The Dissertation Committee for Aristeidis Pantelias certifies that this is the approved version of the following dissertation:

A METHODOLOGICAL FRAMEWORK FOR PROBABILISTIC EVALUATION OF FINANCIAL VIABILITY OF TRANSPORTATION INFRASTRUCTURE UNDER PUBLIC PRIVATE PARTNERSHIPS

Committee:

____

Zhanmin Zhang, Supervisor

____

C. Michael Walton

____

Randy B. Machemehl

____

David W. Fowler

____

Ross Baldick

____

Rob Harrison

A METHODOLOGICAL FRAMEWORK FOR PROBABILISTIC EVALUATION OF FINANCIAL VIABILITY OF TRANSPORTATION INFRASTRUCTURE UNDER PUBLIC PRIVATE PARTNERSHIPS

by

Aristeidis Pantelias, B.Sc.; M.Sc.

Dissertation

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Doctor of Philosophy

The University of Texas at Austin

May 2009

ACKNOWLEDGMENTS

I would like to thank my academic advisor Dr. Zhanmin Zhang for all the guidance and support during my academic years at UT. It has been a very rewarding four-year-long trip during which I have evolved as a person and a scientist to an extend that was unknown to me before.

My sincere thanks also go to the members of my dissertation committee, namely Dr. C. Michael Walton, Dr. Randy Machemehl and Dr. David W. Fowler from the Civil, Architectural and Environmental Engineering department; Dr. Ross Baldick from the Electrical Engineering department; and Mr. Rob Harrison from the Center of Transportation Research at UT. Your help and support was very significant and your feedback indispensable to the development of my dissertation and its successful completion.

I would also like to thank all the friends and current and former colleagues at UT, in Austin and in Athens, Greece, for all the good memories and the support during these years. You were all part of an unforgettable experience and I am grateful to have met and known each and every one of you.

Finally, I want to express my gratitude towards my family for all the love and support during my graduate studies at UT. Thank you for believing in me, for supporting both emotionally and financially my academic adventures and for being there for me in times of hardship and doubt. Without you this degree would have been too formidable to achieve.

A METHODOLOGICAL FRAMEWORK FOR PROBABILISTIC EVALUATION OF FINANCIAL VIABILITY OF TRANSPORTATION INFRASTRUCTURE UNDER PUBLIC PRIVATE PARTNERSHIPS

Aristeidis Pantelias, Ph.D.

The University of Texas at Austin, 2009

Supervisor: Zhanmin Zhang

This research proposes a methodological framework for the probabilistic evaluation of the financial viability of transportation infrastructure projects procured as Public Private Partnerships (PPPs). In doing so a methodological approach is undertaken. First, this research investigates the various risks of PPP projects, in particular the investment risk in terms of both the depth and its corresponding methods of evaluation, yielding a new method for more accurate estimation. Second, it examines the multiple facets of financial viability, stemming from the different meaning that it has for the various project stakeholders, i.e., the public authority, the lenders and the equity investors. From this study a connection between the financial viability and the investment risk is established for the purpose of using the latter for the assessment of the former. Based on this established connection, this research proposes a general methodological framework that can be used for the probabilistic evaluation of the financial viability of other

types of revenue-generating transportation infrastructure projects, procured as PPPs. This framework proposes the evaluation of the financial viability through the estimation of the project's investment risk, using available numerical and/or analytical approximation techniques such as the Method of Moments. The general methodological framework is then utilized for the specific case of highway toll-road concession projects, where detailed and specific quantitative models are devised for the determination of the costs and revenues of these projects. Additionally, and by capitalizing on similar models found elsewhere in the literature, this dissertation also proposes a process to increase the accuracy of the Maintenance and Rehabilitation cost estimates, borrowing concepts stemming from reliability and stochastic processes. The findings of this research are expected to help all project stakeholders with their evaluation of whether or not a project under consideration is capable of achieving their respective financial targets. The proposed methodology can be used as a quantitative tool for project evaluation and investment appraisal by all project stakeholders. However, as in any decision support methodology, the purpose of the proposed framework is not to replace decision makers but to help them make better and informed decisions.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

On Contemporary Transportation Infrastructure Provision and Financing

The landscape of transportation infrastructure provision has changed during the last 30 years. Slowly but steadily, traditional ways of public financing and procurement have given way to project finance and the contribution of private investment in the delivery and operation of public infrastructure. In this model of doing business, public authorities and private entities “partner” together for the development and/or management and operation of capital intensive, large scale transportation infrastructure projects, usually called Public-Private Partnerships (PPPs). In most cases, the anticipated benefits from embarking in such joint ventures are big enough to enact change in what had been “business as usual” for transportation agencies as well as in government policy and legislation.

This change has not been uniform. Slower in some parts of the world and faster in others, this change has usually been attributed to the severity of the challenges faced by transportation agencies regarding infrastructure provision and management as well as governmental flexibility and desire to accommodate this new business model through the appropriate legal framework. As a rule of thumb, the greater the challenges are, the stronger the push is for agency and governmental reform and for moving towards the implementation of this new business model. The change has also not always been smooth. Resistance and friction from the general public has many times been reflected through and communicated by impeding decisions coming from political and legislative representatives (Project Finance 2008(a);(b); The Economist 2008(b)). At the heart of these reactions has most of the times been the traditional belief that public infrastructure should always be under the provision, ownership and stewardship of the public sector and that since it has been paid once already by taxpayers' money, it should be free for everyone to use and should not be paid twice for by users through tolling (Ortiz & Buxbaum 2007; Fortune 2007; Pagano & Perry 2008). Consequently, it is not surprising that the involvement of the private sector in this business, with its user-charging policies, controlled access facilities and inherent appetite for profit, has been treated with suspicion and has sparked controversy in many places where this new model of transportation infrastructure financing and provision has been implemented or proposed for future implementation (Podgorski & Kockelman 2006; Fortune 2007; The Economist 2007(b); 2008(b)). Other concerns pertain also to whether this form of infrastructure procurement is indeed the best choice for a public agency and whether the public agency has the sophistication to properly evaluate such deals and sufficiently protect the public interest (Mayer 2007; Ortiz & Buxbaum 2008). Nevertheless, in the face of pressing challenges it has gradually become apparent to all stakeholders that this model of business represents in some cases the only viable alternative for providing and sustaining public transportation infrastructure (Yescombe 2007).

Public Private Partnerships (PPPs) are becoming an increasingly popular business model in transportation infrastructure provision because of numerous reasons. Top of the reasons is the scarcity of public resources available for extending, upgrading, maintaining and operating public infrastructure (Smith 2003; Giglio 2005; The Economist 2008(b)). The American Society of Civil Engineers (ASCE) estimated that roughly $2.2 trillion dollars are needed over the next five years in order to adequately improve the U.S. infrastructure from its current average score of "D" (ASCE 2009). Then are the continuously increasing travel demand and high expectations regarding mobility and levels of service from the traveling public (Brown 2007; Ortiz &

Buxbaum 2008; The Economist 2008(b)). Public funds usually come either from general government funds or in some cases (like the U.S.) from designated funds specifically for infrastructure. The mere size, however, of the infrastructure network and its maintenance needs, coupled with the need for additional capacity and expansions induced by increased user demand have slowly rendered available public funds insufficient in most countries around the world, calling for the utilization of other sources of capital (Pagano & Perry 2008; NY Times 2008(a); Project Finance 2008(a)). Hence justified has been the call upon the financial strength of the private sector, both in terms of the issuing of debt and the commitment of private equity.

In terms of the commitment of private equity, the common practice of infrastructure financing has changed significantly during recent years. Whereas in the initial versions of PPPs the main contributors of private capital (equity) were the (private) firms participating in the Special Purpose Vehicle (SPV) that would be in charge of the venture, the recent turmoil in the worldwide financial markets has started a different trend. Indeed, the adverse developments in worldwide capital markets regarding regularly traded financial assets (such as stocks, derivatives etc) during the last years have distressed many private investors and motivated them to find new investment opportunities (NY Times 2008(a); Project Finance 2008(c)). At the same time, numerous reports of significant returns on investment by certain large pools of private capital (such as designated funds of certain investment banks and pension funds among others) that pioneered investing into infrastructure projects in various parts of the world have come to light (Brown 2007; The Economist 2004; 2005; 2007(a); 2008(a); Fortune 2007; NY Times 2008(a)). The combination of these two factors has created a new trend in worldwide investment practices (The Economist 2006; Brown 2007; Fortune 2007). More than ever, private investors are willing to commit private equity to long-term investment contracts not just by buying government bonds related to infrastructure projects, as was the case until recently, but also by investing directly in these projects through infrastructure-designated funds (either through investment banks or other special funds) that are looking for low-risk and long-term institutional investment opportunities in all types of infrastructure all around the world (Brown 2007; Fortune 2007; The Economist 2008(a); NY Times 2008(a); Project Finance 2008(b)). The trend has actually been so powerful that has also led to the development of various other unlisted infrastructure funds (Fortune 2007). As of mid-2008, around 71 unlisted infrastructure funds were "on the road" seeking an aggregate $90.8 billion, compared to 4 funds going after $1.8 billion in 2005 (Preqin Infrastructure 2008). This profound change has also been reflected by the increase in the average size of these funds from $159 million in 2003 to $3.3 billion in 2008 (Preqin Infrastructure 2008). However, the magnitude of the reported success as well as the actual sustainability of the implemented investment models had been increasingly scrutinized and questioned, even before the recent adverse economic developments (Fortune 2007; The Economist 2008(c)). Additionally, the recent global economic downturn has further strengthened these voices of concern with many reported cases of such funds getting unwound by their investors (Mercer 2008). Although the demand for such investment opportunities has yet to subside, especially in light of various government-sponsored economic stimuli that plan to allocate funds for infrastructure projects, and as this has indeed been a relatively new investment market whose business model had never been put under stress until now and whose long-term results is still too early to assess and validate, caution has and should still be warranted to all interested parties for avoiding market bubbles and more unexpected downturns as the stakes (the investments) keep on rising (The Economist 2007(a); 2008(a); Fortune 2007; Project Finance 2008(c); InvestmentNews 2009).

Furthermore, PPPs are projects that are usually financed through project finance arrangements rather than traditional public sector financing (Nevitt & Fabozzi 2002). Project finance has the inherent characteristic of being a highly leveraged way of financing, meaning that the funds raised for their development come mostly from the issuing of various forms of debt rather than from the commitment of high levels of private equity (Tinsley 2000). PPP projects have traditionally been leveraged through bank loans and the issuing of bonds, with other methods of financing also being available and increasingly becoming more common and popular (Nevitt & Fabozzi 2002). However, the very recent adverse developments in the worldwide financial markets have affected in an unprecedented way the banking sector as well as the confidence in worldwide credit markets (The Economist 2008(d); NY Times 2008(b)). The exact magnitude, full consequences and collateral damage of this crisis are still unfolding and many governments around the world are looking at stimulus packages in order to protect the banking sector whose collapse would have dire consequences for all other sectors of economic activity. Some of the immediate consequences however already included the collapse, merging or change of status of various banks that would until very recently participate in project financing schemes as well as a general freezing of the worldwide credit markets (The Economist 2008(d); BusinessWeek 2008). Because this lack of liquidity and confidence could potentially further impact the financing of such projects adversely, as the issuing of debt may become more difficult and scarce, and as investing into such projects creates jobs and provides the basis for future long-term growth, announcements of further government spending in such projects have been warmly received and supported by the infrastructure industry.

All the above developments in transportation agency finances, predominant government culture as well as in worldwide capital markets had naturally increased the expectations for new infrastructure projects procured as PPPs (The Economist 2007(a); Fortune 2007). It now remains to be seen if and to what extent these expectations are going to materialize both due to the sudden availability of government funds that could shift the state of the practice - at least in the short term – to traditional public financing procurement, but also due to tighter credit conditions and the lack of available credit supply in worldwide markets that hinder the leveraging of projects procured as PPP. Nevertheless, both the increase in demand for such projects as well as the potential decrease in available debt for structuring project finance deals, should more than ever focus the attention once again to the evaluation of such projects and their capability of delivering the anticipated benefits to all their stakeholders: more and better infrastructure for the public and robust and profitable investments for the private sector. As a result, it would not be surprising if the evaluation of the success of PPP projects should once again be put under the microscope.

The success of PPPs depends on their engineering and financial structuring and the anticipation, mitigation and/or sharing of the various risks that can be found during the various phases of such projects. Risk sharing and bearing is a vital consideration and an element of paramount importance to all involved parties, and business deals succeed or fail based on the balancing of these risks. Although the risks that can be found in such projects are many and can be classified in various categories, it is widely accepted that one of the most important – if not the single most important – consideration for a project to move forward from a planning to an implementation phase has to do with its financial structuring and anticipated financial success. A widely used metric for the financial expectations of PPP projects and at the same time a commonly used metric for investment appraisal for capital investments of such magnitude is the evaluation of their financial viability. The financial viability of PPP projects has different meanings for the different project stakeholders (public owner, lenders, and equity investors) and is also related to the financial and economic risks exhibited by these projects during their economic lifetime. In light of all the above, this dissertation research investigates the parameters that affect the financial viability of PPP projects and proposes a comprehensive methodological framework for its probabilistic assessment.

Research Motivation

PPP projects like any other capital investment project have to appear capable of fulfilling the expectations of all involved stakeholders in order to be selected and financed for further implementation. The assessment of the financial viability of a project has been traditionally one of the most commonly used ways to evaluate a project and determine if it should move forward for further implementation. However, this assessment has usually been undertaken in different ways and with different tools by the various project stakeholders, due to the different meaning that financial viability has to them. As a result there has always been a need for a method of assessing the financial viability of a project that could be used by all parties involved and be encompassing of all their different perceptions and understandings of what makes a project financially viable. In this context, this dissertation proposed and used the evaluation of the investment risk of a project as a measure of its financial viability that can satisfy all project stakeholders either directly or indirectly, for a variety of reasons, as explained during the literature review.

The analysis of risks of PPP projects has also been a very active area of research attracting naturally a big audience from both academia and practitioners in the Civil Engineering industry, as understanding and mitigating these risks has a critical effect in the success of the projects. One particular type of risk that has always been attracting a lot of interest is the investment risk of these projects, or the risk that the various project stakeholders are unable to achieve their investment targets. The investment risk can have various definitions and be evaluated through a variety of methods. In one of its most complete definitions – and the one adopted for the purposes of this dissertation research – the investment risk measures the probability of a project not generating adequate revenues to repay the project debt outstanding and also obtain a required rate of return for its equity investors. Under this definition the investment risk has been evaluated through the use of both numerical and analytical approximation methods, such as Monte Carlo simulation and the Second Moment method. While the first one is undoubtedly the most accurate and widely used method of probabilistic estimation, it has always been considered a "black box", as it involves a "behind the scenes" random number generation process that is outside user influence, except for the specification of the statistical distribution from which these numbers come from. As for the second one, it is also a widely used analytical approximation method which nevertheless has lately been proven to be not as accurate as other, more recently developed analytical approximation methods. As a result, this research proposes the investigation of alternative methods for the evaluation of the investment risk, such the Method of Moments. This method has been proven to be equally accurate with the Monte Carlo simulation while at the same time more accurate than any other analytical approximation method, thus increasing the accuracy of the estimation without sacrificing the traceability of the solution.

Finally, the analysis of the financial viability of transportation PPP projects and in particular highway toll-road projects has usually been undertaken from an "economist's" point of view, lacking the consideration of the exact engineering characteristics of the project under consideration. One of these characteristics that is of crucial importance to toll-road projects is the pavement infrastructure and the corresponding estimation of its life-cycle costs, such as the various maintenance and rehabilitation activities. The magnitude and frequency of these activities can affect the cash flows of the project and, depending on their timing within the project's operational life, can have different impacts on the investment risk and therefore on the financial viability of the project. To this respect this research also uses concepts from pavement reliability and stochastic processes as a mean of taking into account the future needs of maintenance and rehabilitation activities of a facility – both planned and unplanned – and investigating their effect to the life-cycle costs of the project and subsequently to the corresponding investment risk.

Research Objectives

The objectives of this dissertation research have been the following:

1. To review the parameters which constitute the various sources of risk for PPP projects and to focus primarily on the ones affecting their financial success and in particular the investment risk.

2. To investigate the various methods by which the investment risk can be estimated and propose an alternative way to improve this estimation, namely the Method of Moments.

3. To present the various facets of the financial viability measures of such projects and establish a relationship between them and the investment risk, with the purpose of using the latter in order to objectively assess the former.

4. To develop a methodological framework that utilizes all of the above concepts and processes for the evaluation of the financial viability of any transportation infrastructure project developed as a PPP, based on its corresponding investment risk. This framework addresses the planning phase of such projects and is intended to be used (with the necessary modifications) by all parties involved in the negotiation of the final engineering and financing details, be them the public owner, the lenders or the equity investors.

5. To customize the developed methodological framework for the particular case of highway toll-road PPP projects. Under this objective, detailed financial models are put forward taking also into account the pavement characteristics of the infrastructure under consideration.

6. To undertake a case study pertaining to the detailed toll-road-specific framework in order to demonstrate that its use can provide significant insight to the structuring of the project, both in terms of engineering and project financing, as well as enabling decision makers to obtain probabilistic estimates of their likelihood of achieving their (primarily financial) targets during the project's operational life.

Research Scope

This research aims to create a methodological framework that in its general form can be applicable to various types of revenue-generating PPP projects, such as highways, ports, or airports, to name a few of them within the area of transportation. In that respect the backbone of the framework has been designed so as to be as general and flexible as possible to accommodate a wide range of options and assumptions. On the other hand, this research also goes to significant modeling depth in the case of toll-road concession PPP projects where specific details are researched and discussed including: 1) the revenue and cost models; 2) the design characteristics; and 3) future Maintenance and Rehabilitation (M&R) activities and costs. In other words, this research can be considered to have two parts: 1) a generic methodological part intended for different types of revenue-generating PPP projects, and 2) a specific modeling framework for the particular case of highway toll-road PPP projects.

Research Contribution

The findings of this research are expected to provide useful information and insights to both the industry and academia. The proposed research is expected to make the following contributions:

- An identification of the relationship between the investment risk and the various facets of the financial viability of project as perceived by its different stakeholders

- An enhanced and more accurate analytical solution to the estimation of the investment risk

- A methodological framework that can be used to assess the financial viability of different types of PPP projects in transportation infrastructure

- A detailed methodological framework that can be used to evaluated toll-road PPP projects, taking into account the design characteristics of the project and the different possible M&R strategies that can be implemented.

The results of this research can be used by the various project stakeholders (the public authority, the lenders, and the equity investors) to gain insights on the financial viability of the project and ultimately decide on its selection and future implementation. The use of the investment risk, for that purpose, can serve as a straightforward quantitative measure in relationship to the different perceptions of the financial viability, thus providing valuable decision support. The detailed models regarding the case of toll-roads can be used by corresponding road authorities, equity investors, lending institutions and any other project stakeholder to quantitatively assess the probability of success of such projects during their planning phase and decide whether or not they should move forward to tendering, bidding and ultimately financial close.

Dissertation Outline

The remaining chapters of this dissertation are arranged in the following way:

Chapter 2 presents a comprehensive literature review of the various topics that form the background of this research. These topics include: Public Private Partnerships; Project Finance; financial viability for PPP projects; risks in PPP projects; investment risk; the relationship between financial viability and investment risk; methods of appraising investments and investment risk; reliability concepts; the Method of Moments; stochastic processes and the Non-Homogeneous Poisson Process; and models that capture the effects of maintenance and rehabilitation actions.

Chapter 3 presents the research methodology that was followed, as well as an outline of the concepts used for the development of the methodological frameworks proposed in this dissertation.

Chapter 4 contains the presentation of a generic methodological framework for the evaluation of the financial viability of PPP projects in transportation infrastructure. In this chapter the basic components of the framework are identified and explained and the proposed solution methodology presented, without however going into infrastructure-specific details as far as the specific quantitative parts of the methodology are concerned.

Chapter 5 discusses the customization of the generic methodological framework that is specialized for the case of concession toll-road projects, with the presentation of specific revenue and cost financial models. These models capture respectively the annual cash in-flows and out-flows of the project and are essential in the evaluation of the investment risk. This chapter ends with a discussion on the limitation of commonly used models for maintenance and rehabilitation highway costs.

Chapter 6 follows naturally from the discussion on the M&R costs model limitation by presenting an improved methodology for estimating the total M&R costs of a highway toll-road facility. The presented methodology uses results from previous research efforts and concludes the methodological part of this dissertation.

Chapter 7 presents a case study of the proposed methodological framework by applying the methodology to a prospective highway toll-road project in the State of Texas. The majority of the utilized information for this case study comes from the actual planning phase of the project while missing information had to be assumed based on similar projects and information available in the scientific literature.

Chapter 8 discusses the major findings of this dissertation while ultimately providing directions for future research efforts.

Finally, this dissertation concludes with the bibliography that was used to support the undertaken research.

CHAPTER 2: LITERATURE REVIEW

Public Private Partnerships

PPPs are contractual agreements between a private party (which can comprise one or more private partners) and all or part of a government. Under such a contract the private party agrees to perform certain functions or activities that are partially or traditionally considered to be of public responsibility (Li & Akintoye 2003). PPPs are known worldwide with various other alternative names such as Private Participations in Infrastructure (PPI), Private-Sector Participation (PSP), P3, Privately Financed Projects (PFP), and Private Finance Initiatives (PFI). Regardless of the names used, the basic premises behind such contractual agreements are that the public and the private partners agree to enter in a long-term contract, involving the procurement of (usually) public infrastructure under a Project Finance financing structure, with the various risks involved during the various phases of the project allocated to the party that can best handle them with the minimum cost.

According to Yescombe (2007), the structure of such agreements usually falls under two general categories, namely Concessions and Private Finance Initiative (PFI) contracts, both of which have evolved to their current form from the Power Purchase Agreements developed in U.S. in the 1980s. Although both the Concession and the PFI models fall under Project Finance financing structures, their main difference lies in the way the raised debt is repaid: in a Concession agreement this cost is covered by user-charging while in the PFI model payments from the public authority are introduced for the same purpose.

Furthermore, PPPs can be classified based on the legal nature of the involvement of the private sector in the project (Yescombe 2007; Li & Akintoye 2003). In that respect the various names used such as Build-Operate-Transfer (BOT), Build-Transfer-Operate (BTO), Build-Own-Operate-Transfer (BOOT) and so on and so forth, reflect the nature of the contract and the point at which the operation (or the ownership) of the constructed facility is transferred from the public authority to the private party and back again.

Finally, PPP projects can also be classified according to the nature of the contracted service and the risk transfer between the public and the private partners (Yescombe 2007). Under such a classification PPP projects can be Usage- or Availability-based, the former meaning that facility usage risk is transferred to the private sector, while the latter meaning that the private partner assumes the risk of having the facility available for use, without considerations about the expected usage. Usage-based PPP are usually structured as Concession agreements while Availability-based projects are usually structured based on the PFI model.

Project Finance

PPPs are usually financed through Project Finance financing methods rather than traditional public sector financing. Project Finance encompasses financing scenarios where the loans that are raised for the capital costs of a project are then repaid based on cash-flows that are generated from the operation of the project. These loans are financed on a non- or limited recourse basis with the recourse (if applicable) being restricted only to the assets or cash-flows of the project itself (Asenova & Beck 2003).

Raising the necessary capital is usually achieved through a combination of debt and equity with a variety of financing options currently being available, such as bonds, commercial lending through bank debt, leasing, mezzanine debt, mortgage financing, etc. Senior bank debt is the most common form of project financing to date, with other "alternative" sources however being increasingly used towards that end (Asenova & Beck 2003; Nevitt & Fabozzi 2002). It is customary nevertheless for most project financings to have certain specifications for the ranges of the different types of capital present in their structuring, usually as contractual terms coming from the public authority's or the lenders' side. A very common specification of this type is the requirement that the sponsors/developers commit their own equity to the project (usually to the extent of 10 to 15 percent of the total capital costs but sometimes more than that) as a demonstration of their commitment to its successful implementation (Asenova & Beck 2003; Nevitt & Fabozzi 2002).

