for Developing a Network Level Assignment Procedure. Proc., North American Pavement Management Conference, Vol. 2, Toronto, Ontario.

Decorla-Souza, P., and Cohen, H. (1998). "Estimating Induced Travel for evaluation of Metropolitan Highway Expansion". Presented at 77th annual meeting of Transportation Research Board, Washington, D.C., January 1998.

Decorla-Souza, P., and Cohen, H. (1999). "Accounting for Induced Travel in Evaluation of Urban Highway Expansion". Sixth National Conference on Transportation Planning for Small and Medium Sized Communities, Spokane, Washington.

FHWA (1982). Social Impact Assessment: A sourcebook for Highway Planners,Vol. 3, Inventory of Highway related Social Impacts. Federal Highway Administration, US Department of Transportation, Washington, D.C.

FHWA (1998). Highway Statistics, 1997. Office of Highway Information Management, Federal Highway Administration, Washington, D.C.

FHWA (1998). "Life Cycle Cost Analysis in Pavement Design – In Search of better Investment Decisions". Report FHWA-SA-98-079. Federal Highway Administration, US Department of Transportation, Washington, D.C.

FHWA. (1998). "Optimizing Highway Performance: Enhancing Pavement Smoothness". Office of Engineering, Federal Highway Administration, U.S. Department of Transportation, Washington D.C.

FHWA. (1999). Asset Management Primer. Office of Asset Management, Federal Highway Administration, U.S. Department of Transportation, Washington, D.C.

FHWA. (2002). Economic Analysis Primer, Federal Highway Administration, U.S. Department of Transportation Washington, DC.

SHRP. (2009). "Performance Measurement Framework for Highway Capacity Decision Making". Federal Highway Administration and American Association of State Highway and transportation Officials. Strategic Highway Research Program, Transportation Research Board.

Fields, G., Hartgen, D., Moore, A., and Pool Jr, R, W. (2009). "Relieving Congestion by adding road Capacity and Tolling". International Journal of Sustainable Transportation, Vol. 03, Nos. 5-6, pp. 360-372.

Frey, H, C., and Patel, S, R. (2002). “Identification and review of Sensitivity Analysis Methods”. Risk Analysis, 22(3), 553-577.

GASB. (1999). “Statement No. 34: Basic Financial Statements and Management’s Discussion and Analysis for State and Local Governments”. Governmental Accounting Standards Board, Norwalk, CT.

Gillen, D. (2007). “The Role of Intelligent Transportation Systems (ITS) in Implementing Road Pricing for Congestion Management”.

Gwilliam, K. (1997). “The Value of Time in Economic Evaluation of Transport Projects: Lessons from Recent Research, Transport No. OT-5, World Bank, Washington, D.C.

Handy, S., and Boarnet, M. G. (2014). “Draft Policy Brief on Highway Capacity and Induced Travel”. http://arb.ca.gov/cc/sb375/policies/policies.htm.

Harkey, D. L., Srinivasan, R., Zegeer, C. V., Persuad, B., Lyon, C., Eccles, K., Council, F. M., and McGee, H. (2004). “Crash Reduction Factors for Traffic Engineering and Intelligent Transportation System Improvements-State of Knowledge Report NCHRP Results Digest 229, Transportation Research Board, NRC, Washington, D.C.

Hong, T. H., and Hastak, M. (2007). “Evaluation and Determination of Optimal MR&R Strategies in Concrete Bridge Decks”. Journal of Automation in Construction. Vol 16, Elsevier.

Iacono, M., and Levinson, D. (2012). “Rural Highway Expansion and Economic Development: Impacts on Private1 Earnings and Employment.”

Irfan, M., Khurshid, M, B., Anastasopoulos, P., Labi, S., and Moavenzadeh, F. (2010). “Planning Stage Estimation of Highway Project Duration on the basis of anticipated Project Cost, Project Type and Contract Type”. International Journal of Project Management, Vol. 29, No. 01, pp. 78-92, 2011.

Jiwattanakulpaisarn, P., Noland, R, B., and Graham, D, J. (2009). “Marginal Productivity of Expanding Highway Capacity”. Submitted for Presentation at 88th annual meeting of Transportation Research Board, Washington. D.C., 2009.

Kahn, M, E., and Levinson, D, M. (2011). “Fix It First, Expand It Second, Reward It Third: A New Strategy for America’s Highways”. The Hamilton Project, Discussion Paper, February 2011.

Kandil, A, A., Hyari, K, H., and Bisani, M. (2010). “Optimization of Highway Construction Workzones: The Agency and User Cost Tradeoff”. International Conference on Computing in Civil and Building Engineering (ICCCBE), 2010.

Kavitha, K., and Pandian, P. (2012). “Sensitivity Analysis of Costs in Interval Transportation Problems”. Applied Mathematical Sciences, 6 (2012), 4569-4576.

Khan, B. A., (2013). “Prediction of Road Crash Fatalities for Pakistan using Aggregate Data”. MS Thesis, National University of Sciences and Technology, Islamabad.

