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Methodologies for Assessing Infrastructure Projects under Public-Private Partnerships: From Project Financing to Maintenance Scheduling

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Abstract

Public-Private Partnerships (PPPs) are gaining increasing popularity and acceptance worldwide in delivering public infrastructure services. A combination of scarcity of public funds, the never-ending quest of private investors for new and profitable investment opportunities, and the undisputable need for new capacity and/or improvements in most public infrastructure is fostering this worldwide trend. PPPs, which introduce private capital and expertise in public infrastructure projects, are an efficient and cost-effective financing mechanism to solve this budgetary shortage problem while ensuring the best value for money. Even though researchers and scholars have made great efforts to explore this innovative area, there are still problems unsolved that need to be investigated. This report proposes three methodological frameworks in a logical way to solve a sequence of issues associated with PPP projects so that all the stakeholders involved can make more insightful decisions. First, this report presents a systematic genetic-algorithm-based methodology to minimize public funds employed and thus optimize the capital structure that reflects the characteristics of project financing and aims for win-win–win results for public authorities, equity investors, and lenders. Subsequently, a Monte Carlo Simulation based methodological framework for assessing the investment risks of PPP toll highway projects is proposed, where decision makers can obtain direct information to estimate the project's overall financial risks and develop corresponding risk control measures. Finally, the report applies the Fourth Order Method of Moments to determine optimal pavement preventive maintenance intervals based on reliability theory, contributing to cases where the distributions for characterizing variable uncertainties are unknown or difficult to obtain due to incomplete data. Therefore, a series of PPP problems is scrutinized: from project capital structure to investment risk assessment, and finally to the scheduling of preventive maintenance activities. Three case studies were conducted to illustrate the proposed methodologies. The insightful findings can be used by all stakeholders and decision makers to support their decision processes and negotiations toward a PPP infrastructure project for successful implementation.

Table of Contents

List of Tables

List of Figures

1. INTRODUCTION

1.1 Background

With the continuous growth of the economy and urbanization, the demand for delivering basic infrastructure services has increased drastically worldwide in recent years. However, due to limited and restricted public budgets, governments are faced with the challenge of being unable to keep up with the growing infrastructure needs. Traditional funding sources cannot cover all the capital needed to operate and maintain existing infrastructures, much less to construct new ones (Siemiatycki 2009; Markow 2011). According to the 2017 Infrastructure Report Card released by American Society of Civil Engineers (ASCE), the cumulative GPA of U.S. infrastructure is only “D+” (ASCE (a), 2017). It was reported that more than forty percent of America’s urban interstates are congested, and traffic delays cost the country $160 billion in wasted time and fuel in 2014. Twenty percent of highway pavements are in poor condition, and the roads have a significant and increasing backlog of rehabilitation needs. As a result, the U.S. has been underfunding its highway system for years, resulting in an $836 billion backlog of highway and bridge capital needs (ASCE (b), 2017).

Failing to deliver infrastructure projects could lead to a negative influence on economic growth, which can in turn affect the local and regional job market, as well as the economy’s ability to attract new businesses and investments. There is an immediate need for government and public authorities to explore new funding sources. Under these circumstances, public private partnerships (PPPs), which introduce private capital and expertise into a project, have been applied to address this budgetary shortage problem (Pagano 2008; Han 2013). The private sectors have realized that funding public infrastructure projects is profitable in many cases, especially when other potential investments have yielded a lower profit (Savas, 2005). Slowly but steadily, the traditional ways of public financing and procurement have given way to private finance and the contribution of private investment in the delivery and operation of public infrastructure.

1.1.1 PUBLIC PRIVATE PARTNERSHIPS (PPPS)

What are the PPPs? So far, there is no widely accepted definition of PPPs. Among the various definitions provided by different institutions and agencies, one of the most widely adopted definition of PPPs is presented by the National Council for Public-Private Partnerships (NCPPP) as “a contractual arrangement between a public agency and a private sector entity. Through this agreement, the skills and assets of each sector are shared in delivering a service or facility for the use of the general public. In addition to the sharing of resources, each party shares in the risks and rewards potential in the delivery of the service and/or facility” (NCPPP, 2017). Typically, there are three parties involved in a PPP project: the public authority, the private sector (equity investor), and the lender (e.g., banks). These parties work together under a certain project finance structure by undertaking or sharing different tasks.

There are several reasons why PPPs are gaining popularity as an innovative business model to finance public infrastructure projects. First, the level of public resources available for constructing, upgrading, operating, maintaining, and rehabilitating public infrastructures is limited and restricted (Smith 2003; Giglio 2005).

Second, the travel demand and high expectations regarding mobility and level of service from the public are continuously increasing over the recent years (Brown 2007; Ortiz and Buxbaum 2008). According to U.S. Department of Transportation (USDOT) and Federal Highway Administration (FHWA), the number of registered vehicles in the United States from 1990 to 2015 is presented in Figure 1-1(USDOT and FHWA, 2017). As can be seen from the figure, the number of registered vehicles shows an increasing trend. The number of registered vehicles increased from 193 million (year 1990) to 260.3 million (year 2014), which is an increase of more than 67 million vehicles in 24 years. However, based on the information from Bureau of Transportation Statistics, the number of total lane-miles just increased from 8.05 million to 8.77 million during the same time span, which is shown in Figure 1-2 (USDOT, 2017). In other words, only 0.7 million lane-miles were constructed to accommodate a 67 million increase in registered vehicles, resulting in congested roadways and a huge amount of traffic delays. In addition, most of the existing highways were built in mid or late 20th century. The whole system is suffering from serious aging problems. There is an urgent demand from the public on the infrastructure system's maintenance needs, coupled with the need for additional capacity and expansions, which calls for the involvement of other sources of capital (Pagano and Perry 2008).

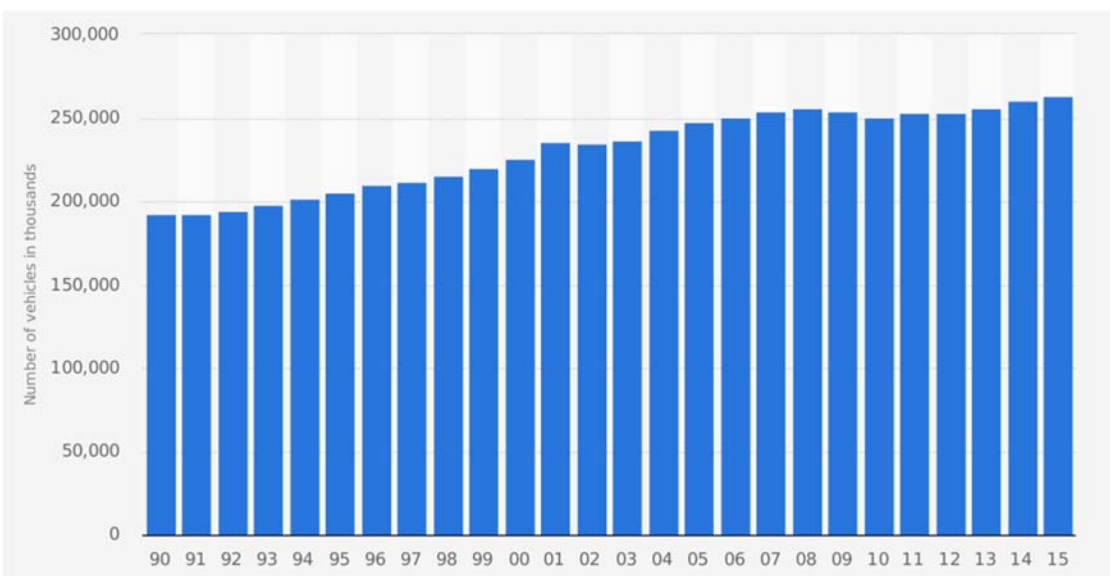

Figure 1-1: Number of Registered Vehicles in the United States from 1990 to 2015 (in 1,000s)

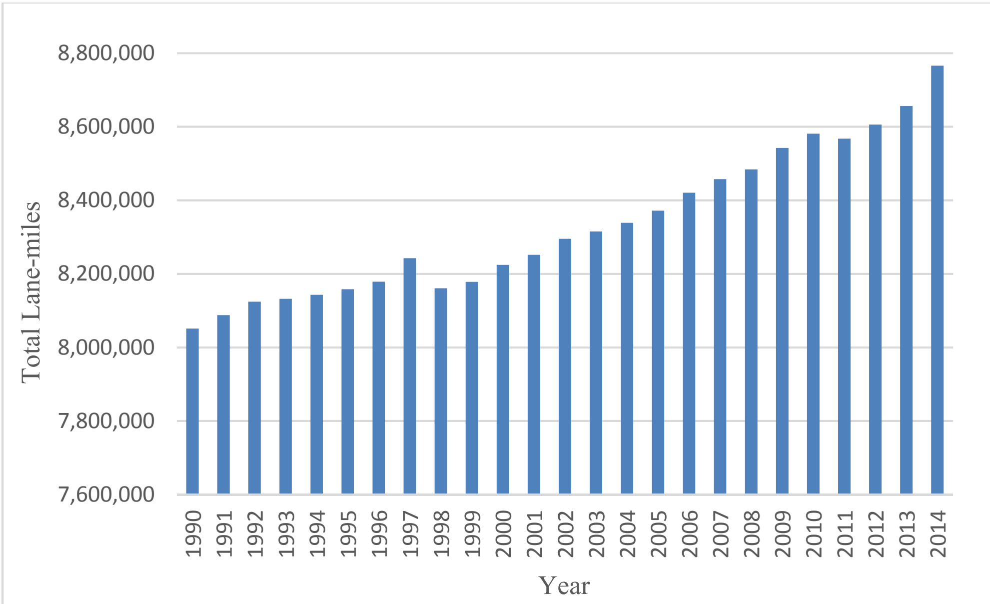

Figure 1-2: Number of Total Lane-miles in the United States from 1990 to 2014

Third, the private sectors have realized the attractiveness and profitability of PPP projects. Numerous reports have mentioned significant investment returns by large pools of private capital (Brown 2007; McLean 2007; The Economist 2008). More than ever, the private sectors are willing to directly commit private equity to long-term contracts through infrastructure-designated investment funds from senior banks or other funding sources.

Finally, even though PPP projects are typically large and complex, they have been delivered on time and on budget more frequently than traditional procurement projects. According to a report released by Infrastructure Partnerships Australia (IPA), during year 2000 to 2007, 18 percent of traditional projects missed deadlines, while only 10 percent of PPP projects had timing overruns. For those timing overrun projects, traditional projects were implemented 26 percent later than original schedule, while PPP projects were delivered only 13 percent later than expected. On the budget side, 45 percent of traditional projects exceeded the expected expenditure, while only 14 percent of PPP procured projects had cost overrun. In addition, for those expenditure overrun projects, traditional projects were 35 percent above budget, while PPP projects were only 12 percent over (IPA 2007).

Governments worldwide have shown increasing initiatives in the private financing of public infrastructure and services. A combination of the scarcity of public funds, the undisputable need for new capacity and/or improvements in most public infrastructure, and the never-ending quest of private investors for new and profitable investment opportunities is fostering this worldwide trend (Grimsey and Lewis, 2007).

1.1.2 Development and Programs of PPPs in Worldwide Infrastructure Delivery

Even though the concept of PPPs is not new, it was not until the 1970s that the PPPs were promoted and popularized. Between 1985 and 2008, over 1,100 PPP projects worth more than $450 billion were implemented globally (AECOM 2005). Special government authorities and departments have been established to facilitate the expanded application of PPPs in many countries, including Australia, Singapore, the United Kingdom, Canada, South Africa, etc. (Garvin and Bosso 2008).

The United Kingdom began its Private Finance Initiative (PFI) in 1992, which is currently responsible for around 14 percent of public investments in most key infrastructure areas. As a response, in 1996, Local Authority (LA) associations established the Public-private Partnership Program Limited to support and encourage partnership arrangements (Beck and Hunter 2003). By mid-October 1998, there were 79 LAs involved in 184 projects. Among all the LA-PFI projects, education-related projects were most prevalent (29 percent), followed by transportation projects (15 percent), administrative/public buildings (15 percent), housing (11 percent), and IT (9 percent) (Akintoye *et al*. 1999). According to European Investment Bank, Her Majesty's Treasury (HM Treasury) established an Infrastructure Finance Unit (TIFU) to support PFIs impacted by the credit crisis. As of April 2012, over 550 PFI projects worth over $59 billion have been signed in England (EIB 2017).

Although the share in total public investment is quite small compared with the U.K., many Western European countries have their own PPP program set up, including Italy, France, Spain, Greece, Germany, the Netherlands, Finland, and Portugal. According to Public Private Infrastructure Advisory Facility (PPIAF), Germany, the Netherlands, Finland, and Portugal have seen the need for large-scale infrastructure investment but their PPPs are in a weak financial position; while Italy, France, and Spain have had a tradition of concessions for motorway development (PPIAF 2017 (a)). There are also some PPP experiences where most of the projects are related to highways in Central and Eastern Europe, such as the Czech Republic, Poland, and Hungary.

Mexico, Columbia, and Chile are the pioneering countries in applying PPPs in Latin American. Mexico had some unsuccessful experiences with PPPs when they were first introduced to finance roadways projects in the 1980s. Since the mid-1990s, Mexico has been adopting PPP programs successfully for a number of public projects, especially in the energy area. Now they have plans to extend the application of PPPs to other public infrastructure services (PPIAF 2017 (a)). Columbia has been utilizing PPPs since the early 1990s with a recent re-launched PPP program emphasizing highway projects. In Chili, there has been a well-established PPP program to serve the development of transportation, agriculture, and other public infrastructures, such as highways, airports, irrigation, and prisons (PPIAF 2017 (a)). Another Latin American country that has broad experiences with PPPs is Brazil. The Brazilian government has prioritized infrastructure investment and privatization since 2009, when the global economic slowed down. Brazil has undertaken PPP projects at both the federal and sub-national levels, especially in road, airport, and urban mobility projects. From 2013 to 2016, Brazil awarded more than 50 PPP projects, most of which are water and waste water projects at a municipal level and transportation projects at a national level (The World Bank 2017 (a)).

In Asia, the application of PPPs continues to increase with a rapidly expanding program in India, a well-established program in South Korea, and an extensive program in China, as well as other programs with different degrees of success and implementation in the Philippines, Singapore, and Indonesia (PPIAF 2017 (a)). India is regarded as one of the leading PPP markets in the world, where PPPs are deemed as an effective way of harnessing private sector participation in the provision of high-priority infrastructures. There are 838 PPP projects that have reached financial closure since 1990. The total investment committed is $230.8 billion. Recently, the National Highways Authority of India (NHAI) awarded 43 PPP road projects to construct more than 2,600 km (1,615 miles) of roads (The World Bank 2017 (b)). Compared with that in India, the experiment of PPPs in China took place much later as the Chinese government did not initiate significant reforms to promote PPPs until late 2013. However, PPPs experienced a dramatic development since then. A central government PPP Center was established by the Ministry of Finance in December 2014, whose responsibility is to research PPP policy, advice, train, and coordinate different agencies in PPP arrangement. As of April 2016, transportation projects worth 4.5 trillion Chinese Yuan ($650 billion) have been funded through PPP procurement. More recently, on October 18, 2016, 668 infrastructure PPP projects adding up to 1.14 trillion Chinese Yuan ($170 billion) were offered to investors by the Department of National Development and Reform Commission, in order to boost the development of private investment. Those projects cover the areas of transportation, water, municipal facilities, and energy (The World Bank 2017 (c)).

South Africa is taking the leading role in employing PPPs in Africa, followed by the countries such as Senegal and Cote d'Ivoire where PPPs are gaining popularity in delivering public infrastructure projects (e.g., power, transportation, and water sectors). The PPP environment in South Africa is strong with a solid record in serving major public projects. South Africa has high standards in regulations and law, a sophisticated financial sector, and a stable infrastructure business (The World Bank 2017 (d)). In addition to those legislation regulating the PPP procurement in general, there are other detailed regulations and legislation that standardize the procurement, feasibility, and implementation of PPPs in South Africa, such as the PPP Manual, the Standardized PPP Provisions (issued in 2004), and Treasure Regulation 16 to the Public Finance Management Act (PFMA) (adopted in 2005 and revised in 2007 and 2013). There are in total 86 PPP projects that have reached financial closure since 1990 with 78 active PPP projects under construction or operation in South Africa, adding up to $41.3 billion total investment committed (The World Bank 2017 (d)).

The development of PPPs in the U.S. is driven by three major forces: the rapid aging and deterioration of existing infrastructure systems, public investment shortfalls for constructing and maintaining vital public systems, and a growing population's demand on public services. Although there were some projects that involved private sectors dating back to the 1930s, the first "modern" PPP project in the U.S. was the E-470 project, which was built in 1989. E-470 project is a 47-mile toll highway outside Denver, Colorado that was built to accommodate the traffic to the to-be-opened Denver International Airport. This project was built with private funds through a $323 million Design-Build contract and opened to public in 1991 (McNichol 2013). After that, more and more toll roads were financed and constructed through PPP procurement, and toll roads have become the leading PPP product in U.S. market, including the Chicago Skyway in 2005, the Indiana toll road and Virginia Pocahontas Parkway in 2006, and the Colorado Northwest Parkway in 2007. With the development of the PPP program, more and more sectors are utilizing PPPs as an effective way to deliver public infrastructures, including energy, healthcare, telecom, transportation, and waste water treatment. It was reported that $1.4 billion worth of projects was competed in 2004. The private investments went up to $6.7 billion in 2009, and there were eight projects adding up to $5.8 billion that reached commercial closure in 2010. Twenty-four states, including Texas, Virginia, Florida, California, etc., and the District of Columbia have used the PPP process to help finance and construct at least 96 transportation projects worth a total $54.3 billion by 2011 (Reinhardt 2011). More recent PPP projects are the Pennsylvania Northampton bridges PPP project ($37.5 million, project signed on February 17, 2017) and the New 37-gate terminal at LaGuardia Airport ($4 billion, project awarded on January 10, 2017) (InfraPPP 2017). It is predicted that private investments in public projects will reach around $15 billion in 2018 (McNichol 2013).

1.2 Research Motivation

Although PPPs have already been embraced in many countries, they are still a relatively new financing approach compared to traditional financing through public funds. There have been unsuccessful experiences with PPPs and failed PPP projects now and then. The PPP project has to be capable of fulfilling the expectations of public authorities, private sectors, and the lenders in order to be selected and financed for further implementation. Like any other projects, there are a series of problems to be considered and accommodated by all the stakeholders involved. Researchers and scholars have made great efforts to explore this innovative area. The analysis of PPP projects has been a very active area of research, naturally attracting a big audience from both academia and industrial practitioners. However, there are still problems unsolved that need to be investigated: 1) how to find the optimal capital structure of the PPP project at the financing stage so that it will increase the probability of bid-winning for the private sectors while satisfying the interests of both the public authorities and the lenders; 2) how to quantify the risks associated with investment in order to evaluate the financial viability of the PPP project; and 3) after the project is constructed, how to determine the most cost-effective maintenance strategy while incorporating various uncertainties associated with the pavement and traffic parameters, especially for PPP projects where readily available information is limited. There is an immediate need to explore these issues related to PPP procurement to secure the successful implementation of the PPP projects. In this context, this report accordingly proposes and applies three methodologies to address the aforementioned three issues. First, a systematic genetic-algorithm-based methodology that minimizes the public funds and optimizes the capital structure is presented, aiming for win-win–win results for public authorities, equity investors, and lenders. Second, a Monte Carlo Simulation based methodological framework for assessing the investment risks of PPP toll highway projects is proposed, so that decision makers can obtain direct information to estimate the project's overall financial risks and develop corresponding risk control measures. Finally, the report applies the Fourth Order Method of Moments to determine optimal pavement preventive maintenance intervals based on reliability theory, and thus contribute to cases where the distributions for characterizing variable uncertainties are unknown or difficult to obtain due to incomplete data.

1.3 Research Scopes and Objectives

This report aims to propose and apply a series of methodological frameworks to address the issues related to PPP projects: from project financing to maintenance scheduling. Although all of the three methodologies were illustrated through highway projects, the methodological frameworks proposed can also be applicable to other types of revenue-generating projects procured under PPP arrangement, such as plants, ports, buildings, or airports. The three individual methodological frameworks proposed in this report were implemented and illustrated through three case studies, which were turned into three papers that have been submitted or published in major journals in transportation area. The three papers are attached as Appendix A, Appendix B, and Appendix C, respectively, where the methodologies are presented and researched in detail, and the findings from the studies are discussed. The proposed methodologies are flexible and can possibly be applicable with a wide range of assumptions and options. Generally speaking, each of the proposed methodologies can be deemed as two parts: a generic methodological framework part designed for different types of revenue-generating PPP projects, and a specific model for particular case studies (e.g., Texas State Highway 130 and a section from the Trans-Texas Corridor).

The objectives of this research are summarized as follows:

1. To conduct a thorough review of PPPs, including the features, classifications, project financing, and especially various sources of risks associated PPP projects with a primary focus on the investment risk which directly influences the financial viability.
2. To investigate the state-of-art methods that are developed or applied to solve problems in optimal PPP project financial structure identification (financing phase), investment risk assessment and financial viability evaluation (planning phase), and optimal preventive maintenance (PM) interval determination (operation and maintenance phase).
3. To identify alternative methodologies based on various literature to improve the current practice, namely Genetic Algorithm (GA) based optimization technique, Monte Carlo Simulation (MCS) technique, and the Fourth Order of the Method of Moments (4M).
4. To propose methodologies from which all the involved stakeholders can benefit. The methodologies take the interests of public authorities, private

sectors, and lenders into consideration so that each of the participants can obtain insightful information from their own perspective.

5. To formulate a systematic GA based model for optimizing the bid-winning potential and capital structure, which minimizes the amount of public funds utilized while thoroughly considering the interests, concerns, and requirements of different participants. The impacts of the maximum committed private equity and minimum annual debt service cover rate (ADSCR) of the senior bank on the optimal capital structure are investigated.
6. To develop a MSC based methodological framework to assess the investment risk of PPP projects by establishing the relationship between the financial viability measurements of each stakeholder and the investment risk. The input variables are stochastic variables instead of traditional deterministic values.
7. To apply 4M to estimate the pavement reliability and determine the optimal PM interval while taking the uncertainties associated with the pavement and traffic parameters into consideration. The impact of preventive maintenance cost and rehabilitation cost on the optimal PM cycle interval is analyzed through a sensitivity analysis.
8. To customize the developed methodological frameworks for specific PPP toll highway projects. The capability of the proposed methodologies is illustrated through three separate case studies, where the interests of all stakeholders are satisfied and the risks associated with input parameters are taken into consideration.