Furthermore, and after recent developments in worldwide financial markets, the project equity used in financing PPP projects is no longer coming only from the companies that are involved in the delivery of the project (e.g., contractors) but also from various other investment sources that are looking to attain long-term, low-risk returns on their investment through the operational revenues and profits of these projects.

Financial Viability of PPP Projects

The financial viability of a project is usually defined/measured by the fulfillment of certain quantitative or qualitative indicators that point to or guarantee the attainment of the financial targets of the various project stakeholders. The existence of these different project stakeholders naturally assigns to the financial viability a different meaning based on their different perspectives and targets. In PPP projects the three parties whose interests have to be bridged in order for the project to be successfully completed and operated are the public authority, the lenders and the equity investors.

From the public authority's point of view, project viability is usually synonymous with increasing social welfare from the project's development and achieving the best Value for Money (VfM) (Yescombe 2007). Most of the times, the major issue for the public authority decision makers is whether such a project will be pursued in the first place, a decision that is made well ahead of the procurement phase of the project and is justified through a cost-benefit analysis and/or the determination of the economic return of the project (including externalities). From that point on the focus is shifted to ensuring the best VfM and affordability; this is done by undertaking comparative studies and analyses, a very popular way being through the use of a Public Sector Comparator (PSC). In many cases, however, there is no real public sector alternative to compare the PPP project to, resulting in a situation such that if the project is not procured through a PPP it will most probably not be procured at all. As a result, the public authority usually aims to achieve the best VfM by making sure that the risk transfer between the different parties has been done in a rational and cost-effective way and by encouraging and sustaining effective competition during the bidding phase.

From the lenders' point of view, the financial viability of the project corresponds to the repayment of the issued debt and is very much dependent on the relation between the project's costs and revenues generated during its operating life. In that respect a macroscopic analysis of the profitability of the project with the corresponding (positive) cash-flows until the end of its operating life (or the time until all loans are repaid) is of much interest, along with the fulfillment of specific Cover Ratios (CRs) that make sure that the project can be repaying the debt as it falls due. From the existing variety of CRs, the ones pertinent to such projects (and most commonly used) are the Annual Debt-Service Cover Ratio[1] (ADSCR) and the Loan-Life Cover Ratio[2] (LLCR). The minimum acceptable CRs are determined by the lenders based on their perceived "riskiness" of the project and have to be fulfilled at all times for the project to be ultimately financed. Furthermore, these CRs determine the actual leverage (ratio of debt to equity) of the project and also to a great extend the realization of the equity investors' returns on the investment, as the project's lenders always have the first call (are senior) on the project's profits.

Finally, from the equity investors' point of view the main interest lays on the actual profitability of the project and in particular on the profit left after the debt obligations have been fulfilled. The equity investors being the last link in the priority chain of the PPP financing in terms of gains and the first ones in terms of losses, close attention should be paid to their measures of financial viability (equity IRR, ROI or ROE) in order for them to be actively involved in the project and not lose interest in it.

[1] The ADSCR assesses the ability of the Project Company to service the debt from its annual cash flows. It is calculated annually (or semi-annually). Lenders usually have a minimum ADSCR requirement which determines the maximum loan that can be raised against the project under consideration (Yescombe 2007).

[2] The LLCR is a measure for the initial assessment of the Project Company's ability to service the debt over its whole term. Lenders usually have a required LLCR which is about 10% higher than the ADSCR. However, ADSCR is more useful as a measure as it measures the ability of the Project Company to service debt as it falls due (Yescombe 2007).

Risks in PPP projects

The notion of risk is a human construct referring to the probability of occurrence of a particular adverse event during a stated period of time and the quantification of its consequences (Edwards & Bowen 2003). Risks are bound to be related to human perception and to the stakeholders that they are affecting, a notion that was recently validated once more in a study by Hardcastle & Boothroyd (2003). PPP projects are subject to many risks during their life-cycle, commonly referred to as "project risks", a term that is in fact referring to the set(s) of individual risks that can be attributed to the different project participants. These risks have also different sources of origin and can be related to different phases of the project's life-cycle, leading to different possible classifications.

A first, generic classification distinguishes project risks into internal and external, denoting the origin of the risks factors and whether they come from within the project and thus can be influenced by the project decision making or are completely outside of the control of the project developers and hence are much more un-expectable and hard to manage (Songer et al 1997). According to another breakdown by the United Nations Industrial Development Organization (UNIDO), risks can be divided into General/Country risks and Specific Project risks. The former are further subdivided into political, commercial and legal risks while the latter in developmental, construction/completion and operating risks (Kalidindi & Thomas 2003; Jeon & Amekudzi 2006). Moreover, another popular classification, based on the project phases that risks belong to, has them falling into four different categories, namely development, construction, operation, and ongoing (also referred to as life-cycle risks) (Songer et al 1997), with other quite similar classifications also available (Edwards & Bowen 2003; Hardcastle &

Boothroyd 2003; Ashley et al 1998; El-Diraby & Gill 2006). In the industry practice, risk classification usually takes place by a combination of the above methods. As an example, in the analysis of risks performed for the Trans-Texas Corridor, a large highway project in the State of Texas, risks were divided in the following groups (TxDOT 2004(a)):

- Technical, design, construction and completion risks;
- Operation and maintenance risks and environmental or other liabilities; and
- Financial, market/price and political risks.

Under this classification it was also recognized in the analysis that some of these risks were restricted to particular project phases (such as design/construction risk and operation risk), while some other were ongoing and present in both phases (political/legal, economic/financing and environmental) (TxDOT 2004(a)). A particular category of risks that is of interest to this research contains the so-called financial project risks, i.e., risks that are related to financing/economic parameters of a project.

The financial risks of a project can be many and also found in many of its life cycle phases. In a recent study by Xenidis & Angelides (2005), the authors identified 27 different financial risks associated with BOT projects, most of which also exist in other types of PPPs. According to the same study, the majority of these risks (21 out of the 27) can be found to occur during the operation/maintenance phase of the projects, a fact that affects the project investment risk under consideration. Financial risks can also be classified in a variety of ways such as: internal/external (Songer et al 1997); systematic/non-systematic and specific/non-specific (Asenova & Beck 2003); based on the project phase they belong to (Asenova & Beck 2003;

Xenidis & Angelides 2005); or based on their sources of origin or content, such as government-, sponsor-, lender-, contractor-, and user-related (Xenidis & Angelides 2005).

Investment Risk

The investment risk of an infrastructure project has had many definitions. In one of its most complete definitions – as far as this dissertation is concerned- it been defined as the probability of failure to secure a required infrastructure-generated revenue used for servicing debt (as a minimum requirement) and/or obtaining an adequate return on the investment (Kakimoto & Seneviratne 2000). Thus it is by definition a financial-type risk and clearly, failure to meet any of the two aforementioned targets is synonymous with financial project failure. Furthermore, any of these two failures can initiate a series of chain-reacting effects starting from loan payment defaults on the side of the concessionaire and ending in the liquidation of the infrastructure asset and the dissolving of the partnership (Nevitt & Fabozzi 2002).

The investment risk is directly dependent on the relationship between the infrastructure-generated revenues and costs. This relationship also defines the existence and magnitude of the generated profit. To date the most widely used mechanism to generate revenues from the operation of an infrastructure facility is through user charges, usually implemented through toll collection. Other types of infrastructure-generated revenues can also be used, such as the leasing of roadside facilities or services, and the implementation of Shadow Toll policies where normal tolls cannot be implemented, to name a few. On the other hand, infrastructure operational and maintenance costs are incurred because of the existence of operating personnel and other fixed and non-fixed operational costs, as well as from the expected (or unexpected) “wear and tear” of the facility from its utilization and aging. Obviously, in order for an infrastructure facility to generate profit, the life-cycle revenues should (always) exceed the life-cycle costs.

From this definition of investment risk, one can also see a variety of engineering parameters that affect it (e.g., maintenance and rehabilitation costs depend on road deterioration, which in turn depends on the engineering design, the construction quality, the utilization and the environment, and so on and so forth). Hence it should be expected that a number of engineering variables (among others) would appear in the quantitative models used for the assessment of investment risk. As a validation of this argument, previous studies in this area have identified investment risk to be a function of the following risk elements (Seneviratne & Ranasinghe 1997; Javid & Seneviratne 2000; Kakimoto & Seneviratne 2000):

- Individual project risk, comprising construction cost overrun risk and delay risks;
- Competitive risk, comprising demand risks and market share risk (planning/feasibility risks); and
- Market risk, comprising interest rate and inflation risks, political risk and general economic environment risk.

These risk elements were also cross-referenced with other studies in the same area within which they were identified (Songer et al 1997; Li & Akintoye 2003; Asenova & Beck 2003; Kalidindi & Thomas 2003; Xenidis & Angelides 2005; Jeon & Amekudzi 2006). Usually for the study of the investment risk of PPP projects various assumptions about these risks are usually made. Some of the most common ones found in the literature and also adopted in this dissertation are the following:

- Individual project risks can be accounted for by the experience of the project contractors in providing accurate and reliable cost estimates and work-plan schedules;

- Competitive risk can be accounted for by a corresponding analysis performed prior to undertaking the project, resulting in accurate estimates of market shares of the project and its competitors. Furthermore, accurate estimates of the probability distributions of the stochastic parameters that are thought to affect the existence and magnitude of the infrastructure-generated revenues are assumed to be available from that same analysis.

- Market risk cannot be accounted in full *ab initio* and therefore will be part of the investment risk modeling, as far as interest, inflation and discount rates are concerned.

- Political risks and general economic environment risks are thought to be irrelevant except for the cases when the project is undertaken in countries with unstable political and economic environments, a condition that is not applicable to this dissertation.

Connection between Financial Viability and Investment Risk

From the literature review undertaken and the presentation of the concepts of Financial Viability and of the Investment Risk it has become clear that that the two are interrelated. More specifically, the investment risk is measured based on the overall project cash flows before equity returns and thus plays a critical role in determining the overall profitability of a project based on its anticipated operational characteristics and proposed financing scenario(s). It can therefore be considered to directly accommodate two of the financial viability criteria that were presented earlier, namely the attainment of a target MARR and the servicing of debt by the end of the project's operational period. It therefore specifically addresses the general requirements of both lenders and equity investors. However, it can also be used by all project stakeholders to support their own hard decisions regarding the procurement of the project and the negotiations towards financial closure in the following ways:

- The public authority can determine the attractiveness of the project to the private sector (which is directly related to bidding competition and thus to Value for Money) and also use it for the development of policies and regulations regarding the procurement of such projects;

- The lenders can evaluate the riskiness of the project with regard to the repayment of the projected outstanding debt (the expected Internal Rate of Return (IRR) is usually used to determine their LLCR (Yescombe 2007)) and therefore determine the final leverage of the project and the other financial structuring details that will make them comfortable in financing the project; and finally

- The equity investors can evaluate the likelihood of their own returns under various scenarios and use the results to further negotiate their contribution to the project financing in order for their minimum requirements to be accommodated.

Based on the above observations it is clear that central to the determination of the viability of a project for all three parties involved is the analysis of the Investment Risk. Therefore the proposed methodological frameworks both for the general case of all types of PPP transportation infrastructure projects and also for the specific case of highway toll-road concession projects are going to focus on the evaluation of the corresponding investment risk as a surrogate and at the same time a more comprehensive measure of their financial viability to the benefit of all stakeholders involved.

Evaluating Investments and Investment Risk

The evaluation of investments in long-term assets such as roadway projects has been implemented through a variety of methods, such as the Payback Period (PBP), the Net Present Value (NPV), the Profitability Index (Benefit-Cost ratio) (PI/BCR) and the Internal Rate of Return (IRR). Among these methods the NPV and IRR are the most popular and widely used to date, with PBP used also but in a secondary level of analysis (Keown *et al* 2005). In general terms, the NPV or the IRR of a project will be given respectively by:

$$NPV = \sum_{t=1}^{n} \frac{FCF_t}{\left(1+r\right)^t} - IO \tag{1}$$

where:

FCF_t: the annual expected free cash flows for period *t*,

IO: the initial cash outlays,

r: the appropriate discount rate, and

n: the analysis period,

and:

$$IO = \sum_{t=1}^{n} \frac{FCF_t}{\left(1 + IRR\right)^t} \qquad (2)$$

where:

FCF_t: the annual expected free cash flows for period *t*,

IO: the initial cash outlays,

IRR: the project's internal rate of return, and

n: the analysis period

Equation (2) is solved iteratively in order for the *IRR* to be determined.

Regardless of the specific method used, the underlying concept in all of them is to evaluate the impact of the investment in terms of the relationship between initial cash outlays and projected future cash-flows (either positive or negative). The financial models used in all of these methods usually discount all initial and projected cash-flows to present values in order to achieve a uniform time value of money, keeping the calculations relevant.

In other existing variations of these methods, NPV-at-risk (Ye & Tiong 2000), possibility theory (Mohamed & McCowan 2001) and mean-semideviation behavior (Jafarizadeh & Khorshid-Doust 2007) among others, have been used in order to assess the investment under consideration and provide an answer to whether it should be selected for future implementation or not.

Accounting for risk with the use of these methods traditionally takes place by performing a stochastic (versus a deterministic) analysis and using either the Certainty Equivalent Approach (CEA) or considering Risk-Adjusted (RA) variables (usually discount rates) in the corresponding financial models (Keown *et al* 2005). In the former case (i.e., CEA) the analysis involves the estimation of the certainty equivalent coefficient (a_t) and the calculation of the certainty equivalent value for each individual risk separately, with the risk premium included in the valuation formula and the use of fixed discount rates. In general terms the *NPV* of the project with this approach will be:

$$NPV = \sum_{t=1}^{n} \frac{a_t FCF_t}{\left(1+r_{rf}\right)^t} - IO \qquad (3)$$

where:

a_t: the certainty equivalent coefficient for period *t*,

FCF_t: the annual expected free cash flows for period *t*,

IO: the initial cash outlays, and

r_{rf}: the risk-free discount rate

In the latter case (i.e., RA) the *NPV* will be given by:

$$NPV = \sum_{t=1}^{n} \frac{FCF_t}{\left(1+r^*\right)^t} - IO \qquad (4)$$

where:

FCF_t: the annual expected free cash flows for period *t*,

IO: the initial cash outlays, and

r^*: the risk-adjusted discount rate

The specification of the risk-adjusted discount rate involves the calculation of the beta (β) of the investment which is a risk measure defined mathematically as:

$$\beta = \frac{\text{cov}\left(\tilde{R}, \tilde{R}_m\right)}{\sigma_m^2} \tag{5}$$

where:

$\text{cov}\left(\tilde{R}, \tilde{R}_m\right)$: the covariance of the return of the investment with respect to the equivalent market portfolio, and

σ_m^2: the variance (or the square of standard deviation) of the market portfolio itself

The beta of the investment can be determined from either the Capital Asset Pricing Model (CAPM) or the Arbitrage Pricing Model (APM). In these models, the risk is assumed to be either the variation in the returns (CAPM), or a function of the expected returns and market variations (APM) (Senerivatne & Ranasinghe 1997; Bodie *et al* 2005). From the estimation of the beta the financial analysts can calculate a very meaningful risk-adjusted rate of return, the Minimum Acceptable Rate of Return (*MARR*) of the investment (also known as the hurdle rate), which is the minimum discount rate that makes the investment profitable and attractive to the investors. The *MARR* as its name implies, is the minimum of all risk-adjusted discount rates and can be determined by assuming it to be equal to the risk-free rate plus a (minimum acceptable) risk premium whose magnitude depends on the estimated beta, or:

$$r^* = r_{rf} + \beta r_p \tag{6}$$

where:

r^*: the *MARR*,

r_{rf}: the risk-free rate,

r_p: the risk premium, and

β: the beta of the investment

This method of estimating the investment risk has traditionally been used by people with a background in finance as this is how the investment risk of financial securities is usually calculated.

Besides the use of these “traditional” methods to evaluate investments and their corresponding risk, a more direct way to estimate the investment risk is by going back to one of its alternative definitions: the risk that the expected rate of return may fall short of a targeted value (*MARR*) (Seneviratne & Ranasinghe 1997). By using this definition one can directly try to quantify the investment risk by estimating the exceedance probability P_f, that is by specifying the probability distribution of the *IRR*, estimating the *MARR* and calculating the probability that the *IRR* is going to be less than or equal to the *MARR*, or:

$$P_f = P\left(R \le r^*\right) = \int_0^{r^*} \varphi_R\left(r\right) dr\,,\ r \in R \tag{7}$$

where:

r^*: the hurdle rate (=*MARR*)

$\varphi_R\left(r\right)$: the probability density function (PDF) of the *IRR*

A similar variation corresponds to finding the risk that the expected *NPV* may fall short of a targeted value (Javid & Seneviratne 2000), in which case the mathematical formulation is:

$$P_f = P\left(NPV \le V\right) = \int_0^{V} \varphi_{NPV}\left(npv\right) dnpv\,, V \in NPV \tag{8}$$

where:

$\varphi_{NPV}\left(npv\right)$: the PDF of the *NPV*

However, all previously mentioned approaches have their shortcomings: in the CEA approach finding suitable certainty equivalent coefficients for every type of risk can be challenging; and in the risk-adjusted discount rate and probability of exceedance approaches, the estimation of the risk-adjusted discount rate (*MARR*) require the estimation of the beta. The estimation of the beta, however, requires as an input an appropriate market portfolio related to the type of investment under consideration. Such a market portfolio is difficult or impossible to obtain in the case of infrastructure projects, since such projects are not traded like other financial assets and such data usually do not exist. As a result, in most analyses undertaken so far with the use of these approaches, the aim had been to obtain the statistical distribution of the infrastructure returns or of the *IRR*, and assess the investment risk by comparing their standard deviations to the individual corresponding standard deviations of similar projects (Seneviratne & Ranasinghe 1997). This approach was used, for example, in the evaluation of investment risk in the case of a highway toll-road project in Sri Lanka by Seneviratne & Ranasinghe (1997) with Monte Carlo simulation used to obtain the statistical distribution of the *IRR* and then compare it to a target *MARR*. Aldrete-Sánchez (1998) also used Monte Carlo simulation for the development of a feasibility evaluation program for toll-road projects that was based on a probabilistic estimation of the *NPV* and *IRR*, with an application to the Mexican toll-road network. Finally, Javid & Seneviratne (2000) used Monte Carlo simulation to obtain a statistical distribution of the *NPV* of an airport parking facility and compare it to a target value.

Another approach that circumvents the problem of finding a suitable and comparable market portfolio and calculating the investment beta is to directly estimate the probability of the investment *IRR* being less or equal to a target *MARR* without going through the estimation of the *IRR* itself. In this case the investment risk problem is transformed; instead of trying to solve for the *IRR* and determine the *MARR*, the aim is to determine the probability of the *IRR* being smaller than a necessary *MARR*. This is done by formulating the failure probability as a conditional probability: the probability of the present value of the infrastructure-generated net operating income being less than zero, conditional on the discount rate being equal to a target *MARR* value or:

$$P_f = \Pr\left\{PV\left(\text{Net Operating Income}\right) < 0 \middle| r = MARR\right\} \tag{9}$$

The only "drawbacks" of this approach is that the *MARR* (which under the previous approaches was usually to be determined) has to be known *a priori* in the analysis (as a target value or a probability distribution), usually by assuming it to be greater than the risk-free rate by an arbitrary risk-premium; and that after the analysis is undertaken the exact *IRR* of the project is not explicitly known unless estimated by some other method. However, the estimation of the exact *IRR* of the project in all previous methods was just a step taken in the evaluation of the investment risk in order to be able to estimate the *MARR* and compare the two together. With this last formulation the investment risk is directly estimated without having to engage in the difficult task of estimating the exact project *IRR*, thus simplifying the analysis. Furthermore, by estimating this failure probability for various scenarios concerning the values (or statistical distributions) of the underlying parameters that affect the generation and magnitude of the profit (including the *MARR*), one can obtain risk estimates in the form of probability or reliability values and be able to assess the riskiness of the investment, conditional on the target value of the *MARR* being realized. This last approach was used by Kakimoto & Seneviratne (2000) in the evaluation of port infrastructure investments, where the investment risk was estimated with the use of the two-moment method.

The Basic Structural Reliability Problem

The definition of the investment risk as stated in (9) has the form of the basic structural reliability problem (Ang & Tang 1984; Melchers 1999). This problem can be found in abundance in the area of civil engineering structural analysis and safety; and many developments regarding the solution of this problem come from research conducted in this particular area of engineering.

The basic structural reliability problem can be cast as a problem of supply versus demand or of a "load" effect (stress) resisted by a "resistance" (strength). This is also known as the “strength-stress interaction” principle or model (Zhang and Damnjanovic 2006(a)). As in real life there is uncertainty about the determination of the required demand and available supply, both of them are usually modeled as random variables. In the basic form of the problem we can define the following basic random variables:

X as the random variable that affects the supply capacity, and

Y as the random variable that affects the demand requirements.

Then, the objective of the reliability analysis will be to ensure that the supply capacity will be greater than the demand requirements of the engineering system, or that $X > Y$. Conversely, the failure event, known also as the violation of the safety limit state, can be defined as the case in which $X < Y$. From all the above we can define a limit state function $G(X,Y)$ based on the stochastic random variables X and Y that affect it (Ang & Tang 1984). With the limit state function defined, the failure region of the problem can consequently be determined by the space in which the limit state function takes negative values, or $\{G(X,Y)<0\}$ (Ang & Tang 1984; Melchers 1999). As a result, the probability of failure can then be defined as $P_F = \Pr\{G(X,Y)<0\}$ which under the assumptions of continuity and independence for the stochastic variables X and Y can be proven to be equivalent to the multi-dimensional probability integral of the joint PDF of X and Y, denoted by $h(X,Y)$, over the failure region of the limit state function, or:

$$P_F = \Pr\{G(X,Y)<0\} = \int_{G(X,Y)<0} h(x,y)dxdy \tag{10}$$

Because the reliability of an engineering system may involve multiple variables, the above formulations can be generalized for the case where X and Y are not simple basic random variables but vectors of basic random variables, i.e., $\mathbf{X}$ and $\mathbf{Y}$. In this case the limit state function is defined as $G(\mathbf{X},\mathbf{Y})$, while the failure "state" and the probability of failure are defined as $\{G(\mathbf{X},\mathbf{Y})<0\}$ and $P_F=\Pr\{G(\mathbf{X},\mathbf{Y})<0\}$ respectively. Finally, similarly to (10), by assuming that the basic random variables in $\mathbf{X}$ and $\mathbf{Y}$ are continuous and statistically independent, the probability of failure can be expressed as:

$$P_F=\Pr\{G(\mathbf{X},\mathbf{Y})<0\}=\int_{G(\mathbf{X},\mathbf{Y})<0} h(\mathbf{x},\mathbf{y})d\mathbf{x}d\mathbf{y} \tag{11}$$

where:

$h(\mathbf{x},\mathbf{y})$: the joint PDF of the basic random variables in vectors $\mathbf{X}$ and $\mathbf{Y}$

This resulting multi-dimensional probability integral in expressions (10) and (11) can be solved analytically in very few cases and under specific assumptions. In general, however, this evaluation is a challenging task and an exact solution to it is very hard – or sometimes impossible – to obtain. As a result this integral has been solved with the use of various approximation methods, both numerical and analytical, such as the Monte Carlo simulation, the First Order Reliability Method (FORM), the Second Order Reliability Method (SORM), the First Order Third Moment (FOTM) Method, as well as the Method of Moments (Zhang & Damnjanovic 2006(a)). Details on the exact solution process of these numerical and analytical approximation methods can be found elsewhere in the literature, such as in Ang & Tang (1984), Melchers (1999), and Zhang & Damnjanovic (2006(a)).

The Method of Moments

The Method of Moments (MOM) is a relatively new higher moment technique that has been developed for the analytical approximation of the solution of multi-dimensional probability integrals. It is based on a method that relates the higher-order central moments of the limit state function and the probability of failure (Zhang & Damnjanovic 2006(a)) and was originally developed in the area of structural reliability and safety by Zhao & Ono (2001).