Khurshid, M. B., Irfan, M., Labi, S. (2011). “Optimal Performance Threshold Determination for Highway Asset Interventions - An Analytical Framework and Application”. ASCE Journal of Transportation Engineering. ASCE. Vol.137 (2), pp.128-139.

Labi, S., and Sinha, K. C. (2005). “Life Cycle Evaluation of Flexible Pavement Preventive Maintenance. ASCE Journal of Transportation Engineering, ASCE, Vol. 131(10).

Lamptey, G. (2004). “Optimal Scheduling of Pavement Preventive Maintenance Using Life Cycle Cost Analysis”. MS Thesis, Purdue Univ., West Lafayette, IN.

Lamptey, G., Ahmed, M., Labi, S., and Sinha, K, C. (2005). “Life Cycle Cost Analysis for INDOT Pavement Design Procedures”. Final Report FHWA/IN/JTRP-2004/28, Purdue University, West Lafayette.

Lewis, D. (2008). "America's Traffic Congestion Problem: Toward a Framework for Nationwide Reform".

Litman, T. (2001). "What's it worth? Economic Evaluation for Transportation Decision-Making". Presented at the Internet Symposium on Benefit-Cost Analysis Transportation Association Of Canada, February 2001. Website: www.tac-atc.ca.

Lu, J., Ashuri, B., Wang, X., and Kashani, H. (2011). "Optimal Timing of Investment in Highway Expansion". Submitted for Presentation at 91st annual meeting of Transportation Research Board (2012), Washington, D.C.

Mamlouk, M. S., Zaniewski, J. P. (2001). "Optimizing Pavement Preservation: An Urgent Demand for every Highway Agency. International Journal of Pavement Engineering. Vol, 2(2).

Marasteanu, M., Velasquez, R., Herb, W., Tweet, J., Turos, M., Watson, M., and Stefan, H. G. (2008). "Determination of Optimum Time for the Application of Surface Treatments to Asphalt Concrete Pavements". Phase 2, Report No. MN/RC 2008-16, Minnesota Department of Transportation (Mn DOT), St. Paul, Minnesota.

MUTCD (2009). "Manual on Uniform Traffic Control Devices for Streets and Highways". Federal Highway Administration. US. Department of Transportation, Washington D.C.

Noland, R, B., and Cowart, W, A. (2000). "Analysis of Metropolitan Highway Capacity and the Growth in Vehicle Miles of Travel". Presented at 79th annual meeting of Transportation Research Board, Washington. D.C., January 2000.

NSC (2001). "Estimating the Costs of unintentional Injuries". 2000 National Safety Council, Spring Lake Drive, Itasca, IL.

O'Fallon, C., and Sullivan, C. (2003). "Understanding and Managing Weekend traffic Congestion". 26th Australian Transport Research Forum, Wellington, New Zealand.

Organization for economic cooperation and development (OECD) and European conference of ministers of transport (ECMT). (2007). "Managing Urban Traffic Congestion".

Pakistan Economic Survey, 2011-12, Economic Adviser's Wing, Finance Division, Government of Pakistan, Islamabad.

Pakistan Infrastructure Report, 2005-10, State Bank of Pakistan, Infrastructure Taskforce, Government of Pakistan, Islamabad.

Peshkin, D. G., Hoerner, T.E., and Zimmerman, K.A. (2004). "Optimal Timing of Pavement Preventive Maintenance Treatment Applications". National Cooperative Highway Research Program (NSHRP) Report 523, Transportation Research Board, National Research Council, Washington D.C.

Peterson, D. E. (1985). "Life Cycle Cost Analysis of Pavements". National Cooperative Highway Research Program, NCHRP, Synthesis of Highway Practice 122, Transportation Research Board, TRB, National Research Council, Washington, D.C.

Polus, A., and Pollatschek, M. A. (2004). "Criteria for Widening of Two-Lane Rural Highway". Transport Policy 2, pp. 379-385.

Poole JR, R. W., and Orski, C. K. (2000). "HOT Lanes: A better way to attack Urban Congestion". Regulation Magazine, Published by Cato Institute.

Rodier, C, J. (2004). "A review of the representation of Induced Highway travel in current travel and Land use Models". Submitted to Transportation Research Board (TRB). July 2004.

Roess, R. P., Prassas, E. S., and McShane, W. R. (2004). Traffic Engineering. Pearson Education, Inc., Upper Saddle River, New Jersey.

Saltelli, A., Chan, K., and Scott, E, M. (2000). "Sensitivity analysis: Gauging the worth of Scientific Models". John Wiley and Sons, Ltd: West Sussex, England.

SHRP (2009). "Performance Measurement Framework for Highway Capacity Decision Making". SHARP 2, Report S2-C02-RR, Strategic Highway Research Program.

Siethoff, B. T., and Kockelman, K. M. (2002). "Property Values and Highway Expansions: An Investigation of Timing, Size, Location, and Use Effects." Presented at 81st annual meeting of Transportation Research Board, Washington, D.C., January 2002.