1.4 Research Contributions

In a broad sense, this report contributes to the mechanism of employing PPPs to deliver transportation infrastructure services in different phases of the project's life cycle. First, during the financing phase of the PPP project, the developed methodology is able to yield a set of optimal solutions for the key decision variables: proportions of public funds, committed equity, and debts/loans. All of the stakeholders benefit from the results: the public authorities utilize the minimum amount of public funds to realize the Value for Money (VfM); the equity investors are able to reach their financial goals, while at the same time the probability of bid-winning potential is maximized; and the requirements on repayment ability from the lenders are satisfied. Second, during the planning phase, various risk sources are identified, and the relationship between financial viability measurements and the investment risk is developed. By conducting MCS, quantitative information is provided to different agencies (public authorities, private sectors, and lenders) to establish investment decision action. Finally, during the operation and maintenance phase of the PPP project, the proposed reliability-based framework is able to incorporate various uncertainties into the determination of optimal PM interval, which provides a cost-effective alternative for the agency which is responsible for the maintenance activities. These three methodologies are included in three separate papers that are currently under review or have been published by major transportation journals. To be more specific, the contributions in these three phases include:

1. This report deals with issues associated with PPP projects, which is regarded as interdisciplinary analysis. It incorporates a wide variety of research techniques, including traditional engineering analysis, optimization technique, simulation, reliability analysis, and financial engineering techniques.
2. A triple win situation is created at the financing phase through the bid-winning potential and capital structure optimal framework. The financial targets from the private sectors and the requirement on the debt repayment abilities from the lenders serve as the constraints of the model. Any violation against any constraint will not yield feasible solutions.
3. The public authorities obtain the VfM by financing and delivering the project using the minimum of public funds. The saved funding (compared with the maximum amount of public funds offered) can be invested into other social welfare infrastructures. The equity investors achieve their financial targets and gain an additional increase to their reputation by winning the bid and successfully implementing the PPP project. The impacts of maximum committed private equity and minimum annual debt service cover rate of senior bank on the optimal capital structure are investigated.
4. The identification of various risk sources (e.g., cost, revenue, and economic facets) related to a PPP project will enable all the stakeholders to have a much better overall understanding of the investment risks associated with PPP projects.
5. The MCS framework procedures are flexible enough for practitioners to adopt different stochastic inputs based on available data or professional judgement in practice. Multiple simulations can be run with different CVs and distributions to assess different levels of risks, allowing "what-if" scenarios to be studied.
6. A reliability based methodology is proposed to determine the optimal PM interval considering various uncertainties associated with the input variables. 4M is applied as the estimation technique to solve the complex multi-dimensional integral.
7. 4M is able to return traceable and close-form analytical solutions with high accuracy. In addition, the 4M approach does not require that the exact distribution for each variable be specified, making it more applicable to real-world engineering problems where the distributions for characterizing variable uncertainties are unknown or difficult to obtain due to incomplete data.
8. The findings and results obtained from the proposed methodologies can be used by all stakeholders and decision makers to support the hard decisions and negotiations required for financial closure and ultimate project successful implementation.

1.5 Report Outline

This report is organized in four chapters and three appendices. This chapter (Chapter 1) introduces the background information, research motivation, research scopes and objectives, and contributions of the research. The remaining chapters of this report are arranged as followings:

Chapter 2 presents a comprehensive literature review of various topics related to PPP mechanism, including features of PPPs, classification of PPPs, project finance, financial viability measurements of PPPs, and risks associated with PPPs. In addition, research and studies on optimal financial structure, financial viability and investment risk assessment, and the determination of optimal PM cycle interval will be reviewed and summarized.

Chapter 3 gives a brief summary of the methodologies used in this research, namely the genetic algorithm (GA), Monte Carlo Simulation (MCS), and the Method of Moments (MOM). Their mechanisms, as well as the advantages over other alternative methods, are highlighted.

Chapter 4 discusses the major findings of this research, addresses limitations, and provides the directions for future research efforts.

Appendix A contains the detailed information of the paper on GA based optimization framework to obtain optimal capital structure of PPP projects, including the formulation of the revenue model and cost model, a case study through a PPP toll highway Texas State Highway 130 together with a sensitivity analysis, the findings, and the conclusions of the study.

Appendix B attaches the paper on the assessment of investment risk associated with PPP projects using MCS, including a comprehensive discussion of risks related to PPP projects, the selection of financial viability for each of the stakeholders, MCS technique, a real-world case study through a section (P12) from the Trans-Texas Corridor (TTC-35), the discussions on stochastic input against deterministic inputs, and the conclusions.

Appendix C fully illustrates the paper on applying the Fourth Order of Method of Moments to incorporate uncertainties into the determination of optimal pavement preventive maintenance intervals, including the basic concepts of reliability theory, stress-strength model, MOM, preventive maintenance interval, the formulation of the strength function and stress function, the application of 4M and cost per unit time function, a numeric study as well as a sensitivity analysis, and the conclusions/discussion of the paper.

Finally, this report concludes with the bibliography that is used to support the undertaken research.

2. LITERATURE REVIEW

Following Chapter 1, this chapter presents a comprehensive literature review of the various topics that form the foundation of this research.

2.1 Features of PPPs

PPPs have several alternative names and are known worldwide as P3, Private Sector Participation (PSP), Private Finance Initiatives (PFI), and Private Participations in Infrastructures (PPI). Regardless of the name used, the basic concept behind such a contractual arrangement is that both public authorities and private sectors agree to fund the project under a project financing structure and enter in a long-session contract, where the risks during various phases of the project are allocated to the corresponding party that can best take care of them (Pantelias 2009).

According to Peters (1998), compared with traditional project delivering methods, PPPs have five general identified features regardless of what specific type of partnerships they are (Peters 1998).

First, more parties are involved in PPP procurements. Based on the definition of PPPs, it is obvious that a PPP project at least involves two parties, namely the public authority and the private sector. Generally speaking, there are always three parties participating in a PPP project: the public authority whose goal is to deliver infrastructure services and realize the value for money, the profit-driven private sectors (equity investors) whose target is to obtain adequate amount of return on their investments, and the lenders (public agencies or commercial banks) who offer loans and debts to cover the capital needed. In addition, besides the profit-oriented companies and organization, scholars have suggested that partnerships between the non-profit private sectors and governments should also be treated as PPPs (Rocky and John 1998).

Second, each participant is independent and a principal in a PPP project. Each of the parties involved has its own goal: public authorities need to realize the value for money and provide public services; private sectors intend to maximize their profitability from the investment; and lenders care more about the project's ability to repay the issued debts and decide the amount of the money that can be issued. When signing the contract, each participant just needs to bargain on its own behalf instead of traditionally depending on other organizations or referring back to other sources of authority.

Third, the partnership among the parties in a PPP project is stable throughout a long-term contract. The average duration for a concession contract is usually 30 to 40 years, with some cases up to 50 years. The partnership between the public authorities and private sectors is not a simple and one-time transaction. The continuing consociation lasts from the parameters negotiated before signing the concession contract until the financial closure of the contract (Middleton 2000).

Fourth, each participant in a PPP project contributes in different ways to secure the successful implementation of the project (Collin 1998). In order to initiate a genuine relationship and build their reputations, each sector will commit or share some resources to the partnership. Those resources could be either materialized (obvious) resources or immaterialized (not obvious) resources depending on the specific situation. The materialized resources include land, money, etc., while the immaterialized resources contain various authorities and other symbolic values (Bennett and Krebs 1991; Tiong 1992).

Finally, there are risk sharing and allocation mechanisms among different sectors in a PPP project (Collin 1998; HM Treasury 2000). In a traditional project delivery process, the public authorities take full control of the project (e.g., policy decisions and rule making) after accepting the recommendations from the private sector (e.g., a consulting company). However, this feature is different under PPP patterns, and each participant shares joint investment, responsibility, liability/risks, and authority, and seeks mutual benefit as one entity (Grant 1996).

2.2 Classifications of PPPs

PPPs can be categorized into different types based on the different classification criteria used. According to how the raised debts are repaid, the PPPs can be categorized as Concession Contracts or Private Finance Initiative (PFI). In a concession arrangement, the debts are paid back by collecting user fees from the infrastructure; while in a PFI contract, payments from the public authorities are usually introduced to cover the issued debts. Both Concession Contracts and PFI evolved to their current forms from the Power Purchase Agreements (PPA) established in the U.S. in the 1980s (Yescombe 2011).

Based on how the risks are transferred between the public authorities and the private sectors and the nature of the contracted services, PPP projects can be classified as availability-based projects and usage-based projects (Yescombe 2011). In a usage-based project, the private sectors do not need to consider the expected usage, and they can assume the risks of having the facility readily available for use; while in an availability-based project, the facility usage risk is fully transferred to the private sectors, and the private sectors are responsible for these risks. Generally speaking, usage-based projects are structured as Concession Agreements, while availability-based PPP projects are usually executed through the PFI model (Pantelias 2009).

In addition, PPPs can involve existing brownfield projects (i.e., the lease of an existing facility), or they can involve proposed new facilities, which are known as Greenfield projects. In the case of a brownfield project, a public entity generates a capital inflow or debt payoff by transferring the rights, responsibilities, and revenues attached to an existing asset to a private sector entity for a defined period. For Greenfield projects, a public agency transfers all or part of the responsibility for project development, construction, and operation to a private sector entity.

Finally, PPP projects can be categorized into different types based on the legal position of the private sectors involved in the project (Li and Akintoye 2003; Yescombe 2011). In this respect, the PPP projects are named as Build-Own-Operate-Transfer (BOOT) projects, Build-Operate-Transfer (BOT) projects, Design-Build-Finance-Operate (DBFO) projects, Build-Transfer (BT) projects, Joint Ventures (JV), etc., which directly reflect the nature of the contract and the stage when the operation (ownership) of the constructed facility is transferred from the public authorities to the private sectors and when the private sectors should return the ownership to the public authorities. One model that is gaining increased popularity and acceptance is the Design-Build-Finance-Operate-Maintain (DBFOM) model. The DBFOM business model is a form of BOT concession, where the private sector obtains a contract to be responsible for designing, financing, building, operating, maintaining, and collecting user fees for a specific period, following which the ownership of the infrastructure is restored to the public authority. According to Public-Private Partnership in Infrastructure Research Center (PPPIRC), BOT projects share some key features. For example, the project is usually a discrete, Greenfield project whose company is a Special Purpose Vehicle (SPV), and the lenders provide non-recourse or limited recourse financing. The contractual structure of a typical BOT project is presented in Figure 2-1 (PPPIRC 2017).

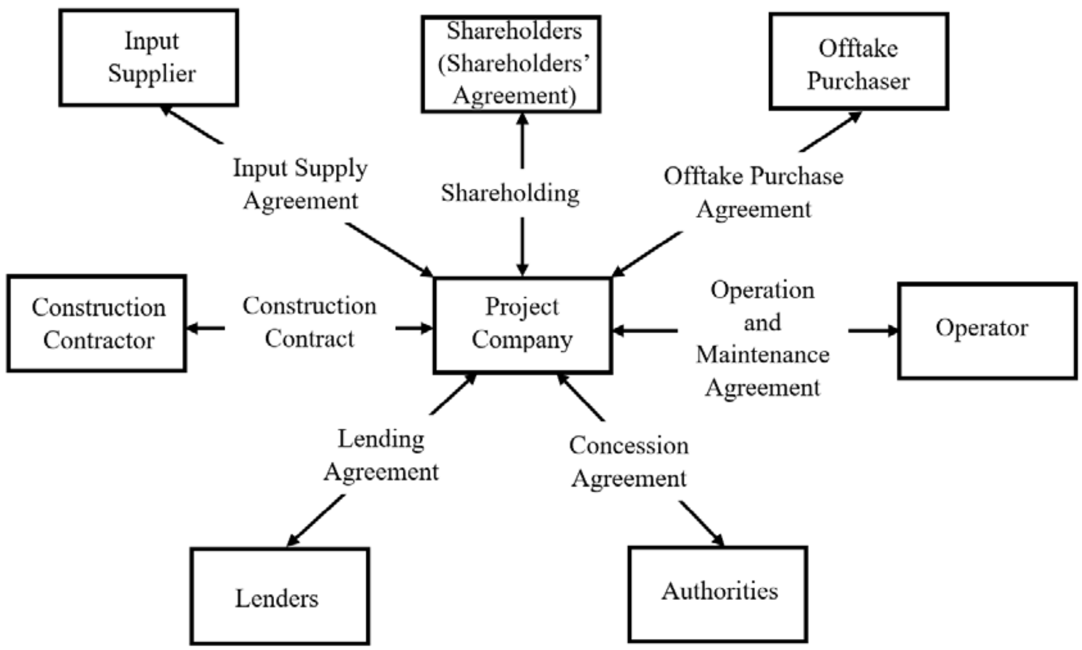

Figure 2-1: Contractual Structural of a Typical BOT Project

It needs to be pointed out that, for current practice, not all the PPP patterns utilized worldwide are the same due to the fact that different countries may have their own preferences for PPP models. Table 2-1 gives eight types of PPP patterns that are authorized by the United Kingdom's government (HM Treasury 2000).

Table 2-1: Eight PPP Models Authorized in the United Kingdom

Model	Definition
Asset Sales	The sale of surplus public party assets
Joint Ventures	The partnerships in order to achieve long-term development in value for both sectors, the public and private parties pool their assets and finance in a joint management way
Partnership Companies	Introducing private party ownership into public-owned business, while at the same time keeping the public interest and policy objectives with the help of rules, regulation, legislation or retention by the government of a special share
Partnership Investments	The partnerships where the public authority makes a contribution to the financing of the investment projects by private sectors, to ensure that the public authority can share the profits generated by the investments
Policy Partnerships	Arrangements in which the private parties or individuals take part in the development and implementation of policy
Private Finance Initiative	The public authority signs long-term contracts with the private sector to purchase quality services, with defined conditions, including the risks, maintaining or constructing the necessary facility; the term also contains financially free-standing projects in which the private sector designs, finances, constructs and operates an asset
Sales of Business	The flotation or trade sale of shares in state-owned business, with the sale of a minority or majority stake
Wider Markets	Introducing the skills, technology, finance and advantage of the private party to help the public authority make better use of their assets both physically and intellectually

2.3 Project Finance

Project finance refers to the development of a stand-alone financing structure, where the debts are financed on a limited recourse or nonrecourse basis, which is restricted only to the cash flows or assets of the project itself (Asenova and Beck 2003). The debts are raised to cover the capital needs of the project and will be repaid based on revenues generated from the project. Project finance provides a practical engineering financial technique for the private sectors to finance a project outside their balance sheet. There are various financing options that can be used to raise the necessary capital in a PPP project, including equity, debt, and mezzanine finance. Equity is permanent capital and contains common stock, retained earnings, and unappropriated profits. Debt is temporary capital and structured in the form of senior debt or subordinate debt. Mezzanine finance is quasi-equity and primarily in the form if debt, but also shares some qualities of equity capitals, which include preferred stock and convertible bonds (Zhang 2005). Senior bank debts and loans have been recognized as the most common form of project financing debt due to the flexible repayment period (e.g., grace period) and floating interest rate (Nevitt and Fabozzi 2002).

The capital cost of a PPP project is the combined proportions of various financial options that finance the project, which is typically raised by public funds (in the forms of grants, subsidies, or right of way), private equity, and publicly and/or commercially issued debts. In most cases, project financings have certain specifications for the ranges of different types of capital present in their structuring, usually as contractual terms coming from the lenders' or public authority's side. One such common specification is that the developers commit their own equity to a certain percentage of the total capital cost, which is deemed to be a demonstration of their commitment to the project's successful implementation (Nevitt and Fabozzi 2002; Pantelias and Zhang 2010). A PPP project can be implemented under a variety of financing scenarios. These scenarios correspond to the contribution and utilization of different capital sources in the project's financial structure, which can be obtained by changing the proportions (magnitude) of the public funds, committed equity, and issued debts/loans. The resulting financial structures directly affect the financial viability of the project since they have a direct impact on the cash flows. For example, the equity cost is usually higher than the debt cost because equity holders normally require a rate of return that is higher than the interest rate of debt. A lower proportion of equity reduces the total cost. However, a lower equity proportion indicates a higher risk to repay the debts. The proportion of the developers' equity is usually 10 percent to 15 percent (sometimes larger than 15 percent) of the total capital, which is required as a guarantee for them to implement the project successfully (Pantelias 2009). The selection of a financing method for a specific project is based on the project's particular requirements, including the risks in the partnership, the amount of the equities that are available, and the perceived quality of the corporation (Asenova and Beck 2003).

It is also noteworthy that the project equity raised in financing the PPP projects is no longer solely from the private companies that are involved in delivering the project, but also from 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 (Pantelias 2009).

2.4 Financial Viability Measurements of PPPs

As previously mentioned, the three parties involved in the PPP projects are public authorities, equity investors, and the lenders. Their interests have to be balanced in order for the project to be successfully implemented and operated. The financial viability of a project can be measured by the accomplishment of specific qualitative and/or quantitative goals or by securing the realization of the financial targets of various stakeholders involved in the project. Since the responsibility and obligation are different among the various stakeholders, the financial viability criteria have different meanings for those stakeholders.

For public authorities, project viability usually corresponds to increasing social welfare from the project's development and achieving the best value for money (VfM) (Pantelias and Zhang 2010; Yescombe 2011). Public authorities privatize the project and develop policies and regulations regarding the procurement of the project. In order to know whether the project will be pursued in the first place, the public authority decision makers usually conduct cost-benefit analysis and/or determine the economic return of the project ahead of the procurement phase. After that, the focus becomes to ensure the best VfM and affordability. Public authorities will perform comparative studies and analyses using various methods, such as public sector comparator (PSC). However, there are many cases where there is no real public sector alternative to compare the PPP project to, resulting in a situation such that the project has to be procured through a PPP, as otherwise it will probably not be procured at all (Grimsey and Lewis 2007; Pantelias and Zhang 2010; Yescombe 2011). According to Zhang, the four main issues that concern the public authorities in a privatized infrastructure project are: timely completion of construction within the budgeted cost; smooth operation and quality performance in the operation period; public affordability to the service and products of the project; and low total project life-cycle cost. Successfully addressing these issues requires a suitable capital structure and the long-term commitment of project participants (Zhang 2005). In addition, public authorities offer a certain amount of public funds (in the forms of grants, subsidy, or right of way) to attract private sectors to bid. As a result, the goal of the public authority is to achieve the best VfM while using the minimum amount of public funds by making sure that the capital structure is rational and cost-effective, and by encouraging and sustaining effective competition during the bidding phase.

For the private sectors (equity investors), the main interest always lays on the profitability of the project and particularly on the profit left after the debt obligations have been fulfilled. Various financial viability criteria can be used by the equity investors, such as the Net Present Value (NPV), the Internal Rate of Return (IRR), the Benefit-cost ratio (Profitability Index), and Return on Equity (RoE). Among these criteria, NPV and IRR are the most popular and widely accepted criteria used to measure the profitability of capital investments, with the profitability index applied in a secondary level of analysis (Keown *et al.*, 2005). NPV is the difference between the present value of the expected cash inflows and the cash outflows, which compares the value of a dollar today to the value of that same dollar in the future, taking inflation and returns into account. IRR gives the profitability of an investment when NPV equals zero. NPV solves for the present value of a stream of cash flows, given a discount rate, while IRR solves for a rate of return when setting the NPV equal to zero. Thus NPV and IRR are related and will move together. For each specific PPP project, the equity investors will set their targeted NPV and/or IRR values. As long as the targeted financial (e.g. NPV and/or IRR) values are reached, the equity investors should be satisfied with their investments.

For lenders, the financial viability of a project is synonymous with the repayment ability of the issued debt and therefore depends on the relationship between the project's costs and revenues during its life-cycle. Cover Ratios (CRs) are the criteria that measures the project's ability to repay the debts as they fall due. Annual Debt-Service Cover Ratio (ADSCR) and Loan-Life Cover Ratio (LLCR) are two of the most commonly used CRs.

The ADSCR is an annual-based criterion that assesses the ability of the project company to service the debt from its annual cash flows. The LLCR is a measure for the initial assessment of the project company's ability to service the debt over its whole term. Lenders may not be willing to finance a project that seems unbankable. A bankable project should satisfy a minimum level of ADSCR and/or LLCR set by the lenders. In practice, the ADSCR is more useful as a measure than LLCR, as it measures the ability of the project company to service debt as it falls due (Yescombe 2011). Based on the perceived "riskiness" of the project, the minimum acceptable CRs are determined by the lenders and have to be fulfilled at all times for the project to be ultimately financed. Furthermore, these CRs determine the actual leverage of the project and also, to a great extent, the realization of the equity investors' returns.

The equations to calculate NPV, IRR, and ADSCR have been well documented and are presented in Equations 2.1 to 2.4, respectively (PPIAF 2017 (b)).

$$NPV = \sum_{i=i_0}^{i_0+N} \frac{TCF_{i-i_0}}{(1+r)^{i-i_0}} \tag{2.1}$$

Where:

TCF_{i-i_0} : the total cash flow for year $i-i_0$;

r : the appropriate discount rate;

i_0 : the project base year;

N : the end year of the concession.

In addition, the total cash flow (TCF) can be calculated as:

$$\begin{aligned} TCF &= Total\ Revenues - Total\ Costs \\ &= Operating\ Revenues + Other\ Revenues - Construction\ Cost - Operation\ Cost \\ &\quad - Maintenance\ Cost - Rehabilitation\ Cost - Repay\ Debts - Other\ Costs \end{aligned} \tag{2.2}$$

For the IRR,

$$\sum_{i=i_0}^{i_0+N} \frac{TCF_{i-i_0}}{(1+IRR)^{i-i_0}} = 0 \tag{2.3}$$

Where:

TCF_{i-i_0} : the total cash flow for year $i-i_0$;

i_0 : the project base year;

N : the end year of the concession.

In terms of *ADSCR*, the expression of the *ADSCR* for year $i-i_0$ is:

$$ADSCR_{i-i_0} = \frac{TCF_{i-i_0}}{\sum_{j=1}^{J}(Principal\ Repayment + Interest\ Payment)_j^{i-i_0}} \tag{2.4}$$

Where:
j : the jth debt service;
J : total debt services.

2.5 Risks Associated with PPP Projects

In practice, risks exist in different phases during a project's life cycle. Compared to traditional publicly financed projects, the risk allocation between the government and the private sector provider is much more complex in a PPP project. Both parties should clearly understand the various risks involved and agree to an allocation of risks between each other. According to Edwards and Bowen, the notion of risk is a human construct that refers to the probability of the occurrence of a particular adverse event during a stated period of time together with the quantification of its consequences (Edwards and Bowen 2003). The risks can be categorized into different types based on the source of origin and occurrence of time during different phases of a project. Traditional classification divides risks into external and internal on the basis of the origin of the risk factors. Internal risks come within the project and are impacted by the decision of the project, such as construction risk and maintenance risk. External risks come from outside of the project and usually are hard to control, such as the sudden change of the economic situation and political issues (Songer *et al.* 1997). The United Nations Industrial Development Organization (UNIDO) distinguishes the risks into General/Country risks and Specific Project risks. General/Country risks contain political, commercial, and legal risks; Specific Project risks include developmental, construction (completion), and operating risks (Jeon and Amekudzi 2007; Kalidindi and Thomas 2008).