The MOM is based on two steps: First the four central moments of the limit state function are estimated by using point estimates obtained in standard normal space, i.e., the probability space of the standard normal distribution. These point estimates, that can be either five or seven (Zhao & Ono 2000), allow for an improvement in the accuracy of the estimation of the central moments. Second, with the use of the obtained four central moments, the reliability index and the corresponding probability of failure are estimated using existing standardized functions (Zhao & Ang 2003; Zhang & Damnjanovic 2006(a)).

In order to find the higher-order moments of the limit state function $G(\mathbf{X},\mathbf{Y})$, Zhao & Ono (2001) proposed the use of an equivalent linear approximation given by:

$$G^*(\boldsymbol{X},\boldsymbol{Y}) = \sum_{i\in\{\boldsymbol{X}\cup\boldsymbol{Y}\}} \left(G_i - G_\mu\right) + G_\mu \tag{12}$$

where:

G_i ($i \in \{\boldsymbol{X} \cup \boldsymbol{Y}\}$): functions with the same form as the limit state function but in which the basic random variables are evaluated with their mean values except the one that appears in the index of the function,

G_{μ} : the limit state function evaluated at the mean value of all its random variables

By considering all four central moments of the approximated limit state function, the resulting four-moment reliability index β_{4M} can be determined by the following formula (Zhao & Ono 2001):

$$\beta_{4M} = \frac{3\left[\alpha_{4G^*} - 1\right]\left[\mu_{G^*} / \sigma_{G^*}\right] + \alpha_{3G^*}\left\{\left[\mu_{G^*} / \sigma_{G^*}\right]^2 - 1\right\}}{\left\{\left[9\alpha_{4G^*} - 5\alpha_{3G^*}^2 - 9\right]\left[a_{4G^*} - 1\right]\right\}^{0.5}} \tag{13}$$

where:

$$\mu_{G^*} = \sum_{i \in \{\boldsymbol{X} \cup \boldsymbol{Y}\}} \left(\mu_{G_i} - G_{\mu}\right) + G_{\mu} \tag{14}$$

$$\sigma_{G^*}^2 = \sum_{i \in \{\boldsymbol{X} \cup \boldsymbol{Y}\}} \sigma_{G_i}^2 \tag{15}$$

$$\alpha_{3G^*}\sigma_{G^*}^3 = \sum_{i \in \{\boldsymbol{X} \cup \boldsymbol{Y}\}} \alpha_{3G_i}\sigma_{G_i}^3 \tag{16}$$

$$\alpha_{4G^*}\sigma_{G^*}^4 = \sum_{i \in \{\boldsymbol{X} \cup \boldsymbol{Y}\}} \alpha_{4G_i}\sigma_{G_i}^4 + 6 \sum_{i \in \{\boldsymbol{X} \cup \boldsymbol{Y}\}} \sum_{\substack{j \in \{\boldsymbol{X} \cup \boldsymbol{Y}\} \\ i \neq j}} \sigma_{G_i}^2 \sigma_{G_j}^2 \tag{17}$$

and also:

$$\mu_{G_i} = \sum_{k=1}^{m} P_k G_i\left[T^{-1}\left(u_k\right)\right] \tag{18}$$

$$\sigma_{G_i}^2 = \sum_{k=1}^{m} P_k \left\{G_i\left[T^{-1}\left(u_k\right)\right] - \mu_{G_i}\right\}^2 \tag{19}$$

$$\alpha_{rG_i}\sigma_{G_i}^r = \sum_{k=1}^{m} P_k \left\{G_i\left[T^{-1}\left(u_k\right)\right]-\mu_{G_i}\right\}^r \tag{20}$$

where:

μ_{G^*}: is the mean,

σ_{G^*}: is the variance, and

$\alpha_{nG^*}\sigma_{G^*}^n$: the n^{th} dimensionless central moment of the linearly approximated limit state function G^*;

and also:

μ_{G_i}: the mean,

σ_{G_i}: the variance,

$\alpha_{rG_i}\sigma_{G_i}^r$: the r^{th} dimensionless central moments of the function G_i,

$T^{-1}(.)$: is the inverse Rosenblatt transformation,

u_k ($k=1,...,m$): the estimating points, and

P_k ($k=1,...,m$): the corresponding weights, as defined by Zhao & Ono (2000)

With the use of the four-moment reliability index, the probability of failure can be directly obtained by:

$$P_F = \Pr\left\{G\left(\boldsymbol{X},\boldsymbol{Y}\right) < 0\right\} = \int_{G(\boldsymbol{X},\boldsymbol{Y})<0} h\left(\boldsymbol{x},\boldsymbol{y}\right) d\boldsymbol{x} d\boldsymbol{y} = \Phi\left[-\beta_{4M}\left(\boldsymbol{X},\boldsymbol{Y}\right)\right] \quad (21)$$

Furthermore, the corresponding reliability can be obtained by:

$$R\left(\boldsymbol{X},\boldsymbol{Y}\right) = 1 - P_F = 1 - \Phi\left[-\beta_{4M}\left(\boldsymbol{X},\boldsymbol{Y}\right)\right] \quad (22)$$

where:

$\Phi\left(.\right)$: the cumulative density function of the standard Normal probability distribution

The main advantage of the MOM over other higher moment statistical methods is that it provides better estimates of the first four moments of the limit state function and thus of the probability of failure, even for highly non-linear limit state functions. This is due to the fact that the point estimation takes place in standard normal space, rather than in the original probability space of the explanatory variables. Also, the evaluation of the failure probability by the MOM is computationally simple and provides for the analytical traceability of the solution, a clear advantage over numerical (simulation) techniques (Zhang & Damnjanovic 2006(b); Damnjanovic & Zhang 2008).

Stochastic Counting Processes

Stochastic point processes represent an extension of reliability theory in the case of repairable systems. Under the theory of repairable systems, each time a failure occurs emergency repairs are undertaken restoring the system to a functioning state without the need for complete replacement. The time between consecutive failures is referred to as the inter-arrival time. A stochastic point process describes a sequence of inter-arrival times.

The behavior of the number of failures $N(t)$ in a time interval can be modeled through a stochastic counting process. According to Ross (1983) a stochastic process $\left[N(t), t \geq 0\right]$ is said to be a counting process if $N(t)$ satisfies the following:

- $N(t) \geq 0$

- $N(t)$ is integer

- If $s < t$ then $N(s) \leq N(t)$

- For $s < t$ then $\left[N(s) - N(t)\right]$ represents the number of failures in the interval $(s, t]$

Three of the most common types of stochastic counting processes used in engineering applications are:

1. The homogenous Poisson Process (HPP), in which the inter-arrival times are independent and exponentially distributed

2. The non-homogeneous Poisson Process (NHPP), in which the inter-arrival times are neither independent nor identically distributed

3. The Renewal Process (RP), in which the inter-arrival times are independent and identically distributed but not necessarily through an exponential distribution

From these three types the NHPP has been extensively used as a model of emergency repairs in complex systems, under the assumption that the repairs leave the system in an "As Bad As Old" (ABAO) state. This is usually a realistic assumption in the cases where the emergency repair does not affect the entire system but just a part of it. In terms of modeling, the ABAO assumption translates to not changing the overall trend of the rate of occurrence of failures (ROCOF) function, a function that characterizes the shape and evolution in time of the NHPP.

In more detail, a stochastic counting process is the NHPP with the ROCOF function $\lambda(t)$ for $t \geq 0$ if (Ross 1983):

- $N(0) = 0$
- $\left[N(t), t \geq 0\right]$ has independent increments,
- $\Pr\left\{N(t+\Delta t) - N(t) \geq 2\right\} = o(\Delta t)$, the system will not experience more than one failure occurring simultaneously, and
- $\Pr\left\{N(t+\Delta t) - N(t) = 1\right\} = \lambda(t)\Delta t + o(\Delta t)$

From the above it can be seen that the ROCOF function $\lambda(t)$ actually defines the NHPP, for the particular case of which it is also called "peril rate" or "failure intensity function".

Mathematically, the ROCOF function $\lambda(t)$ can be defined as:

$$\lambda(t) = \lim_{\Delta t \to 0} \frac{\Pr\left\{N(t+\Delta t) - N(t) \geq 1\right\}}{\Delta t} = \frac{d}{dt} E\left[N(t)\right] \tag{23}$$

From this definition it is easy to see that the expected number of failures is equal to the cumulative intensity of the process $\Lambda(t)$ at time t, or:

$$E\left[N(t)\right]=\Lambda(t)=\int_0^t \lambda(u)\,du \tag{24}$$

Furthermore, the distribution of the number of failures in the interval $\left(t_1,t_2\right]$ can be easily verified to be following a Poisson distribution (Ross 1983):

$$\Pr\left\{N(t_2)-N(t_1)=n\right\}=\frac{\left[\Lambda(t_2)-\Lambda(t_1)\right]^n}{n!}e^{-\left[\Lambda(t_2)-\Lambda(t_1)\right]}\text{, for } n=0,1,2,\ldots,\infty \tag{25}$$

where:

n: the number of failures in the interval $\left(t_1,t_2\right]$

Finally, if T_1 represents the time to the first failure in the process, then the survival function of the NHPP for the first repair cycle is:

$$S_1(t)=\Pr\left\{T_1>t\right\}=\Pr\left[N(t)=0\right]=e^{-\Lambda(t)}=e^{-\int_0^t \lambda(u)du} \tag{26}$$

The NHPP has been successfully utilized by Damnjanovic & Zhang (2008) in the modeling of the risk cost of pavement systems, i.e., the cost of unexpected pavement failures, during the evaluation of long-term performance-specified maintenance contacts. In this work the authors argue that the use of the NHPP is suitable as a modeling tool, as a localized pavement failure may be fixed in the majority of cases by a local patch, an action that restores the pavement to a functioning state but does not improve its structural capacity or change its overall deterioration process. However, many more modeling options of the effect of maintenance and rehabilitation actions on repairable systems are available and the literature on this particular subject is very rich.

Models for the Effect of Preventive Maintenance and Rehabilitation actions

From the various available types of maintenance and rehabilitation, preventive maintenance as well as periodic rehabilitation play an important role in the management of transportation infrastructure, not only because of the implication that they have on the life of the facility but also of the effect they have on its life-cycle costs. In effect, the application of both these actions directly affects the deterioration process of the facility in a proactive way, meaning that they are usually applied before the facility has reached failure. In this case their application is synonymous to the planned expenditures of the facility, i.e., actions that are undertaken in order to preserve the existing infrastructure. However, rehabilitation, as well as other types of repair, is also related to expenditures that aim to improve or enhance the existing system, i.e., actions that need to be undertaken in a corrective manner, as a consequence of unexpected failures. Obviously, one would expect to find a direct connection between the number of these unexpected failures that require corrective actions and the number of proactive actions undertaken during the life of the facility, as the more proactive one tends to be the more one would expect to reduce the number of unexpected failures.

To understand the impact of preventive maintenance and periodic rehabilitation, one needs to begin by recognizing that their corresponding effects on facility performance are different. Preventive maintenance actions can decrease the actual, measured defects of the facility (e.g. pavement surface distresses) but they cannot decrease the future frequency of occurrence of such defects/failures. On the other hand, periodic rehabilitation usually being a more substantial action can decrease both the current level of defects as well as the future rate of their occurrence, by changing the actual deterioration intensity of the facility.

The effects of preventive maintenance and periodic rehabilitation have been modeled in a variety of ways, resulting in significant research and numerous publications. In terms of applications in the area of transportation infrastructure significant research has been done in the area of pavement facilities, which are also the focal point of this dissertation. From the available scientific literature one can observe that one of the most common ways to model these effects is through the use of the transition probabilities of stochastic Markov Decision Processes (MDP). There have also been approaches based on the concept of remaining life (although this concept was later questioned and subsequently modified.), as well as on traditional reliability theory and stochastic processes. A more thorough review of such applications can be found in Damnjanovic (2006).

As mentioned previously, the determination of the effects of preventive maintenance and periodic rehabilitation is extremely important because of their effect on the number of unexpected failures during the life time of a facility. This number of failures can be modeled by a random variable where stochastic processes can provide a statistical description of it. One of the fundamental concepts pertaining to the modeling of repair actions through stochastic processes has to do with the effectiveness of the repair. The two most general assumptions for this repair effectiveness are the “minimal repair”, i.e., repair actions that leave the system in an “as-bad-as-old” (ABAO) condition, or the “perfect repair”, i.e., repair actions that are assumed to restore the system to “as-good-as-new” (AGAN) condition. Furthermore, since in reality the effects of preventive maintenance and periodic rehabilitation are neither minimal nor perfect, there have been other models developed that consider “imperfect” repair actions. These models originate from a multidisciplinary research field that encompasses areas such as the reliability of repairable systems, maintenance theory, and reliability-centered maintenance to name a few; and theoretical results and more details about them can be found in Ebeling (1997), Rigdon & Basu (2000), Osaki (2002), and Nakagawa (2005), as well as in Damnjanovic (2006). However, these models have, for most of the times, been developed originally for applications in areas other than civil engineering and transportation infrastructure; and as a result their utilization in the area of infrastructure systems needs to be undertaken with caution because of the differences that exist in the way these systems behave in reality. Among other differences, these original theoretical models cannot take into account one significant category of repair actions that is very common in transportation infrastructure systems: actions that leave the system in a “better-than-new-condition”. An example of such an action can be the application of a thick overlay on a pavement structure that increases the structural capacity above its original value (Damnjanovic 2006).

Based on these observations, Damnjanovic (2006) proposed a novel combination of some results from reliability theory and stochastic processes for the modeling of repair actions of pavement structures. The developed models consider a time-dependent measure of pavement reliability which is based on the principle of stress-strength interaction, an element of the basic structural reliability problem that has been presented previously. Based on this basic reliability measure, a modified function can be used in order to consider the effect of preventive maintenance. Furthermore, this reliability measure can also be combined with stochastic point processes, namely the Non-Homogeneous Poisson Process, for the determination of the effects of periodic rehabilitation, as well as the estimation of the expected number of failures, under the assumption of minimal repair. This approach and methodology is also adopted for the purposes of this dissertation and presented in more detail in the following chapter in the section regarding the estimation of the total maintenance and rehabilitation costs of pavement infrastructure. A more complete presentation of the methodology and its original applications to the analysis of performance-specified short- and long-term pavement warranties can be found in Damnjanovic (2006), Zhang & Damnjanovic (2006(a), (b)), and Damnjanovic & Zhang (2008).

Summary

This chapter presented the literature review that supports the methodological frameworks proposed in this dissertation. The literature review started with a review of basic concepts such as Public Private Partnerships, Project Finance and Financial Viability measures and moved on to the identification of the risks of PPP projects with an emphasis on investment risk. Based on these basic concepts and their definitions a relationship between financial viability and investment risk was established thus justifying the use of the latter for the assessment of the former. Further on, the literature review covered different available methods for evaluating investments and investment risk, highlighting an investment risk definition and approach that forms the basis of the proposed methodological frameworks presented in this dissertation. Based on the investment risk definition, concepts from the basic reliability problem were presented along with the theory behind the Method of Moments, an analytical approximation technique that is adopted in this dissertation as the preferred solution method for evaluating investment risk. Finally, this chapter closed with the presentation of a few concepts regarding stochastic processes, engineering reliability, and maintenance theory, in terms of modeling different maintenance and rehabilitation (M&R) actions. The next chapter presents the research methodology that was followed in this dissertation and an overview of the proposed methodological frameworks that serves as the basis for the subsequent chapters.

CHAPTER 3: RESEARCH METHODOLOGY

Research Methodology

This dissertation research followed a well defined process where major steps taken are shown in Figure 1.

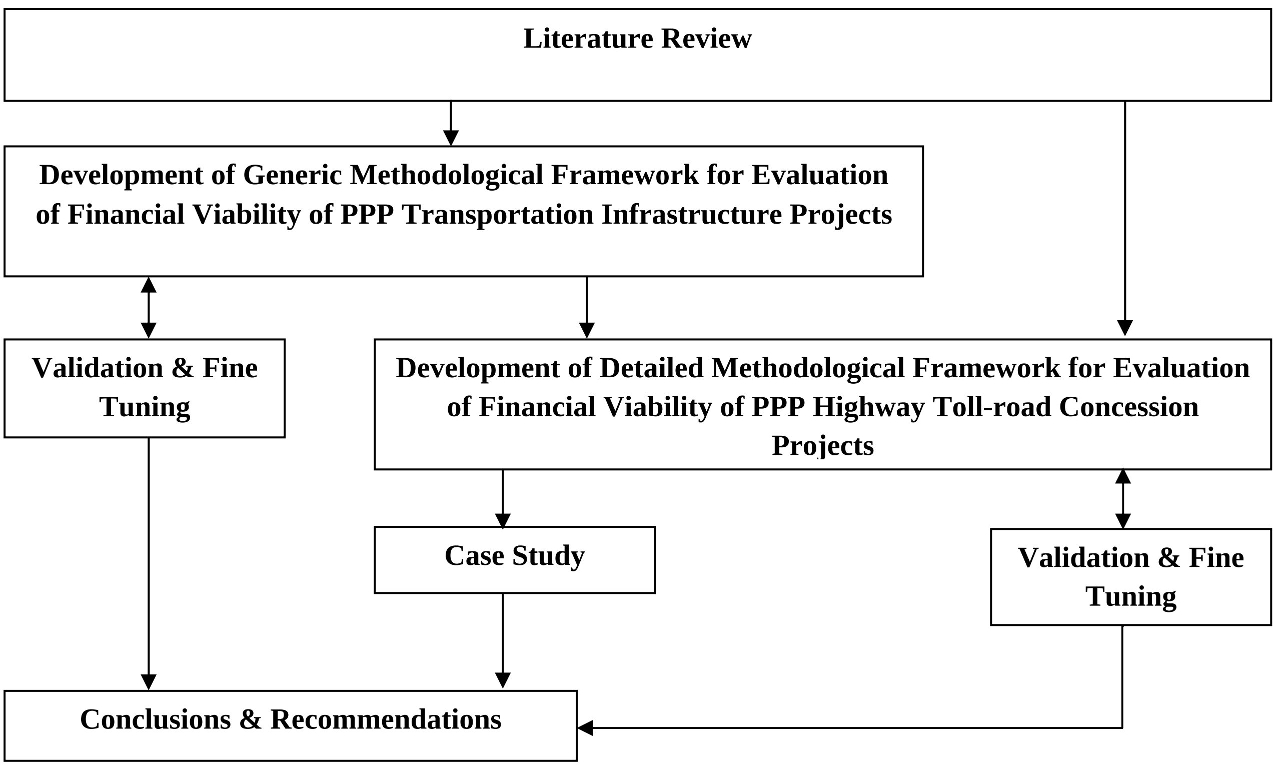

FIGURE 1. Dissertation Research Methodology

The research effort started with a comprehensive literature review. The literature review covered a variety of topics that are relative to this research such as Public Private Partnerships (PPP) and Project Finance, risks in PPPs, investment risk, methods of evaluating investments and investment risk, definition and measures of the financial viability of PPP projects, the basic structural reliability problem and available solution methodologies, the Method of Moments, stochastic processes and the Non-Homogeneous Poisson Process (NHPP) in particular, and models pertaining to capturing the effects of preventive maintenance and periodic rehabilitation.

Based on the information obtained through the literature review the relationship between the investment risk and the financial viability of PPP projects has been formally identified with the purpose of using the former for the evaluation of the latter.

After establishing this relationship, a generic methodological framework was developed for the evaluation of the financial viability of PPP transportation projects through the determination of their investment risk. This framework aims to be useful for various different options and types of PPP projects and as a result has been designed so as to allow for such flexibility.

Subsequently the proposed generic framework has been customized for the case of highway toll-road PPP projects. During this process specific quantitative models have been devised based on the characteristics of these projects. The modeling work for this specific framework also comprises the presentation of an approach for the determination of the exact maintenance and rehabilitation (M&R) costs of pavement projects, based on both expected and unexpected failures. This approach draws heavily from previous research in the field of pavement warranties and has been adopted in this dissertation due to its suitability.

Both the generic as well as the toll-road-specific methodological frameworks have been validated through some preliminary analysis with the purpose of fine tuning the proposed models.

Furthermore, a case study has been undertaken in the area of highway toll-roads. Through this case study the usefulness of the proposed methodology is demonstrated in terms of serving as a solid alternative decision support tool for the analysis of sensitivity and ultimately for the selection of PPP projects for implementation, based on probabilistic estimates of their investment risk.

Finally, observations and conclusions from all the above outlined parts of this research approach have been put together and form the basis of the recommendations for further research and possible extensions to the presented work.

Overview of Proposed Methodology

This dissertation proposes a comprehensive methodological framework for the assessment of the financial viability of PPP projects in transportation infrastructure. In order to do so a number of different concepts and methods from various academic fields are examined and integrated together. The conceptual framework of the methodology along with the various parts is shown in Figure 2.

Conceptually the methodology starts with obtaining and understanding the characteristics of the PPP project under consideration: contractual obligations, methods of financing, engineering parameters, etc. This information is combined with the financial viability criteria as outlined earlier in order to evaluate the projects investment risk.

In order for the investment risk to be evaluated different stochastic quantitative models need to be put into place regarding the project’s revenues and costs. These models describe the cash-flows of the projects during the various years and serve as basis for the investment risk formulation.

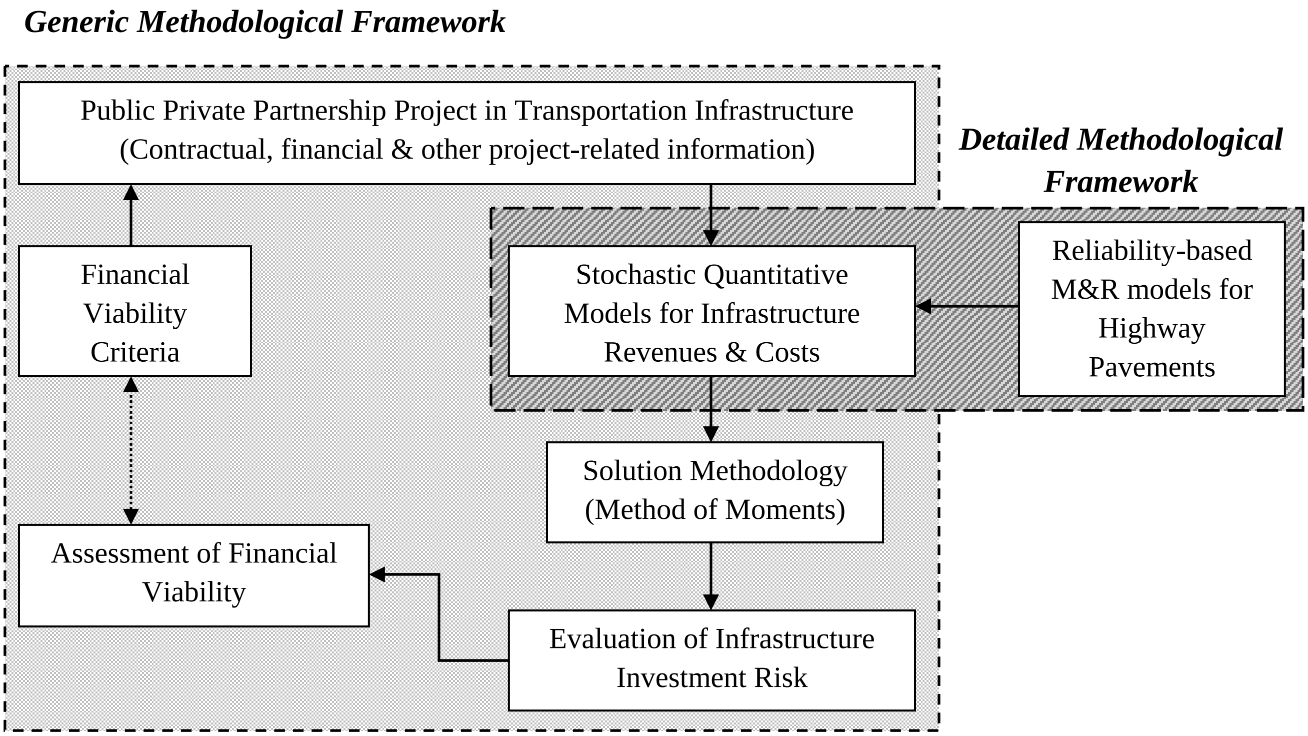

FIGURE 2. Outline of Conceptual Parts of Proposed Methodological Frameworks

The overall problem is subsequently solved with one of the various available solution methodologies. In this dissertation the solution methodology that has been adopted is the Method of Moments because of its various advantages over other methods, as discussed in the literature review. Once the investment risk has been evaluated, the financial viability of the project can be assessed for all stakeholders, either directly or indirectly, based on the relationship between the two as identified in the literature review. These conceptual parts form the subsequently presented Generic Methodological framework that aims to be flexible enough so that it can be applied to different PPP projects in transportation infrastructure.