Sinha, K, C., and Labi, S. (2007). "Transportation Decision Making-Principles of Project Evaluation and Programming". John Wiley & Sons, Inc.

Sinha, K. C., Labi, S., and Bai, Q. (2011). "Benchmarks Based on Traffic for Widening of Major Arterials vis-à-vis Construction of Expressways". National Transport Development Policy Committee (NTDPC) of India. 4th report provided by the World Bank.

Technical Coordinating Committee of the Strategic Highway Research Program 2 and Transportation Research Board of the National Academies. (2009). "A Framework for Collaborative Decision Making on Additions to Highway Capacity".

Transportation Research Board. (2000). Highway Capacity Manual 2000. Transportation Research Board, Washington, D.C.

TTI (2005). "Freeway traffic conditions and trends in the Phoenix region, 2004". Prototype Annual Report.

Vidya, R., Santhakumar, S, M., and Mathew, S. (2012). "Impact of Workzones on speed variation during Widening of the Highway –A case study". International Journal of Engineering Science and Technology (IJEST), Vol. 4, No.02, February 2012.

VTPI (2005). "Transportation Cost and Benefit Analysis: Travel Time Costs, Victoria Transportation Policy Institute, Victoria, BC, Canada, http://www.vtpi.org/tca/tca0502.pdf. Accessed Aug, 19, 2005.

Walls, J., and Smith, M, R. (1998). "Life Cycle Cost Analysis in Pavement Design, Technical Rep". FHWA-SA-98-079, Federal Highway Administration, Washington, DC.

Williams-Derry, C. (2007). "Increases in Greenhouse-gas emissions from Highway-widening Projects".

Yang, J. (2012), "Nested Markov Decision Framework For Coordinating Pavement Improvement with Capacity Expansion". ASCE Journal of Transportation Engineering. ASCE. Vol. 138, pp.387-394.

Yu, W., and Lo, S. (2005). "Time-dependent Construction Social Costs Model". Construction Management and Economics, Vol. No. 23, pp. 327-337.

Zhang, J., Rufolo, A, M., Dueker, K, J., and Strathman, J, G. (2000). "The effects of Roadway Capacity on Peak Narrowing". Presented at 80th annual meeting of Transportation Research Board, Washington. D.C., July 2000.

Zhao, T., Sundararajan, S. K., and Tseng, C. (2004). "Highway Development Decision-Making under Uncertainty: A Real Options Approach". ASCE Journal of Infrastructure Systems. ASCE. Vol. 10, pp.23-32.

Appendix

Appendix A. Consumer Price Index Values for Pakistan

Year	Consumer Price Index	Year	Consumer Price Index	Year	Consumer Price Index
1985	23.26	1995	54.83	2005	100
1986	24.08	1996	60.52	2006	107.92
1987	25.21	1997	67.41	2007	116.12
1988	27.43	1998	71.61	2008	139.68
1989	29.59	1999	74.57	2009	158.74
1990	32.26	2000	77.83	2010	180.78
1991	36.07	2001	80.28	2011	202.32
1992	39.5	2002	82.92	2012	225.32
1993	43.44	2003	85.34	2013	247.44
1994	48.81	2004	91.69	2014	271.23

(www.indexmundi.com/facts/pakistan/consumer-price-index)

Appendix B. Travel Time Values for Pakistan (2003 Constant $)

Vehicle Class	Travel Time Value
Motor Cycle	0.98
Automobile/Car	2.11
Hiace	2.89
Bus	2.15
Truck	1.45

(Gwilliam, 1997)

Appendix C. Crash Cost (2003 Constant $)

Crash Type	Crash Count per 100 million VMT	Unit Crash Cost ($ Million)
Fatality	1.3	0.047
Injury	124.69	0.0038
Property Damage	124.69	0.00039

(FHWA, 1998; NSC, 2001)

Appendix D**.** Fuel Consumption Cost (2003 Constant $)

Free Flow Speed (mile/hour)	Motor Cycle	Automobile/Car	Hiace	Bus	Truck	Trailor
20	0.68	1.90	2.85	7.13	10.90	24.54
25	0.81	2.42	3.35	8.37	13.57	30.00
30	0.92	2.79	3.97	9.91	17.92	35.20
35	1.11	3.22	4.58	11.47	21.81	40.53
40	1.30	3.65	5.33	13.32	25.90	45.74
43.5	1.48	4.05	5.85	14.63	29.24	49.39
45	1.55	4.21	6.07	15.19	30.66	50.95
50	1.73	4.71	7.06	17.67	34.46	56.16
55	1.98	5.33	8.06	20.14	38.92	61.36
60	2.29	6.01	9.05	22.62	43.45	66.56
65	2.60	6.69	10.29	25.72	48.03	71.64
70	2.92	7.44	11.65	29.13	52.68	76.85
75	3.29	8.25	13.01	32.54	57.39	81.93

(AASHTO, 2003)