Another widely used risk classification method, life cycle risk classification, is based on the project phases that the risks belong to. These risks fall into four different categories: development, construction, operation, and ongoing (Songer *et al.* 1997). A more generally accepted classification approach categorizes the risks in PPP projects into nine categories (The Constructor 2017):

- Design risks. Design risk is an inherent risk that relates to the defect in the design parameters of the infrastructure facility or the design requirements in the contract designated for the project. Generally speaking, it is the design contractor who should be responsible for this risk.
- Construction risks. Construction risk is a combination of several individual risks that occur during the construction period of the PPP project and have a negative impact on the construction of a project within the scheduled time frame, the standards specified for the facility, and the budget projected. These individual risks include land expropriation, cost and time overruns, defect

quality, contractor default, cost and scope of identified but unspecified variations and work, increased financing costs, default by the Concession Company, force majeure event, and environmental damage.

- Operation risks. Operation risks are the risks encountered during the operation and maintenance phase of the project, and the Concession Company should be responsible for them. Some of the operation risks to the Concession Company include performance risk, operation cost overrun, operating contractor default, force majeure, environmental damage, and any defaults from a third party.
- Market and revenue risks. Market and revenue risks are the uncertainties that are related to the revenue generated by the PPP infrastructure. The causes of this risk are grouped into three main categories: insufficient income from fares or tolls, insufficient income from other operations, and insufficient traffic (especially for traffic-generated revenue projects, such as toll roads).
- Political risks. Political risks refer to the risks that the PPP project execution may be affected by the regulations of the contracting public authorities, another agency of the government, and/or the legislature of the hosting country, including changes in law, adverse government action or inaction, increases in taxes, nationalization of project, development approvals, political force majeure (including changes in government), unexpected concession termination by the government (unplanned competition), and payment failure by government.
- Financial risks. Financial risks come from two categories: exchange rate risk and interest rate risk. Exchange rate risk is connected with the probability of potential changes in foreign currency exchange rates which can directly change the cash flow of the project. Interest rate risk relates to the possible changes in the interest rates, which is significant for a PPP project since large proportions of capital are raised through debts and/or loans for long-term duration.
- Environmental risks. Environmental risks relate to the occurrence of environmental incidents during the completion of the project, which are within the control of the construction, operation, and maintenance entities.
- Legal risks. Legal risk arises from failure to comply with regulatory or statutory obligations, including ownership of assets, title/lease of property, financial failure or insolvency of Concession Company, corporate and security structure, breach of financing documents, and enforceability of security.
- Force majeure risks. Force majeure risks are the events that are out of control of any parties and thus cannot be prevented. These risks generally have no connections with the PPP project. However, practitioners cannot ignore this, especially for those markets in unstable political environments. Force majeure events include natural force majeure events, direct political force majeure events, and indirect political force majeure events.

Furthermore, risks can also be classified as systematic/non-systematic and specific/non-specific, as well as government-, sponsor-, lender-, contractor-, and user-related (Asenova and Beck 2003; Xenidis and Angelides 2005). Within the current industry practice, risk classification is usually more project-related and involves a combination of the above methods. Generally speaking, Greenfield projects present higher risks than brownfield projects due to greater uncertainties surrounding traffic forecasts, permitting, and construction.

2.6 Optimal Capital Structure of PPP Projects

A series of literature has been developed to study the optimal financial structure of a project. Researchers proposed models to examine the relationship of debt capacity and optimal capital structure in the context of the Sharp-Lintner-Mossin Capital Asset Pricing Model (Kim 1978; Dias and Ioannou 1995). Bakatjan *et al*. presented a simplified linear programming model to determine the optimum financing structure so that the return of the project is maximized on the equity holder's side (Bakatjan *et al*. 2003). Zhang established a methodology for capital structure optimization and financial viability analysis using simulation and financial engineering techniques (Zhang 2005). Yun *et al*. came up with an optimized capital structure model for both creditors and operators with the use of Monte Carlo simulation and a multi-objective generic algorithm (Yun *et al*. 2009). Sharma *et al*. suggested a structured approach to determining optimal equity structure in PPP projects using linear programming and probability programming models (Sharma *et al*. 2010). Moszoro presented a model to assess the efficiency of the capital structure in PPPs and showed how different knowledge transfer schemes determine an optimal shareholding structure (Moszoro 2010). Svědík and Tetřevová characterized the process of PPP project financial structure optimization within project financing, and assessed the possibility of utilization of mezzanine capital as a source of PPP project financing (Svědík and Tetřevová 2012). Iyer and Sagheer yielded a set of optimal financial solutions for the key decision variables using a genetic algorithm based model (Iyer and Sagheer 2011). Donkor and Duffey developed a stochastic financial model that uses simulation optimization to select an optimal mix of fixed-rate debt options from different sources, with the objective of maximizing net present value (NPV) while limiting default risk (Donkor and Duffey 2013). Chen *et al*. emphasized the importance of optimal financing mix and introduced a model to determine the optimal debt ratio for financing PPP projects. They found the relationship between debt ratio and hurdle rates of projects' financial indices (Chen *et al*. 2015).

Although these efforts significantly advanced the ability to optimize the capital structure in PPP projects, the inherent limitation is that most of the approaches presented are from the perspective of profitability and debts repayment ability. The amount of available public funds are usually fully employed. There are few studies on optimizing the financial structure on the public authority's side. However, in practice, the financial structure has to be adjusted to make sure that the interest of the public authority is taken into consideration. Iyer and Sagheer revealed that in BOT road projects of the National Highways Authority of India, the grant sought from the government is the only bid variable that determines the selection of a concessionaire. A lower quoted grant amount increases the probability of winning the concession (Iyer and Sagheer 2011). The Federal Highway Administration (FHWA) also lists lowest public subsidy as one of the project selection options (FHWA, 2017). Therefore, a systematic model for optimizing the bid-winning potential and capital structure is needed. The corresponding paper is attached in Appendix A.

2.7 Investment Risk Assessment of PPP Projects

Investment risk is a financial-type risk, which is defined as the probability of failure to secure a required infrastructure-generated revenue used for servicing debt (as a minimum requirement) and/or failure to obtain an adequate return on the investment (Kakimoto and Seneviratne 2000). Failure to meet either of the two aforementioned goals can be deemed as financial project failure. The investment risk directly depends on the infrastructure-generated costs and revenues, and is a key factor in determining the overall financial viability of a PPP project based on the expected operation characteristics and the proposed financing scenarios. Assessing the investment risk correctly and precisely to ensure the successful procurement of PPP projects is critically important.

Various studies have been carried out to develop methodologies to assess and quantify the investment risk associated with a PPP project. Several researchers used real option models to valuate infrastructure investments and PPP projects (Vandoros and Pantouvakis 2006; Blank *et al*. 2009; Lee 2011; Vajdić and Damnjanović 2011; Rakić and Rađenović 2014). Ye and Tiong proposed an NPV-at–risk method by combining the weighted average cost of capital and dual risk-return methods (Ye and Tiong 2000). Mohamed and McCowan came up with a methodology using interval mathematics and possibility theory to model the effects of both monetary and non-monetary aspects of an investment option (Mohamed and McCowan 2001). Jafarizadeh and Khorshid-Doust suggested the framework of mean-semideviation behaviour, which has the advantage in the collective assessment of the firm's risk by all market participants (Jafarizadeh and Khorshid-Doust 2008). Pantelias and Zhang evaluated the financial viability of revenue-generating transportation infrastructure projects using the method of moments (Pantelias and Zhang 2010). There are also some toolkits developed by the Public Private Infrastructure Advisory Facility (PPIAF) and the World Bank, which are available online to analyze the viability of a project (PPIAF 2016).

However, most of these methodologies are deterministic, which return a closed form solution indicating the viability of the project, and are not able to assess the potential investment risks. Risk assessment provides a way to estimate the probability that a project will meet its budget and time goals, allowing "what-if" scenarios to be studied. Traditional risk assessment uses deterministic risk analysis, which is based on single point estimation and provides discrete outcomes, but no information on the likelihood of the outcome. Stochastic risk analysis integrates the range of possible values for each of the variables in analysis and provides the outcomes, as well as their likelihood, based on various combinations of different input data with different values, which can reflect the impacts of risks on the outcome more intuitively. This report formulates a flexible framework to perform stochastic risk analysis to assess investment risk using the Monte Carlo Simulation technique. The corresponding paper can be found in Appendix B.

2.8 Pavement Optimal Preventive Maintenance Interval

Over the past decades, the traffic volumes on primary highway systems have experienced tremendous increases, leading in many instances to premature failures of the highway pavements. In addition, the aging of the existing highway systems, especially those built during the 1950s and 1960s, has resulted in the expenditure of a large portion of highway funds on pavement maintenance and rehabilitation. Practically, transportation agencies understand that a pavement should not be allowed to deteriorate to the point at which rehabilitation is necessary. It is more worthwhile to perform preventive maintenance (PM) or a combination of PM and rehabilitation to keep the pavement condition above an acceptance level. Compared with rehabilitation, PM provides a relatively cost-effective alternative for pavement preservation without increasing structural capacity. Therefore, more and more transportation agencies are adopting PM treatments, especially when faced with increasing road-user expectations, higher traffic loading, aging infrastructure, and limited maintenance funding.

There are different types of pavement PM techniques (e.g., seal coat, slurry seal, fog seal, etc.), and it is important to select an appropriate technique based on project-specific information. Just as important as the selection of techniques is the selection of a PM interval. Numerous research has focused on PM along with its interval (Mamlouk and Zaniewski 1998; Hicks *et al.* 1999; Johnson 2000; Peshkin *et al.* 2004). More recently, Lamptey *et al*. (2008) suggested that optimization could be a valid tool to help make decisions on highway PM scheduling. They presented a case study for optimizing decisions on the best combination of PM treatments and timings to be applied in the resurfacing life-cycle for a given highway pavement section (Lamptey *et al*. 2008). Guan *et al.* (2008) and Li *et al.* (2010) introduced methodologies for PM treatment selection and the optimal timing based on matter element analysis (Guan *et al*. 2008; Li *et al*. 2010). Weiguo (2010) proposed a methodology of net annual value difference to assess the contribution value of PM to roadway life-cycle costs and benefits (Weiguo 2010). Haider and Dwaikat (2011) developed the Area 2_T Model to estimate the optimal timing of different maintenance treatments (Haider and Dwaikat 2011). Harvey *et al.* (2012) investigated a probabilistic approach to addressing the influence of PM. The results revealed that, compared with rehabilitation alone, PM reduced long-term cost of pavement maintenance (Harvey *et al.* 2012).

One of the challenges for determining the optimal PM interval is how to appropriately deal with various assumptions and uncertainties, such as assumptions made to simplify the behavior of pavement characteristics and uncertainties associated with material properties. Due to these uncertainties, it is difficult to predict the performance of a pavement with absolute certainty. Researchers have explored different methodologies to solve this problem, such as Monte Carlo Simulation (MCS), Taylor Expansions, and Markov Chain. Among these methods, MCS has been widely utilized in different research areas because of its accuracy and practicability. Mills *et al*. (2011) applied a hierarchical

Markov-chain MCS to model the propagation of transverse cracks and predict the spread of the transverse cracks without neglecting uncertainties (Mills *et al*. 2011). Dilip and Babu (2012) studied the pavement design reliability and back analysis by using the Markov-chain MCS (Dilip and Babu 2012). Other probabilistic models, such as First-Order Reliability Method and Second-Order Reliability Method, are also commonly applied (Melchers 1999; Ang and Tang 2007; Deshpande et al. 2009).

Based on the literature review, there are few studies on determining optimal PM interval through reliability-based approach. This report provides a reliability-based comprehensive framework to apply the fourth order of method of moments to optimize PM interval for highway pavements. The detailed methodology and findings can be obtained from the paper exhibited in Appendix C.

2.9 Summary

In this chapter, a comprehensive literature review is presented, from basic concepts to current research status related to PPP mechanism, which forms the foundation of this research. Features of PPPs, classification of PPPs, project finance, financial viability measurements of PPPs, risks associated with PPPs are discussed. In addition, research and studies on optimal financial structure, investment risk assessment, and the determination of optimal PM cycle interval are reviewed and summarized. Chapter 3 introduces the discussions on the methodologies adopted by this report.

3. SUMMARY OF ADOPTED METHODOLOGIES AND TECHNIQUES

Based on the literature review in Chapter 2, this chapter introduces the methodologies and techniques adopted by this research to fill in the gaps of current research, namely the Genetic Algorithm, Monte Carlo Simulation, and the Method of Moments.

3.1 Genetic Algorithm (GA)

Genetic algorithms (GAs) were first introduced by Holland in the early 1970s as an optimization approach, which followed Darwin's classical rules about natural evolution and used random steps to converge to a nonrandom optimal solution (Holland, 1975). GAs are commonly used to generate high-quality solutions to optimization and search problems by relying on bio-inspired operators such as mutation, crossover, and selection (Mitchell, 1998). GAs perform searches in complex, large, and multimodal landscapes, and provide near-optimal solutions for the objective or fitness function of an optimization problem. Although there is no absolute guarantee that they will find the global optimum, GAs are especially beneficial when the search space is complex with many local minima (or maxima) so that conventional techniques fail to find the global minimum (or maximum) and a full search is not feasible (Wehrens *et al*., 1999). GAs have been widely applied in various fields, such as online optimization (Coffey, 2008), green building design optimization (Wang et al., 2005), control engineering (Li *et al*., 1996; Patrascu, 2015), mechanical engineering (Nelson, 1997; Gen and Cheng, 2000), real options valuation (Zhang and Babovic, 2011), etc. These studies, as well as others, have proven that GAs are very efficient approaches even with non-differentiable and non-linear functions and have shown significant improvements in the optimization results.

The general steps involved in GAs are presented in Figure 3-1 (John and Krishnakumar 2017).

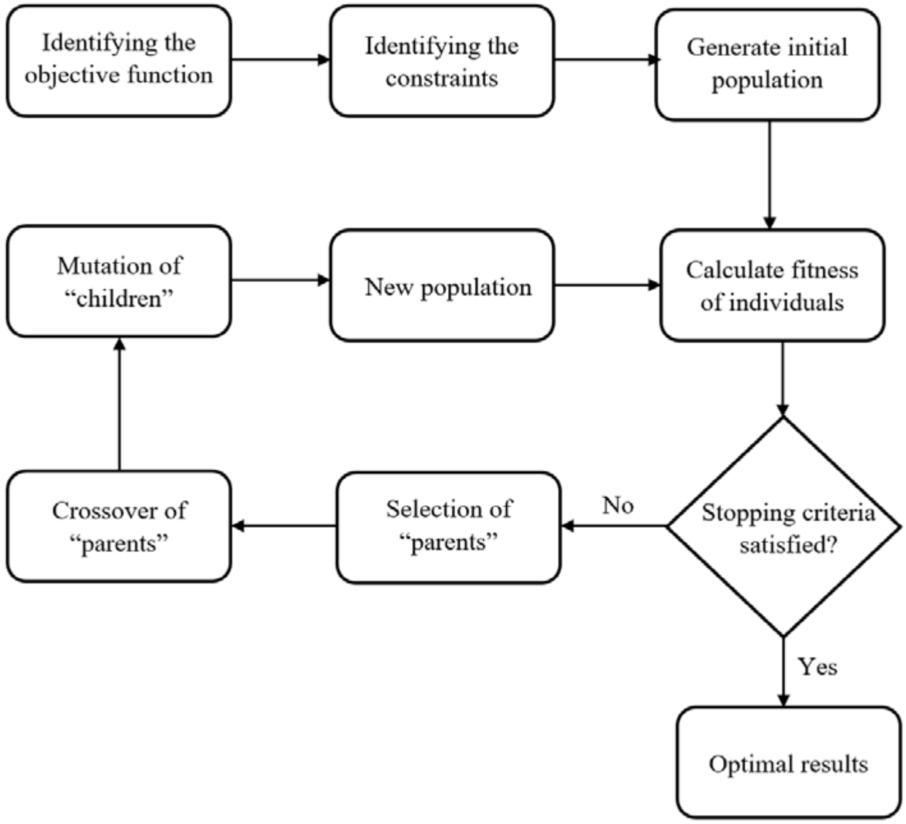

Figure 3-1: General Steps Involved in Genetic Algorithms

A comprehensive genetic algorithm based methodological framework is proposed in this report to optimize the capital structure of PPP projects. The developed model is a departure from the conventional financial analysis models as it minimizes the amount of public funds utilized while thoroughly considering the interests, concerns, and requirements of different participants. The detailed information about the model formulation (e.g., revenue model and cost model), the real-world case study as well as the sensitivity analysis, and the findings can be obtained from the paper attached in Appendix A.

3.2 Monte Carlo Simulation (MCS)

Monte Carlo Simulation (MCS) is a widely applied computational algorithm which is based on a repeated random sampling process to calculate numerical results. This method uses parameters which can reflect the probability density function of variables as inputs, and the repetitive calculations take the randomly selected combinations of the inputs into consideration. The outputs of the simulation are the results, which are presented in a cumulative density function or probability density function. Certain weaknesses exist within this technique: for instance, it can be time consuming if there are too many input variables and a large number of sampling is generated. Large variance may also be produced by the simulation.

In order to run MCS to conduct stochastic risk analysis, practitioners need to identify the input variables and their associated distributions, which usually can be obtained from historical data or based on empirical assumptions. Using the variables and associated distributions as the inputs, a sampling process is usually employed to simulate the distributions of output variables with a pre-specified number of iterations. Risks are assessed by comparing the output distributions with the targeted values of each output variable, e.g., the proportion of the output distribution that is less than the targeted value. MCS has been utilized in different areas to conduct stochastic risk analysis. Ridlehoover applied MCS and risk analysis to help solve facility location problem (Ridlehoover 2004). MCS has also been applied by rating agencies (e.g., Standard & Poor's and Moody's) to evaluate investment and credit risks at the country and industrial levels (Fender and Kiff 2004). Carrasco and Chang employed MCS and risk assessment for ammonia concentrations in wastewater effluent disposal (Carrasco and Chang 2005). Au *et al*. utilized advanced MCS in conducting compartment fire risk analysis (Au *et al*. 2007). Da Silva Pereira *et al*. presented a methodology based on MCS to estimate the behavior of economic parameters in power generation (Da Silva Pereira *et al*. 2014). Arnold and Yildiz conducted economic risk analysis of decentralized renewable energy infrastructure using MCS (Arnold and Yildiz 2015).

Although MCS has been widely employed in the evaluation of infrastructure projects, there are few literature and studies on assessing the investment risk of specific PPP highway projects. This report proposes a flexible framework to apply this sophisticated technique to conduct stochastic risk analysis to numerically assess the investment risks associated with the tolled PPP highway projects. NPV, IRR and ADSCR (for both senior bank debt and combined debts) are selected to be the outcomes. The outcome values, as well as their probability distribution, are calculated and analyzed. The comprehensive framework and highlights are exhibited in Appendix B.

3.3 3Method of Moments (MOM)

In practice, simulation-based approximation techniques (e.g., MCS) have been applied to accurately calculate very complex integral problems (e.g., multidimensional problems). Other probabilistic models, such as First-Order Reliability Method (FORM) and Second-Order Reliability Method (SORM), are also adopted by various researchers (Melchers 1999; Ang and Tang 2007; Deshpande *et al*. 2009). However, MCS is a computational algorithm that relies on repeated random sampling to determine open-form numerical results. The accuracy depends on the distribution of the variables and the sample size, making it difficult to implement when the true distributions of the variables cannot be determined with information available. On the other hand, FORM is an analytical method based on the linear approximation of a nonlinear limit state at the design point. The primary advantages of FORM are its analytical traceability and satisfactory level of accuracy, even for extremely small probabilities, whereas its shortcomings include its lack of accuracy for highly nonlinear limit state functions and its difficult iteration-based process of searching for the design point (Damnjanovic 2006). FORM shortcomings can be addressed by using SORM and other high orders of moments.

The Method of Moments (MOM), which was originally proposed by Zhao and Ono to analyze the reliability of structural systems, is able to solve these problems. MOM uses central moments to address complex estimations, especially multidimensional integrals (Zhao and Ono 2001). The procedure requires neither the computation of derivatives or mutual correlations among failure modes, nor the determination of the design point (Zhao and Ang 2003). MOM has proven to be a feasible closed-form alternative to analyze the reliability. Madsen *et al.* used the reliability method to evaluate the complex *n*-dimensional probability integral (Madsen *et al.* 2006). Zhang and Damnjanovic applied the MOM to model the reliability of pavement infrastructure. The results showed that the MOM represents a viable approach to estimating the failure probability (Zhang and Damnjanovic 2006). Pantelias and Zhang employed the MOM to evaluate the financial viability of revenue-generating transportation infrastructure projects in terms of investment risk (Pantelias and Zhang 2010). Ma *et al*. employed the MOM to model the reliability of deteriorating performance of asphalt pavement under freeze-thaw cycles in cold regions (Ma *et al*. 2014). As for the accuracy of the method of moments, Zhang and Damnjanovic indicate that the Fourth Order Method of Moments (4M) yields the most accurate predictions of failure probability; in general, the quality of estimation improves as the order of moments increases (Zhang and Damnjanovic 2006).

Compared with other methodologies, MOM has the advantage in that it is an efficient and computationally effective procedure that uses information from high-order moments to determine reliability indices for complex nonlinear limit state functions with many basic random variables. MOM represents a robust and universal approach to estimating reliability functions because it can accommodate different types of failure mechanisms and transfer functions in the limit state function (Zhang and Damnjanovic 2006). Additionally, MOM uses only the mean and coefficient of variation (CV) of the input variables, and no assumptions on variable distributions are needed. This makes MOM beneficial in cases where the variable distributions are unknown and difficult to identify due to defective data, especially for PPP projects where readily available information is limited. MOM is able to offer solutions in closed-form with high accuracy (Rosenblueth 1975). Considering that the estimation accuracy increases as the order of moments becomes higher, this report provides a reliability-based comprehensive framework to apply the fourth-order of moments (4M) to optimize PM interval for highway pavements. The reliability model, MOM formulation, numerical study, sensitivity analysis, as well as the discussion, and conclusions are included in the paper presented in Appendix C.

3.4 Summary

This chapter gives an overall introduction to the three methodologies adopted by this report, namely the Genetic Algorithm, Monte Carlo Simulation, and the Method of Moments. These three methodologies and techniques serve as the root and hardcore mechanisms of this research. The three papers (either currently under review or accepted to be published) attached in Appendix A, Appendix B, and Appendix C were developed based on the Genetic Algorithm, Monte Carlo Simulation, and the Method of Moments, respectively. The major findings and directions for future research are presented in Chapter 4.

4. CONCLUSIONS AND DIRECTIONS FOR FUTURE RESEARCH

This report addresses a sequence of issues related to PPP projects in a logical way, namely the determination of optimal capital structure, investment risk assessment, and the identification of pavement optimal preventive maintenance interval. Three methodological frameworks are proposed to implement this. The major findings from the research as well as the recommendations for future research are presented in the following sections.