Finally, for the Detailed Methodological framework that addresses the case of highway toll-road PPP, the M&R costs can be determined with the use of reliability-based cost models.

These models have been originally developed in the area of pavement maintenance warranties and have been modified where appropriate according to the needs of this dissertation. The justification for using these particular models is explained in a later chapter of this dissertation, after the presentation of some more generic M&R cost models that have been commonly used in practice.

Summary

This chapter presented the research methodology behind the work that was undertaken in this dissertation. This dissertation was based on a thorough literature review which subsequently led to the development of two frameworks: a generic one for the evaluation of the financial viability of PPP projects in transportation infrastructure and a detailed one specialized for highway toll-road concession projects. Both frameworks were validated through the course of the work while the detailed framework that pertained to highway toll-road concession projects was used in a case study in order to demonstrate its capabilities. Finally, this chapter also presented the general concepts behind the generic and the detailed methodological frameworks as well as the models for the estimation of the total M&R costs of a highway toll-road facility and identified the relations among them. The proposed frameworks and M&R models follow in the next three chapters.

CHAPTER 4: GENERIC METHODOLOGICAL FRAMEWORK FOR TRANSPORTATION INFRASTRUCTURE UNDER PPP

This research proposes a generic methodological framework for assessing the financial viability of PPP projects in transportation infrastructure by evaluating their investment risk. The proposed framework is depicted in Figure 3, where all of the related concepts, parameters and models ranging from the PPP terms and characteristics, the various financial viability criteria (and in particular the ones that are directly addressed by the investment risk) to the necessary quantitative models for evaluating the investment risk, are integrated together. The details of the framework are described in the following sections.

General Concept

Conceptually, the proposed methodology follows the information flow that is shown in Figure 3: based on the terms and characteristics that are specified in a PPP agreement, parameters important to the analysis of the investment risk are identified and defined as the decision variables. These variables are incorporated in quantitative models that aim to capture the cash inflows (revenues) and outflows (costs) of the project. The *NPV* of the difference between revenues and costs, i.e., the infrastructure generated net operating income, is defined as the limit state function of the investment risk problem. The investment risk can be expressed as the probability of not obtaining a positive present value (PV) of the infrastructure-generated net operating income, conditional on the discount rate being equal to a target *MARR*. As discussed in the literature review, this formulation comes from the seminal work of Kakimoto & Seneviratne (2000) and treats directly two measures of financial viability (the attainment of a target equity IRR and the servicing of the outstanding debt) while indirectly helping with the assessment of the remaining ones (Value for Money, Return on Equity, Cover Ratios). The limit state function is subsequently evaluated through a solution methodology, leading to the probabilistic evaluation of the project's investment risk. Based on this probabilistic investment risk estimate, an assessment of the project's financial viability can ultimately be made.

In this formulation, the implicit assumption is that the investment risk is directly related to the relationship between project revenues and total costs, both of which can be defined as statistical models of the explanatory random variables. By defining their difference as the limit state function, it is clear that the investment risk will be proportional to the failure region where the total costs exceed the revenues of the project. This concept is explored more rigorously in the following section.

Limit State Function

In the proposed formulation, the project Revenues can be regarded, in the general case, as functions of n explanatory random variables and the Total Costs as being functions of m explanatory random variables. These explanatory variables can be considered as elements of the random vectors $\boldsymbol{X} = \left[x_1, x_2, ..., x_n\right]^T$ and $\boldsymbol{Y} = \left[y_1, y_2, ..., y_m\right]^T$ and therefore their present values, $PV\left(R\right)$ and $PV\left(TC\right)$, can be expressed as $PV\left(R\left(\boldsymbol{X}\right)\right)$ and $PV\left(TC\left(\boldsymbol{Y}\right)\right)$.

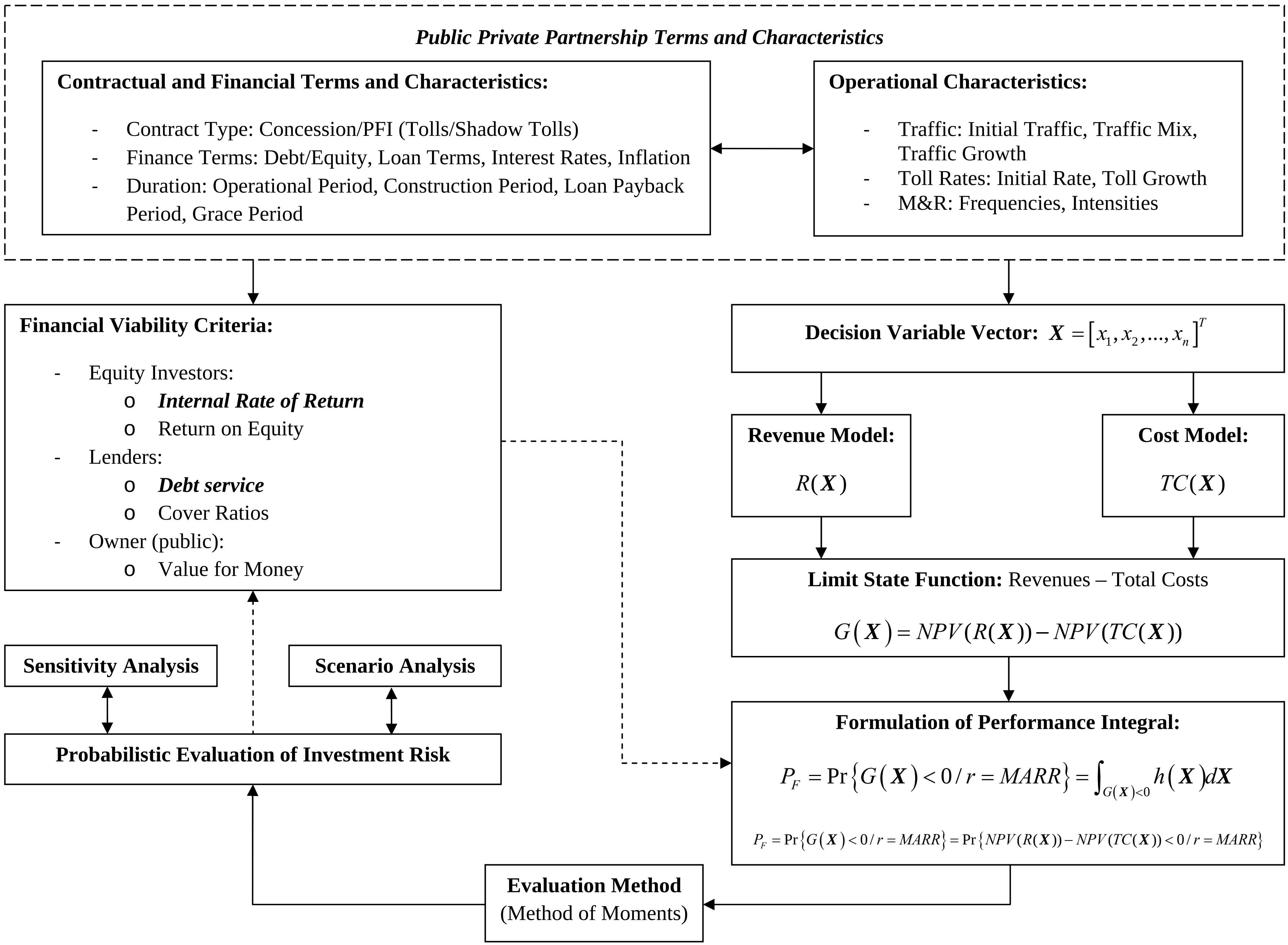

FIGURE 3. Generic Methodological Framework

By defining the PV of the difference between the infrastructure-generated revenues and costs as the limit state function $G(.)$ of the investment risk problem, we get:

$$G(\boldsymbol{X},\mathbf{Y}) = NPV\left(R(\boldsymbol{X}) - TC(\mathbf{Y})\right) = PV\left(R(\boldsymbol{X})\right) - PV\left(TC(\mathbf{Y})\right) \tag{27}$$

From the definitions of both the limit state function and the infrastructure-generated net operating income we also have:

$$P_F = \Pr\left\{G(\boldsymbol{X},\mathbf{Y}) < 0 \middle| r = MARR\right\} = \Pr\left\{PV\left(R(\boldsymbol{X})\right) - PV\left(TC(\mathbf{Y})\right) < 0 \middle| r = MARR\right\} \tag{28}$$

where:

$$PV\left(R(\boldsymbol{X})\right) = \sum_{t=0}^{T} \frac{R_t(\boldsymbol{X})}{(1+r)^t}:$$ PV of project Revenues

$$PV\left(TC(\mathbf{Y})\right) = \sum_{t=0}^{T} \frac{\left(IC_t(\mathbf{Y}) + Q_t MROC_t(\mathbf{Y})\right)}{(1+r)^t}:$$ PV of Total Costs

and

r: the discount rate,

T: the financial/operating life of project in years

The mathematical representation of the problem has the form of the basic reliability problem outlined in the literature review of this dissertation and therefore can be treated as such. By assuming that all the basic explanatory variables in $\boldsymbol{X}$ and $\boldsymbol{Y}$ are continuous and independent, it can be shown that the investment risk can be expressed as an $n+m$ -dimensional probability integral of their joint probability density function over the failure region of the problem where the limit state function takes negative values, or:

$$P_F = \Pr\left\{G\left(\boldsymbol{X},\boldsymbol{Y}\right) < 0 \middle| r = MARR\right\} = \int_{G(\boldsymbol{X},\boldsymbol{Y})<0} h\left(\boldsymbol{x},\boldsymbol{y}\right) d\boldsymbol{x} d\boldsymbol{y} \tag{29}$$

where:

$h\left(\boldsymbol{X},\boldsymbol{Y}\right)$: the joint probability density function of the basic random variables in $\boldsymbol{X}$ and $\boldsymbol{Y}$

In this dissertation, it is assumed that $\boldsymbol{X}$ and $\boldsymbol{Y}$ are independent to each other. This assumption is supported by the work of Kakimoto and Seneviratne (2000) which concludes that the investment risk estimate is not affected significantly by the consideration of potential correlation between variables or by the form of their probability density functions but rather by their assumed mean values and their coefficients of variation, which are mostly dependent on the robustness of their forecasting techniques and the quality of the available information. In the case where the explanatory variables in $\boldsymbol{X}$ and $\boldsymbol{Y}$ are correlated and this correlation needs to be taken into account, the original variables can be transformed to their uncorrelated counterparts through the use of the orthogonal transformation. The specifics of this transformation depend on the probability density functions of the individual random variables; in particular, depending on whether they are normal or non-normal, the transformation can be simple or quite cumbersome respectively. More information on the details of this transformation can be found in Ang & Tang (1984), Melchers (1999), and Kakimoto & Seneviratne (2000).

Revenue and Cost Models

In order for the limit state function to be formulated and subsequently evaluated, the Revenue and Cost models need to be specified. This is however a task that is infrastructure-specific as different types of transportation infrastructure may have different sources of revenue and different costs that need to be accounted for. Furthermore, based on the actual revenues and costs of each infrastructure, different variables may need to be considered as being stochastic in the corresponding formulations, leading to different possible vectors of $\boldsymbol{X}$ and $\boldsymbol{Y}$. Due to these potential differences, such models are not defined explicitly in this section but are left to the modeler's discretion based on the infrastructure project under consideration. The only prerequisite for these models is that they can be incorporated in the overall presented probabilistic framework, a requirement that is generally easy to adhere to for the proposed strength-stress formulation. Such models will be specified in detail for the case of highway toll-road PPP projects in the next chapter.

Evaluation Method

The solution to the problem is clearly to be obtained by the evaluation of the multi-dimensional probability integral in (29). As also discussed in the literature review, the exact evaluation of this integral can be challenging or impossible to obtain, as the derivation of the joint probability function of the $n+m$ basic random variables can itself be a challenge, even in the case where the probability distributions of the individual random variables are known. Research in the area of structural reliability and safety has resulted to a variety of approximating methods for the evaluation of such integrals. These methods can be numerical such as the Monte Carlo simulation (MCS), or analytical such as the First Order Reliability Method (FORM), the Second Order Reliability Method (SORM), the First Order Third Moment (FOTM) Method, as well as the Method of Moments (MOM) (Zhang & Damnjanovic 2006(a)). In this dissertation the method that is adopted for the evaluation of the investment risk is the MOM. As briefly discussed in the corresponding part of the literature review, the MOM presents many advantages over other analytical approximation methods while maintaining a reasonable level of accuracy compared to the MCS. With the use of the MOM, the investment risk can be estimated both accurately and analytically, providing a significant improvement over previous studies in that area.

Financial Viability Assessment

Through the use of the MOM, a probabilistic estimate of the investment risk can be obtained. This estimate corresponds to the characteristics and numerical values of the "base case" scenario for the infrastructure under consideration. Although it gives valuable information, this individual risk estimate does not show which of the various variables contribute mostly to the risk and what the magnitude of their contribution is. In order for all this information to be attained, various sensitivity analyses need to be undertaken, aiming at identifying the variables whose change would have the most significant impact on the investment risk and as a result would pose the biggest threat to the project's financial viability. Furthermore, additional combinations of different numerical values of the underlying variables can and should also be undertaken in order to evaluate different potential scenarios that could arise or that could be pursued in implementing the project under consideration. Such scenarios could correspond, for example, to different ways of financing the project, to considering different sources of revenues or costs or considering different financial expectations from the project's stakeholders.

By evaluating the investment risk for all these different scenarios and by performing the aforementioned sensitivity analyses, the financial viability can ultimately be assessed. In effect, by obtaining the probabilistic estimates of investment risk for potential changes of the project's stochastic variables and possible implementation scenarios, the project stakeholders can assess first whether these changes and scenarios are plausible or possible to actually happen, and second how much they would affect their financial expectations should some or all of them actually be materialized.

As a final note, through the use of the methodology, the actual *NPV* of the project can also be estimated, corresponding to the mean values of the revenue and cost variables and other project parameters. The simultaneous consideration of the actual *NPV*, the investment risk and the additional sensitivity and scenario analyses can provide all project stakeholders with significant insight regarding ultimately attaining their respective financial targets and help them with the corresponding decisions and negotiations, subsequently making the project being selected to move successfully from a planning to an implementation phase.

Summary

This chapter presented a Generic Methodological framework for the evaluation of the financial viability of PPP projects in transportation infrastructure. The framework is based on the probabilistic evaluation of the investment risk of such projects, through a risk definition that comes from previous research in this area. Subsequently, the various parts of the methodology were presented and explained while the solution to the problem would be attained with the use of the Method of Moments, representing an improvement to this estimation from previous research efforts. The implementation of this framework depends on the particular type of infrastructure under consideration; and with the addition of various sensitivity and scenario analyses it can ultimately provide an assessment of the financial viability of the project for all identified stakeholders.

In order for the methodological framework to be applied in practice, the Revenue and Total Cost models need to be specified and the stochastic variables of the formulation explicitly defined. Such more detailed models are discussed in the next chapter for the case of toll-road infrastructure projects developed as PPP concessions.

CHAPTER 5: DETAILED METHODOLOGICAL FRAMEWORK FOR HIGHWAY TOLL-ROAD CONCESSION PROJECTS

This chapter presents a detailed methodological framework for the evaluation of the financial viability of highway toll-road concession projects. These projects form a significant part of the overall number of projects that are developed as PPPs and enjoy worldwide interest. The detailed framework is based on the generic model formulation presented in Chapter 4. In fact the basic components of the formulation are exactly the same, with the difference that in the detailed framework specific revenue and cost models are presented for one specific type of infrastructure projects. Besides the specification of these models, the remaining part of the methodology can be considered identical to the generic one described in Chapter 4, proving that the generic methodological framework can be used for various types of transportation infrastructure, at least for the case of highway toll-roads. More specifically, the investment risk of highway toll-road projects will be evaluated from the limit state function to be generated from the specification of the revenue and cost models, using the Method of Moments. Then, the financial viability of such projects can be determined through various sensitivity and scenario analyses.

Because the major parts of this detailed framework are similar to the generic one, the emphasis in this chapter will be placed on the parts that are different, i.e., the identification of the decision variables and the specification of the revenue and cost models. These are presented in the following sections.

Decision Variables and Stochastic Quantitative Models

The decision variables and the subsequent stochastic quantitative models presented in this chapter draw elements from various similar seminal analyses, namely from Kakimoto & Seneviratne (2000), Seneviratne & Ranasinghe (1997) and Javid & Seneviratne (2000), and to a lesser extend from Vassalo & Izquierdo (2002) and Abdel Aziz & Russell (2006). In these studies the stochastic parameters that affect the infrastructure-generated net operating income come after the analysis of the various sources of risk that such projects are subject to, as presented in detail in the literature review of this dissertation. In these studies the stochastic parameters are assumed to be the following: infrastructure demand (traffic), user-charges (toll rate), traffic and toll rate growth factors, initial construction, operating, maintenance and rehabilitation cost estimates, and price escalation rates. These variables are also considered to be the basis of the models presented in this dissertation (with departures made through extensions and modification where deemed necessary). The proposed models are described in detail and the various stochastic variables are identified in the following sections.

Revenue model

The revenue of the facility under consideration is toll-generated during the operational period of the project; and as such it is traffic and toll-rate dependent. Traffic is assumed to be a stochastic variable, while toll-rate is assumed to be growing steadily based on a stochastic growth factor (inflation) from its initial value at the beginning of the operating period. The toll rate is also assumed different for different vehicle classes. The percentage of the different classes in the overall traffic is assumed to remain constant for the entire life of the project.

Based on the above assumptions the tolling revenue for year t is given by:

$$R_t = \begin{cases} 0 & ,t \in [0, \kappa] \\ \sum_{c \in \Theta} q_t^c r_t^c \tau d_{ave} & ,t \in [\kappa + 1, T] \end{cases} \tag{30}$$

where:

q_t^c : the amount of traffic for year t and traffic class c

r_t^c : the toll rate for year t and traffic class c

τ : the average number of toll transactions per trip

d_{ave} : the average trip length

Θ: the set of all vehicle classes

κ: construction period in years

Also:

$$q_t^c = \beta_c Q_t \tag{31}$$

where:

β_c : the percentage of traffic class c in the overall traffic

Q_t : the total traffic in year t

The total traffic Q_t for year *t* is assumed to be growing from its initial estimated value Q_0 during the first year of operations based on specific annual stochastic growth factors according to the following equation:

$$Q_t = Q_0 \prod_{j=\kappa+1}^{t-1} \left(1 + g_j^Q\right) \tag{32}$$

where:

g_j^Q: the annual traffic growth factor for year *j*, where *j* counts the years from the end of construction until the year before *t*.

Furthermore, the toll-rate for traffic class *c* will be growing from its value during the first year of operation based on a stochastic growth factor (inflation), according to the following equation:

$$r_t^c = r_0^c \left(1 + f_r\right)^{t-\kappa-1} \tag{33}$$

where:

r_t^c: the toll-rate for traffic class *c* at year *t*

r_0^c: is the toll-rate for traffic class *c* at the first year of operations

f_r: the annual toll-rate growth factor for all traffic classes

The above revenue equations are only considering the infrastructure-generated income from toll-collection. Other sources of income that could potentially be considered, such as the leasing of roadway right-of-way, advertizing, utilities fees etc, are ignored for the purpose of this dissertation.

Cost model

The Total Cost of infrastructure development (*TC*) is assumed to have two parts: 1) the initial construction cost (*IC*) and the way it is initially covered and then repaid during the project's operational period; and 2) the maintenance, rehabilitation and operation cost (*MROC*) which is incurred on a yearly or interval basis from operating the facility and maintaining it at a condition that is acceptable to the traveling public (usually based on the contractual responsibilities of operation).

Therefore, the *TC* at year *t* is represented by the following function:

$$TC_t = IC_t + MROC_t \tag{34}$$

The IC_t depends on the Total Initial Capital Cost (*TICC*), the financing method and also on the terms and conditions of the mix of loans, equity, grants, subsidies, etc., that are used to finance the project's development. During the years of construction, the IC_t is assumed to be equal to the part of the *TICC* covered by the equity committed by the developers/sponsors. During the project's operational years, it is equal to the debt repayment annuities, which can exist or not, based on the debt terms and conditions (such as interest rates, repayment periods, and grace periods). The debt is assumed to be issued on the first year of construction. Based on these assumptions, the IC_t can therefore be expressed as follows:

$$IC_t = \begin{cases} \alpha_e d_t TICC & ,t \in [0,\kappa] \\ \dfrac{\alpha_d TICC}{\nu}(1+i)^{\delta} & ,t \in [\kappa+1,T] \end{cases} \tag{35}$$

where:

α_e: the portion of committed equity as a percentage of the total initial capital cost

d_t: the percentage of C_0 drawn in year *t* of construction

α_d: the portion of issued debt as a percentage of the total initial capital cost

i: the stochastic interest rate of debt (where applicable)

δ: the duration of the debt in years

v: the number of debt repayment annuities (= number of repayment years)

The *TICC* is in essence the project financing or capital investment cost which is made over the duration of construction and therefore will be the sum of the yearly incurred construction costs growing with inflation, as follows:

$$TICC = \sum_{t=0}^{\kappa} \sum_{\gamma \in \Gamma} \alpha_{\gamma} ICC_t \tag{36}$$

where:

ICC_t: the initial capital cost at year *t* of construction

α_{γ}: portion of type of debt or equity *γ* as a percentage of the total initial capital cost, $\gamma = \{e,d\}$, $\gamma \in \Gamma$

Γ: set of all possible types of capital debt in the project's financing (public funds, equity or debt)

Also:

$$ICC_t = d_t C_0 \left(1 + f\right)^t \tag{37}$$

where:

C_0: initial construction cost estimate (excluding construction loan interest payments, inflation and fees)

f: the annual price escalation rate (inflation)

In this dissertation the initial construction cost estimate C_0 is considered to be a stochastic variable increasing with a stochastic growth factor (inflation) on an annual basis.

The $MROC_t$ consists of an annual Operating Cost (*OC*) and an annual Maintenance and Rehabilitation Cost (*MRC*) which can be existing or non-existing for any given year during operation based on the scheduled maintenance and/or rehabilitation activities of the project. Following the example of similar studies the (*OC*) and (*MRC*) are both expressed in relation to the initial construction cost estimate C_0 and grow with inflation as follows:

$$MROC_t = \begin{cases} 0 & ,t \in \left[0, \kappa\right] \\ OC_t + MRC_t & ,t \in \left[\kappa + 1, T\right] \end{cases} \tag{38}$$

Also:

$$OC_t = a_t^o C_0 \left(1+f\right)^{t-\kappa-1} \qquad (39)$$

where:

a_t^o: the cost of operation on year t as a percentage of the total initial project cost C_0

f: the annual price escalation rate (inflation)

and

$$MRC_t = \sum_{w=1}^{W} a_t^w C_0 \left(1+f\right)^{t-\kappa-1} \qquad (40)$$

where:

a_j^w: cost of maintenance/rehabilitation alternative w on year t as a percentage of the total initial project cost C_0

f: the annual price escalation rate (inflation)

W: the number of all available maintenance and rehabilitation options

The above presented revenues and costs for year t are then discounted to the first year of construction (or the base year of the financial analysis) and added together in order to determine their corresponding total *NPV*, as shown in equation (28). This discount factor, being is equal to the *MARR* by definition of the investment risk, is also considered in this dissertation as a stochastic variable. Once the modeling process has been completed, a solution method such as the MOM can be used to estimate the project's investment risk and assess its financial viability.