4.1 Summary of Research Findings

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

- Different stakeholders involved in a PPP project have different financing goals and financial viability criteria. All of those goals must be satisfied to secure the successful implementation of the PPP project. Public authorities aim to attain the Value for Money, while they should make sure that the infrastructure project is attractive enough for competitive bids from the private sectors. The private sectors are concerned more about the return on their investments, namely the profitability of the project. However, profitability should not be the only goal for the equity investors in practice. They must take the probability of winning the bidding process into consideration when they make any investment decisions. The lenders place more values on the repayment ability of the issued debts.
- Life-cycle analysis is conducted in order to analyze the cash flow of the PPP project. Both revenue model and cost model were built sophisticatedly. Revenue model considers revenues generated by user fee collection from the infrastructures, such as toll roads; while the cost model includes initial capital cost and the maintenance, rehabilitation, and operation cost. Furthermore, the maintenance, rehabilitation, and operation cost contains operational expenditures (OPEX) and capital expenditures (CAPEX). Each of the factors that may have an influence on the revenue and cost of the project needs to be clearly and correctly defined. Risks exist in all phases of the development of PPP projects, which may result in failures of those projects. Different risk classifications categorize the risks into different categories. The potential success of PPP projects has been most commonly undertaken through the assessment of investment risk. This report focuses on the assessment of the investment risk, which directly affects the financial viability of the PPP projects. High investment risk indicates a high probability of not obtaining the financial targets, and further negotiations may need to be made.

- The risks are simulated by treating an input variable as stochastic (e.g., with specific distribution) instead of deterministic. Six major stochastic variables are considered in this report (see Appendix B): the initial construction cost, the initial traffic estimation, 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. In practice, these factors directly impact the cash flow and thus the financial viability of the PPP project.
- Compared with rehabilitation, preventive maintenance (PM) provides a relatively cost-effective alternative for pavement preservation without increasing structural capacity. Just as important as the selection of preventive maintenance techniques is the selection of a preventive maintenance interval. The concept of cost per unit time (CPUT) is introduced (see Appendix C). The optimal preventive interval corresponds with the point which minimizes the total CPUT cost.
- Stress-strength model from reliability theory is applied to calculate the reliability of the pavement (see Appendix C). In the area of pavement engineering, "stress" can be regarded as the accumulated number of Equivalent Single Axle Loads (ESALs), and "strength" can be deemed as the structural capacity of the pavement. In this report, uncertainties associated with seven input variables are considered: structure number, reduction of serviceability index, subgrade resilient modulus from strength function, initial average daily traffic, percentage of trucks, truck factor, and traffic growth rate from stress function. A relatively new analytical approximation method, the Method of Moments, is applied to calculate the reliability function, as it provides a clear improvement over the existing practices.
- The report first proposes a genetic algorithm based optimization framework to optimize the capital structure of a PPP project (see Appendix A). The objective of this methodology is to find the minimum amount of public funds that is needed while satisfying all the financial requirements from the private sectors and lenders. NPV and IRR are selected as the financial criteria for the equity investors, and ADSCR is selected as the measurement for the lenders. Their financial needs serve as constraints in this framework. In this report, the methodological framework is customized for a specific real-world PPP toll road project Texas State Highway 130, where detailed revenue and cost information is provided. Through the calculation of the base case scenario and by undertaking a number of carefully selected sensitivity analyses (impact of maximum committed private equity and minimum ADSCR from senior bank on the optimal capital structure), it was shown that all project stakeholders can actually use this methodology to develop insights. This framework helps various stakeholders in different ways: the lenders ensure the repayment ability

of the project; the private sectors benefit from the methodology with increased potential bid-winning probability and achievement of financial goals; and public authorities use the minimum amount of funds to deliver infrastructure services and to attain the value for money. The saved funds can be invested into other social welfare facilities.

- This report then formulates a flexible framework to perform stochastic risk analysis to assess investment risk using Monte Carlo Simulation technique (see Appendix B). Instead of a deterministic value, the distributions of the variables are used as inputs to simulate the risks. NPV, IRR, and ADSCR are selected criteria for the investors and lenders to evaluate the project's financial viability and ability to repay the debts. A detailed case study of a section (P12) from the Trans-Texas Corridor (TTC-35) was conducted. The results are interpreted so that quantitative information was provided to agencies to establish investment decision criteria. The proposed framework works in conjunction with other models, such as cost and revenue prediction models. The procedures are flexible for practitioners to adopt. The coefficient of variation and distribution of an input variable are not limited to a specific value or form. Instead, practitioners can customize input variables associated with their coefficient of variation and distribution based on available data or professional judgement in practice. Multiple simulations can be run with different coefficients of variation and distribution to assess different levels of risks, allowing "what-if" scenarios to be studied.
- This report finally provides a reliability-based comprehensive framework to optimize PM interval for highway pavements (see Appendix C). Closed-form solutions are obtained by evaluating the time-dependent multidimensional probability integral using the Fourth Order Method of Moments (4M). In addition to the existing basic random variables describing the mathematical relation to the failure event, the formulation of the limit state can be extended to allow for the explicit consideration of epistemic uncertainty. The feasibility and applicability of the proposed methodology is illustrated by a numerical case study where the CPUT values are calculated and the optimal PM interval is determined. The sensitive analysis shows the impact of PM and rehabilitation costs on the optimal PM interval, providing insightful information to the maintenance agencies in terms of making the most-cost-effective PM treatment decisions.

Overall, the three methodologies proposed in this report can be used by all stakeholders and decision makers to support the hard decisions and negotiations toward financial closure and ultimate project implementation. Although the applicability and feasibility are illustrated through highway projects, the proposed methodologies can be applied to other general infrastructure projects (e.g., stadiums or bridges) as long as the input variables are well defined.

4.2 Directions for Future Research

This report improves the available knowledge regarding a series of issues related to PPP projects, including the optimal capital structure, investment risk assessment, and the scheduling of pavement preventive maintenance. These efforts will support the successful implementation of the PPP projects in a more cost-effective way. As with every similar effort, the overall results of this research are subject to the validity of mentioned assumptions and the remaining inevitable 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 research was not intended to solve all problems related to the PPP projects. In that perspective, there are a few directions on which future research in this area can embark on and ameliorate the presented frameworks and corresponding results. Some of these directions are presented as follows:

1. The consideration of performing stochastic risk analysis of the methodology proposed in Appendix A. Under the current approach, the cost and revenue variables used in the GA based framework are deterministic, which are obtained from the real-world project. However, due to the nature of risks in construction and operational phases, the uncertainties that impact the cost and revenue may need to be considered in future research since they directly affect the cash flow. The process would require a significant effort in programming techniques to embed the stochastic analysis into the existing optimization framework.
2. The development of more accurate revenue models, including traffic prediction model, willingness to pay model, and toll elasticity model. In this report, the revenue analysis still applies the traditional way, where the initial annual traffic, the growth rate, and the initial toll rate are estimated based on existing and historical information. A more sophisticated model in predicting or analyzing these inputs (e.g., by running simulation in software like VISSIM) will improve the accuracy of the approach. In addition, a dynamic toll rate model is preferred based on current practice. This process would require additional knowledge in traffic prediction, new price making mechanisms, and proficiency in related software.
3. The investigation of true probability distributions of the explanatory random variables used in the framework presented in Appendix B. This report adopts the distribution of each of the variables from past research in this area, where the probability distributions are demonstrated. However, considering the time and location bias, the actual distributions of these variables need to be identified to further enhance the results. This process would require significant efforts in collecting real data for these variables and fitting possible distributions to them.
4. When determining the optimal PM intervals, different PM techniques performed at different timings have different impact on the salvage value of the pavement. Future work may take the salvage value of the pavement into consideration, which requires sophisticated salvage models.

5. Finally, this report proposes three methodological frameworks whose feasibilities and capabilities are demonstrated only through highway projects. Future research could expand the application in two possible directions: 1) apply these models to other transportation infrastructures (e.g., bridges), thus supplementing the existing framework and expanding it to ultimately encompass all possible infrastructures; and 2) employ these frameworks to other revenue-generating infrastructure projects procured as PPPs, such as energy plants or parking lots. This process would require the development and specification of different infrastructure-specific revenue and cost models but could ultimately validate the usefulness and flexibility of the proposed frameworks in assessing the issues related to these projects from the perspective of all stakeholders.

Appendix A

Paper 1: Genetic Algorithm Based Optimization of Capital Structure in Build-Operate-Transfer Toll Highway Infrastructures

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Paper in preparation for *Journal of Infrastructure Systems*

A.1 Abstract

Governments worldwide have increased initiatives in private financing of public infrastructure and services across a wide range of industries and sectors as an effective way to bridge the budget gap. One such scheme that is gaining popularity and acceptance is the build-operate-transfer (BOT) arrangement. The capital structure determination of a privatized infrastructure project is complex and challenging due to long contract duration, non-recourse financing, complex contractual arrangements, and multiple stakeholders with different motives and interests. Improved financial engineering techniques are required to overcome the limitations of traditional financial analysis techniques in addressing this problem. This paper presents a systematic genetic-algorithm-based methodology to optimize the capital structure by minimizing the public funds employed, which aims to reflect the characteristics of project financing and create win-win–win situations for public authorities, equity investors, and lenders. The result yields a set of optimal solutions for the key decision variables: proportions of public funds, committed equity, and debts/loans. A case study with sensitivity analyses based on a real life BOT toll highway project was conducted to illustrate the proposed model. The outputs will significantly facilitate all the stakeholders in evaluating a privatized project's financial viability and collectively determining an optimal capital structure that satisfies their respective interests.

Keywords: Build/Operate/Transfer; Public Private Partnerships; Financial Management; Infrastructure; Genetic Algorithm; Optimization.

A.2 Introduction

With the continuous development of the economy and urbanization, the demand for basic infrastructure services has increased drastically in recent years. According to the 2017 Infrastructure Report Card released by American Society of Civil Engineers (ASCE), the cumulative GPA of U.S. infrastructure is only "D+" (ASCE (a) 2017). It was reported that more than forty percent of America's urban interstates are congested, and traffic delays cost the country $160 billion in wasted time and fuel in 2014. Twenty percent of highway pavements are in poor condition, and the roads have a significant and increasing backlog of rehabilitation needs (ASCE (b) 2017). However, public funds, which usually come from designated funds specifically for infrastructure or general government funds, alone cannot cover all the infrastructure's construction, operation, maintenance, and replacement costs. As a result, the U.S. has been underfunding its highway system for years, resulting in an

$836 billion backlog of highway and bridge capital needs. Several alternatives approaches have been explored to address this budgetary shortage problem. Public private partnerships (PPPs), which introduce private capital utilization and involvement into a project, have emerged as one such innovative funding mechanism. Slowly but steadily, traditional public works financing and procurement methods have given way to PPPs in most countries around the world (Pantelias and Zhang 2010). A combination of scarcity of public funds, the never-ending quest of private investors for new and profitable investment opportunities, and the undisputable need for new capacity and/or improvements in most public infrastructure is fostering this worldwide trend (Grimsey and Lewis 2007).

The National Council for Public-Private Partnerships (NCPPP) defines the PPPs as "a contractual arrangement between a public agency and a private sector entity. Through this agreement, the skills and assets of each sector are shared in delivering a service or facility for the use of the general public. In addition to the sharing of resources, each party shares in the risks and rewards potential in the delivery of the service and/or facility" (NCPPP, 2017). PPP projects are financed through project financing methods rather than traditional public sector financing, which means that bigger contributions of debt financing are utilized instead of equity commitment (Grimsey and Lewis 2007). Different proportions of public funds, private equity, and public and/or commercial debts are raised to cover the project's total initial capital cost. The collaboration between different parties and the satisfaction of their individual goals are key factors to the project's successful development and implementation. In order to make the project attractive enough to private sectors to bid, the public authority usually provides a certain amount of public funds.

The purpose of this paper is to propose and formulate a genetic algorithm (GA) based optimization framework for identifying the optimal financing structure of PPP projects from the perspective of public funds utilized. The proposed model is able to determine different proportions of public funds, private equity, and public and/or commercial debts so that the minimum amount of public funds is employed while synchronizing both profitability and repayment capability. The proposed model will benefit collaborators in two ways: For private sectors, under the premise that the financial targets are reached, fewer public funds usually lead to a higher probability of winning the bidding process. For public authorities, a large amount of public funds can be saved so that they can be invested into other social welfare infrastructures.

The remaining sections of this paper are arranged as follows: First, the basic concepts of PPPs, project financial structure, financial viability criteria, and genetic algorithm are presented. Subsequently, the optimization methodological framework is presented and formulated. Third, the framework is applied and solved through a case study, which involves the development of a toll highway project as a BOT concession. Sensitivity analyses are conducted to investigate the impact of changes in minimum annual debt-service cover ratio and maximum committed equity on optimal capital structure. Finally, the conclusions are summarized and discussed.

A.3 Public-Private Partnerships

As travel demand and the public's high expectations regarding mobility and level of service continue to increase, PPPs are adopted by more and more transportation agencies as an effective way to finance infrastructure projects (Brown 2007; Ortiz *et al*. 2008). Typically, there are three parties involved in a PPP project: the public authority, the private sector (equity investor), and the lender (e.g., banks). These parties work together under a certain project finance structure by undertaking or sharing different tasks. There are different types of PPPs based on different classification criteria. According to how the raised debts are repaid, PPPs can be categorized as Private Finance Initiative (PFI) or Concession contracts. In the PFI model, payments from the public authority are used to cover the debts, while the debts in a concession contract are repaid by user charging (Pantelias 2009; Yescombe 2011). The PPPs can also be regarded as availability-based or usage-based on the basis of the transfer of risks between the private sector and public authority. Furthermore, based on the legal position of the private sector involved in the project, PPPs can be classified as Build-Operate-Transfer (BOT), Build-Transfer (BT), and Joint Ventures (JV) (Grimsey and Lewis 2007; Yescombe 2011). One model that is gaining increased popularity and acceptance is the Design-Build-Finance-Operate-Maintain (DBFOM) model. The DBFOM business model is a form of BOT concession, where the private sector obtains a contract to be responsible for designing, financing, building, operating, maintaining, and collecting user fees for a specific period, following which the ownership of the infrastructure is restored to the public authority. PPPs can involve existing brownfield projects (i.e., the lease of an existing facility), or they can involve proposed new facilities, which are known as greenfield projects. In the case of a brownfield project, a public entity generates a capital inflow or debt payoff by transferring the rights, responsibilities, and revenues attached to an existing asset to a private sector entity for a defined period. For Greenfield projects, a public agency transfers all or part of the responsibility for project development, construction, and operation to a private sector entity.

A.4 Project Financial Structure

Project finance refers to the development of a stand-alone financing structure, where the debts are financed on a limited recourse or nonrecourse basis, which is restricted only to the cash flows or assets of the project itself (Asenova and Beck 2003). The debts are raised to cover the capital needs of the project and will be repaid based on revenues generated from the project. Project finance provides a practical engineering financial technique for the private sectors to finance a project outside their balance sheet. There are various financing options that can be used to raise the necessary capital in a PPP project, including equity, debt, and mezzanine finance. Equity is permanent capital and contains common stock, retained earnings, and unappropriated profits. Debt is temporary capital and structured in the form of senior debt or subordinate debt. Mezzanine finance is quasi-equity and primarily in the form of debt but also shares some qualities of equity capitals, which include preferred stock and convertible bonds (Zhang 2005). Senior bank debts and loans have been recognized as the most common form of project financing debt due to the flexible repayment period (e.g., grace period) and floating interest rate (Nevitt and Fabozzi 2002).

The capital cost of a PPP project is the combined proportions of various financial options that finance the project, which is typically raised by public funds (in the forms of grants, subsidies, or right of way), private equity, and publicly and/or commercially issued debts. In most cases, project financings have certain specifications for the ranges of different types of capital present in their structuring, usually as contractual terms coming from the lenders' or public authority's side. One such common specification is that the developers commit their own equity to a certain percentage of the total capital cost, which is deemed as a demonstration of their commitment to the project's successful implementation (Nevitt and Fabozzi 2002; Pantelias and Zhang 2010). A PPP project can be implemented under a variety of financing scenarios. These scenarios correspond to the contribution and utilization of different capital sources in the project's financial structure, which can be obtained by changing the proportions (magnitude) of the public funds, committed equity, and issued debts/loans. The resulting financial structures directly affect the financial viability of the project since they have a direct impact on the cash flows. For example, the equity cost is usually higher than the debt cost because equity holders normally require a rate of return that is higher than the interest rate of debt. A lower proportion of equity reduces the total cost. However, a lower equity proportion indicates higher risk to repay the debts. According to Pantelias, the proportion of the developers' equity is usually 10 percent to 15 percent (sometimes larger than 15 percent) of the total capital, which is required as a guarantee for them to implement the project successfully (Pantelias 2009). Therefore, how to find an optimal financial structure becomes critically important for the successful procurement of a PPP project.

A series of literature has been developed to study the optimal financial structure of a project. Researchers proposed models to examine the relationship of debt capacity and optimal capital structure in the context of the Sharp-Lintner-Mossin Capital Asset Pricing Model (Kim 1978; Dias and Ioannou 1995). Bakatjan et al. presented a simplified linear programming model to determine the optimum financing structure so that the return of the project is maximized on the equity holder's side (Bakatjan *et al*. 2003). Zhang established a methodology for capital structure optimization and financial viability analysis using simulation and financial engineering techniques (Zhang 2005). Yun et al. came up with an optimized capital structure model for both creditors and operators with the use of Monte Carlo simulation and a multi-objective generic algorithm (Yun *et al*. 2009). Sharma et al. suggested a structured approach to determining optimal equity structure in PPP projects using linear programming and probability programming models (Sharma *et al*. 2010). Moszoro presented a model to assess the efficiency of the capital structure in PPPs and showed how different knowledge transfer schemes determine an optimal shareholding structure (Moszoro 2010). Svědík and Tetřevová characterized the process of PPP project financial structure optimization within project financing, and assessed the possibility of utilization of mezzanine capital as a source of PPP project financing (Svědík and Tetřevová 2012). Iyer and Sagheer yielded a set of optimal financial solutions for the key decision variables using a genetic algorithm based model (Iyer and Sagheer 2011). Donkor and Duffey developed a stochastic financial model that uses simulation optimization to select an optimal mix of fixed-rate debt options from different sources, with the objective of maximizing net present value (NPV) while limiting default risk (Donkor and Duffey 2013). Chen et al. emphasized the importance of an optimal financing mix and introduced a model to determine the optimal debt ratio for financing PPP projects. They found the relationship between debt ratio and the hurdle rates of projects' financial indices (Chen *et al*. 2015).

Although these efforts significantly advanced the ability to optimize the capital structure in PPP projects, the inherent limitation is that most of the approaches presented are from the perspective of profitability and debts repayment ability. The amount of available public funds are usually fully employed. There are few studies on optimizing the financial structure on the public authority's side. However, in practice, the financial structure has to be adjusted to make sure that the interest of the public authority is taken into consideration. Iyer and Sagheer revealed that in BOT road projects of the National Highways Authority of India, the grant sought from the government is the only bid variable that determines the selection of a concessionaire. A lower quoted grant amount increases the probability of winning the concession (Iyer and Sagheer 2011). The Federal Highway Administration (FHWA) also lists the lowest public subsidy as one of the project selection options (FHWA 2017). Therefore, a systematic model for optimizing the bid-winning potential and capital structure is needed.

A.5 Financial Viability Criteria

As previously mentioned, the three parties involved in the PPP projects are public authorities, equity investors, and the lenders. Their interests have to be balanced in order for the project to be successfully implemented and operated. The financial viability criteria have different meanings for different stakeholders.

For public authorities, project viability usually corresponds to increasing social welfare from the project's development and achieving the best value for money (VfM) (Pantelias and Zhang 2010; Yescombe 2011). Public authorities privatize the project and develop policies and regulations regarding the procurement of the project. In order to know whether the project should be pursued in the first place, the public authority decision makers usually conduct cost-benefit analysis and/or determine the economic return of the project ahead of the procurement phase. After that, the focus becomes ensuring the best VfM and affordability. Public authorities will perform comparative studies and analyses using various methods, such as public sector comparator (PSC). However, there are many cases where there is no real public sector alternative to compare the PPP project to, resulting in a situation where the project has to be procured through a PPP; otherwise it will probably not be procured at all (Grimsey and Lewis 2007; Pantelias and Zhang 2010; Yescombe 2011). According to Zhang, the four main concerns for the public authorities in a privatized infrastructure project are: timely completion of construction within the budgeted cost; smooth operation and quality performance in the operation period; public affordability of the service and products of the project; and low total project life-cycle cost. Successfully addressing these issues requires a suitable capital structure and the long-term commitment of project participants (Zhang 2005). In addition, public authorities offer a certain amount of public funds (in the forms of grants, subsidy, or right of way) to attract private sectors to bid. As a result, the goal of the public authority is to achieve the best VfM while using the minimum amount of public funds by making sure that the capital structure is rational and cost-effective, and by encouraging and sustaining effective competition during the bidding phase.

For private sectors (equity investors), the main interest always lays on the profitability of the project, in particular the profit left after the debt obligations have been fulfilled. Various financial viability criteria can be used by the equity investors, such as the Net Present Value (NPV), the Internal Rate of Return (IRR), the Benefit-cost ratio (Profitability Index), and Return on Equity (RoE). Among these criteria, NPV and IRR are the most popular and widely accepted criteria used to measure the profitability of capital investments, with the profitability index applied in a secondary level of analysis (Keown *et al*. 2005). NPV solves for the present value of a stream of cash flows, given a discount rate, while IRR solves for a rate of return when setting the NPV equal to zero. Thus NPV and IRR are related and will move together. For each specific PPP project, the equity investors will set their targeted NPV and/or IRR values. As long as the targeted financial (e.g., NPV and/or IRR) values are reached, the equity investors should be satisfied with their investments.

For lenders, the financial viability of a project is synonymous with the repayment ability of the issued debt and therefore depends on the relationship between the project's costs and revenues during its life-cycle. Cover Ratios (CRs) are the criteria that measure the project's ability to repay the debts as they fall due. Annual Debt-Service Cover Ratio (ADSCR) and Loan-Life Cover Ratio (LLCR) are two of the most commonly used CRs. The ADSCR is an annual-based criterion that assesses the ability of the project company to service the debt from its annual cash flows. The LLCR is a measure for the initial assessment of the project company's ability to service the debt over its whole term. Lenders may not be willing to finance a project that seems unbankable. A bankable project should satisfy a minimum level of ADSCR and/or LLCR set by the lenders. In practice, the ADSCR is more useful as a measure than LLCR, as it measures the ability of the project company to service debt as it falls due (Yescombe 2011). Based on the perceived "riskiness" of the project, the minimum acceptable CRs are determined by the lenders and have to be fulfilled at all times for the project to be ultimately financed. Generally, the ADSCR should be at least equal to or larger than 1.0 to be acceptable. A project is bankable when ADSCR is in the range of 1.10–1.25, satisfactory, and comfortable when ADSCR is between 1.30 and 1.50, and above 1.50 is preferable (Zhang 2005). Furthermore, these CRs determine the actual leverage of the project and also, to a great extent, the realization of the equity investors' returns.

In this paper, NPV and IRR are selected as the financial criteria for the equity investors, and ADSCRs (for both single issued debt/loan and the combined debts) are selected for the lenders.

A.6 Genetic Algorithm

Genetic algorithms (GAs) were first introduced by Holland in the early 1970s as an optimization approach, which followed Darwin's classical rules about natural evolution and used random steps to converge to a nonrandom optimal solution (Holland 1975). GAs are commonly used to generate high-quality solutions to optimization and search problems by relying on bio-inspired operators such as mutation, crossover, and selection (Mitchell 1998). GAs perform searches in complex, large, and multimodal landscapes, and provide near-optimal solutions for the objective or fitness function of an optimization problem. Although there is no absolute guarantee that they will find the global optimum, GAs are especially beneficial when the search space is complex with many local minima (or maxima) so that conventional techniques fail to find the global minimum (or maximum) and a full search is not feasible (Wehrens *et al*. 1999). GAs have been widely applied in various fields, such as online optimization (Coffey 2008), green building design optimization (Wang *et al*. 2005), control engineering (Li *et al*. 1996; Patrascu, 2015), mechanical engineering (Nelson 1997; Gen and Cheng 2000), real options valuation (Zhang and Babovic 2011), etc. These studies, as well as others, have proven that GAs are a very efficient approach even with non-differentiable and non-linear functions and have shown significant improvements in the optimization results.

A.7 Methodological Framework

The proposed GA based methodology is designed to minimize the public funds utilized and maximize the chances for winning the concession for the prospective concessionaire while considering profitability and repayment capability of the project. First, the input GA parameters (e.g., number of generations and crossover rate) and PPP project characteristics (e.g., cost and revenue information, financial parameters) are identified. Second, a thorough life-cycle cash flow analysis is performed, and the optimization model is formulated. Subsequently, the population is initialized, and the GA is conducted. The generational process is repeated until a termination condition has been reached. Two of the most commonly used stopping rules are (1) a maximal number of generations are attained, or (2) the best current solution shows no signs of improvement in the subsequent generation. The GA will stop if either of the two criterion is satisfied. Finally, the optimal solution is obtained. In addition, the optimal solution is searched in the following manner: for non-linear optimization problems, multiple GAs are undertaken with different initial values with very small intervals in case that the solution (if any) obtained is a local minimum. The optimal solution is regarded as the minimum value of all the results returned by each GA process. The methodological framework is presented in Figure A-1.

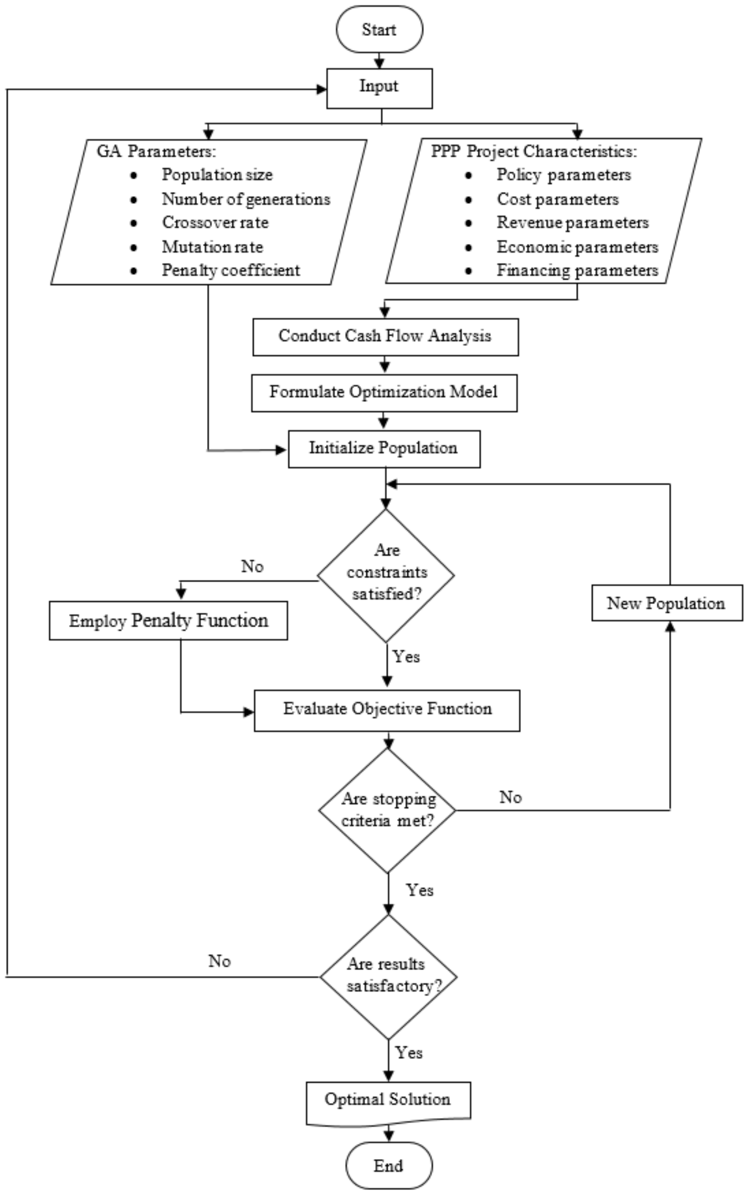

Figure A-1: Methodological Framework

In this paper, the proposed methodological framework is illustrated through a BOT toll road infrastructure under DBFOM partnerships.

A.8 Revenue Model

User fee collection during the operation period is the main source of revenue for a toll road facility. Therefore, the infrastructure-generated revenue is closely related to the traffic volume and toll rate. The information on the initial traffic volume of different vehicle classes and their annual growth rate can be obtained through the contract or the project's master development plan. The total tolling revenue (TR) before tax in year t is modeled by:

$$TR_t = \begin{cases} 0, & t \in [0, n] \\ \sum_{\eta \in \Omega} v_t^\eta r_t^\eta l_{avg}, & t \in [n+1, N] \end{cases} \tag{A.1}$$

where n is the construction period in years; N is the concession period; v_t^η is the traffic volume for traffic class η in year t; r_t^η is the toll rate for traffic class η in year t (dollars per vehicle per mile); Ω is the set of all vehicle classes; l_{avg} is the average trip length (mile).

The total number of transactions in year t (total traffic volume, V_t) is given by:

$$V_t = \sum_{\eta \in \Omega} v_t^\eta \tag{A.2}$$

where

$$v_t^\eta = v_{n+1}^\eta (1 + g^\eta)^{t-n-1}, \qquad t \in [n+1,\ N] \tag{A.3}$$

v_{n+1}^η is the initial traffic volume value for vehicle class η during the first year of operation; and g^η is the annual traffic growth factor for vehicle class η.

Since the level of service of a highway will be significantly compromised when the traffic volume reaches a certain capacity, an upper limit of the demand is set so that traffic volume will not exceed the capacity and the level of service is guaranteed:

$$V_t \le V_{desire} \tag{A.4}$$

where V_{desire} is the desired capacity of the highway.

It is assumed that customers will not choose the toll road option if its capacity exceeds the desired capacity. Therefore:

$$V_t = \begin{cases} \sum_{\eta \in \Omega} v_t^\eta & \text{if } V_t < V_{desire} \\ V_{desire} & \text{if } V_t \ge V_{desire} \end{cases} \tag{A.5}$$

Similarly, the toll rate for class η vehicle will grow from its initial value based on a growth rate, given as follows:

$$r_t^\eta = r_{n+1}^\eta (1 + f^\eta)^{t-n-1}, \qquad t \in [n+1,\ N] \tag{A.6}$$

where r_{n+1}^η is the initial toll rate for vehicle class η during the first year of operation; and f^η is the annual toll rate growth factor for vehicle class η.

A. 9 Cost Model

The total monetary cost (TC_t) of a DBFOM partnership project consists of the initial construction cost (ICC_t); the maintenance, rehabilitation, and operational cost ($MROC_t$); and the business tax (T_t) paid in year t. In addition, even though depreciation does not represent a cash outflow, it is suggested by various researchers to be included in the model since depreciation is the cost of a useful asset over its estimated life (Bakatjan *et al*., 2003; Zhang, 2005; Yun *et al*., 2009). Therefore, the TC in year t is expressed as:

$$TC_t = ICC_t + MROC_t + \varphi_t T_t + DEP_t \tag{A.7}$$

where φ_t is a binary variable, $\varphi_t = \{0,\ 1\}$. In some cases, the business tax is exempted according to the contract signed by the concessionaire and government, consequently $\varphi_t = 0$; otherwise, a certain amount of business tax should be paid each year, $\varphi_t = 1$. DEP_t is the depreciation in year *t*. Various depreciation methods have been proposed by researchers, such as straight line, declining balance, double-declining balance, sum of the years' digits, and the modified accelerated cost recovery system. In practice, the selection of depreciation model depends on the taxpayer's opportunity cost of capital (Steiner 1996).

ICC depends on the total initial capital cost ($TICC$) and the way in which the project is financed. It also relies on the conditions and proportions of the mix of loans, grants, equity, etc. that are used to finance the project's development. There are two stages for ICC: construction stage and operation stage. During the construction period, ICC is equal to the part of $TICC$ covered by the equity committed by the sponsors and/or developers. During the operation stage, ICC equals to the debt repayments, which can exist or not, depending on the debt terms and conditions, such as grace periods, payback periods, interest rates, etc. All debts are assumed to be issued on the first year of construction and re-paid by an equal amount installment payment method. Therefore, ICC in year *t* can be presented by:

$$ICC_t = \begin{cases} (\alpha_{ce} + \alpha_p)\beta_t TICC, & t \in [0, n] \\ \sum_{j \in \Pi} \alpha_{d_j} TICC \times \dfrac{i_{d_j}(1+i_{d_j})^{\theta_{d_j}}}{(1+i_{d_j})^{\theta_{d_j}} - 1}, & t \in [n+1, N] \end{cases} \tag{A.8}$$

where α_{ce} is the proportion of committed private equity as a percentage of $TICC$; α_p is the proportion of public funds as a percentage of $TICC$; β_t is the percentage of C_0 drawn in year *t* during the construction period, where C_0 is the estimated total construction cost which excludes loan interest payments and fees; α_{d_j} is the proportion of issued type *j* debt as a percentage of $TICC$; Π is the set of all possible types of issued debts, including debts/loans from commercial (senior banks) and/or public; θ_{d_j} is number of repayment years for type *j* debt; and i_{d_j} is the interest rate of type *j* debt.

$TICC$ is the sum of the annually incurred construction costs considering inflation, which is essential to project financing or capital cost that is invested over the construction period. $TICC$ is denoted as:

$$TICC = \sum_{t=0}^{n} \sum_{\delta \in \Lambda} \alpha_\delta IC_t, \quad t \in [0, n] \tag{A.9}$$

where α_δ is the proportion of different types of debt, committed equity or public funds as a percentage of $TICC$, $\delta = \{ce, p, d_j\}$, $j \in \Pi$; Λ is the set of all possible types of capital in the project's financing process (public funds, equity, loan, or debt); and IC_t is the initial capital cost in year *t* during construction period. In addition, IC_t can be expressed as:

$$IC_t = \beta_t C_0 (1 + f_e)^t, \quad t \in [0, n] \tag{A.10}$$

where f_e is the annual price escalation rate or inflation rate. For a DBFOM partnership toll road project, C_0 can be estimated by considering employee salaries, overhead costs, intelligent transportation system (ITS) and toll collection system (TCS) initial investments, facility construction costs, and the costs of hazardous material remediation and other construction risks.

The $MROC$ consists of operational expenditures ($OPEX$) and capital expenditures ($CAPEX$).

$$MROC_t = \begin{cases} 0, & t \in [0, n] \\ OPEX_t + CAPEX_t, & t \in [n+1, N] \end{cases} \tag{A.11}$$

$OPEX$ involves ordinary expenses related to annual operation activities, which include overhead expenses (OE), costs of roadway maintenance and operations (RMO), systems maintenance (SM), toll collection risk (TCR), and insurance (In). $OPEX$ in year *t* is given by:

$$OPEX_t = \begin{cases} 0, & t \in [0, n] \\ OE_t + RMO_t + SM_t + TCR_t + In_t, & t \in [n+1, N] \end{cases} \tag{A.12}$$

OE_t is the cost incurred in staffing the concession company with personnel to manage the project over the duration of the concession term, which can be expressed as:

$$OE_t = \kappa_{n+1} (1 + f_e)^{t-n-1}, \quad t \in [n+1, N] \tag{A.13}$$

where κ_{n+1} is the annual overhead expenses during the first year of operation.

RMO_t covers the roadway inspection, minor maintenance and operation cost in year t, including the salaries and benefits of related personnel, material, and equipment maintenance costs.

$$RMO_t = \lambda_{n+1}(1+f_e)^{t-n-1}, \quad t \in [n+1, N] \tag{A.14}$$

where λ_{n+1} is the annual roadway maintenance and operation cost during the first year of operation.

SM_t considers the cost of maintaining intelligent transportation systems and toll collection systems, which is usually determined by the number of maintenance personnel, mainline gantries, and back-office systems in the project.

$$SM_t = \gamma_{n+1}(1+f_e)^{t-n-1}, \quad t \in [n+1, N] \tag{A.15}$$

where γ_{n+1} is the annual system maintenance cost during the first year of operation.

TCR_t accounts for the costs per transaction of the toll system to the toll agency, as well as the potential risk of unpaid bills and toll system malfunction leakage. Based on previous studies, TCR_t can be modeled as 4.5 cents per transaction plus four percent of the toll revenues before tax, and the system malfunction leakage is estimated to be one percent of all transactions (Pearson *et al*. 2001; Persad and Walton 2007; Fleming *et al.* 2012), as follows:

$$TCR_t = 0.99(0.045V_t + 0.04TR_t), \quad t \in [n+1, N] \tag{A.16}$$

In_t is the cost of insurance for the project, which is obtained from the concessionaire's normal brokerage company.

$$In_t = \psi_{n+1}(1+f_e)^{t-n-1}, \quad t \in [n+1, N] \tag{A.17}$$

where ψ_{n+1} is the annual insurance cost during the first year of operation.

The main elements to be analyzed in $CAPEX$ include major maintenance and/or rehabilitation of pavements, structures, tolling systems, and maintenance equipment.

$$CAPEX_t = \begin{cases} 0, & t \in [0, n] \\ \mu_t^{\omega_i} \sum_{\omega \in \Gamma} \sum_{i=1}^{L} \zeta_{n+1}^{\omega_i} (1+f_e)^{t-n-1}, & t \in [n+1, N] \end{cases} \tag{A.18}$$

where $\zeta_{n+1}^{\omega_i}$ is the maintenance and/or rehabilitation cost for the ith treatment activity of alternative category ω (cost values are converted to the first year of operation); ω represents different alternative categories, and $\omega \in \Gamma$; Γ is the set of all possible maintenance and/or rehabilitation alternatives, which includes pavement, structures, and ITS/TCS; L is the total number of treatment activities performed; and $\mu_t^{\omega_i}$ is a binary variable, where $\mu_t^{\omega_i} = \{0,\ 1\}$. If one or more major maintenance/rehabilitation treatment activities of alternative category ω is performed in year *t*, then $\mu_t^{\omega_i} = 1$; otherwise, $\mu_t^{\omega_i} = 0$.

In addition, T_t can be calculated as:

$$T_t = \begin{cases} 0, & t \in [0, n] \\ \varepsilon_t TM_t, & t \in [n+1, N] \end{cases} \tag{A.19}$$

where ε_t is the business tax rate in year *t*; and TM_t is the amount of taxable margin. ε_t and TM_t are project-based, which depend on the contract and state/local government's policy.

In terms of DEP_t, various depreciation methods have been proposed by researchers, such as straight line, declining balance, double-declining balance, sum of the years' digits, and the modified accelerated cost recovery system. In practice, the selection of depreciation model depends on the taxpayer's opportunity cost of capital (Steiner, 1996). This paper adopts the widely used straight line depreciation method, which can be presented as:

$$DEP_t = \begin{cases} 0, & t \in [0, n] \\ \dfrac{C_T - Sal}{n_u}, & t \in [n+1, N] \end{cases} \tag{A.20}$$

where C_T is the total project cost discounted to the end of the construction period; Sal is salvage value of the project at the end of its useful life; and n_u is the useful life of the project.

A.10 Model Formulation

With the revenue and cost models formulated, the total cash flow (TCF) of year *t* can be presented by Equation A.1 and Equation A.7, as follows (Iyer and Sagheer, 2011):

$$\begin{aligned} TCF_t &= TR_t - TC_t + DEP_t \\ &= TR_t - ICC_t - MROC_t - \varphi_t T_t \end{aligned} \tag{A.21}$$

The depreciation term is canceled out when Equation A.7 substitutes TC_t in Equation A.21 because the fact that depreciation is noncash expense and does not actually impact the cash flow.

The total cash flow per year *t* is then discounted to the base year (Year 0) and added together to determine the previously mentioned financial viability criteria. The equations to calculate NPV, IRR, and ADSCR have been well documented and shown in Equations A.22 to A.25, respectively (PPIAF 2016).

$$NPV = \sum_{t=0}^{N} \frac{TCF_t}{(1+f_a)^t} \tag{A.22}$$

where f_a is the appropriate discount rate, which is usually set as the minimum acceptable rate of return (*MARR*).

IRR is determined when *NPV* equals zero, that is:

$$\sum_{t=0}^{N} \frac{TCF_t}{(1+IRR)^t} = 0 \tag{A.23}$$

In terms of *ADSCR*, the expression of the *ADSCR* for year t when there is debt repayment is given by:

$$ADSCR_t^{d_j} = \frac{TCF_t + D_t}{D_t} = 1 + \frac{TCF_t}{\alpha_{d_j} TICC \times \frac{i_{d_j}(1+i_{d_j})^{\theta_{d_j}}}{(1+i_{d_j})^{\theta_{d_j}} - 1}} \tag{A.24}$$

where D_t is the debt instalment in year *t*.

Similarly,

$$ADSCR_t^{comb} = 1 + \frac{TCF_t}{\sum_{j \in \Pi} \alpha_{d_j} TICC \times \frac{i_{d_j}(1+i_{d_j})^{\theta_{d_j}}}{(1+i_{d_j})^{\theta_{d_j}} - 1}} \tag{A.25}$$

Equation A.24 represents the *ADSCR* for specific type *j* debt in year t; and Equation A.25 measures the combined debt repayment ability for all of the different types of debt services involved.

Finally, the optimization model can be stated as finding control variables α_{ce}, α_p, and α_{d_j} ($j \in \Pi$) to minimize the proportion of public funds with defined constraints:

$$\underset{\{\alpha_{ce}, \alpha_p, \alpha_{d_{j, j\in\Pi}}\}}{minimize} \ \alpha_p \tag{A.26}$$

Such that:

$$\alpha_{ce} + \alpha_p + \sum_{j \in \Pi} \alpha_{d_j} = 1 \tag{A.27}$$

$$\alpha_{ce} \leq \alpha_{ce}^{max} \tag{A.28}$$

$$\alpha_p TICC \leq PF_{max} \tag{A.29}$$

$$NPV \geq NPV_{tar} \tag{A.30}$$

$$IRR \geq IRR_{tar} \tag{A.31}$$

$$ADSCR_t^{d_j} \geq ADSCR_{min}^{d_j}, \qquad \forall j \in \Pi \tag{A.32}$$

$$ADSCR_t^{comb} \geq ADSCR_{min}^{comb} \tag{A.33}$$

$$\alpha_{ce}, \alpha_p, \alpha_{d_j} \geq 0, \qquad \forall j \in \Pi \tag{A.34}$$

where α_{ce}^{max} is the maximum proportion of private equity that can be committed; PF_{max} is the maximum amount of available public funds; NPV_{tar} is the project's targeted net present value; IRR_{tar} is the project's targeted internal rate of return; $ADSCR_{min}^{d_j}$ is the minimum annual debt-service cover ratio for type j debt; and $ADSCR_{min}^{comb}$ is the minimum annual debt-service cover ratio for the combined debts. All of this information can be collected from the contract or the project's master development plan.

By solving this model, the minimum proportion of public funds is obtained, while all the financial viability criteria required by the private sector and lenders are satisfied. The proposed model provides a useful tool to make more informed decisions regarding the financing structure of a BOT project.

A.11 Case Study

To illustrate its capabilities, the proposed formulation was applied to a real BOT highway project under DBFOM partnerships, specifically segments 5 and 6 of State Highway 130 (SH-130) in Texas. SH-130 is a toll road from Interstate 35 (I-35) in Georgetown to US-183 and SH-45 at Mustang Ridge in Central Texas. It was designed as a bypass for I-35 in order to share parts of the heavy traffic and reduce congestion on the I-35 corridor. Several firms in private sectors, including Lone Star Infrastructure and Cintra-Zachry, participated in the SH-130 project. Most of the data (e.g., cost and traffic volume information) used for the case study were from sources of information on the SH-130 project (Wiki 2017; SH-130 2017). Data not directly available from these sources were derived from common knowledge, other published works, and similar real-life projects, such as parts of the Trans-Texas corridor in the state of Texas (TxDOT 2004; Pantelias and Zhang 2010). In the original development plan, it was reported that the toll road construction began in 2015. Therefore, all the costs, revenues, and profits are expressed in 2015 dollars (otherwise stated). The detailed project information is summarized and presented in Table A-1 and Table A-2.