Discussion on Maintenance and Rehabilitation Cost Models

In the above presented *MROC* models the Maintenance and Rehabilitation (M&R) costs are estimated from an "economist's" point of view, i.e., they are treated as percentages of the initial construction costs incurred at various points of the life cycle of the project. This is very a common practice that is used in order to maintain a connection between the magnitude of these costs and the size of the overall infrastructure, as well as in order to simplify the corresponding calculations. Although this approach is generally not wrong, it is also not as accurate as it could be because of the following limitations: the model accounts only for planned M&R expenditures without considering the corrective maintenance actions which need to be undertaken in order to fix unexpected failures of the infrastructure and restore it to acceptable operating conditions. Such types of corrective repair for the case of the pavements of a highway tool-road project can be full rehabilitation, for failures that compromise the structural capacity of the facility, or localized patching, which is applied in order to fix small, localized failures that occur during the project's life cycle, among others.

Additionally, the current representation of the M&R costs fails to establish a connection between the facility utilization and the consumption of the infrastructure that results in these costs. Although this relationship can be represented mathematically through the utilization of a correlation factor between the corresponding explanatory variables, a more direct method that addresses this relationship from an engineering point of view would be more accurate and appropriate.

These limitations cannot be addressed without introducing a more sophisticated method to estimate the M&R costs. Such a method is introduced in this dissertation based on the rationale that the unexpected costs due to unplanned corrective actions would be translated to cash out-flows that could prove to be threatening to the investment risk and therefore to the financial viability of the project. The proposed method for pavement M&R cost estimation is described in the following chapter.

Summary

In this Chapter a detailed methodological framework for the evaluation of the financial viability of highway toll-road projects has been outlined. The framework is in effect identical to the generic framework presented in Chapter 4 with the difference that the various stochastic variables and revenue and cost models are explicitly defined. The revenue and cost models presented in this chapter draw elements from past similar analyses with extensions and modifications introduced where deemed appropriate. From these models the stochastic parameters that are identified to affect the investment risk and therefore the financial viability of highway toll-road projects include: the initial construction cost estimate; the initial traffic estimate at the first year of operations; the traffic growth factor(s); the various price and toll-rate escalation factors, assumed equal to the inflation rate; the interest rate of the outstanding debt; and the *MARR* which is equal to the discount rate of the formulation. Finally, as far as the usual formulations for the M&R costs are concerned, it was indentified that this formulation has a serious limitation regarding the absence of consideration for unplanned M&R actions that needs to be mitigated through a suitable methodology. Such a methodology is the topic of the next chapter.

CHAPTER 6: PROBABILISTIC METHOD FOR ESTIMATING TOTAL M&R COSTS

This dissertation utilizes concepts from engineering reliability and stochastic processes for the estimation of the total maintenance and rehabilitation (M&R) costs of the pavements of toll-road projects, comprising costs from both planned and unplanned M&R actions. An additional characteristic of the proposed method is the explicit consideration of the effect of traffic on the failure frequencies and intensities and therefore on the magnitude of such costs. The method for the determination of the Total M&R costs of toll-road PPP projects is conceptually presented in Figure 4.

From Figure 4 it can be seen that the process begins with the consideration of the initial design parameters and characteristics of the pavement structure of the project. Based on these characteristics, various alternative strategies of M&R can be proposed in order to keep the infrastructure in a condition that is acceptable to the public and/or as specified in the operation contracts of the concession agreement. These strategies usually include: a pre-specified frequency for routine maintenance (cleaning of ditches, painting of lines, cleaning of signs, etc.); and/or a pre-specified frequency for preventive maintenance (if applicable), such as chip sealing, fog sealing, crack sealing, etc.; and/or a pre-specified frequency and intensity for rehabilitation activities, such as thick overlays, reconstruction, etc. The determination and selection of these strategies is not the subject of this research and as a result such M&R strategies are going to be considered as external inputs to the presented process.

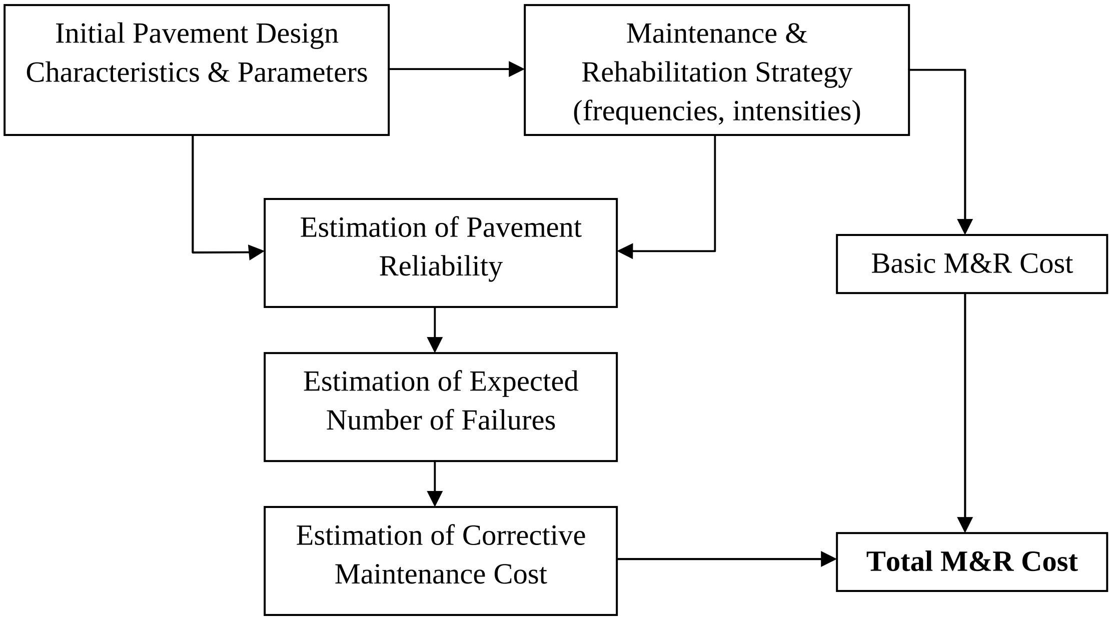

FIGURE 4. Process for the Estimation of Total M&R Costs

Once a basic M&R strategy for the project has been determined then the corresponding M&R cost can be determined. This cost can be estimated by equation (40) of the facility cost model, among other possible ways. As discussed in the previous chapter however, this cost estimate does not consider the expenses incurred by unexpected M&R actions that are mandated due to unexpected failures of the pavement infrastructure and are not accounted for by the regularly scheduled/planned M&R activities. In order to account for these additional M&R costs, this research adopted and customized concepts from an already established methodological framework developed by Damnjanovic & Zhang (2008) which was originally developed for the valuation of performance specified pavement maintenance contracts. This particular methodology was adopted because it fits perfectly the needs of this dissertation. This methodology is based on concepts emanating from the areas of structural reliability, and probability and stochastic processes, outperforming other similar models (some of them discussed in the literature review), in the sense that it can consider the effects of M&R actions that leave the system in a condition better than its original one. In a nutshell, the proposed methodology has the following characteristics:

- Quantifies the reliability of a pavement infrastructure at various points of its service life (both for new and for existing pavements),
- Takes into account the effect of various planned M&R actions on pavement reliability (both for preventive maintenance and for rehabilitation actions)
- Estimates the expected number of unexpected failures (and corresponding number of corrective M&R actions) between the originally planned M&R activities, and
- Quantifies the corrective maintenance actions in dollar values

Furthermore, through the determination of the pavement reliability, the design parameters and the utilization of the facility are explicitly taken into account, which will become apparent in the detailed discussion of the methodology in the following sections. Based on these characteristics, it is clear that this methodology can be perfectly applied for the purposes of this dissertation, treating successfully the various steps of the process outlined in Figure 4. The basic conceptual parts of the process are presented in the following sections.

Estimation of Pavement Reliability

The reliability of pavements is measured based on the principle of stress-strength interaction, i.e., the formulation of the basic structural reliability problem, as defined in the literature review of this dissertation. The formulation utilizes different models depending on whether the pavement structure under consideration is new, or has been in use for some time.

For the case of new pavements the following time-dependent limit state function is defined (Zhang & Damnjanovic 2006(a)):

$$G(\boldsymbol{x},\boldsymbol{y},t) = q(\boldsymbol{x}) - z(\mathbf{y},t) \ , \ \mathbf{x} \in \mathbf{R}^{l}, \mathbf{y} \in \mathbf{R}^{m} \tag{41}$$

where:

$q(\boldsymbol{x})$: a function defining the pavement strength, or the allowable load repetitions

$z(\mathbf{y},t)$: a function defining pavement stress, or the accumulated load repetitions

Based on this limit state function, the probability of pavement failure can be expressed as the following $l+m$ -dimensional probability integral:

$$F(t) = \Pr\{G(\boldsymbol{x},\boldsymbol{y},t) \le 0\} = \int_{G(\boldsymbol{x},\boldsymbol{y},t)\le 0} f(\boldsymbol{x},\boldsymbol{y},t) d\mathbf{x} d\mathbf{y} \tag{42}$$

where:

$f(\boldsymbol{x},\boldsymbol{y},t)$: the joint PDF of the basic random variables at time t

This probability of failure can also be estimated based on the previously presented Method of Moments (MOM), through the corresponding higher-moment reliability index β_{4M}. The corresponding pavement reliability and hazard rate functions are the following:

$$R\left(\boldsymbol{x},\boldsymbol{y},t\right)=1-F\left(\boldsymbol{x},\boldsymbol{y},t\right)=1\text{-}\Phi\left[\text{-}\beta_{4M}\left(\boldsymbol{x},\boldsymbol{y},t\right)\right] \tag{43}$$

and

$$h\left(\boldsymbol{x},\boldsymbol{y},t\right)=-\frac{d}{dt}\ln\left\{1\text{-}\Phi\left[\text{-}\beta_{4M}\left(\boldsymbol{x},\boldsymbol{y},t\right)\right]\right\} \tag{44}$$

For the case of in-service pavements the reliability is defined as a conditional reliability that naturally takes into account the previous pavement utilization. The conditional reliability function is defined as:

$$R\left(\boldsymbol{x},\boldsymbol{y},t\middle|A\right)=\frac{R\left(\boldsymbol{x},\boldsymbol{y},A,t\right)}{R\left(\boldsymbol{x},A\right)} \tag{45}$$

where:

A: the estimated load applications that have been accumulated until the time of reliability measurement t,

$R\left(\boldsymbol{x},\boldsymbol{y},t\middle|A\right)$: the conditional reliability function,

$R\left(\boldsymbol{x},\boldsymbol{y},A,t\right)$: the joint reliability function, and

$R\left(\boldsymbol{x},A\right)$: the probability that the pavement has not failed up to the beginning of the time of the reliability assessment

Furthermore, the limit state function at the beginning of the time of the reliability assessment is defined as:

$$G(\boldsymbol{x}, A) = q(\boldsymbol{x}) - A \tag{46}$$

The joint reliability function is defined by the following limit state function:

$$G(\boldsymbol{x}, \mathbf{y}, A, t) = q(\boldsymbol{x}) - A - z(\mathbf{y}, t) \tag{47}$$

According to Damnjanovic & Zhang (2008) the value of A can be estimated by either a direct or an indirect method: the first one pertains to directly summing the measurements of load repetitions for all years in service starting from the time of the construction of the pavement until the time of the reliability measurement. The second one pertains to deducing the level of accumulated load applications through condition measurements, such as deflection, roughness or others. The selection of the method to be used depends largely on the availability of traffic data, since in the absence of which the direct method cannot be applied and A has to be estimated indirectly. More information on the estimation of A can be found in Damnjanovic & Zhang (2008) and Damnjanovic (2006(a)).

Estimation of Expected Number of Failures

For the estimation of the expected number of failures between the various planned rehabilitation actions Damnjanovic & Zhang (2008) propose an approach that uses the concept of stochastic point processes and in particular the Non-Homogenous Poisson Process (NHPP). Based on the characteristics of the NHPP presented in the literature review and the definition of pavement reliability as described in the previous section, Damnjanovic & Zhang (2008) observed that the hazard rate function from reliability theory $h(t)$ defines the ROCOF function of the

NHPP $\lambda(t)$, since the hazard rate function of the first inter-arrival time is equal to the ROCOF function of the NHPP. As a result and because pavement reliability can be obtained from the above formulation through the use of the MOM, the ROCOF function and the cumulative intensity of the NHPP can be respectively defined as:

$$\lambda(\mathbf{x},\mathbf{y},t)=\frac{d}{dt}E\left[N(\mathbf{x},\mathbf{y},t)\right]=\frac{d}{dt}\left[-\ln R(\mathbf{x},\mathbf{y},t)\right] \tag{48}$$

And

$$\Lambda(\mathbf{x},\mathbf{y},t)=-\ln R(\mathbf{x},\mathbf{y},t) \tag{49}$$

Equation (49) represents the expected number of failures of the facility under the assumptions that the reliability is determined by the limit state function $G(\boldsymbol{x},\boldsymbol{y},t)$ and that after each failure only minimal repair actions (such as localized patching) are applied. The estimated expected number of failures is obviously equal to the expected number of corrective M&R actions that need to be undertaken, thus providing a basis for estimating the expected amount of expenditures for such corrective actions. However, since the pavement reliability depends on the structural characteristics of the pavement structure (as well as on its utilization) and since these characteristics are affected by the various undertaken M&R actions, it is necessary to model the effect of these actions and integrate them in the overall process of Total M&R cost estimation. The M&R actions whose effect on pavement life and performance are modeled in the following sections are preventive maintenance and periodic (structural) rehabilitation.

Models for the Effects of Preventive Maintenance and Rehabilitation Actions

As mentioned earlier in the literature review, preventive maintenance and periodic rehabilitation have different effects on the life and performance of pavement structures. Based on Damnjanovic & Zhang (2008), the modeling process for capturing their respective effects is naturally bound to be different: in the case of preventive maintenance the proposed model captures the effect of the action on the pavement reliability, while in the case of rehabilitation another model is used which considers the impact of the action on the rate of occurrence of failures function (ROCOF).

Correspondingly, the model that captures the effects of preventive maintenance is mathematically defined as (Damnjanovic & Zhang 2008; Zhang & Piepmeyer 2005; Ebeling 1997):

$$R\left(\boldsymbol{x},\boldsymbol{y},t\right)=\begin{cases} R(\boldsymbol{x},\boldsymbol{y},t) & \text{for } 0<t\le T \\ R\left(\boldsymbol{x},\boldsymbol{y},T\right)^{n} R\left(\boldsymbol{x},\boldsymbol{y},t-nT\right) & \text{for } nT\le t\le \left(n+1\right)T \end{cases} \tag{50}$$

where:

T: preventive maintenance interval

n: number of times that preventive maintenance is applied

The underlying assumption in this model is that PM does not increase the reliability of the pavement but rather changes its hazard rate (reduces the deterioration rate). For the case of pavements, PM is assumed to be able to restore the functional condition of the pavement to its original value but to be unable to add any new structural capacity to them (Damnjanovic & Zhang 2008; Zhang & Piermeyer 2005).

For the case of proactive periodic rehabilitation, the models are formulated in a way that reflects the effect of these actions to the structural parameters of the limit state function (i.e., parameters that reflect the strength of the pavement structure), which are also called design variables. These variables have values that decrease with age and utilization, causing the overall strength to decrease. Such a variable is the Structural Number (SN) for the case of flexible pavements. In the models devised by Damnjanovic & Zhang (2008), two components are identified: a component that predicts the deterioration of the design variables in the limit state function; and a component that quantifies the impact of the rehabilitation actions on the design variables. The recursive function that is used for predicting the level of the design variable x_d given the effect of the rehabilitation Δx_d is the following:

$$x_d(t) = w\big(t, x_d(t-1)\big) + \Delta x_d(t-1) \tag{51}$$

where:

$w(.)$:	the deterioration function
$\Delta x_d(t-1)$:	increase in the level of the design variable as a result of applying the rehabilitation action at time *t-1*

Based on (51) the reliability and the ROCOF functions are updated as a result of the update of the limit state function with the new level of strength that takes place after applying the rehabilitation actions and updating the level of the design variables. This approach is based on the fundamental assumption that immediately after the rehabilitation actions, the probability of failure is 0, i.e., the reliability is restored to 1. This is reasonable as in the absence of construction blunders a facility (e.g., a pavement) is very unlikely to fail immediately after the application of a rehabilitation action (e.g., an overlay).

Based on this model for the update of the limit state function and the reliability and ROCOF functions, Damnjanovic & Zhang (2008) also estimated the expected number of failures based on the level of strength of the facility before and after and after a rehabilitation action, as a result of this action. This is given mathematically by:

$$E\left[N\left(2T\right)\right] = -\ln R\left(x_d = a, \mathbf{x}, \mathbf{y}, T\right) - \ln R\left(x_d = b, \mathbf{x}, \mathbf{y}, T\right) \tag{52}$$

where:

$$x_d\left(T\right) = w\left(t, x_d\left(T-1\right)\right) + \Delta x_d\left(T-1\right)$$

and

$E\left[N\left(2T\right)\right]$: the expected number of failures at the time interval $\left[0, 2T\right]$

$x_d = a$: the level of the design variable before the application of the rehabilitation action Δx_d

$x_d = b$: the level of the design variable after the application of the rehabilitation action Δx_d

More details about the above presented methodology can be found in Damnjanovic (2006) and Damnjanovic & Zhang (2008).

Quantification of the Total M&R Cost

Based on the above presented models that are used for capturing the effects of M&R actions and determining the expected number of unexpected failures that require corrective maintenance actions, the following models are devised to capture the total cost of M&R of the pavements for a project developed as a toll-road concession.

The Total M&R cost *TMRC* is the sum of the cost of the originally planned M&R actions *MRC* plus the cost of the corrective M&R actions *CMRC*, or:

$$TMRC = MRC + CMRC \tag{53}$$

The *MRC* can be estimated either by using the originally presented function (40) which can account for both preventive maintenance and periodic rehabilitation actions (as well as for the routine maintenance costs), as a percentage of the initial construction cost estimate; or by simply multiplying the unit costs of these actions per mile per lane, with the treated lane-miles of the facility, if this information is available.

The *CMRC* can be determined for two different cases, depending on whether or not the facility has received any originally planned M&R. It should be noted that these models draw elements from similar models presented in Damnjanovic & Zhang (2008) for the estimation of the risk-cost in performance-specified pavement maintenance warranties.

In the case where the facility has not received preventive maintenance or rehabilitation during the time of the concession agreement then the *CMRC* can be expressed as:

$$CMRC\left(\mathbf{x}, x_d, \mathbf{y}, T_c\right) = C_F E\left[N\left(\mathbf{x}, x_d, \mathbf{y}, T_c\right) \middle| A\right] = -C_F\left[\ln R\left(\mathbf{x}, x_d, \mathbf{y}, T_c \middle| A\right)\right] \tag{54}$$

where:

C_F : the average cost of pavement failure (i.e., cost of corrective action)

T_c : the duration of the concession agreement

$\ln R\left(\mathbf{x}, x_d, \mathbf{y}, T_c \middle| A\right)$: conditional expectation given that the facility has survived A load applications at the beginning of the concession agreement (for the case of an existing facility)

For the case of facility that has a planned rehabilitation action for time t_{rhb} during the concession period T_c, so that $t_{rhb} \in \left[0, T_c\right]$, and if $\Delta x_d\left(t_{rhb}\right)$ is the effect of the action to the design variable x_d, then the *CRMC* can be estimated by the following equation:

$$CMRC = -C_F\left[\ln R\left(\mathbf{x}, x_d, \mathbf{y}, t_{rhb} \middle| A\right)\right] - C_F\left[\ln R\left(\mathbf{x}, x_d, \Delta x_d, \mathbf{y}, T_c - t_{rhb}\right)\right] \quad (55)$$

In the case where more than one rehabilitation actions are planned during the period of the concession agreement, equation (55) can be modified accordingly. Finally, in the case where the facility has no accumulated load repetitions prior to the beginning of the concession agreement, equations (54) and (55) can be modified so that the original unconditional reliability functions are used, since A is 0 in this case.

Summary

In this chapter a detailed methodological framework for the estimation of the Total M&R costs of a highway toll-road facility was presented based on the results of previous research coming from the area of pavement maintenance warranties. The proposed models utilize concepts from structural reliability and stochastic processes in order to quantify the time-dependent pavement reliability, to estimate the expected number of unexpected failures of the facility and to quantify the expenses for fixing them.

The integration of the above methodology for the estimation of the total M&R costs in the Total Cost model of the detailed methodological framework concludes the methodological part of this dissertation. Based on all the presented models in Chapters 4, 5 and 6, the financial viability of a highway toll-road project can be investigated through the determination of its investment risk. The investment risk can be estimated through the use of the presented detailed models for the infrastructure-generated revenues and life-cycle costs. Finally, in terms of the M&R costs of the facility, they can be accurately estimated not only by considering the unplanned actions that are undertaken due to unexpected failures but by explicitly accounting for the relationship between traffic and M&R cost as well. The basic capabilities of this comprehensive methodological framework are demonstrated in the next chapter through a real-life toll-road project case study.

CHAPTER 7: CASE STUDY

After the presentation of the proposed methodological framework and its corresponding individual models in detail, a comprehensive case study was undertaken in order to demonstrate the capability of the methodology to serve as a decision-support tool for all stakeholders involved in the development of a highway toll-road project procured as a PPP. The presented case study pertains to a real highway toll-road concession agreement, specifically a section from the Trans-Texas Corridor (TTC-35), which is a mega-project planned for implementation in the State of Texas.

Case Study Targets

The main target of this case study was to demonstrate the capability of the proposed methodological framework and its individual components with a real toll-road project. Through this modeling effort that has culminated in the development of a comprehensive decision-support spreadsheet tool, various analyses can be undertaken to provide decision makers with the necessary decision support information. These types of analyses are the following:

- The evaluation of (the "base case" of) a development plan of a highway project in terms of its anticipated investment risk and corresponding financial viability

- The investigation of the sensitivity of its various parameters to the financial viability of the project

- The investigation of alternative scenarios pertaining to various aspects of the initial “base case” plan, such as alternative financing and alternative M&R strategies among others, and their effect to the financial viability of the project.

The case study that was undertaken contained examples of all three possible types of analyses that this methodology is capable of undertaking. The detailed presentation of the case study begins in the following section with the information about the real-life project that was investigated.

The Trans-Texas Corridor

The Trans-Texas Corridor (TTC) is a Texas mega-project that entails the development and construction of a multimodal transportation corridor which transverses the State of Texas from the borders of Mexico to the borders with the state of Oklahoma. The TTC contains two primary projects: I-69/TTC which extends from Texarkana/Shreveport to Mexico (possibly to the Rio Grande Valley or Laredo), and TTC-35, which generally runs parallel to I-35 from north of Dallas/Fort Worth to Mexico. The TTC-35 has originally been planned to be approximately 600 miles long and contain separate traffic lanes for passenger cars and freight vehicles, as well as have a wide enough right-of-way to encompass freight and passenger rail tracks and various utility lines running parallel to the highway (TxDOT 2006(a)).