Table A-1: PPP Highway Project General and Cost Information

Project Parameters	Units	Value	Comments
General Information:			
Concession Period (N)	Years	52	
Construction Period (n)	Years	3	
Operation Period (n_u)	Years	49	Useful life
Length	Miles	41	Four-lane Highway
Cost Information:			
Initial Construction Cost (C_0)	$	1.046 billion	Initial Estimate
Construction Capital Draw:			
Year 1 (β_1)	%	25	
Year 2 (β_2)	%	50	
Year 3 (β_3)	%	25	
OPEX:			
Overhead Expenditure (κ_{n+1})	$	1.88 million	Annual Cost
Roadway Maintenance and Operations (λ_{n+1})	$	2.63 million	Annual Cost
System Maintenance (γ_{n+1})	$	1.20 million	Annual Cost
Insurance (ψ_{n+1})	$	0.90 million	Annual Cost
CAPEX:			
Pavement (ζ_{n+1}^{p})	$	12 million	Every five years. Functional intervention will be performed at the end of the 15th and 30th year with an additional cost of 5 million
Structural (ζ_{n+1}^{s})	$	20.20 million	Every eight years. Structural intervention will be performed at the end of the 24th and 40th year with an additional cost of 10 million
ITS/TCS (ζ_{n+1}^{ITS})	$	10 million	Every eleven years

Table A-2: PPP Highway Project Revenue, Economic, and Financing Information

Project Parameters	Units	Value	Comments
Revenue Information:			
Initial AADT for Passenger Cars (v_{n+1}^{c})	Vehicles	15,296	Estimated based on existing and historical corridor traffic conditions
Initial AADT for Trucks (v_{n+1}^{T})	Vehicles	6,118	
Desired Capacity (V_{desire})	Vehicles	33,600	
Annual Growth Rate for Passenger Cars (g^{c})	%	2.5	
Annual Growth Rate for Trucks (g^{T})	%	2	
Initial Toll Rate for Passenger Cars (r_{n+1}^{c})	$/veh/mile	0.125	
Initial Toll Rate for Trucks (r_{n+1}^{T})	$/veh/mile	0.48	
Average Distance Travelled (l_{avg})	mile	26	
Annual Toll Rate Growth (f^{c}, f^{T})	%	2.5	
Economic Information:			
Inflation Rate (f_{e})	%	2.5	Initial Estimate
Discount Rate (f_{a})	%	12	Target value for private sectors ($IRR_{tar} = 12\%$)
Financing Information:			
Public Issued Loan:	%	α_{d_L}	Control variable
Interest Rate (i_{d_L})	%	6.0	
Grace Period	Years	10	
Payback Period (θ_{d_L})	Years	35	
Minimum ADSCR ($ADSCR_{min}^{d_L}$)	Number	1.5	
Senior Bank Debt:	%	α_{d_S}	Control variable
Interest Rate (i_{d_S})	%	5.55	
Grace Period	Years	10	
Payback Period (θ_{d_S})	Years	40	
Minimum ADSCR ($ADSCR_{min}^{d_S}$)	Number	1.75	
Payback Terms	Interest plus principal in equal installments after end of grace period		
Combined Debt Minimum ADSCR ($ADSCR_{min}^{comb}$)	Number	1.10	
Developer's Committed Equity	%	α_{ce}	Control variable
Public Funds	%	α_{p}	Objective variable. Maximum available amount of public subsidy (PF_{max}) is $500 million

According to Pantelias, the commonly acceptable and historically reported maximum proportion of committed private equity is 30% (Pantelias 2009). Therefore, α_{ce}^{max} is set as 30%. For illustration purposes, the targeted NPV value for the private sector is set as \$13 million (NPV_{tar} = \$13 million), which indicates decent profitability; and the salvage value of the roadway is assumed as \$100 million by the end of the designed life cycle. In accordance with the current practice in Texas, the tax rate for most businesses is 1% of the taxable margin. The taxable margin is equal to the least of the following three amounts: 70% of total revenue, 100% of total revenue minus cost of goods sold, or 100% of total revenue minus compensation (Nolo 2017). Based on the calculation, the taxable margin is set as 70% of the revenue generated in this case study. Therefore, the business tax paid for year *t* can be modeled as:

$$T_t = 1\% \times 70\% \times R_t \tag{A.35}$$

In light of the aforementioned input information, the proposed model was implemented using the software, Evolver 7, developed by Palisade Corporation. Evolver is an add-in for Microsoft Excel, which applies GA based optimization techniques to find optimal solutions to complex non-linear problems which are "unsolvable" for standard linear and non-linear optimizers. The input GA parameters adopted in this paper are the default values in Evolver, where Evolver stops if 20000 trials have passed and the target value has not improved by more than 0.01% (Palisade 2017). Evolver has the ability to search for the best overall solution to a problem and has been widely applied by researchers in their studies (Carter and Ragsdale 2002; Roper 2004; Doğan and Günaydın 2006). The results are shown in Table A-3.

Table A-3: Optimization Results

Parameter		Value	Comments
Objective Variable	$\alpha_{p,min}$	34.61%	Minimum amount of public funds
Control Variable	α_{ce}	30%	Equals to α_{ce}^{max} (30%)
	α_{d_S}	23.02%	
	α_{d_L}	12.37%	
Constraints*	Public Funds Used	$362.19 million	Less than PF_{max} ($500 million)
	NPV	$43.73 million	Larger than NPV_{tar} ($13 million)
	IRR	14.68%	Larger than IRR_{tar} (12%)
	$\alpha_{ce} + \alpha_p + \sum_{j \in \Pi} \alpha_{d_j}$	1	Equals to 1
	$min\left\{ ADSCR_t^{d_S}, t \in [0, N] \right\}$	1.75	Equals to $ADSCR_{min}^{d_S}$ (1.75)
	$min\left\{ ADSCR_t^{d_L}, t \in [0, N] \right\}$	2.96	Larger than $ADSCR_{min}^{d_L}$ (1.5)
	$min\left\{ ADSCR_t^{comb}, t \in [0, N] \right\}$	1.10	Equals to $ADSCR_{min}^{comb}$ (1.10)

Note: Constraints*: All the constraints are met.

According to Table A-3, the optimal capital structure to cover the total initial capital cost consists of 34.61 percent public funds, 30 percent private equity, 23.02 percent senior bank debt, and 12.37 percent public issued loan. The minimum amount of public funds utilized is $362.19 million, and all the constraints are met. Any lower amount of public funds will lead to the violation of the constraints (violation of financial viability). In addition, Equation A.28, Equation A.32 (for *j* = senior bank debt), and Equation 33 turn out to be the binding constraints, which indicates that any changes in their values changes the optimal solution. For equity investors, the NPV and IRR are $43.73 million and 14.68 percent respectively, which are evidently larger than the targeted values. This indicates excellent profitability of the project, and the equity investors should be very satisfied with the investment. For the lenders, due to different debt terms and conditions (e.g., payback periods and interest rates), different proportions of debts/loans are raised (23.02 percent for senior bank debt, and 12.37 percent for public issued loan). The results show reliable debt repayment ability since all the minimum ADSCRs goals are reached. In particular, the project is trustworthy to pay back the public issued loan since its minimum ADSCR is 2.96. Compared with the current practice or profitability maximization capital scheme where the available public funds are usually entirely utilized, the proposed methodology saves $137.81 million (27.5 percent) in public funds while both the private sectors and the lenders are content. The public authorities could apply the saved public funds into other social welfare infrastructures.

A.12 Sensitivity Analysis

With the case study serving as the base case, sensitivity analyses were undertaken to explore how the change in the binding constraints (e.g., $ADSCR_{min}^{d_S}$ and α_{ce}^{max}) would affect the optimal capital structure. The results will provide the stakeholders with significant insight regarding ultimately attaining their respective financial targets and help them with the corresponding decisions and negotiations so that the project moves successfully from a planning to an implementation phase. Throughout the sensitivity analyses, Equation 28, Equation 32 (for *j* = senior bank debt), and Equation 33 remain the binding constraints.

IMPACT OF $ADSCR_{min}^{d_S}$ ON OPTIMAL CAPITAL STRUCTURE

In order to analyze the impact of $ADSCR_{min}^{d_S}$ on the optimal capital structure, the $ADSCR_{min}^{d_S}$ is set to 1.45, 1.55, 1.65, 1.85, 1.95, and 2.05, respectively, while the other input parameters remain the same. The proposed model was executed and the results are presented in Figure A-2 and Figure A-3.

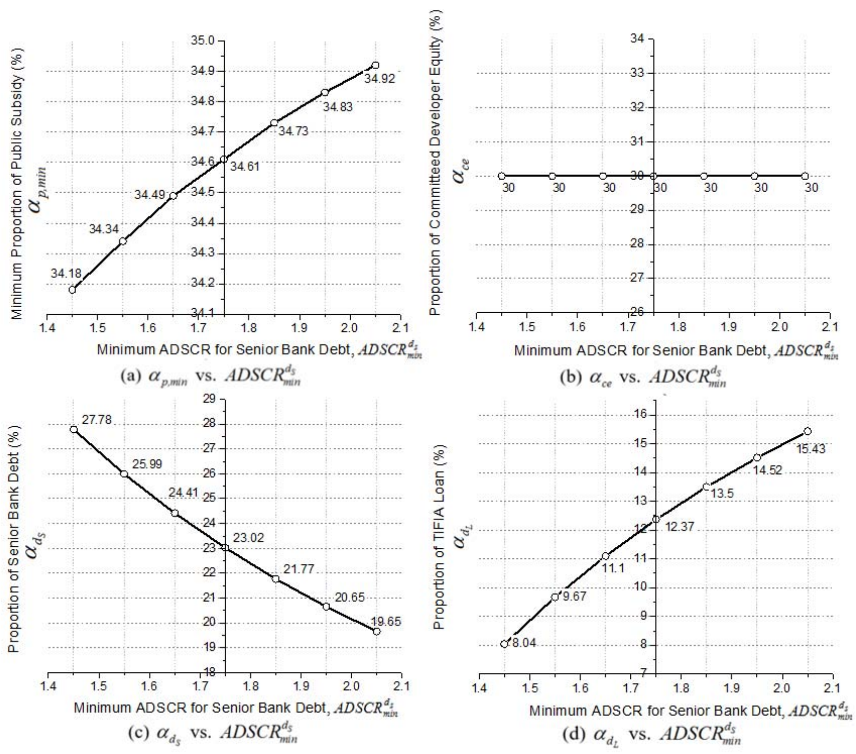

Figure A-2: Impact of $ADSCR_{min}^{d_S}$ on Optimal Capital Structure

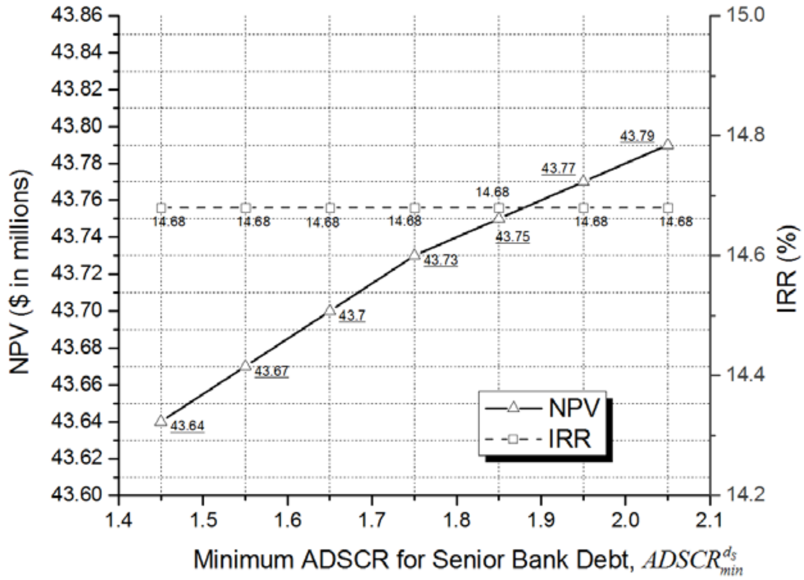

Figure A-3: Impact of $ADSCR_{min}^{d_S}$ on NPV and IRR

Figure A-2 (a) to (d) shows how $\alpha_{p,min}$, α_{ce}, α_{d_S}, and α_{d_L} change with $ADSCR_{min}^{d_S}$, respectively. Higher $ADSCR_{min}^{d_S}$ means a higher requirement on senior bank debt repayment. In order to minimize the public funds, the private sector should commit sufficient equity and α_{ce} is expected to reach α_{ce}^{max} (30 percent) in every case, which can be verified from Figure A-2 (b). Figure A-2 (a) indicates that an increase in $ADSCR_{min}^{d_S}$ increases $\alpha_{p,min}$ while a deduction lowers it. $\alpha_{p,min}$ improves from 34.18 percent to 34.92 percent as $ADSCR_{min}^{d_S}$ increases from 1.45 to 2.05. This is because more public funds have to be introduced so that the higher senior bank debt repayment requirement is satisfied. In addition, in order to keep the mandatory debts servicing ability, debtors will switch part of the senior bank debt to other debt options (public issued loans) as $ADSCR_{min}^{d_S}$ increases, which results in lower values of α_{d_S} and higher values of α_{d_L}. These trends can be observed from Figure A-2 (c) and Figure A-2 (d). α_{d_S} drops from 27.78 percent to 19.65 percent, and α_{d_L} rises from 8.04 percent to 15.43 percent with $ADSCR_{min}^{d_S}$ changing from 1.45 to 2.05.

Figure A-3 provides more insightful information on NPV and IRR for the private sectors. The left y-axis is NPV in million dollars, and the right y-axis represents the IRR value. As can be seen from Figure A-3, as $ADSCR_{min}^{d_S}$ changes from 1.45 to 2.05, the NPV value increases from $43.64 million to $43.79 million and the IRR values remain the same at 14.68 percent. This is expected because the committed equity α_{ce} stays the same (Figure A-2 (b)), and therefore the IRR calculation should not be affected. On the other hand, as

$ADSCR_{min}^{d_S}$ increases, more public funds are introduced (Figure A-2 (a)) and less capital is raised from the lenders (Figure A-2 (c) and (d) combined), which leads to the increase in NPV values.

IMPACT OF α_{ce}^{max} ON OPTIMAL CAPITAL STRUCTURE

Similarly, another sensitivity analysis was conducted to investigate the impact of α_{ce}^{max} on the optimal capital structure. α_{ce}^{max} is valued from 27 percent to 33 percent with an increment of 1 percent while the other input parameters remain the same. The proposed model was executed, and the results are presented in Figure A-4 and Figure A-5.

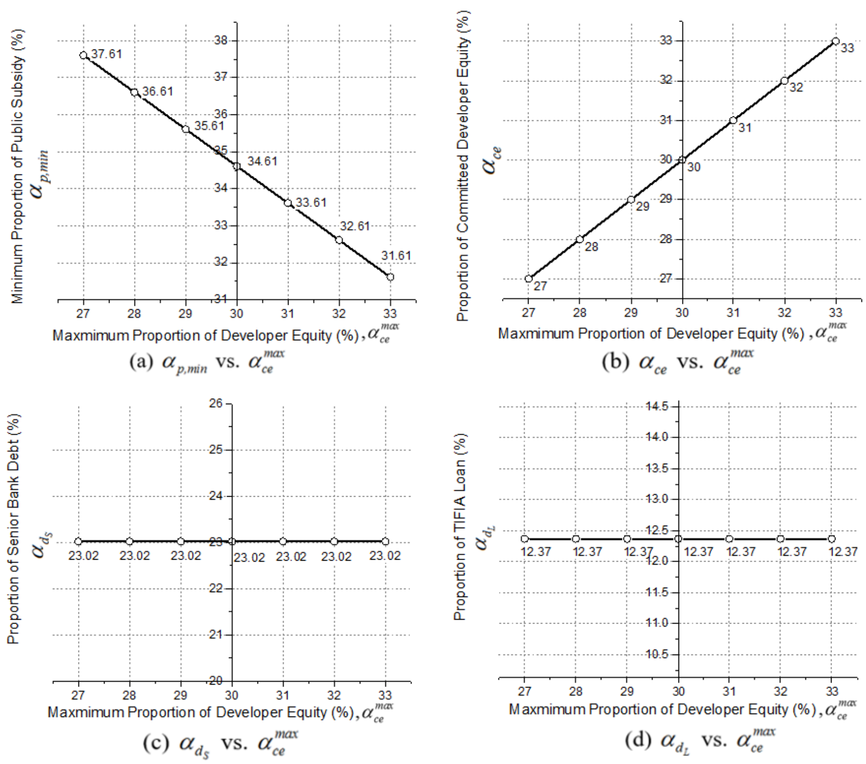

Figure A-4: Impact of α_{ce}^{max} on Optimal Capital Structure

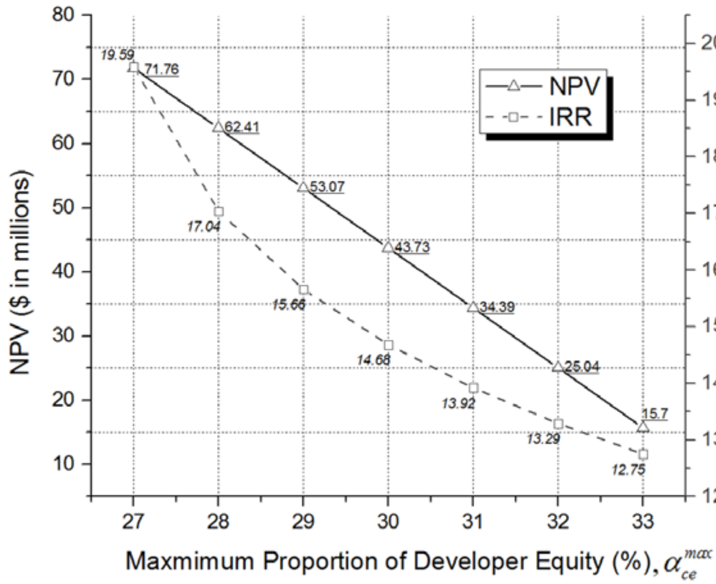

Figure A-5: Impact of α_{ce}^{max} *on NPV and IRR*

The base case is capable of obtaining the optimal capital structure, which means that α_{d_S} and α_{d_L} are the optimal proportions for senior bank debt and public issued loan under current financing information, respectively. Under this analysis, all the financing parameters (including the interest rate, grace period, payback duration, and minimum ADSCRs) stay the same with base case. Therefore, the values of α_{d_S} and α_{d_L} should not change since they only depend on the project financing parameters, which can be justified from Figure A-4 (c) and (d). α_{d_S} remains at 23.02 percent, and α_{d_L} equals to 12.37 percent no matter how α_{ce}^{max} changes. However, $\alpha_{p,min}$ and α_{ce} are influenced by α_{ce}^{max}. As long as the financial goals are reached, equity investors will commit as much equity as possible in order to minimize public funds and thus win the bidding. Therefore, α_{ce} should always be equal to α_{ce}^{max}. As a consequence, $\alpha_{p,min}$ decreases as more committed equity is raised when α_{ce}^{max} increases. These trends can be observed from Figure A-4 (a) and (b). $\alpha_{p,min}$ reduces from 37.61 percent to 31.61 percent and α_{ce} is identical with α_{ce}^{max} as α_{ce}^{max} moves from 27 percent to 33 percent.

Based on the information obtained from Figure A-4, α_{ce}^{max} only impacts $\alpha_{p,min}$ and α_{ce} since the optimal values of α_{d_S} and α_{d_L} have been fixed under current financing parameters. An increase in α_{ce}^{max} decreases $\alpha_{p,min}$ while it increases α_{ce}, which means that as α_{ce}^{max} increases, less public funds will be used and more private equity will be committed instead. This will decrease the NPV and IRR values due to the fact that the commitment of equity is a more expensive way to supplement the financing of a project compared with other capital sources, which can be confirmed by Figure A-5. As can also be observed from Figure A-5, both NPV and IRR curves show the expected trend, where both curves decrease with α_{ce}^{max}. NPV drops from $71.76 million to $15.70 million and IRR decreases dramatically from 19.59 percent to 12.75 percent as α_{ce}^{max} increases from 27 percent to 33 percent. However, it is noteworthy to point out that although NPV and IRR values are decreasing, they are still larger than the targeted values. The equity investors should be satisfied with the investment.

A.13 Discussions and Conclusions

A wide variety of public infrastructure projects has been privatized worldwide for improved quality, efficiency, and effectiveness. Over the past decades, several financial models have been established to analyze the financial viability and determine the optimal capital structure of BOT projects. These models have focused on preparing a viable capital structure, where profitability maximization has always been treated as the most vital issue and listed as the first priority. However, formulating a financially competitive proposal, which can increase the probability of winning the concession, is a challenging issue for the prospective bidders. Because the public funds sought from the government are one of the non-negligible factors that determines the successful concessionaire in BOT projects, the bidders should make a realistic assessment of the public funds amount rather than only focusing on maximizing the profit. Past research did not incorporate enough of the issue of bid-winning potential by integrating the quantum of government funds with the optimal capital structure.

This paper proposed a comprehensive genetic algorithm based methodological framework to optimize the capital structure of PPP projects. The developed model is a departure from the conventional financial analysis models as it minimizes the amount of public funds utilized while thoroughly considering the interests, concerns, and requirements of different participants. This quantitative methodology reflects the characteristics of project finance and incorporates both optimization and financial engineering techniques. A detailed case study along with sensitivity analyses was carried out with data derived from a real-world BOT highway project, State Highway 130 (SH-130) in Texas. The results are interpreted so that quantitative information was provided to agencies to establish investment strategies and make more insightful decisions. To summarize, the conclusions from this paper are as follows:

- The proposed methodology directly accommodates the requirements of all the parties involved in a BOT project, and can be used by all stakeholders and decision makers to support the hard decisions and negotiations toward financial closure and ultimate project implementation. It works in conjunction with other models, such as cost and revenue prediction models, and is flexible enough to be applied to other types of PPP infrastructures.
- The developed framework is able to create a win-win-win situation: the public authorities can evaluate if the project is attractive enough to the private sector

for competitive bids, through which the VfM target will be attained. More importantly, part of the public funds are saved so that they can be invested to other social welfare infrastructures, which introduces an effective way to help solve the budgetary shortage problem while delivering public services. For equity investors, the profitability of the project can be assessed through NPV and IRR. On the premise that all the financial targets are met, using the minimum proportion of public funds increases the potential bid winning probabilities, which helps to build their reputations. By estimating the ADSCRs, the lenders will have an overall command of the repayment ability of the project. They should be willing to provide debts/loans as long as their required cover ratios are fulfilled.

- As illustrated with the case study, the methodology is capable of analyzing a wide variety of investment options through sensitivity analyses, yielding information that can be of great value to all stakeholders in making informed decisions on infrastructure investments. Through such analyses, various stakeholders can investigate the effect of different parameters and implementation scenarios on the financial viability and identify possible sources of risk that need to be treated or mitigated in order for the project to be able to deliver their respective financial expectations.

This methodology can serve as a basis for future research. There are a few directions on which future research can embark and improve the presented framework and corresponding results, including: perform stochastic analysis to consider cost and revenue risks that arise during the construction and operational phases of the project; and to incorporate uncertainties in willingness to pay and toll elasticity in the revenue calculation.

Appendix B

Paper 2: Monte Carlo Simulation Based Assessment of Risks Associated with PPP Investments in Toll Highway Infrastructure

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B.1 Abstract

The demands for delivering highway services keep growing worldwide. However, funding from government and public agencies alone cannot cover the capital needed to operate and maintain existing highway systems, much less to construct new ones. Public-Private Partnerships (PPPs) are an innovative funding mechanism for highway agencies to utilize private capital and expertise in transportation infrastructure projects, so as to increase funding options to bridge the budget gap. Even though parties involved in PPPs take different roles and responsibilities, there are still risks taken or shared by the public and private sectors. In particular, assessing risks associated with the potential returns of investments is of great importance to both the private and public sectors. This paper presents a methodological framework for assessing the investment risks of PPP toll highway projects, which may help decision makers. The financial viability associated with the components of a project is considered and analysed, and the Monte Carlo Simulation technique is applied to evaluate the overall project risks. Finally, a numerical case study is conducted to demonstrate the application of the proposed methodology. The risk analysis provides statistical distribution of investment returns for the project under analysis, which will supply decision makers with direct information to estimate the project's overall financial risks and develop corresponding risk control measures. The risk simulation results are interpreted so that quantitative information can be provided to agencies to establish investment decision criteria.

Keywords: Public-Private Partnerships (PPPs), risk analysis, viability of PPP investments, Monte Carlo Simulation.

B.2 Introduction

With the continuous development of the economy and urbanization, the demand for basic infrastructure services has increased drastically in recent years. According to American Society of Civil Engineers, it was estimated that around $2.2 trillion dollars would be needed during the next five years in order to improve the U.S. infrastructure from its current average score of "D" (ASCE 2009). In addition, travel demand and high expectations regarding mobility and level of service from the public will continue to increase (Brown 2007; Ortiz *et al*. 2008). However, public funds, which usually come from designated funds specifically for infrastructure or general government funds, alone cannot cover all the infrastructure's construction, operation, maintenance, and replacement costs. There is a call for the utilization and involvement of other capital sources. Under these circumstances, public private partnerships (PPPs), which introduce private capital and expertise into a project, have been applied to address this budgetary shortage problem (Pagano and Perry 2008; Han 2013). Although PPPs are regarded as an innovative funding mechanism, slowly but steadily, traditional public financing and procurement ways have given way to private involvement in the delivery of public infrastructure services.