TTC-35 is being procured through a Comprehensive Development Agreement (CDA) and preliminary studies on its development have been performed by a consortium led by CINTRA/Zachry with J.P. Morgan Chase as financial advisors. The developing consortium has prepared a Master Development Plan (MDP) in which it has identified a toll-road system of seven Primary Roadway Facilities to be developed in the near-term. The development plan provides for a private delivery of the toll-road system under a Design-Build-Finance-Operate (DBFO) concession agreement with maintenance included for a period of 50 years for five of the seven near-term roadway facilities. These facilities have a combined length of more than 260 miles and were planned to be first opened to traffic by 2014. They are also deemed "positive" due to their self-supporting financial characteristics and could provide the State of Texas with a concession payment of approximately $2.6 billion (TxDOT 2006(a); (e)). For the remaining two near-term facilities totaling 69 miles and deemed "negative" or not self-sustaining, a public sector subsidy would be needed in order to entice the private sector into getting into a concession agreement for building, operating and maintaining them (TxDOT 2006(e)). However, the analysis results from the MDP financial analysis show that these facilities could be cross-financed with a portion of the concession payment and still not require any public funding. Overall, for the funding and development of all seven facilities the developers have estimated the injection of approximately $2.7 billion of private equity with the remaining development costs being financed through debt financing. The general characteristics of these seven facilities are presented in Table 1 (TxDOT 2006(a)).

For these near-term facilities the MDP provides detailed information for the ones that are deemed positive regarding their cost and revenues, as well as regarding the details of their planned financing. This information can be accessed online for free at: http://keeptexasmoving.com/index.php/ttc_35_mdp. In this dissertation one facility from the available "positive" near-term ones was selected for analysis. This was facility P12 but any other from P3, P4, P13 and P17A could have been selected without any difference in the methodological analysis undertaken except for the difference in the individual characteristics of these facilities. In the following sections, the analysis methodology as applied in this case study is presented in detail, followed by the analysis assumptions, a presentation of the types of sensitivity and scenario analysis undertaken, a summary of the numerical characteristics of the facility and finally the presentation of the results from the numerical application.

TABLE 1. Proposed Highway Sections in Trans-Texas Corridor Master Development Plan (TxDOT 2006(a))

Reference	Name	Initial Design, Construction and ROW Cost ($000s)	Project Length (miles)	Concession/ (subsidy) ($000s)	Developer Equity
P3	Dallas NE Connector	931,948	47.5	354,559	358,675
P4	Dallas SE Connector	1,504,424	56.8	492,014	498,828
P12	Hillsboro to Temple	1,101,475	57.0	580,253	583,388
P13	Temple to Georgetown	1,018,357	49.6	418,112	514,295
P17A	San Antonio SE Loop	1,307,737	52.3	408,804	416,539
Sub Totals		*5,863,941*	*263.2*	*2,253,741*	*2,371,726*
P1_2	NW and D/FW North Connector	1,184,903	46.1	(294,250)	278,147
P17B	San Antonio South Loop	422,253	23.3	(269,050)	92,281
Sub Totals		*1,607,156*	*69.4*	*(563,300)*	*370,428*
Totals		**7,471,098**	**332.6**	**1,690,441**	**2,742,154**

Application of Methodology

The analysis undertaken for the case study was customized based on the input requirements of the proposed methodological framework as well as on the available information that could be obtained from the TTC-35 Master Development Plan (MDP) regarding the various characteristics and parameters of facility P12. The analysis entails two probabilistic evaluations: the evaluation of the financial viability of the project through the assessment of its investment risk; and the evaluation of the total pavement M&R costs, which determine the final M&R costs to be included in the evaluation of the financial viability of the project. Both evaluations were undertaken with the use of the MOM using 5 estimating points (Zhang & Damnjanovic 2006(a), (b), Damnjanovic & Zhang 2008).

Investment Risk Analysis

The analysis for the determination of the investment risk was performed based on the limit state function and the revenue and cost models presented in Chapters 3, 4 and 5 of this dissertation. Based on the considered six stochastic parameters the limit state function takes the following form:

$$\begin{aligned} G\left(C_0, Q_0, g_j^Q, i, f, MARR, \mathbf{x}_d\right) = PV\left[R_t\left(Q_0, g_j^Q, MARR\right)\right] \\ - PV\left[TC_t\left(C_0, Q_0, g_j^Q, i, f, MARR, \mathbf{x}_d\right)\right] \end{aligned} \tag{56}$$

where:

C_0: the initial construction cost estimate

Q_0: the initial traffic estimate (first year of operations)

g_j^Q: the annual traffic growth factor

i: the interest rate of the senior bank loan

f: the annual inflation rate (assumed constant throughout the concession period)

$MARR$: the minimum acceptable Rate of Return (equal to the discount rate of the *NPV* calculations)

$\mathbf{x}_d$: the vector of design variables that affect the total M&R cost estimation (as explained in the following section)

Based on the calculation of the reliability as explained previously with the use of the MOM, the investment risk is going to be given by:

$$\begin{aligned} P_F &= \Pr\left\{G\left(C_0, Q_0, g_j^Q, i, f, MARR, \mathbf{x}_d\right) < 0 \middle| r = MARR\right\} \\ &= \Phi\left[-\beta_{4M}\left(C_0, Q_0, g_j^Q, i, f, MARR, \mathbf{x}_d\right)\right] \end{aligned} \quad (57)$$

The corresponding investment reliability can be obtained by:

$$R\left(C_0, Q_0, g_j^Q, i, f, MARR, \mathbf{x}_d\right) = 1 - P_F = 1 - \Phi\left[-\beta_{4M}\left(C_0, Q_0, g_j^Q, i, f, MARR, \mathbf{x}_d\right)\right] \quad (58)$$

M&R Total Cost Analysis

According to the TTC-35 MDP all pavement sections in the project were assumed to be constructed from hot-mixed asphalt concrete. As a result, the total M&R costs were determined through the customized application of the methodology of Damnjanovic & Zhang (2008) for the case of flexible pavements. The details of the customization of the methodology are presented in detail in the following.

For the determination of the pavement reliability and the definition of the limit state function, strength and stress functions had to be defined. Similarly to Zhang & Damnjanovic (2006(a)) and Damnjanovic & Zhang (2008) the AASHTO 1993 design equations were selected and used for the definition of the strength function of the limit state function. Other strength models could also be used upon their availability.

The AASHTO 1993 design equation was also used in this study without the term that adjusts for the overall reliability and therefore has the following form:

$$\log W_{18} = 9.36\log\left(SN+1\right) - 0.20 + \frac{\log\left[\Delta PSI/\left(4.2-1.5\right)\right]}{0.4+1094/\left(SN+1\right)^{5.19}} + 2.32\log M_r - 8.07 \qquad (59)$$

where:

$\log W_{18}$: the allowable number of equivalent 18-kip single axle loads (ESALs) that cause the reduction of the present serviceability by ΔPSI

SN: the structural number of the pavement

$\Delta PSI = 4.2 - PSI_f$: the loss of serviceability until the failure PSI is reached

M_r: the effective resilient modulus of the pavement’s subgrade

It should be noted that the exclusion of the original reliability term from equation (59) renders the minimum pavement reliability at failure to 50%. For the minimum pavement reliability at failure to be greater than 50%, the original reliability term should be re-introduced (Zhang & Piepmeyer 2005). Furthermore, in this study pavement failure is defined as a reduction of the Present Serviceability Index (PSI) from its initial value of 4.2 to a value of 3.5. This failure PSI value was selected based on pavement performance standards for high-speed highways in the State of Texas set by TxDOT (Stampley *et al* 1995).

The stress function of the limit state function was defined as the accumulated number of ESALs during the time period from the beginning of the concession until the time of the reliability assessment. The predicted accumulated ESALs for a time period *t* can be obtained by using:

$$N(t) = ESAL_0 \frac{(1+\rho_t)^t - 1}{\rho_t} \tag{60}$$

where:

$ESAL_0$: the modified initial traffic (traffic at first year of operations) in ESALs

ρ_t: the annual rate of traffic growth for year *t*

Equation (60) can be used for the time intervals where the traffic growth rate is constant. Then, all the accumulated ESALs from all time periods need to be summed together for the overall number of ESALs from time 0 until time *t* to be determined.

Based on the above strength and stress equations the limit state function for the reliability of newly constructed pavements is defined as (Zhang & Damnjanovic (2006(a)):

$$G\left(SN, M_r, ESAL_0, \rho_t, t\right) = \log W_{18} - \log N\left(t\right) \tag{61}$$

From equation (61), it can be seen that the vector of design variables that affect the M&R total cost estimation is $\mathbf{x}_d = \left\{SN, M_r, ESAL_0, \rho_t\right\}$, where $\rho_t = g_j^Q$ is the annual traffic growth factor.

The determination of $ESAL_0$ comes from the initial traffic estimate Q_0 and the consideration of appropriate conversion factors for all traffic classes considered, namely passenger cars and trucks. The detailed conversion factors are contained in the section of the numerical application in Table 10. These factors are a simplified approximation by the Washington Asphalt Pavement Association (WAPA 2002) of the process of evaluating ESALs from original traffic counts that is specified by AASHTO (Huang 2004). Furthermore, the values of the conversion factors used in this case study are applicable only to pavements of similar materials (flexible) and thicknesses, as they are dependent on the pavement structural number and should therefore be used with caution outside the purposes of this dissertation.

The above limit state function can be easily evaluated with the use of the MOM and thus the pavement reliability can be determined by:

$$R\left(SN, M_r, ESAL_0, \rho_t, t\right) = 1 - \Phi\left[-\beta_{4M}\left(SN, M_r, ESAL_0, \rho_t, t\right)\right] \tag{62}$$

Since the pavement would be subject to a number of rehabilitation activities, the reliability had to be updated after the application of each such action. For that purpose the reliability after rehabilitation was modeled based on the equations developed for existing pavements, since after the application of rehabilitation the pavement would be considered to have a reliability of 1, but it would have accumulated ESALs from its utilization before the rehabilitation occurred.

For the case of existing or in-service pavements, the reliability has to be calculated with the use of the conditional reliability approach based on equations (45) to (47). In this case the limit state function takes the following form:

$$G\left(SN, M_r, ESAL_0, \rho_t, t, A\right) = \log W_{18} - \log\left[N\left(t\right) + A\right] \tag{63}$$

The reliability can then be determined with the use of the MOM and be expressed as:

$$R\left(SN, M_r, ESAL_0, \rho_t, t \middle| A\right) = \frac{R\left(SN, M_r, ESAL_0, \rho_t, t, A\right)}{R\left(SN, M_r, A\right)} \tag{64}$$

In the case of the reliability after rehabilitation the number of accumulated load repetitions A would be equal to the number of load repetitions before the rehabilitation took place. As a result, the limit state function equation (63) will take the following form:

$$G\left(SN, M_r, ESAL_0, \rho_t, t, t_{rhb}\right) = \log W_{18} - \log\left[N\left(t\right) + N\left(t_{rhb}\right)\right] \tag{65}$$

where:

t_{rhb} : the time from the beginning of the concession period until the application of the first rehabilitation action

In equation (65) the expected number of the accumulated load applications until the time of the first rehabilitation $N\left(t_{rhb}\right)$ can be determined with the use of equation (60).

Once a rehabilitation action has been undertaken, the strength of the pavement structure needs to be updated in order to reflect the added structural capacity. For that purpose and assuming that the rehabilitation action has taken place at time t_{rhb}, the following equation can be used based on Damnjanovic & Zhang (2008):

$$SN_{eff}\left(t_{rhb}\right) = SN\left[1 - 0.7 \times \exp\left[-\left(\frac{W_{18} - A - N\left(t_{rhb}\right)}{W_{18}} + 0.85\right)^{2}\right]\right] + \Delta SN\left(t_{rhb} - 1\right) \qquad (66)$$

where:

$SN_{eff}\left(t_{rhb}\right)$: the effective structural number of the pavement at time t_{rhb} (immediately after the rehabilitation action)

$\frac{W_{18} - A - N\left(t_{rhb}\right)}{W_{18}} = R_L$: the remaining life of the pavement after the accumulation of A and $N\left(t_{rhb}\right)$ ESALs

A: the accumulated number of ESALs before the beginning of the concession period

$N\left(t_{rhb}\right)$: the accumulated number of ESALs from the beginning of the concession until the rehabilitation

Equation (66) has its most general form and can also be used for the case of pavements that were in service before the beginning of the concession period. For the case of a new facility, as in this case study, the equation can be used by setting A=0. Also, it is worth noting that according to equation (66) the effective structural number at the time of failure is reduced to roughly two thirds of its initial value (Damnjanovic & Zhang 2008; Easa 1990). This is reasonable as even at failure (i.e., when the PSI has been reduced to 3.5) the pavement still has some structural capacity left. Finally, the effect of the rehabilitation $\Delta SN\left(t_{rhb}-1\right)$ is considered to be known in the analysis, as an external input decided during the design of the facility.

Based on the above equations, the expected number of failures and corresponding corrective M&R costs (CMRC) can be obtained from equations (52) to (55), as explained previously.

Analysis Assumptions

For both probabilistic evaluations presented above, numerous assumptions were made in order to adhere both to the proposed methodological framework and to keep the calculations within a reasonable level of complexity. These assumptions pertain to a few modeling assumptions but mainly to information about the procurement characteristics of facility P12 that were either missing and therefore had to be hypothesized or were unnecessarily complicated for the purpose of this case study and had to be simplified.

In terms of the probabilistic modeling of the investment risk and the reliability of the pavement structures, the following parameters were considered to be stochastic:

- In the estimation of the investment risk:
  - The initial construction cost estimate
  - The initial traffic estimate (AADT at the first year of operation)
  - The annual traffic growth factor, which was assumed to be constant for all years
  - The senior bank loan interest rate
  - The inflation rate, and
  - The Minimum Acceptable Rate of Return (MARR), which was also the discount rate for the NPV calculations of the methodology
- In the estimation of the pavement reliability:
  - The structural number of the pavement
  - The initial number of ESALs at the first year of operation
  - The annual traffic growth factor (assumed to be constant for all the years of the concession)
  - The subgrade resilient modulus

The remaining variables of the models presented in Chapter 3 were considered to be deterministic.

Furthermore, all the stochastic variables that are part of the proposed methodological framework of this dissertation are considered independent to each other and their respective probability distributions normal. These assumptions, as well as the magnitude of their corresponding means and coefficient of variations considered in this study, were based on similar studies and on the more general assumption of the predominant economic conditions being relatively similar to current conditions. It should be noted that in times or cases where the economic and business environment is significantly altered from current operating conditions, such assumptions should be revisited in order to assess their validity under these new conditions.

In terms of the procurement information of facility P12 the following assumptions and modifications to the MDP information were made:

- In the facility <u>Design and Construction</u> characteristics and variables:
    - The Design, Construction and ROW cost of the facility was assumed to be \$822,330,830. This initial cost estimate comprises the cost of design and engineering at \$60,973,868, the cost of ROW at \$169,445,455, and the cost of 57 miles of main lane and frontage pavements, 21 interchanges as well as 50 bridges and other structures at \$591,911,501 (TxDOT 2006(g)). The cost estimate excludes an adjustment factor of 1.46 which was considered in the MDP due to the discounting the cost values to a different base year (2007). Also, in this study the initial construction cost estimate is considered to be stochastic with a COV of 20%.
    - The pavement design of the facilities was not specified in the MDP except for the general thickness limits being between 10½ and 12 inches of asphaltic concrete pavement over 30 inches of a granular or lime stabilized base course (TxDOT

2006(c)). As a result, the pavement design considered for P12 was based on a combination of the provided information with reasonable assumptions regarding the material properties of these layers and resulted in an estimated initial pavement Structural Number (SN) of 9.5, indicative of a very strong pavement. As mentioned earlier, the SN was also assumed to be a stochastic variable with a COV of 10%. The estimation of the SN was based on the AASHTO design procedure as described in Huang (1993). The material property-related assumptions were also guided by the pre-defined M&R plan of the facility as well as reliability considerations. In particular, it was assumed that the initial design and the subsequent M&R actions as defined in the MDP maintained the pavement at an acceptable reliability level of 99% or above throughout the duration of the concession. From the material-related pavement design parameters, the subgrade resilient modulus were assumed to be 7,500 psi based on similar studies (Damnjanovic & Zhang 2008). The subgrade resilient modulus was also assumed to be a stochastic variable with a COV of 15%. Finally, this initial pavement design was assumed to correspond to the initial construction cost estimate mentioned previously.

- The facility was assumed to remain with its original geometric design and capacity characteristics of 2 lanes plus shoulder per direction for the entire duration of the concession. In the MDP the facility was planned to undertake various stages of expansions that would sequentially increase capacity (TxDOT 2006(c)). These expansions were not included in the models used in this study.

- In terms of the <u>Operation and Maintenance & Rehabilitation (M&R)</u> cost characteristics and variables:

    - The cost of operations of the facility was defined at 3.5% of the initial construction cost estimate in order to match the annual planned operating cost estimate in the MDP (TxDOT 2006(g)). No individual breakdown of the cost according to number of transactions, administrative expenses or any other category was considered in order to keep the calculations simple, although an analytical list of the operating cost components can be found in the MDP (TxDOT 2006(c)).

    - The base case M&R strategy was assumed to be as defined in the TTC-35 MDP, consisting of annual routine maintenance with major maintenance actions (rehabilitations) taking place every 10 years (TxDOT 2006(g)). The effect of the rehabilitation actions was assumed such in order to maintain 99% reliability in the pavement structure at all times, based also on the initial pavement design (SN).

    - The base case M&R costs were assumed as follows:

        - Routine maintenance costs were assumed to be 0.45% of the initial construction cost estimate, increasing annually with inflation. This percentage matched numerically the original routine maintenance estimate in the MDP (TxDOT 2006(c); (g)).

        - Rehabilitation costs were assumed at 3% of the initial construction cost estimate in order to match the original cost estimate included in the MDP

(TxDOT 2006(c); (g)). Individual estimations of the price of each rehabilitation action based on the required structural improvement of SN to maintain a minimum of 99% pavement reliability were also undertaken. However, the estimates based on the percentage of the initial construction cost estimate were ultimately kept because the risk of inflation variability could be incorporated into them in a more straightforward manner.

    - Corrective maintenance (localized patching) was also introduced although not originally included in the MDP, as a way to treat unexpected pavement failures. The corresponding cost was assumed to be $75,000 based on Damnjanovic and Zhang (2008). This cost is more expensive per mile per lane than the rehabilitation cost as it involves localized mobilization of machinery, personnel and equipment and therefore does not present the economies of scale that can be expected in rehabilitation actions.

    - All M&R costs were assumed to be growing with inflation from their initial prices in the base year (2009).

- In terms of the Traffic and Revenue characteristics and variables:

  - The initial AADT of facility P12 at the time of opening to traffic in year 2014 was assumed to be 24,278 vehicles, as in the TTC-35 MDP (TxDOT 2006(f)). The initial AADT estimate was assumed to be a stochastic variable with a COV of 10%.

- In terms of the vehicle classes using the facility, only passenger cars and trucks were considered in this study, as in the MDP. The percentage of trucks in the overall traffic was assumed to be 35%, remaining constant for the entire concession period. This assumption was based on the projections contained in the MDP where the truck traffic was 24.3% of the overall traffic in year 2014 growing to 44.7% by year 2060 (TxDOT 2006(f)). As a result an average value of 35% for the entire concession period was considered to be a reasonable assumption.

- The toll rates per vehicle class were assumed to be $0.152 per mile for passenger cars and $0.585 per mile for trucks, as in the MDP (TxDOT 200(f)). The toll rates were assumed to be growing annually with inflation, despite the fact that in the MDP they are recalibrated to higher rates per mile at Year 30 and Year 60 of the concession and inflation is not considered in the facility revenue calculations.

- The MDP traffic growth projections were based on sophisticated travel demand econometric models that did not specify growth factors but rather full traffic projections for the different years of the analysis. In this study, a constant traffic growth factor was assumed, with overall traffic (AADT) growing 6.5% annually for all years in the concession. This growth factor was used in order to simplify the analysis but was also considered to be stochastic in order to address potential variability in its original estimation. Although the growth factor was overestimating the original overall traffic projections found in the MDP, it nevertheless compensated for the lost revenues due to the increase in the toll-rates at Years 2030 and 2060 which were both more than their respective value would be if just growing with inflation from their original values in 2014.

  - An Average Vehicle Trip Length and a number of transactions per trip were also introduced in this study, although not included in the original MDP. Both of them were used in order to customize the revenue projections of the model in order to match as closely as possible the original revenue projections of the MDP when combined with the above traffic and revenue characteristics and variables (TxDOT 2006(i)). Based on this rationale, the average trip length was assumed to be 30 miles while the average number of transactions per trip was assumed to be 1.3.

- In terms of the Financial and Economic characteristic and variables:

  - The initial construction cost estimate was assumed to be drawn on equal annual percentages of 20% during all 5 years of construction, as also assumed in the MDP (TxDOT 2006(c); (e); (h)). It was also assumed to be simultaneously growing with inflation during these 5 years, a departure from the original MDP.

  - In the original MDP the project was assumed to be financed with a combination of debt and equity targeting a 12% return on equity. This target return was used as the discount rate for all NPV calculations. This assumption was used in this study too, further assuming the equity rate of return to be stochastic with a COV of 10%.

- The original financing plan combined a maximum equity contribution of 20%; a Transportation Infrastructure Finance and Innovation Act (TIFIA) loan for 33% of construction costs; and bond financing for the remaining costs. In this study the financing structure was assumed the same except that a Senior Bank Loan was assumed to be covering the remaining construction costs instead of bond proceeds. This change was made in order to avoid the financial modeling of the bond financing which was composed of Current Interest Bonds (CIBs) and Capital Appreciation Bonds (CABs) and which was deemed unnecessarily complicated for the purpose of this case study. The Senior Bank Loan assumed in this study had the same maturity as the original bonds and was assumed to accumulate interest at the same interest rate as the original bonds. The detailed financing characteristics of the project are presented in Table 6. Furthermore, the interest rate of the Senior Bank Loan was assumed to be a stochastic variable with a COV of 5%.

- The inflation rate was used for all cost and price escalations and was assumed to be 2.5% as specified also in the MDP (TxDOT 2006(e)). Furthermore, inflation was assumed to be a stochastic variable with a COV of 10%.

- The payments for the various outstanding debts were not designed in detail based on the minimum required cover ratios, as specified in the MDP, but rather based just on the grace periods specified in the MDP, since part of the aim of the methodology is for the overall debt repayment capability of the project to be investigated. The rationale behind this assumption is that the debt payments can be re-structured based on the required cover ratios if necessary, once it has been proven that the project can overall be profitable. Also, the exact magnitude of the cover ratios could also be influenced from the overall financial assessment of the project through the evaluation of its financial viability.

- Finally, the financial modeling assumed no taxes, no debt payment insurance, no debt refinancing and no transaction costs and did not consider the development of construction or maintenance reserve funds.

The above assumptions were used for the analysis of the "base case" scenario which was modeled as closely as possible to the original project characteristics described in the TTC-35 MDP. This "base case" scenario was supplemented by various sensitivity and scenario analyses that are presented in the following section.

Sensitivity and Scenario Analyses

The presented methodology was used to evaluate the financial viability of the "base case" scenario as well as to demonstrate the capability of the proposed methodological framework to analyze various alternative sensitivities and scenarios. Although a great number of sensitivity and scenario analyses could have been performed, the ones that were ultimately undertaken and presented in this case study are based on three sources: partly on similar financial sensitivity analyses found in the Facility Financial Analysis of the TTC-35 MDP (TxDOT 2006(e); (h)); partly on the Risk Analysis of the TTC-35 MDP (TxDOT 2006(d)); and partly on other similar studies (Damnjanovic & Zhang 2008; Seneviratne & Ranasinghe 1999; Kakimoto & Seneviratne

2000). Ultimately the results from all sensitivity and scenario analyses are discussed in terms of their usefulness to all project stakeholders and their contribution in highlighting possible threats to the project's financial viability.

In the MDP Facility Financial Analysis (TxDOT 2006(e)), the project's financing sensitivity is tested for the cases of two scenarios, a negative and a positive:

Negative Scenario: The base case project characteristics remain the same except that the inflation rate and the loan interest rates increase by 1.50% from their base case values.

Positive Scenario: The base case project characteristics remain the same except that the inflation rate and the loan interest rates decrease by 1.00% from their base case values.

Furthermore, in the MPD Facility Risk Analysis (TxDOT 2006(d)), risk matrices were developed based on expert opinion identifying the various sources of risk to the project, as well as quantifying with an index from 1 to 6 their overall "threat". The rating came from a combination (multiplication) of two individual ratings for the probability of occurrence of a risk factor (ranging from 1 to 3) and the impact of the risk factor to the project (ranging from 1 to 3). From these matrices the risk elements from the various specified risk categories that were identified to have a rating of 4, 5 or 6, signifying both a high probability of occurrence and/or a high impact are presented in Table 2.

TABLE 2. Critical Risk Categories and Elements for TTC-35 Projects (TxDOT 2006(d))

Risk Category	Risk Element	Rating
Design	Changes in Design Standards and Criteria	4
Construction	Failures; Non conforming work and defects discovered prior- and post-acceptance	4
	Adverse Weather	4
	Contractual non-performance	4
	Breach of site – Health and Safety	6
Political/Legal	Change in Law (including taxes)	6
Financing	Traffic projections are not realized	4
	Inflation	6
	Insufficient TIFIA funds available	6
	Insufficient Private Activity Bonds available or delays in introducing them	4
Environmental	Environmental permissions approvals, modifications and negotiations	6
	Discoveries of hazardous/contaminated materials; remediation and liabilities	6
Planning and Approval	Procurement and performance of Federal, States agencies and Local Agencies permits and approvals (environmental and other)	6
Operation and Maintenance	Liability to users	4
Other Event Risks	Residual value risk	4

The above presented sensitivity scenarios and risk elements contained in the TTC-35 MDP could – in the case of a full blown analysis of financial viability – form the basis for a more thorough investigation of the sensitivity of the model variables that can best contain them. The conceptual task of mapping the above identified sources of risk to the various variables contained in the models of the proposed methodological framework was undertaken with the obvious caveat that when a risk element was irrelevant to the presented methodological framework, its sensitivity could not be investigated. This mapping lead to the following list of variables:

- Initial Construction Cost estimate: Because this variable encompassed design, construction and ROW costs, it was deemed appropriate to reflect the critical design, construction, environmental and planning and approval risks of the MDP, as all of them would result in an increase (or more rarely a decrease) of the initial cost estimate which the financing of the project is based upon through changes in designs, construction delays, and contracting cost overruns.

- Initial traffic estimate: The AADT of the opening year is a variable that is directly related to the non-realization of the traffic projections, which was considered a financing risk element in the MDP.

- Traffic growth factor: This variable was also thought to be directly related to the non-realization of traffic projections, which was part of the financing risk in the MDP.

- Inflation: This variable was explicitly modeled in the proposed methodological framework and was highlighted in the MDP both as part of the financing sensitivity scenarios as well as by the identification of its critical nature in the risk matrices.

- Senior Bank Loan interest rate: This variable was also explicitly modeled as a stochastic variable in the proposed framework and its importance was also highlighted in the MDP both in the financing sensitivity scenarios as well as in the risk matrices.

- Discount rate: Finally, this variable should also be part of a sensitivity investigation because it is directly related to the different financial expectations of the developer.

From the above list of potential sensitivity analyses, the only one that was undertaken in this case study was the one pertaining to the initial construction cost estimate. This variable was selected based on the fact that changes in this initial estimate are reported often in the literature due to either bad estimation practices or to construction delays/accidents that, although may not throw the project completely off its original schedule, they nevertheless increase the initial cost estimate.

From the remaining risk elements, the risk pertaining to insufficient TIFIA funds, although relevant to the proposed framework, could not be investigated through the sensitivity of any of the individual model variables but could be investigated in terms of the consideration of alternative scenarios of financing where the percentages of each source of finance were modified, as explained in the following. All other critical risk elements of the MDP were not relevant to the proposed methodological framework and cannot therefore be investigated any further.

Based on the concern regarding the existence of insufficient TIFIA funds and by assuming the possibility of shifting the financial burden of the missing funds to the other available sources of finance, a number of different financing scenarios can be defined. From these scenarios, the following characteristic ones were chosen:

FIN Scenario 1: **TIFIA funds 20%, Senior Bank Loan 50%, Private equity 30%**

In this scenario the missing TIFIA funds were assumed to be covered by the developer committing more private equity to the project (to the commonly acceptable and historically reported maximum of 30%) with a simultaneous small adjustment to the senior bank loan.

FIN Scenario 2: **TIFIA funds 20%, Senior Bank Loan 47%, Private Equity 30%, Public Agency Subsidy 13%**

In this scenario it was assumed that the public sector had to step in and save the project, as neither the market conditions nor the financial ability of the developer was adequate to complete the financing of the project.

Finally, in terms of other scenario analyses performed in similar studies, different M&R strategies and their impact on the financial viability of the project can be investigated, as they have a significant impact in terms of the engineering life-cycle design involved in the project. Two characteristic scenarios that were considered in this case study were as follows:

M&R Scenario 1: **Annual RM, Rhb every 15 years, Reliability 99%**

In this scenario the frequency of the rehabilitation actions was reduced from once every 10 years to once every 15 years. The impact of every rehabilitation action was selected such that the facility maintained the 99% reliability target at all times.

M&R Scenario 2: Annual RM, Rhb every 10 years, Reliability 95%

In this scenario the base case frequency for the rehabilitation actions was kept, but the overall pavement reliability target was reduced to 95% overall.

The results of the base case analysis, the sensitivity analyses and the scenario analyses are presented and discussed in the following section after the presentation of a summary of the numerical values of the project variables of the presented models.

Summary of Numerical Application

The numerical characteristics of the toll-road project P12 under investigation are summarized in Tables 3-10.

TABLE 3. Project P12 General Parameters

General Parameters	Units	Mean	CV(%)	Comments
Concession Period (T)	[years]	50	N/A	
Construction Period (m)	[years]	5	N/A	
Project Length	[miles]	57.0	N/A	
Number of Lanes per direction	[number]	3	N/A	Including shoulder

TABLE 4. Project P12 Cost Variables

Cost Variables	**Units**	**Mean**	**CV(%)**	**Comments**
Initial Construction Cost (C_0)	[$]	822,330,830	20	Initial estimate
Initial Operating Cost (a_t^o)	[%]	3.50	N/A	As a % of C_0
Initial Annual Maintenance Cost:			N/A	
Routine Maintenance (a_t^{rtn})	[%]	0.60	N/A	As a % of C_0
Preventive Maintenance (a_t^{prv})	[$]	20,000	N/A	Per mile, per lane
Rehab. Cost (a_t^w)	[%]	3.00	N/A	As a % of C_0
Corrective action Cost (C_F)	[$]	75,000	N/A	Per lane, per mile
Annual Price Escalation Rate (f)	[%]	2.5	N/A	Equal to inflation

TABLE 5. Project P12 Traffic and Revenue Variables

Traffic and Revenue Variables	**Units**	**Mean**	**CV(%)**	**Comments**
Initial AADT (Q_0)	[vehicles]	24,278	15	Initial estimate
Vehicle Classes (Θ):				
Cars	[%]	60	N/A	
Trucks	[%]	35	N/A	
Traffic Growth (g_j^Q):	[%]	6.5	10	Constant for all years
Average Trip Length (d_{ave})	[miles]	30	N/A	
Average Transactions per trip	[number]	1.3	N/A	
Toll Rates (r_t^c):				
Cars	[$/mile]	0.152	N/A	
Trucks	[$/mile]	0.585	N/A	
Annual Toll Rate Growth (f_r)	[%]	2.5	N/A	Equal to inflation

TABLE 6. Project P12 Financing Variables

Financing Variables		Units	Mean	CV(%)	Comments
Construction Capital Draw (d_t):					
	Year 1	[%]	20	N/A	
	Year 2	[%]	20	N/A	
	Year 3	[%]	20	N/A	
	Year 4	[%]	20	N/A	
	Year 5	[%]	20	N/A	
TIFFIA loan:		[%]	33		As a % of total construction costs
	Interest Rate (i)	[%]	5.10	N/A	fixed
	Grace Period	[years]	11	N/A	Including construction period
	Payback Period (κ)	[years]	35	N/A	
	Payment Terms	Interest plus principal in equal installments after end of grace period, minimum principal payment of $1,000,000			
Senior Bank Debt:		[%]	47		As a % of total construction costs
	Interest Rate (i)	[%]	5.55	5%	
	Grace Period	[years]	5	N/A	Equal to construction period
	Payback Period (κ)	[years]	40	N/A	
	Min ADSCR	[number]	1.75x	N/A	
	Payment Terms	No payments during grace period, interest plus principal after the end of grace period			
Combined debt minimum ADSCR		[number]	1.10x	N/A	
Developer's Equity:		[%]	20	N/A	As a % of total construction costs

TABLE 7. Project P12 Economic Variables

Economic Variables	Units	Mean	CV(%)	Comments
Inflation Rate (f)	[%]	2.5	10	Initial estimate
Discount Rate (r =MARR)	[%]	12	10	Target value

TABLE 8. Project P12 Pavement Design Variables

Pavement Design Variables	Units	Mean	CV(%)	Comments
Initial Structural Number (SN)	[number]	9.5	10	
Subgrade Resilient Modulus (M_r)	[psi]	7,500	15	
Equivalent Single Axle Load ($ESAL_0$)	[number]	$Q_0 \times LEF$	10	Based on initial traffic estimate
Traffic Growth factor ($\rho_t = g_j^Q$)	[%]	6.5	10	
Failure PSI	[number]	3.5	N/A	

TABLE 9. Project P12 Pavement Cost Variables

Pavement Cost Variables	Units	Mean	CV(%)	Comments
Structural Number (SN) unit cost	[$]	25,000	N/A	Per mile, per lane
Corrective Maintenance (CM) unit cost	[$]	75,000	N/A	Per mile, per lane

TABLE 10. Assumed Load Equivalency Factors (WAPA 2002)

Vehicle Type	ESALs per vehicle
Passenger car	0.0007
Loaded 18-wheeler	1.35

Results & Discussion

The results from the base case financing scenario as well as the sensitivity and scenario analyses are presented in the following.

<u>Base case scenario:</u>

The financial viability of the project was estimated through the determination of the investment risk based on the numerical values presented in Tables 3-10. The base case investment risk was estimated both with and without the consideration of corrective maintenance (CM) actions. The estimation of the annual CM cost was based on considering the reliability of the pavements of the project and estimating the expected number of failures as explained in the proposed methodology.

Based on the above considerations the reliability actions were modeled so as to provide for a pavement structure that would maintain a minimum 99% reliability until the next rehabilitation. The selection of the effectiveness (in terms of added SN capacity) of each rehabilitation action was based on this assumption. It was also assumed that adding 0.45 SN to the pavement structure corresponds to applying a 1-inch thick asphalt overlay. By estimating the corresponding expected number of failures at each one of the rehabilitation intervals the total expected corrective maintenance cost was found to be $1,083,585 which corresponded to an annual average cost of $21,672 for the entire duration of the concession. Based on these cost estimates, the overall investment risk with and without the corrective maintenance costs is shown in Table 11.

TABLE 11. Base Case Scenario Investment Risk with and without CM cost

Investment Risk with CM cost	Investment Risk without CM cost
1.19%	1.19%

From Table 11 it can be seen that the effect of the corrective maintenance cost on the overall investment risk is insignificant, as the orders of magnitude of the remaining costs and revenues are much bigger.

Overall the base case scenario has a very low investment risk which signifies a highly probable financial viability for the project. This financial viability however could be compromised should some of the parameters/variables of the project change to unfavorable values. The impact of such changes for the stochastic variables of the model (which have also been identified externally as the ones influencing most of the important risk elements of such projects) is examined for the case of the initial construction cost estimate.

Sensitivity and Scenario Analyses:

In effect the deviation of the construction cost estimate from its initial value could be attributed to two reasons: bad estimation, meaning that the various quantities of the project were overestimated or underestimated; construction delays due to various factors. In any of these two cases, the result may be an increase of the initial estimate (most likely case) or a decrease of it (least likely case). The sensitivity of such difference in the initial construction cost estimate were investigated for possible increases of 5%, 10%, 15% and 20% and for a decrease of 5% and 10% of the mean value of the variable. The COV was left unchanged to 20%. The results are shown in Figure 5.

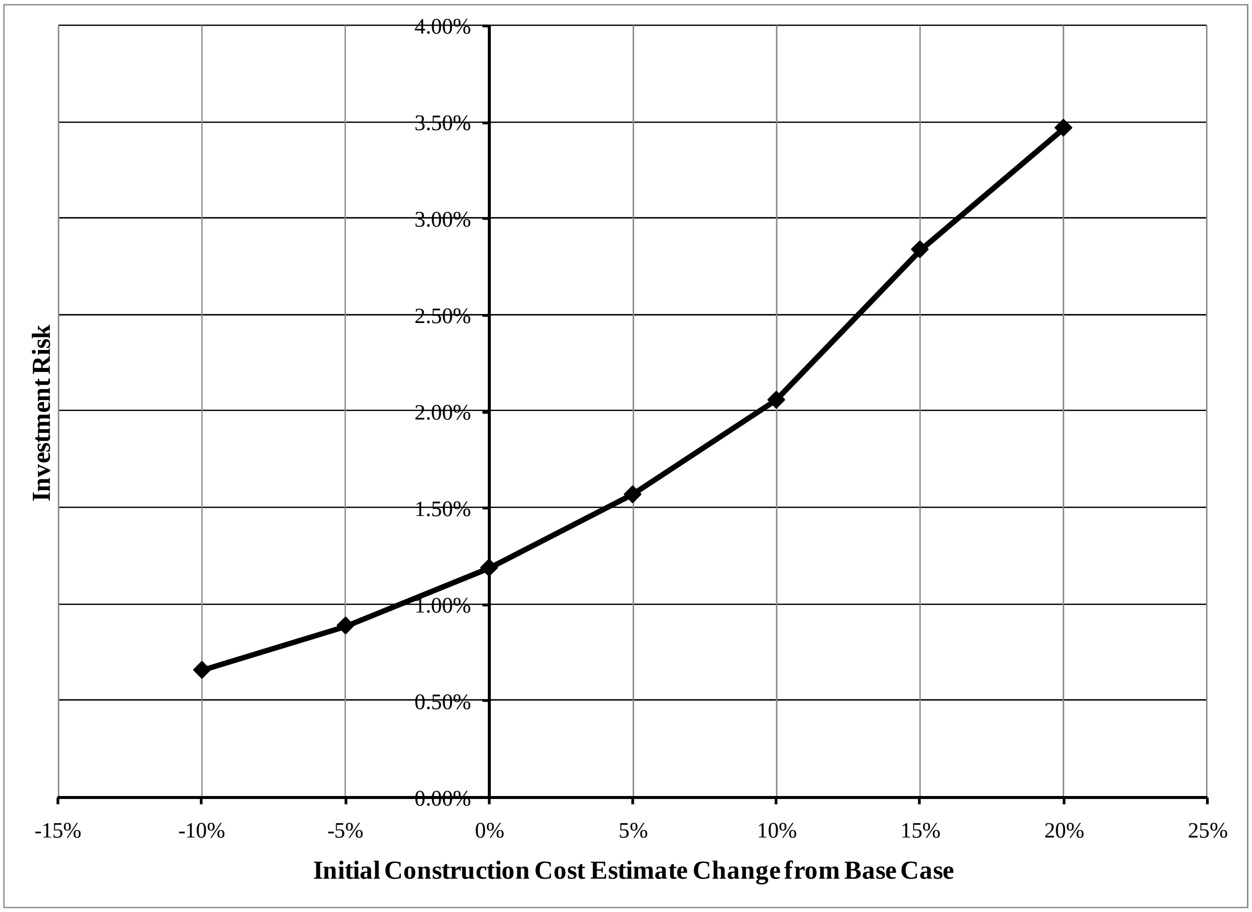

FIGURE 5. Sensitivity of Investment Risk to Changes in Initial Construction Cost Estimate

From Figure 5 it can be seen that, as expected, the investment risk is increasing when the initial construction cost estimate is increasing. This can be explained from the fact that higher costs would result in bigger loans as well as higher initial commitment of equity to the project thus affecting the cash flows of the project and culminating in changes to the investment risk estimates. Similar sensitivity analyses can be run for all the stochastic variables of the proposed framework leading to a better understanding of their effect to the investment risk and ultimately to the financial viability of the project.

Regarding the aforementioned scenario analyses, the results from the two financial scenarios and the two M&R scenarios are presented in Tables 12 and 13 respectively.

TABLE 12. Investment Risk Estimates for Alternative Financial Scenarios

	Base Case	**FIN Scenario 1**	**FIN Scenario 2**
	SBL: 47% TIFIA: 33% Equity: 20%	SBL: 50% TIFIA: 20% Equity: 30%	SBL: 47% TIFIA: 20% Equity: 20% Subsidy: 13%
Investment Risk	1.19%	1.72%	0.85%

From Table 12 it can be seen that the changes in the financing sources of the project changes the investment risk. In the case of the first scenario, the increase of the committed equity in conjunction with the increase of the senior bank loan makes the investment risk increase. This increase is however not that significant as the project has significant profit margins due to steady and large revenue inflows. This change however would result in significantly higher risk if the cash left after debt service was marginal in order for the target *MARR* to be accomplished, as there is more equity committed early in the project, which affects negatively the equity *IRR*.

In the case of the second scenario the contribution of the subsidy from the public authority decreases the risk as expected, as there are less initial funds committed by the developer and smaller loans taken, resulting in smaller future loan repayment annuities. In this case the developer is the party that is more positively affected as by committing the same equity as in the base case scenario the risk of achieving the target equity *IRR* is much smaller. This would be a typical case in which the public authority would step in to “rescue” a project that was deemed necessary, but was short of financing resources. The public authority could however try to regain the committed funds through other methods, such as revenue sharing based on some threshold value of profits achieved by the developer.

TABLE 13. Investment Risk Estimates for Alternative M&R Scenarios

	Base Case		**M&R Scenario 1**		**M&R Scenario 2**	
	RM: Annual Rhb: Every 10 years Reliability: 99%		RM: Annual Rhb: Every 15 years Reliability: 99%		RM: Annual Rhb: Every 10 years Reliability: 95%	
	With CM	Without CM	With CM	Without CM	With CM	Without CM
Investment Risk	1.19%	1.19%	1.21%	1.21%	1.13%	1.12%

From Table 13 it can be seen that the different M&R scenarios also affect the investment risk of the project. In the case of the first alternative M&R scenario, the investment risk increases from 1.19% to 1.21% both with and without the consideration of CM. This is because in order to achieve a 99% reliability at all times the initial pavement structural number had to be increased from 9.5 to 9.9, assuming a corresponding increase of 1% in the initial construction cost estimate. At the same time the rehabilitation actions were assumed more expensive by 0.2% of their base case value. These changes were the ones responsible for the change in the investment risk. On the other hand, the 99% reliability target resulted in a very small annual CM cost of $19,283 which had no effect on the investment risk due to its relatively small magnitude.

In the second alternative M&R scenario the investment risk changes from the base case estimate to 1.12% without and 1.13% with the consideration of CM. In this case, the lower target reliability of 95% resulted in a smaller initial structural number of 8.5 and a subsequent assumed decrease of the initial construction cost estimate by 1%. The cost of rehabilitation was assumed to remain the same at 3% of the initial construction cost estimate. We can see that in this case the lower initial construction cost estimate reduces the overall risk as there are less funds committed initially in the project and smaller loans to repay. However, the lower reliability target results in bigger CM cost that increases the risk by 0.01% as it incurred an annual corresponding cost of $122,472. Although this increase is very small, it shows that the CM cost can actually affect the investment risk estimate especially when the reliability of the pavement is not adequately considered. In such cases the CM cost could potentially be the decisive factor for selecting or not selecting a project or deciding to restructure its finances in order to accommodate this additional source of risk. A further implication of the CM cost consideration is that the developer should be prudent to take into consideration the target design reliability of the project and the reliability impact of the proposed M&R strategy as they both have a direct influence of the expected number of failures and the corresponding CM cost.

From the consideration of all the above information coming from the evaluation of the base case scenario, the sensitivity of the initial construction cost estimate and the alternative financing and M&R scenarios, the financial viability of the project under investigation can be assessed as very favorable and probable. Indeed the project under its base case scenario has a very small investment risk which does not seem to be under severe threat under any of the alternative scenarios. Regarding the sensitivity of the initial construction cost estimate, its fluctuations could potentially cost problems, but with careful project and construction management, can be mitigated or avoided in its entirety.

Looking at the above observations from the different perspectives of the various project stakeholders the following individual assessments can be made:

- Public authority: The project seems very robust and highly profitable, a fact that will definitely draw the attention of the private sector developers as well as the various potential lenders. As a result the public can expect a high competition during the bidding phase of the project which can lower profit margins and increase the value for money for the public sector. Furthermore, if the project is going to generate excess profit for the developer, a risk-sharing regime can be negotiated or required as part of the concession agreement that can further benefit the public authority. As a result this project fulfills the financial requirements of the public authority.

- Lenders: The project seems to have steady and annually increasing revenues that overall cover the debt repayment requirements. In the cases where the annual cash-flows are not adequate for debt repayment, a reserve account may be set or the payment profile re-negotiated prior to financial close in order for the specific cover ratios to be fulfilled. Macroscopically, however, the project seems robust and therefore the loans can ultimately be repaid, thus fulfilling the financial requirements of the lenders.

- Equity investors: From the developer's perspective this project provides overall a very strong indication of being able to generate a 12% internal rate of return on the committed equity. For the years that M&R expenses or debt repayments cannot be met by the current year's revenues, maintenance and/or loan repayment reserve accounts can be established. Finally, even if the public authority requires further negotiations pertaining to revenue sharing, this project nevertheless looks strong enough to deliver the required equity *IRR*. As a result this project also fulfills the financial requirements of the equity investors.

Conclusively, the project under investigation is overall financially viable for all project stakeholders.

Summary

This chapter presented a case study for the purpose of demonstrating the capabilities of the proposed methodological framework in investigating the sensitivity of the stochastic parameters of the formulation as well as for assessing the impact of different alternative scenarios on the investment risk of the project. The case study pertained to a highway toll-road project projected to be constructed in the State of Texas as part of the Trans-Texas Corridor 35 megaproject. From the case study it was shown that different parameter sensitivities and alternative implementation scenarios can be successfully investigated thus providing significant insight to the project stakeholders regarding the achievement of the respective financial targets and ultimately assessing the project's financial viability.

In the following and final chapter of this dissertation, the major findings and topics for future research are presented.

CHAPTER 8: SUMMARY OF FINDINGS AND TOPICS FOR FUTURE RESEARCH

This dissertation research addressed a topic of contemporary transportation infrastructure capital investment projects, namely the assessment of the financial viability of such projects procured as Public Private Partnerships. The major findings from the course of this research as well as recommendations for future research in this area are presented in the following sections.

Summary of Research Findings

This dissertation research began by setting a number of objectives to be accomplished through the course of its work. The accomplishment of these objectives has also led to the identification of the key findings of this dissertation, which are discussed as follows:

- Risks are present in all phases of the development of PPP projects. Various risk classifications currently exist and there are many reasons that can cause such projects to fail in various parts of their life. One particular type of risk, the investment risk, has been the main focus of this dissertation, as this is the risk that is related to the attainment of the financial targets of the project: if the project has a high risk of financial failure then it is almost certain that it cannot be developed under its current specifications and changes and/or further negotiations need to be made in many of its procurement aspects, these being the structure of their financing, or their design parameters to name a few.

- The investment risk is represented in this dissertation by the probability that the net operating income of the facility, i.e., the net difference between the project revenues and total costs, is going to be insufficient to service the outstanding project debt and also achieve a specific Minimum Acceptable Rate of Return for the project's equity investors. The investment risk under this definition had been already estimated through the use of the Second Moment Reliability Method (SORM), while similar formulations have been evaluated through the use of Monte Carlo simulation (MCS). However, the MCS does not provide an analytical solution and the SORM has been surpassed in terms of accuracy by another analytical method, the Method of Moments. As a result this relatively new analytical approximation method was adopted in this dissertation research for the evaluation of the investment risk, as it provided a clear improvement over already existing practices.