There are always three parties involved in a PPP project: the public authority, the private investor, and the lender (e.g., banks). These parties work together by undertaking or sharing different tasks. There are different types of PPPs based on different classification criteria. According to how the raised debt is repaid, PPPs can be categorized as Private Finance Initiative (PFI) or Concession contracts (Pantelias 2009; Yescombe 2011). The PPPs can also be regarded as availability-based or usage-based on the basis of the transfer of risks between the private sector and public authority. Furthermore, based on the legal position of the private sector involved in the project, PPPs can be classified as Build-Own-Operate-Transfer (BOOT), Build-Operate-Transfer (BOT), Build-Transfer (BT), and Joint Ventures (JV) (Grimsey and Lewis 2007; Yescombe 2011). PPPs can involve existing brownfield projects (i.e., the lease of an existing facility), or they can involve proposed new facilities, which are known as Greenfield projects. In the case of a brownfield project, a public entity generates a capital inflow or debt payoff by transferring the rights, responsibilities, and revenues attached to an existing asset to a private sector entity for a defined period. For Greenfield projects, a public agency transfers all or part of the responsibility for project development, construction, and operation to a private sector entity.

Due to the ability to attract private investments and cost effectiveness, PPPs are becoming more and more popular worldwide and have been applied in various fields such as waste water treatment, environmental infrastructure, power plant construction, transportation, telecom, and many other areas (Wang *et al*. 2000; Sachs *et al*. 2007). In U.S., 24 states, including Texas, Florida, California, etc., and the District of Columbia have used the PPP process to help finance and construct at least 96 transportation projects worth a total $54.3 billion by 2011 (Reinhardt 2011).

Of those implemented projects, toll highway infrastructure projects are important part. The first major toll PPP project in the U.S. was the E-470 Tollway project, which was located east of the Denver-Aurora metropolitan area and began construction in July, 1989 through a $323 million Design-Build contract. User fee collection is the main source of revenue for that project, and is expected to meet the required revenue. After that, more PPP toll highway projects were signed and constructed, including the Chicago Skyway in 2005, the Indiana toll road and Virginia Pocahontas Parkway in 2006, and the Colorado Northwest Parkway in 2007. In addition, a number of highway PPP projects have been signed since 2008, which account for around 11 percent of the total investment in new highway capacity provided by national capital in 2011. Most of the projects are express lanes that can be tolled, and are constructed next to existing freeways in heavily congested urban areas.

Although PPPs have been proven as an effective way to provide funding flexibility and relieve budget shortfalls, not all the PPPs are successful experiences. Failure cases have occurred during the development and exploration processes due to the fact that the investment risks were not adequately estimated. For example, Hungary M1/M15, which was built in 1995, was the first toll PPP motorway tendered and implemented in Central and Eastern Europe. However, after it was opened to the public, the traffic volumes were about 40% lower than anticipated. As a result, the concessionaire was unable to service its debt and ultimately the government had to take over the concession at a high cost (Cuttaree 2008). The South Bay Expressway (SBX), SR 125, is a 13-mile PPP toll road east of San Diego that runs north-south beginning near the Mexican border. Due to the housing crisis, recession, and slowdown of truck traffic from Mexico, traffic and revenue fell more than 50% short of projections. Furthermore, the project experienced a series of problems that increased costs, including that the construction took 41 months longer than anticipated. As a consequence, the San Diego Association of Governments had to purchase SBX back from the private operator (MnDOT 2016). Therefore, it is important to thoroughly understand the risks associated with PPP projects and develop quantitative methods to fully assess these risks.

B.3 Risks Associated with PPP Projects

Risks exist in different phases during a project's life cycle. Compared with traditional publicly financed projects, the risk allocation between the government and the private sector provider is much more complex in a PPP project. Both parties should clearly understand the various risks involved and agree to an allocation of risks between each other. According to Edwards and Bowen, the notion of risk is a human construct that refers to the probability of the occurrence of a particular adverse event during a stated period of time together with the quantification of its consequences (Edwards and Bowen 2003). The risks can be categorized into different types based on the source of origin and occurrence of time during different phases of a project. Traditional classification divides risks into external and internal on the basis of the origin of the risk factors. Internal risks come within the project and are impacted by the decision of the project, such as construction risk and maintenance risk. External risks come from outside of the project and usually are hard to control, such as the sudden change of the economic situation and political issues (Songer *et al*. 1997). The United Nations Industrial Development Organization (UNIDO) distinguishes the risks into General/Country risks and Specific Project risks. General/Country risks contain political, commercial, and legal risks; Specific Project risks include developmental, construction (completion), and operating risks (Jeon and Amekudzi 2007; Kalidindi and Thomas 2008). A more generally accepted classification, life cycle risk, is based on the project phases that the risks belong to. These risks fall into four different categories: development, construction, operation, and ongoing (Songer *et al*. 1997). The risks can also be classified as systematic/non-systematic and specific/non-specific, as well as government-, sponsor-, lender-, contractor-, and user-related (Asenova and Beck 2003; Xenidis and Angelides 2005). Within current industry practice, risk classification is usually more project-related and involves a combination of the above methods. Generally speaking, Greenfield projects present higher risks than brownfield projects due to greater uncertainties surrounding traffic forecasts, permitting, and construction.

This paper focuses on the assessment of the investment risk of PPP projects. Investment risk is a financial-type risk, which is defined as the probability of failure to secure a required infrastructure-generated revenue used for servicing debt (as a minimum requirement) and/or failure to obtain an adequate return on the investment (Kakimoto and Seneviratne 2000). Failure to meet either of the two aforementioned goals can be deemed as financial project failure. The investment risk directly depends on the infrastructure-generated costs and revenues, and is a key factor in determining the overall financial viability of a PPP project based on the expected operation characteristics and the proposed financing scenarios. Assessing the investment risk correctly and precisely to ensure the successful procurement of PPP projects is critically important.

Various studies have been carried out to develop methodologies to assess and quantify the financial viability of a project, such as the Net Present Value (NPV), the Internal Rate of Return (IRR), the Benefit-cost ratio (Profitability Index), Return on Equity (RoE) and the Payback Period (PBP). Among these methods, NPV and IRR are the most popular and widely accepted criteria used to measure the profitability of capital investments, with the profitability index applied in a secondary level of analysis (Keown *et al*. 2005). NPV is the difference between the present value of the expected cash inflows and the cash outflows, which compares the value of a dollar today to the value of that same dollar in the future, taking inflation and returns into account. IRR gives the profitability of an investment when NPV equals zero. NPV solves for the present value of a stream of cash flows, given a discount rate; while IRR solves for a rate of return when setting the NPV equal to zero. Thus NPV and IRR are related and will move together. A negative NPV indicates that the IRR is less than the cost of capital and the investment should be rejected; a positive NPV implies that the IRR is more than the cost of capital and the investment should be considered.

Several researchers used real option models to valuate infrastructure investments and PPP projects (Vandoros and Pantouvakis 2006; Blank *et al*. 2009; Lee 2011; Vajdić and Damnjanović 2011; Rakić and Rađenović 2014). Ye and Tiong proposed an NPV-at–risk method by combining the weighted average cost of capital and dual risk-return methods (Ye and Tiong 2000). Mohamed and McCowan came up with a methodology using interval mathematics and possibility theory to model the effects of both monetary and non-monetary aspects of an investment option (Mohamed and McCowan 2001). Jafarizadeh and Khorshid-Doust suggested the framework of mean-semideviation behavior, which has the advantage in the collective assessment of the firm's risk by all market participants (Jafarizadeh and Khorshid-Doust 2008). Pantelias and Zhang evaluated the financial viability of revenue-generating transportation infrastructure projects using the method of moments (Pantelias and Zhang 2010). There are also some toolkits developed by the Public Private Infrastructure Advisory Facility (PPIAF) and the World Bank, which are available online to analyse the viability of a project (PPIAF 2016). From the lenders' view, the investment risk and financial viability of the project depends on the ability to repay the issued debt, which also corresponds to the relationship between the project's costs and revenues during its life-cycle. Cover Ratios (CRs) are the criteria that measures the project's ability to repay the debts as they fall due. Annual Debt-Service Cover Ratio (ADSCR) and Loan-Life Cover Ratio (LLCR) are two of the most commonly used CRs. In practice, based on the perceived "riskiness" of the project, the minimum acceptable CRs are determined by the lenders and have to be fulfilled at all times for the project to be ultimately financed.

However, most of these methodologies are deterministic, which return a closed form solution indicating the viability of the project, and are not able to assess the potential investment risks. Risk assessment provides a way to estimate the probability that a project will meet its budget and time goals. Traditional risk assessment uses deterministic risk analysis, which is based on single point estimation and provides discrete outcomes, but no information on the likelihood of the outcome. Stochastic risk analysis integrates the range of possible values for each of the variables in analysis and provides the outcomes, as well as their likelihood, based on various combinations of different input data with different values, which can reflect the impacts of risks on the outcome more intuitively. There are different stochastic risk analysis techniques, such as the Bayesian algorithm, the MCS, and the fuzzy logic method. This paper formulates a flexible framework to perform stochastic risk analysis using MCS.

B.4 Monte Carlo Simulation

Monte Carlo Simulation (MCS) is a widely applied computational algorithm which is based on a repeated random sampling process to calculate numerical results. This method uses parameters which can reflect the probability density function of variables as inputs, and the repetitive calculations take the randomly selected combinations of the inputs into consideration. The outputs of the simulation are the results, which are presented in a cumulative density function or probability density function. Certain weaknesses exist within this technique: it can be time consuming if there are too many input variables and a large number of sampling is generated. Large variance may also be produced by the simulation.

In order to run MCS to conduct stochastic risk analysis, practitioners need to identify the input variables and their associated distributions, which usually can be obtained from historical data or based on empirical assumptions. Using the variables and associated distributions as the inputs, a sampling process is usually employed to simulate the distributions of output variables with a pre-specified number of iterations. Risks are assessed by comparing the output distributions with the targeted values of each output variable, e.g., the proportion of the output distribution that is less than the targeted value. MCS has been utilized in different areas to conduct stochastic risk analysis. Ridlehoover applied MCS and risk analysis to help solve facility location problem (Ridlehoover 2004). Arnold and Yildiz conducted economic risk analysis of decentralized renewable energy infrastructure using MCS (Arnold and Yildiz 2015). Da Silva Pereira et al. presented a methodology based on MCS to estimate the behaviour of economic parameters in power generation (Da Silva Pereira *et al*. 2014). Carrasco and Chang employed MCS and risk assessment for ammonia concentrations in wastewater effluent disposal (Carrasco and

Chang 2005). Au *et al*. utilized advanced MCS in conducting compartment fire risk analysis (Au *et al*. 2007). MCS has also been applied by rating agencies (e.g., Standard & Poor's and Moody's) to evaluate investment and credit risks at the country and industrial levels (Fender and Kiff 2004).

Based on the literature review, while MCS has been widely employed in the evaluation of infrastructure projects, there are few literature and studies on assessing investment risk of specific PPP highway projects. The objective of this paper is to apply this sophisticated technique to conduct stochastic risk analysis to numerically assess the investment risks associated with the tolled PPP highway projects. NPV, IRR and ADSCR (for both senior bank debt and combined debts) are selected to be the outcomes. The outcome values, as well as their probability distribution, are calculated and analysed. The results are compared with the deterministic values (no risk scenario), which should provide additional information to facilitate public agencies, private sectors, and lenders in making more insightful decisions regarding the financial viability of the project. This methodology can be applied to different scenarios where different combinations of risks are considered.

B.5 Methodology

In general, typical project financing risks include construction risk, operational risk, supply risk, offtake risk, repayment risk, political risk, currency risk, authorization risk, and dispute resolution risk. Studies have identified that the investment risk is a function of individual project risk, competitive risk, and market risk (Seneviratne and Ranasinghe 1997; Javid and Seneviratne 2000). Individual project risks can arise from inexperienced project contractors who may provide inaccurate and unreliable cost estimates and work-plan schedules. Competitive risks are caused by insufficient analysis prior to undertaking the project, which will lead to imprecise infrastructure-generated revenues and inaccurate estimates of the market shares of the project and its competitors. Market risks are the risks of losses in positions arising from movements in market prices. The methodological framework of this paper is presented in Figure B-1.

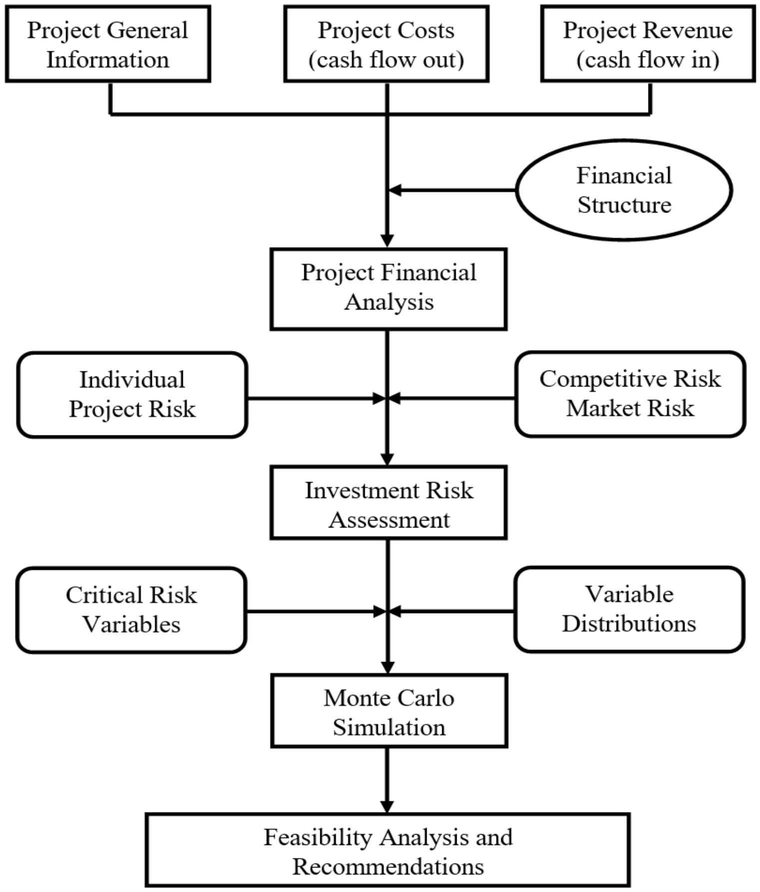


Figure B-1: Methodological Framework

More specifically, to illustrate the methodology, several types of investment risks are considered in this paper:

- Individual project risks: in which the risks in initial construction cost, initial operating cost, and maintenance and rehabilitation cost are considered;
- Competitive risks: the risks in initial Average Annual Daily Traffic (AADT) when predicting the traffic volume that will use the toll highway facility, and traffic growth rate; and
- Market risks: the Senior Bank interest rate, and initial estimate inflation rate.

Due to these risks, the variable values will fluctuate around the expected mean value rather than a deterministic number. In this paper, the impact of risks is simulated by setting an appropriate coefficient of variation (CV) and reasonable probability distribution of the variables. Different levels of uncertainties can be simulated and assessed by changing the coefficient of variation.

The equations to calculate NPV, IRR, and ADSCR are presented in Equations B.1 to B.4 respectively (PPIAF 2017 (b)).

$$NPV = \sum_{i=i_0}^{i_0+N} \frac{TCF_{i-i_0}}{(1+r)^{i-i_0}} \tag{B.1}$$

where:

TCF_{i-i_0} : the total cash flow for year $i-i_0$;

r : the appropriate discount rate;

i_0 : the project base year;

N : the end year of the concession.

Furthermore, the total cash flow can be calculated as:

$$\begin{aligned} TCF &= Total\ Revenues - Total\ Costs \\ &= Operating\ Revenues + Other\ Revenues - Construction\ Cost - Operation\ Cost \\ &\quad - Maintenance\ Cost - Rehabilitation\ Cost - Repay\ Debts - Other\ Costs \end{aligned} \tag{B.2}$$

For the IRR,

$$\sum_{i=i_0}^{i_0+N} \frac{TCF_{i-i_0}}{(1+IRR)^{i-i_0}} = 0 \tag{B.3}$$

where:

TCF_{i-i_0} : the total cash flow for year $i-i_0$;

i_0 : the project base year;

N : the end year of the concession.

In terms of ADSCR, the expression of the ADSCR for year $i-i_0$ is:

$$ADSCR_{i-i_0} = 1 + \frac{TCF_{i-i_0}}{\sum_{j=1}^{J} (Principal\ Repayment + Interest\ Payment)_j^{i-i_0}} \tag{B.4}$$

where:

j : the jth debt service;

J : total debt services.

B.6 Case Study

A case study was conducted to illustrate the proposed methodology and demonstrate how the methodology could serve as an analysis tool to help all stakeholders make decisions. The presented case study pertains to a real PPP highway toll road concession agreement, specifically a section (P12) from the Trans-Texas Corridor (TTC-35), which is a mega-project planned for implementation in the State of Texas. Although existing concessions were allowed to continue, the State Legislature stopped further development of the Trans Texas Corridor and placed a 2-year moratorium on new PPP projects due to some issues (KWTX 2005; KXII 2016; Taylor 2007).

Since the investment risks have been identified, the coefficients of variation (CV) and distribution were assigned to the variables to simulate the risk. CV is a dimensionless parameter and is used to describe the variability of the non-deterministic variables, which equal to the standard deviation divided by its expected mean value. Based on some of the unsuccessful experiences, it is likely that agencies might provide inaccurate estimates on the cost and revenue information (Cuttaree 2008; MnDOT 2016). In practice, the statistical CVs can be identified by translating massive historical cost- and revenue-related data through appropriate models, or based on assumptions that are supported by empirical analysis. Skitmore and Ng analysed 29 projects and showed that the CV of total project cost ranged from 15.90 percent and 31.29 percent, with an average cost of 22.06 percent (Skitmore and Ng 2002). Based on that, the CV of the initial construction cost is set to be 20 percent in this case study. Wright *et al*. studied 21 sites in Florida and found that the CV of AADT ranged from 8 percent to 22 percent (Wright *et al*. 1997). Other studies have indicated similar ranges (Turner *et al*. 1998; Aunet 2000). Therefore, the initial AADT and annual traffic growth rate are set with a CV of 15 percent and 10 percent, respectively. References on financial management also provided insightful information on various economic rates (Jain and Khan 2005; Brigham and Ehrhardt 2013). The CVs of inflation rate and discount rate are set at 10 percent, and the interest rate of senior bank debt has a CV of 5 percent.

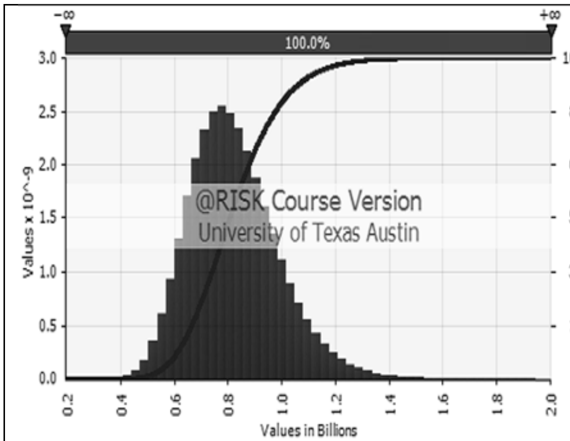
In terms of the variable distribution, according to various previous studies, the cost risk variable and market risk variable are assumed to have a lognormal distribution, while the initial AADT and annual traffic growth rate are placed as normally distributed (Wall 1997; Milterson *et al*. 1997; Piyatrapoomi *et al*. 2005; Van Haastrecht and Pelsser 2011; Baker and Trietsch 2013). Note that the CVs and distributions of each variable can be changed and customized depending on the available data and preference of the practitioners. The project P12 information is obtained from the original master development plan and summarized in Table B-1 (Pantelias 2009).

Table B-1: Project P12 Information

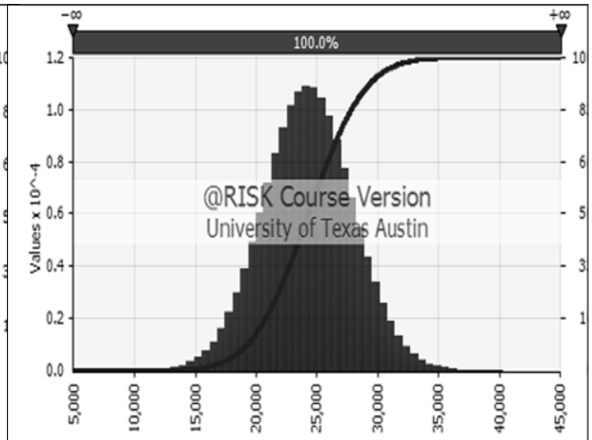
Project Parameters	Units	Mean	CV (%)	Comments
General Information:				
Concession Period	Years	50	N/A	
Construction Period	Years	5	N/A	
Project Length	Miles	57.0	N/A	
Number of Lanes per Direction	Number	3	N/A	Including shoulder
Project Cost:				
Initial Construction Cost (C_0)	$	822,330,824	20	Initial construction estimate= design cost + ROW[1] cost + structure cost. Lognormal distribution
Operation Cost	%	3.50	N/A	As a % of C_0, annual cost
Route Maintenance Cost	%	0.60	N/A	As a % of C_0, annual cost
Rehabilitation Cost	%	3.00	N/A	As a % of C_0, every 10 years
Annual Price Escalation Rate	%	2.5	10	Same with inflation rate
Traffic and Revenue:				
AADT	Vehicles	24,278	15	Initial estimate. Normal distribution
Cars	%	65	N/A	
Trucks	%	35	N/A	
Annual Traffic Growth	%	6.5	10	Normal distribution
Average Trip Length	Miles	30	N/A	
Average Transaction per Trip	Number	1.3	N/A	
Average Transaction Cost	$/veh/transaction	0.15	N/A	Per vehicle per transaction
Toll Rate for Cars	$/car/mile	0.152	N/A	Per car per mile
Toll Rate for Trucks	$/truck/mile	0.585	N/A	Per truck per mile
Annual Toll Rate Growth	%	2.5	10	Same as inflation rate
Economic Variables:				
Inflation Rate	%	2.5	10	Initial estimate. Lognormal distribution
Discount Rate	%	12	10	Target value for private sectors
Financing Variables:				
Construction Capital Draw				
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	
TIFIA[2] Loan	%	33		As a % of total construction costs
Interest Rate	%	5.10	N/A	
Grace Period	Years	11	N/A	
Payback Period	Years	35	N/A	
Payment Terms	Interest plus principal in equal instalments after end of grace period, minimum principal payment of $1,000,000			
Senior Bank Debt	%	47		As a % of total construction costs
Interest Rate	%	5.55	5	Lognormal distribution
Grace Period	Years	5	N/A	
Payback Period	Years	40	N/A	
Min ADSCR	Number	1.75x	N/A	Required and targeted value
Payment Terms	No payments during grace period, interest plus principal after the end of grace period			
Combined Debt Min ADSCR	Number	1.10x	N/A	Required and targeted value
Developer's Equity	%	20	N/A	As a % of total construction costs

ROW[1]: Right of Way.
TIFIA[2]: Transportation Infrastructure Finance and Innovation Act.