- Through the course of this dissertation research it was found that the potential success of PPP projects has been most commonly undertaken through the assessment of their financial viability. The definition of viability however changes among the different project stakeholders as each one of them has their own financial targets, which ultimately however need to be bridged in order for the project to be developed. From the investigation of these different facets of the financial viability it subsequently became clear that the financial viability of a transportation infrastructure project can be successfully assessed through the evaluation of the investment risk, as this risk could be used either directly or indirectly by all project stakeholders in order to decide whether the accomplishment of their respective financial targets was probable or not and also have a quantitative measure of it.

- This dissertation proposed the integration of the all the above concepts for the development of a probabilistic framework for the assessment of the financial viability of different types of transportation infrastructure projects developed under PPP. The developed framework combines the selected definition of the investment risk, based on the concept of "stress-strength interaction", with the various characteristics of the PPP project and the various definitions of the financial viability of each project stakeholder. One aim of the framework was to be flexible to accommodate primarily different types of transportation infrastructure projects; it can also be used for various other revenue-generating projects procured as PPPs..Another aim was to provide for the simultaneous assessment of the financial viability of all project stakeholders. This last aim was based on the fact that in every PPP project the stakeholders are usually the same regardless of the actual nature of the project under investigation. The investment risk in this framework is evaluated with the Method of Moments and the financial viability assessment is obtained through sensitivity and scenario analyses that can highlight the variables that can potentially pose the greatest threat to it. This framework was also generic enough not to present specific models for the revenues and costs, as these are usually project-specific.

- The generic methodological framework was customized in this dissertation for the specific case of highway toll-road concession projects. For this purpose, the basic components of the methodology remained the same, as the only ones that needed to be further specified were the Revenue and Cost models for this specific category of projects. In order to specify these models, already existing ones were used as the basis with extensions and modifications were deemed appropriate. The utilized models can enable the consideration of six stochastic variables in the determination of the investment risk, namely: the initial construction cost estimate; the initial traffic estimate (AADT of first year of operations); the traffic growth factor; the interest rate of the project debt issued in the financing; the inflation rate (which is assumed equal to all price and cost escalation rates); and the discount rate, which is equal to the Minimum Acceptable Rate of Return of the equity investors. During the discussion of these models, it was observed that the usual and current approaches in terms of estimating the M&R costs of such projects do not take into account the unplanned M&R costs that are incurred due to unexpected failures. As a result a methodology for the evaluation of the Total M&R costs was deemed necessary.

- As a supplement to the customized framework for highway toll-road concession projects, an already existing method, originally developed for the evaluation of the risk cost of pavement M&R warranties, was utilized and customized in order to evaluate the total M&R costs of such projects. This methodology is based on evaluating the pavement reliability and then estimating the expected number of unexpected pavement failures between planned M&R intervals with the use of stochastic processes. In particular, this methodology is also based on the concept of “stress-strength interaction”, for the modeling of the pavement reliability, and the Non-Homogeneous Poisson Process, for the estimation of the expected number of unexpected failures. Through the implementation of this methodology for the needs of the investment risk analysis, the proposed framework is also further improved by explicitly considering the relationship between roadway utilization and M&R costs.

- Finally, a case study was undertaken for the demonstration of the capability of this framework to actually be used by all project stakeholders in order to assess the financial viability of the project from their own individual perspectives. The case study was undertaken for a real highway toll-road project that was envisioned to be implemented in the State of Texas, as part of a highway megaproject named Trans-Texas Corridor (TTC-35). The selected project was modeled through the use of the developed models and subsequently evaluated. During this process a number of assumptions were inevitably made, keeping however the project characteristics as close to its real development plan as possible. Through the evaluation of the base case scenario and by undertaking a number of carefully selected sensitivity and alternative scenario analyses, it was shown that all project stakeholders can actually use this methodology to develop insights regarding the various project variables and be able to decide on the gravity of their impact to the project's investment risk and ultimately to their own measures of financial viability.

Overall, the presented methodological framework provides an alternative evaluation methodology for a problem that is very well known in the transportation infrastructure industry and among the related decision makers. The financial viability of a project can be evaluated in many ways and all project stakeholders have their own measures and preferred methods of performing these evaluations. This dissertation research demonstrated that using the investment risk as a measure of financial viability can actually be useful to all project stakeholders at the same time, and that it can be used as a quantitative tool for improving the analysis of such projects and determining the probability of their financial success. It also demonstrated that a number of parameters can be used as stochastic variables in this analysis process thus enabling the introduction of various sources of uncertainty in the risk evaluation. Finally, this dissertation research introduced the Method of Moments for the estimation of the investment risk providing a clear improvement over previously used methods, due to the favorable characteristics of this analytical approximation technique. In conclusion, this dissertation research presented a methodological framework that aims to be of assistance to decision makers regarding transportations infrastructure project development. As any decision support system, the developed methodological framework is not intended to make decisions but to provide quality information that can help decision makers make informed decisions.

Topics for Future Research

This dissertation undertook a significant amount of work in establishing a methodological framework for the evaluation of the financial viability of PPP projects in transportation infrastructure. Several concepts were used, models were developed and assumptions were made during that process. As with every similar effort, the overall results of this dissertation are subject to the validity of these assumptions and the remaining unavoidable limitations that such efforts present due to the very nature of the modeling process, which is in the end an approximation of the real world. As a result, this dissertation research was not intended to solve all problems related to the assessment of the financial viability of PPP projects in transportation infrastructure. In that perspective, there are a few directions on which future research in this area can embark on and ameliorate the presented framework and corresponding results. Some of these directions are discussed as follows:

1. The investigation of the true probability distributions of the explanatory random variables of the problem formulation. Under the current approach, all the variables were

assumed to be normally distributed. Although past research in this area has demonstrated that the actual probability distribution (or the existence of correlation among the model variables for that matter) is not as significant as obtaining accurate estimates of their means and standard deviations, the accuracy of the approach would be further enhanced through the consideration of the actual distributions. This process would require a significant effort in obtaining real data for these variables and fitting possible distributions to them.

2. The consideration of different models that can be used for the estimation of the Total M&R costs of highway facilities. The current approach relies on previous research in the area of pavement maintenance warranties area and has numerous assumptions, such as the utilization of the Non-Homogeneous Poisson Process for the estimation of expected number of failures during the intervals between subsequent M&R actions. Although this approach was deemed to fit in the best possible manner the needs of this dissertation, the possibility of using other methodologies for this purpose should also be investigated. This could reveal limitations of the currently used approach and/or enhance the estimation of the Total M&R costs and therefore increase the accuracy of the entire methodological framework.

3. Finally, this dissertation research presented a methodological framework that can be customized for various transportation infrastructure projects but whose capabilities were demonstrated only for the case of highway toll-road concession projects and in particular for the case of their pavement structures. Future research could expand in two possible directions: 1) By introducing models for the consideration of bridge and other structures

that are part of highway toll-roads, thus supplementing the existing framework and expanding it to ultimately encompass all possible structures that are part of such projects; and 2) by employing the proposed formulation for the modeling and evaluation of the investment risk of other revenue-generating infrastructure projects procured as PPPs, either within transportation (i.e., airports, ports or railways) or from other areas of engineering (stadiums, buildings, parking lots, etc.). This process would entail the development and specification of different infrastructure-specific revenue and cost models but could ultimately validate the flexibility and usefulness of the proposed framework in assessing the financial viability of these projects from the perspective of all stakeholders.

BIBLIOGRAPHY

Abdel Aziz, A.M. and A.D. Russell. (2006). Generalized Economic Modeling for Infrastructure and Capital Investment Projects, *Journal of Infrastructure Systems*, Vol. 12, No.1, ASCE

Akintoye, A. *et al*. (2003). A Framework for the Risk Management of Private Finance Initiative Projects, *Public-Private Partnerships – Managing Risks and Opportunities*, Blackwell Science Ltd, Oxford, UK

Aldrete-Sánchez, R.M. (1998). *Feasibility Evaluation Model for Toll Highways*, Doctoral Dissertation, The University of Texas at Austin

American Society of Civil Engineers (ASCE). (2009). *2009 Report Card for America's Infrastructure*, retrieved online at: http://www.asce.org/reportcard/2009/

Ang, A.H-S. and W. Tang. (1984). *Probability Concepts in Engineering Planning and Design*, Vol.II Decision, Risk and Reliability, Wiley, New York, NY

Asenova, D. and M. Beck. (2003). A Financial Perspective on Risk Management in Public-Private Partnership, *Public-Private Partnerships-Managing Risks and Opportunities*, Blackwell Science Ltd, Oxford, UK

Ashley, D. *et al*. (1998). Evaluating Viability of Privatized Transportation Projects, *Journal of Infrastructure Systems*, Vol.4, No.3, ASCE

Bodie, Z., A. Kane and A.J. Marcus. (2005). *Investments- Sixth Edition*, McGraw-Hill/Irwin, New York, NY

Brown, K. (2007). Are Public-Private Transactions the Future of Infrastructure Finance?, Commentary, *Public Works Management & Policy*, Vol.12, No.1, 320-324, Sage Publications

BusinessWeek. (2008). *Corporate Financing in a Pintch*, by Ben Levisohn, retrieved online at: http://www.businessweek.com/bwdaily/dnflash/content/sep2008/db20080917_614448.htm?chan=investing_investing+index+page_stocks+%2Bamp%3B+markets

Damnjanovic, I. (2006). *A Risk-Based Approach to Modeling Life-Cycle Costs Associated with Warranty Specifications for Transportation Infrastructure*, Doctoral Dissertation, The University of Texas at Austin

Damnjanovic, I. and Z. Zhang. (2008). Risk-Based Model for Valuation of Performance-Specified Pavement Maintenance Contracts, *Journal of Construction Engineering and Management*, Vol.134, No.7, ASCE

Easa, S.M. (1990). Extension of AASHTO Remaining-Life Methodology of Overlay Design, *Transportation Research Record 1272*, TRB, Washington, D.C.

Ebeling, C.E. (1997). *An Introduction to Reliability and Maintainability Engineering*, Waveland Press, Long Grove, IL

Edwards, P. and P. Bowen. (2003). Risk Perception and Communication in Public-Private Partnerships, *Public-Private Partnerships – Managing Risks and Opportunities*, Blackwell Science Ltd, Oxford, UK

El-Diraby, T.A. and S.M. Gill. (2006). A Taxonomy for Construction Terms in Privatized-Infrastructure Finance: Supporting Semantic Exchange of Project Risk Information, *Construction Management and Economics*, 24, 271-285, Taylor & Francis

Fortune. (2007). *Would you buy a bridge from this man?*, by Bethany McLean, from the Fortune Magazine print edition, October 2, 2007

Giglio, J.M. (2005). *Mobility – America's Transportation Mess and How to Fix it*, Hudson Institute, Washington, D.C

Hardcastle, C. and K. Boothroyd. (2003). Risk Overview in Public-Private Partnership, *Public-Private Partnerships – Managing Risks and Opportunities*, Blackwell Science Ltd, Oxford, UK

Huang, Y.H. (1993). *Pavement Analysis and Design*, Prentice-Hall, Englewood Cliffs, N.J.

InvestmentNews. (2009). *Infrastructure Funds Gamble on Increase in Projects*, by Sue Asci, retrieved online at: http://www.investmentnews.com/apps/pbcs.dll/article?AID=/20090201/REG/901309979

Jafarizadeh, B. and R.R. Khorshid-Doust. (2007). A Method of Project Selection Based on Capital Asset Pricing Theories in A Framework of Mean-Semideviation Behavior, *International Journal of Project Management*, Elsevier Science Ltd

Javid, M. and P.N. Seneviratne. (2000). Investment Risk Analysis in Airport Parking Facility Development, *Journal of Construction Engineering and Management*, Vol.126, No.4, ASCE

Jeon, C.M. and A.A. Amekudzi. (2006). Risk Management for Public Private Partnerships (PPP): Using Scenario Planning and Valuation Methods, *Proceedings of the 86th Annual TRB Meeting*, Washington, D.C

Kakimoto, R. and P.N. Seneviratne. (2000). Investment Risk Analysis in Port Infrastructure Appraisal, *Journal of Infrastructure Systems*, Vol.6, No.4, ASCE

Kalidindi, S.N. and A.V. Thomas. (2003). Private Sector Participation Road Projects in India: Assessment and Allocation of Critical Risks, *Public-Private Partnerships – Managing Risks and Opportunities*, Blackwell Science Ltd, Oxford, UK

Keown. A.J. *et al*. (2005). *Financial Management: Principles and Applications,* 10th Edition, Pearson Prentice Hall, Upper Saddle River, NJ

Li, B. and A. Akintoye. (2003). An Overview of Public-Private Partnership, *Public-Private Partnerships – Managing Risks and Opportunities*, Blackwell Science Ltd, Oxford, UK

Li, B. *et al*. (2005). Critical Success Factors for PPP/PFI Projects in the UK Construction Industry, *Construction Management and Economics*, 23, 459-471, Taylor & Francis

Mayer, J. (2007). Private Returns, Public Concerns: Addressing Private Sector Returns in Public-Private Highway Toll Concessions, *Transportation Research Record 1996*, TRB, Washington, D.C.

Melchers, R.E. (1999). *Structural Reliability Analysis and Prediction*, Second Edition, Wiley, Chichester, UK

Mercer. (2008). *Unwinding of Infrastructure Funds*, by Amarik Ubhi, retrieved online at: http://www.mercer.com/summary.htm;jsessionid=SoOuqjWFgJzYaUF4xZCP6w**.mercer02?siteLanguage=100&idContent=1324620

Mohamed, S. and A.K. McCowan. (2001). Modelling Project Investment Decisions under Uncertainty using Possibility Theory, *International Journal of Project Management*, 19, 231-241, Elsevier Science Ltd

Nakagawa, T. (2005). *Maintenance Theory of Reliability*, Springer-Verlag, London, UK

Nevitt, P.K and F.J. Fabozzi. (2002). *Project Financing,* Seventh Edition, Euromoney Books, London, UK

Ortiz, I.N. and J.N. Buxbaum. (2008). Protecting the Public Interest: The Role of Long-Term Concession Agreements for Providing Transportation Infrastructure, *Public Works Management & Policy*, Vol.13, No.2, 126-137, Sage Publications

Osaki, S. (2002). *Stochastic Models in Reliability and Maintenance*, Springer-Verlag, Berlin, Germany

Pagano M.A. and D. Perry. (2008). Financing Infrastructure in the 21st Century City, *Public Works Management & Policy*, Vol.13, No.1, 22-38, Sage Publications

Podgorski, K.V. and K.M. Kockelman. (2006). Public Perceptions of Toll Roads: A Survey of the Texas Perspective, *Transportation Research Part A*, 40, 888-902, Elsevier Ltd

Preqin Infrastructure. (2008). *The 2008 Preqin Infrastructure Review - An Examination of the Unlisted Infrastructure Fund Market*, Private Equity Intelligence Ltd, retrieved online at: www.preqin.com/ID2008.aspx

Project Finance. (2008)(a). *Anyone for US PPP?*, Article A180734091, Euromoney Publications PLC, UK

Project Finance. (2008)(b). *The Challenges of Change*, Article A180734093, Euromoney Publications PLC, UK

Project Finance. (2008)(c). *Seconds Away*, Article A182260951, Euromoney Publications PLC, UK

Rigdon, S.E. and A.P. Basu. (2000). *Statistical Methods for the Reliability of Repairable Systems*, Wiley, New York, NY

Ross, S.M. (1983). *Stochastic Processes*, Wiley, New York, NY

Seneviratne, P.N. and M. Ranasinghe. (1997). Transportation Infrastructure Financing: Evaluation of Alternatives, *Journal of Infrastructure Systems*, Vol.3, No.3, ASCE

Smith, A.L. (2003). Public-Private Partnership Projects in the USA: Risks and Opportunities, *Public-Private Partnerships – Managing Risks and Opportunities*, Blackwell Science Ltd, Oxford, UK

Songer, A.D., J. Diekmann, and R.S. Pecsok. (1997). Risk Analysis for Revenue Dependent Infrastructure Projects, *Construction Management and Economics*, 15, 377-382, Taylor & Francis

Stampley, B.E., Miller, B., Smith, R.E., and Scullion, T. (1995). "*Pavement Management Information System Concepts, Equations, and Analysis of Pavements"*, Research Report 1989-1, Texas Transportation Institute, The Texas A&M University System

Texas Department of Transportation (TXDOT). (2006)(a). Executive Summary, *TTC-35 Master Development Plan*, retrieved online at: http://keeptexasmoving.com/var/files/File/TTCPrjctsTTC35/PrjctPlanDvlpmnt/First_MDP/Executive_Summary.pdf

TXDOT. (2006)(b). Chapter 3-A: Traffic and Revenue (Roadway), *TTC-35 Master Development Plan*, retrieved online at: http://keeptexasmoving.com/var/files/File/TTCPrjctsTTC35/PrjctPlanDvlpmnt/First_MDP/Chapter_3-1_Traffic_and_Revenue_A-Roadway.pdf

TXDOT. (2006)(c). Chapter 4: Project Cost (Roads, Rail and Utilities), *TTC-35 Master Development Plan*, retrieved online at: http://keeptexasmoving.com/var/files/File/TTCPrjctsTTC35/PrjctPlanDvlpmnt/First_MDP/Chapter_4_Facility_Cost.pdf

TXDOT. (2006)(d). Chapter 5: Risk Analysis, *TTC-35 Master Development Plan*, retrieved online at: http://keeptexasmoving.com/var/files/File/TTCPrjctsTTC35/PrjctPlanDvlpmnt/First_MDP/Chapter_5_Facility_Risk_Analysis.pdf

TXDOT. (2006)(e). Chapter 6: Facility Financial Analysis, *TTC-35 Master Development Plan*, retrieved online at: http://keeptexasmoving.com/var/files/File/TTCPrjctsTTC35/PrjctPlanDvlpmnt/First_MDP/Chapter_6_Facility_Financial_Analysis.pdf

TXDOT. (2006)(f). Chapter 8: Near-Term Facility Analysis, *TTC-35 Master Development Plan*, retrieved online at: http://keeptexasmoving.com/var/files/File/TTCPrjctsTTC35/PrjctPlanDvlpmnt/First_MDP/Chapter_8_Near_Term_Facility_Analysis.pdf

TXDOT. (2006)(g). Appendix 2: Detailed Primary and Connecting Roadway Facility Cost and Revenue Estimates, *TTC-35 Master Development Plan*, retrieved online: http://keeptexasmoving.com/var/files/File/TTCPrjctsTTC35/PrjctPlanDvlpmnt/First_MDP/Appendix-2.pdf

TXDOT. (2006)(h). Appendix 5: Detailed Financial Analysis of Primary Facilities, *TTC-35 Master Development Plan*, retrieved online at: http://keeptexasmoving.com/var/files/File/TTCPrjctsTTC35/PrjctPlanDvlpmnt/First_MDP/Appendix-5.pdf

TXDOT. (2006)(i). Appendix 6: Detailed Cost and Revenue for Positive Near-Term Facilities, *TTC-35 Master Development Plan*, retrieved online at: http://keeptexasmoving.com/var/files/File/TTCPrjctsTTC35/PrjctPlanDvlpmnt/First_MDP/Appendix-6.pdf

TXDOT. (2006)(j). Appendix 7: Detailed Financial Analysis of Positive Near-Term Facilities, *TTC-35 Master Development Plan*, retrieved online at: http://keeptexasmoving.com/var/files/File/TTCPrjctsTTC35/PrjctPlanDvlpmnt/First_MDP/Appendix-7.pdf

The Economist. (2004). *Serial networker*, Macquarie Bank, from The Economist print edition, September 9th, 2004

The Economist. (2005). *London calling*, Macquarie Bank, from The Economist print edition, October 13th, 2005

The Economist. (2006). *On the move*, from The Economist Global Agenda, April 25th, 2006

The Economist. (2007)(a). *Road runners*, Buttonwood, from The Economist print edition, January 18th, 2007

The Economist. (2007)(b). *Should Texans have to pay to drive?*, Texas toll roads, from The Economist print edition, March 8th, 2007

The Economist. (2008)(a). *For whom the tolls swell*, Macquarie Group, from The Economist print edition, April 17th, 2008

The Economist. (2008)(b). *The cracks are showing*, Infrastructure, from The Economist print edition, June 26th, 2008

The Economist. (2008)(c). *Taking its toll*, Australian finance, from The Economist print edition, August 28th, 2008

The Economist. (2008)(d). *Wall Street's bad dream*, The financial crisis, from The Economist print edition, September 18th, 2008

The New York Times. (2008(a)). *Cities Debate Privatizing Public Infrastructure*, by Jenny Anderson, retrieved online at: www.nytimes.com/2008/08/27/business/27fund.html

The New York Times. (2008(b)). *Financial Crisis Enters New Phase*, by Vicas Bajaj, retrieved online at: http://www.nytimes.com/2008/09/18/business/18markets.html

Tinsley, R. (2000). *Advanced Project Financing, Structuring Risk*, First Edition, Euromoney Books, London, UK

Vassallo, J.M. and R. Izquierdo. (2002). Modeling Road Maintenance Management and Financing, *Journal of Transportation Engineering*, Vol. 128, No. 6, ASCE

Washington Asphalt Pavement Association (WAPA). (2002). Asphalt Pavement Guide, online resource: http://www.asphaltwa.com/wapa_web/modules/04_design_factors/04_loads.htm

Xenides, Y. and D. Angelides. (2005). The Financial Risks in Build-Operate-Transfer Projects, *Construction Management and Economics*, 23, 431-441, Taylor & Francis

Ye, S. and R.L.K. Tiong. (2000). NPV-at-Risk Method in Infrastructure Project Investment Evaluation, *Journal of Construction Engineering and Management*, Vol.126, No.3, ASCE

Yescombe, E.R. (2007). *Public-Private Partnerships – Principles of Policy and Finance*, Elsevier Ltd, UK

Zhang, Z. and I. Damnjanovic. (2006)(a). Applying Method of Moments to Model Reliability of Pavement Infrastructure, *Journal of Transportation Engineering*, Vol.132, No.5, ASCE

Zhang, Z. and I. Damnjanovic. (2006)(b). Quantification of Risk Cost Associated with Short-Term Warranty-Based Specifications for Pavements, *Transportation Research Record 1946*, TRB, Washington, D.C.

Zhang, Z. and Z. Piepmeyer. (2005). Reliability-based Approach to Optimizing Preventive Maintenance for Pavements, *Proceedings of the 84th Annual TRB Meeting*, Washington, D.C

Zhao, Y-G and A.H-S Ang. (2003). System Reliability Assessment by Method of Moments, *Journal of Structural Engineering*, Vol. 129, No.10, ASCE

Zhao, Y-G and T. Ono. (2000). New Point Estimates for Probability Moments, *Journal of Engineering Mechanics*, Vol. 126, No. 4, ASCE

Zhao, Y-G and T. Ono. (2001). Moment Methods for Structural Reliability, *Structural Safety*, 23, 47-75, Elsevier Science Ltd

VITA

Aristeidis Pantelias is a graduate of the Athens College high school in Athens, Greece. He obtained his Diploma in Civil Engineering with a specialty in Transportation from the National Technical University of Athens (NTUA). Following his graduation from NTUA, he was admitted to the Virginia Polytechnic Institute and State University (Virginia Tech) in Blacksburg, VA from which he obtained a Master of Science in Civil Engineering. His studies at Virginia Tech focused mainly on transportation infrastructure management. After his graduation from Virginia Tech, he was admitted to the University of Texas at Austin (UT) where he pursued his studies towards a Doctor of Philosophy degree in Civil Engineering. His studies at UT focused on infrastructure management, project finance, and probabilistic investment risk assessment for public private partnership projects in transportation infrastructure. Aristeidis is a licensed Civil Engineer in Greece and the European Union.

Permanent Address: 24 Andromedas St., Vironas, Athens, 16231, Greece

This dissertation was typed by the author