The distributions of initial construction cost and AADT are illustrated as two examples of the input variables, which are presented in Figure B-2.



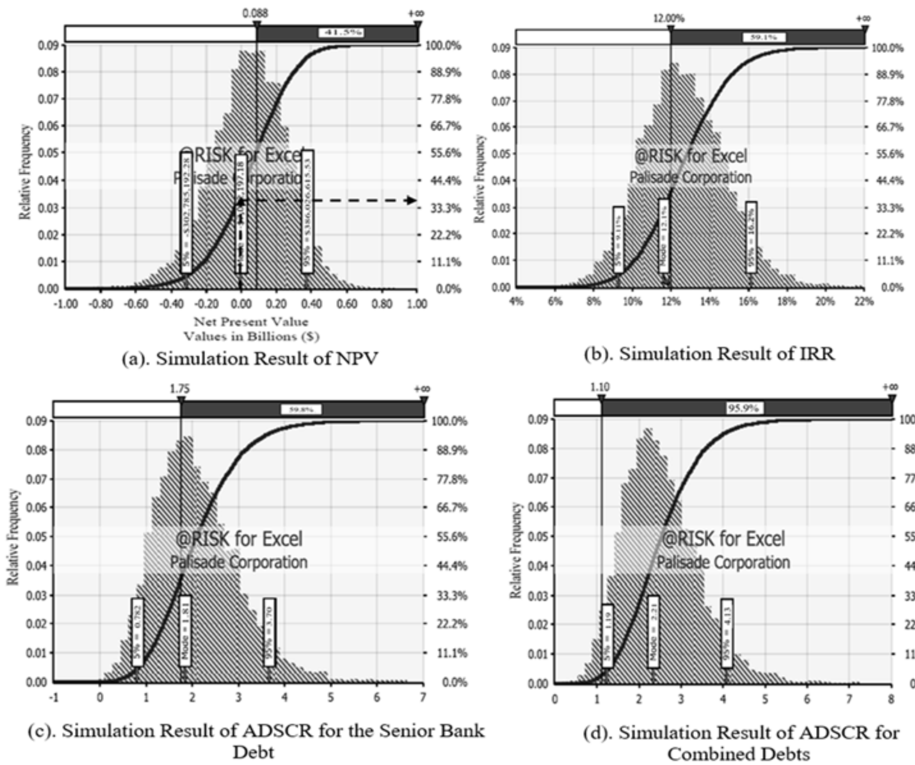
(a) Input Distribution for Initial Construction Cost



(b) Input Distribution for Initial AADT

Figure B-2: Input Distribution Examples

Based on Equation (B.1) to Equation (B.4), MCS was conducted using the software, @Risk® 6, developed by Palisade Corporation. Technically speaking, the greater the number of iterations performed, the better the precision of the method. The results will converge after a certain number of iterations. In order to better reflect the investment risks and obtain more accurate results, 10,000 iterations were performed. Risk simulation results on NPV, IRR and ADSCRs are presented in Figure B-3 (a) to (d), respectively.



(a). Simulation Result of NPV

(b). Simulation Result of IRR

(c). Simulation Result of ADSCR for the Senior Bank Debt

(d). Simulation Result of ADSCR for Combined Debts

Figure B-3: Simulation Results

B.7 Findings and Discussions

As can be seen from the simulation results, rather than a deterministic value, the relative frequency (left y axis) and the cumulative percentage curve (right y axis) are provided for each of the outcomes. The larger the relative frequency is, the more likely it is that the outcome will occur. The decision making process is conducted by adjusting the delimiters in the analysis tool. Agencies can adjust the positions of delimiters to analyze the probability of achieving their objective returns. Take Figure B-3 (a) as an example: if the target NPV is $88 million, then there is a possibility of 41.5 percent to make the NPV equal or larger than the expected value. In other words, there is a probability of 58.5 percent to fail this target. The output also indicates that the NPV has a mean of $45.8 million, and there is a probability of 36.1 percent for negative NPV. Figure B-3 (b) shows the behaviour for IRR. The most likely value, with an 8.4 percent probability of occurrence, is around 12.1 percent. There is a probability of 59.1 percent to obtain an IRR which is equal to or above 12 percent. Since 12 percent is the target value for private sectors (see Table B-1), there is a probability of 40.9 percent to fail the target because of the risks. Based on Figure B-3 (c) and (d), debtors could have an overall estimation of the project's ability to meet the annual debt payment. According to Table B-1, the minimum ADSCRs for Senior Bank Debt and combined debts are 1.75 and 1.10, respectively. Figure B-3 (c) shows that the probability of the project to meet the Senior Bank Debt's ADSCR requirement is 59.8 percent, and Figure B-3 (d) suggests that there is a 95.9 percent probability that the project can meet the combined debts' ADSCR requirement. This indicates that the project can be considered to reliably repay the combined debts. The private investors and senior banks should be aware of the risks and make cautious decisions regarding this. Furthermore, the results using deterministic values are calculated, and both results are summarized and listed in Table B-2.

Table B-2: Results Comparison

Evaluation Method		**Comparison of Results**			
		NPV ($million)	**IRR (%)**	**ADSCR for Senior Bank Debt**	**ADSCR for Combined Debts**
Deterministic Analysis		$45.4	12.4	1.94	2.38
Risk Simulation	Mean	$45.8	12.5	2.03	2.48
	Standard Deviation	$272.47	2.46	1.015	0.992
	Probability to Fail	36.1%	40.9%	40.2%	4.1%
t-statistic		0.002	0.041	0.089	0.101

According to Table B-2, the mean values from risk simulation are close to those from deterministic analysis. In addition, all the t-statistic values are less than 1.96, indicating that the deterministic analysis and stochastic analysis are not significant at a 95 percent confidence level. The deterministic values cannot reflect the potential investment risk; while the stochastic analysis provides the distributions of the outputs, which makes the investor more insightful. In the deterministic (no risk) scenario, all four indices indicate that the project is profitable and feasible. However, investors should aware that there is a probability to suffer a deficit when the investment risks are considered.

It also can be noticed that the failure probabilities for NPV, IRR and ADSCR for Senior Bank debt are high. This is because this paper involves too many risk factors and only toll-generated revenues for illustration purposes. Generally speaking, the more uncertainties there exist in a project, the higher the failure probability will be. The failure probabilities will be reduced if only one or some of the risks are concerned. Considering that the initial construction is $822 million, the target IRR is 12 percent, and various risks involved in this case study, the project is acceptable, but may not be so attractive to the investors under so many risk factors. For the lenders, the project can reliably repay the combined debts. Although it might be unbalanced since some factors are not considered in the simulation process, the case study illustrates how the risk simulation conception works, as well as the process of investment risk assessment. The agencies can assess certain project-based risks using this methodology and make the decision practically. Minimization approaches for each type of risk are suggested for stakeholders as listed in Table B-3 (Marques and Berg 2011). An input variable with lower risk should concentrate around its mean value with a smaller CV value.

Table B-3: Minimization Approaches for Each Type of Risk

Risks	Minimization Approaches
Capacity	Increase studies accuracy; Cost-benefit analysis
Competition	Sensitivity analysis; Public disclosure of indicators
Conception	Careful selection of project designers; Realism in studies planning; Auditing studies and projects; Contracts with premiums and fines
Construction	Strict management; Fixed-price contracting; Insurance contracting
Collection	Sensitivity analysis; Service interruption; Making payment easier; Customers and collection management
Demand (consumption)	Sensitivity analysis; Sensitizing actions; Making payment easier
Environmental	Sensitizing actions; Supervision and research; Pressure near the authorities
Expropriation	Experienced work teams; Project compatibility; Fixed-price contracting
Financial	Long-term financing; hedging polices; backup funding(bank account)
Force majeure	Mostly protected; Insurance contracting
Inflation	Indexation of revenues to inflation; Fixed-price contracting; Forward contracts
Legal	Protected by contract
Maintenance/repairs	Association to specialized companies; Fixed-price contracting; Insurance contracting
Operation	Association to specialized companies; Fixed-price contracting; Insurance contracting
Performance	Systematic control; Fixed-price contracting
Planning	Careful selection of project designers; Increase detail in studies
Public contestation	Sensitivity analysis; Public disclosure of indicators
Regulation	Keep with international trend; Systematic control of performance; Benchmarking policies
Technological	Contracts with warranties; Insurance contracting
Unilateral changes	Protected by contract

B.8 Conclusions

PPPs have been widely applied over the years, and certain lessons have been learned. Both public authority and private sectors should pay attention to common problems that occur during the PPP process, such as risk and reward allocation, public and private sector capacity evaluation, project governance, and affordability issues. This paper presents a methodological framework for assessing the investment risks associated with PPP toll highway projects. Instead of a deterministic value, the distributions of the variables are used as inputs to simulate the risks. NPV, IRR, and ADSCR are commonly-used criteria for the investors and lenders to evaluate the project's financial viability and ability to repay the debts. A detailed case study of a section (P12) from the Trans-Texas Corridor (TTC-35) was conducted. The results are interpreted so that quantitative information was provided to agencies to establish investment decision criteria. The stochastic risk analysis helps agencies to make more insightful decisions.

The proposed framework works in conjunction with other models, such as cost and revenue prediction models. The procedures are flexible for practitioners to adopt. The CV and distribution of an input variable are not limited to a specific value or form. Instead, practitioners can customize input variables associated with their CV and distribution based on available data or professional judgement in practice. Multiple simulations can be run with different CVs and distributions to assess different levels of risks, allowing "what-if" scenarios to be studied. The methodology can serve as a basis for future research. There are a few directions on which future research can embark and improve the presented framework and corresponding results, including: simulate the cost risk at the line item level, namely to model operating cost, maintenance cost, and rehabilitation cost as independent costs with individual CV and distribution; and incorporate uncertainties in willingness to pay and toll elasticity in the revenue risk evaluation.

Appendix C

Paper 3: Incorporating Uncertainties into Determination of Optimal Pavement Preventive Maintenance Intervals

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C.1 Abstract

The continual pavement deterioration creates ongoing problems in providing adequate transportation services. Conducting appropriate preventive maintenance (PM) with optimal intervals not only preserves the pavement at a desired performance level, but also provides a cost-effective approach to economizing maintenance budget. Due to the complexity of obtaining closed-form solutions under uncertainties, simulation techniques have been utilized to determine the optimal PM intervals. This paper applies the Fourth Order Method of Moments to determine optimal PM intervals based on pavement reliability. The proposed methodology contributes to cases where the distributions for characterizing variable uncertainties are unknown or difficult to identify due to defective data. The results showed that the proposed method is capable of incorporating uncertainties into the analytical process of obtaining optimal PM cycles through closed-form solutions. The sensitivity analysis provided insightful information on how the changes in PM or rehabilitation cost would influence the choice of optimal PM intervals.

Keywords: pavement, preventive maintenance, optimal interval, method of moments, reliability.

C.2 Introduction

Over the past decades, the traffic volumes on primary highway systems have experienced tremendous increases, leading in many instances to premature failures of highway pavements. In addition, the aging of the existing highway systems, especially those built during the 1950s and 1960s, has resulted in the expenditure of a large portion of highway funds on pavement maintenance and rehabilitation. Practically, transportation agencies understand that a pavement should not be allowed to deteriorate to the point at which rehabilitation is necessary. It is more worthwhile to perform preventive maintenance (PM) or a combination of PM and rehabilitation to keep the pavement condition above an acceptance level. Rehabilitation, defined as corrective treatment that extends the service life of an existing pavement and/or improves its structural capacity through structural enhancements, is often much more expensive than PM in terms of its impact on agency resources and traffic disruptions (extensive and extended lane closures). Compared with rehabilitation, PM provides a relatively cost-effective alternative for pavement preservation without increasing structural capacity. Therefore, more and more transportation agencies are adopting PM treatments, especially when faced with increasing road-user expectations, higher traffic loading, aging infrastructure, and limited maintenance funding.

There are different types of pavement PM techniques, and it is important to select an appropriate technique based on project-specific information. Just as important as the selection of techniques is the selection of a PM interval. Numerous research has focused on PM along with its interval (Mamlouk and Zaniewski 1998, Hicks *et al*. 1999, Johnson 2000, Peshkin *et al*. 2004). More recently, Lamptey *et al*. (2008) suggested that optimization could be a valid tool to help make decisions on highway PM scheduling. They presented a case study for optimizing decisions on the best combination of PM treatments and timings to be applied in the resurfacing life-cycle for a given highway pavement section (Lamptey *et al*. 2008). Guan *et al*. (2008) and Li *et al*. (2010) introduced methodologies for PM treatment selection and the optimal timing based on matter element analysis (Guan *et al*. 2008; Li *et al*. 2010). Weiguo (2010) proposed a methodology of net annual value difference to assess the contribution value of PM to roadway life-cycle costs and benefits (Weiguo 2010). Haider and Dwaikat (2011) developed Area 2T Model to estimate optimum timing of different maintenance treatments (Haider and Dwaikat 2011). Harvey *et al*. (2012) investigated a probabilistic approach to addressing the influence of PM. The results revealed that, compared with rehabilitation alone, PM reduced long-term cost of pavement maintenance (Harvey *et al*. 2012).

One of the challenges for determining the optimal PM interval is how to appropriately deal with various assumptions and uncertainties, such as assumptions made to simplify the behavior of pavement characteristics and uncertainties associated with material properties. Due to these uncertainties, it is difficult to predict the performance of a pavement with absolute certainty. Researchers have explored different methodologies to solve this problem, such as Monte Carlo Simulation (MCS), Taylor Expansions, and Markov Chain. Among these methods, MCS has been widely utilized in different research areas because of its accuracy and practicability. Mills *et al*. (2011) applied a hierarchical Markov-chain MCS to model the propagation of transverse cracks and predict the spread of the transverse cracks without neglecting uncertainty (Mills *et al*. 2011). Dilip and Babu (2012) studied the pavement design reliability and back analysis by using the Markov-chain MCS (Dilip and Babu 2012). Other probabilistic models, such as First-Order Reliability Method and Second-Order Reliability Method, are also commonly applied (Melchers 1999, Ang and Tang 2007, Deshpande *et al*. 2009).

Recently, the method of moments (MOM) has proven to be a feasible closed-form alternative to analyze the reliability. Madsen *et al*. (2006) used the reliability method to evaluate the complex *n*-dimensional probability integral (Madsen *et al*. 2006). Zhang and Damnjanovic (2006) applied the MOM to model the reliability of pavement infrastructure. The results showed that the MOM represents a viable approach to estimating the failure probability (Zhang and Damnjanovic 2006). Pantelias and Zhang (2010) used the MOM to evaluate the financial viability of revenue-generating transportation infrastructure projects in terms of investment risk (Pantelias and Zhang 2010). Ma *et al*. (2014) employed the MOM to model the reliability of deteriorating performance to asphalt pavement under freeze-thaw cycles in cold regions (Ma *et al*. 2014). As for the accuracy of the method of moments, Zhang and Damnjanovic (2006) indicate that the Fourth Order Method of

Moments (4M) yields the most accurate predictions of failure probability; in general, the quality of estimation improves as the order of moments increases (Zhang and Damnjanovic 2006).

Based on the literature review, there are few studies on determining optimal PM interval through reliability-based approach. The main objectives of this paper are to:

- Deal with situations where the specific distributions for characterizing variable uncertainties are unknown or difficult to identify due to defective information or data;
- Apply the 4M to quantitatively characterize the time-dependent pavement reliability, taking into consideration uncertainties associated with input variables;
- Determine the optimal PM intervals by utilizing the cost per unit time (CPUT) function; and
- Explore the impact of PM and rehabilitation cost on optimal PM interval.

The proposed reliability-based methodology can help transportation agencies develop better understanding of the optimal intervals and make more cost-effective PM scheduling decisions.

The remaining sections of this paper are organized as follows. Section C.3 introduces some key concepts. Section C.4 presents the methodological framework. Section C.5 focuses on the procedure of problem solutions step by step. Section C.6 provides a numerical study to illustrate the proposed methodology. Section C.7 introduces a sensitivity analysis to explore the impact of changes in PM and rehabilitation costs on optimal PM interval. Finally, Section C.8 provides the conclusions and recommendations.

C.3 Key Concepts

C.3.1 Reliability Theory

Reliability is defined as the probability that a component or system will perform a required function for a given period of time when used under stated operating conditions (Ebeling 2004). One of the most traditional structural reliability methods is the stress-strength (load-capacity) inference method. The term “stress” refers to any applied load or load-induced response quantity that has the potential to cause failure. The term “strength” can be considered as the capacity of the system to withstand the applied “stress.” This method compares a random variable that defines the level of capacity with another random variable that specifies the applied loads. A failure occurs when the level of load exceeds that of capacity. A conceptual representation of the stress-strength inference method is illustrated in Figure C-1 (Sundararajan 2012; Ditlevsen and Madsen 1996).

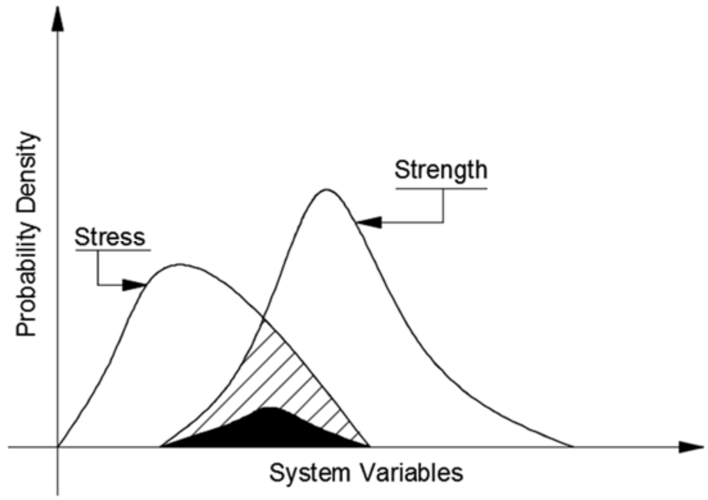

Figure C-1: Conceptual Illustration of Stress-Strength Inference Method

As shown in Figure C-1, the failure occurs in the overlapped (shaded) area of stress and strength distributions. It should be pointed out that the overlapped area is not equal to the failure probability. However, as long as the mean value of stress is less than the mean value of strength, the failure probability (the black area) is qualitatively proportional to the overlapped area. Mathematically, the reliability is formulated in terms of n basic random variables $X = [x_1, ..., x_n]^T$ and a time-dependent limit state function $G(X,t)$, where x denotes a vector of basic variables and t represents the time. The limit state function is expressed as:

$$G(X,t) = Strength - Stress \tag{C.1}$$

With a defined limit state function, the failure is expressed as an event $\{G(X,t) \le 0\}$. The probability of failure can be established as an n-dimensional probability integral:

$$F(t) = P(failure) = P[G(t) \le 0] = P(strength \le stress) = \int_{G(X,t)\le 0} g(X,t)dt \tag{C.2}$$

Where $g(X,t)$ is the joint probability density function of the basic random variable X.

In this paper, the stress of a pavement comes from traffic loading, and is represented by the accumulated number of equivalent single axle loads (ESALs). The strength of a pavement is defined as the amount of ESALs a pavement is designed to withstand over its design life. It needs to be pointed out that the design method and equation for flexible pavement and rigid pavement are different. This paper applies the widely-used 1993 American Association of State Highway and Transportation Officials (AASHTO) design method for flexible pavements to execute the proposed methodology. Each of the stress and strength functions can be represented by a set of independent random variables.

C.3.2 Method of Moments (MOM)

Even if the strength and stress functions are well defined, it is very difficult to solve the integral described in Eq. C.2 analytically, except for a few special forms of the strength and stress functions. Simulation-based approximation techniques (e.g., MCS) have been used to obtain open-form solutions, yielding all possible output values along with their probability distributions. However, MCS is a computational algorithm that relies on repeated random sampling to determine open-form numerical results. The accuracy depends on the distribution of the variables and the sample size, making it difficult to implement when the true distributions of the variables cannot be determined with information available.

On the other hand, First-Order Reliability Method (FORM) is an analytical method based on the linear approximation of a nonlinear limit state at the design point. The primary advantages of FORM are its analytical traceability and satisfactory level of accuracy, even for extremely small probabilities, whereas its shortcomings include its lack of accuracy for highly nonlinear limit state functions and its difficult iteration-based process of searching for the design point (Damnjanovic 2006). FORM shortcomings can be addressed by using Second-Order Reliability Method (SORM) and other high orders of moments.

The MOM, which was originally proposed by Zhao and Ono to analyze the reliability of structural systems, is able to solve these problems. MOM uses central moments to address complex estimations, especially multidimensional integrals like Eq. C.2 (Zhao and Ono 2001). The procedure requires neither the computation of derivatives or mutual correlations among failure modes, nor the determination of the design point (Zhao and Ang 2003). As previously mentioned, MOM has been applied to estimate failure reliability by several researchers (Zhang and Damnjanovic 2006, Pantelias and Zhang 2010, Ma *et al.* 2014).

Compared with other methodologies, MOM has the advantages that it is an efficient and computationally effective procedure that uses information from high-order moments to determine reliability indices for complex nonlinear limit state functions with many basic random variables. MOM represents a robust and universal approach to estimating reliability functions because it can accommodate different types of failure mechanisms and transfer functions in the limit state function (Zhang and Damnjanovic 2006). Additionally, MOM uses only the mean and coefficient of variation (CV) of the input variables, and no assumptions on variable distributions are needed. This makes MOM beneficial in cases where the variable distributions are unknown and difficult to identify due to defective data. MOM is able to offer solutions in a closed-form with high accuracy (Rosenblueth 1975). Considering that the estimation accuracy increases as the order of moments becomes higher, this paper applies the fourth-order of moments (4M) to analyze the limit state function of reliability.

C.3.3 Preventive Maintenance (PM)

According to Federal Highway Administration (FHWA), preventive maintenance was defined in 1997 by the AASHTO Standing Committee on Highway as "a planned strategy of cost effective treatments to an existing roadway system and its appurtenances that preserves the system, retards future deterioration, and maintains or improves the functional condition of the system (without increasing structural capacity)" (FHWA 2016). Although effective preventive maintenance has some positive effects on different structural problems, its main purpose is to address potential or existing functional problems instead of increasing the structural capacity. Pavement PM techniques include treatments such as seal coats, micro-surfacing, crack sealing, and thin asphaltic concrete pavement overlays, etc. Different techniques have different costs. In practice, PM techniques are project-based, where each treatment alternative should be carefully selected based on specific project details.

According to Ebeling (2004), PM can reduce aging or wearout and have a significant impact on the life of a system. Let *R(t)* be the pavement reliability without maintenance, *T* be the interval of time between PM activities, and $R_m(t)$ be the reliability of the pavement with PM. The relationship becomes:

$$R_m(t) = R(t) \qquad \text{for } 0 \le t < T \tag{C.3}$$

and $$R_m(t) = R(T)R(t-T) \qquad \text{for } T \le t < 2T \tag{C.4}$$

where *R(t)* is the probability of survival until the first PM and *R(t-T)* is the probability of surviving the additional time *t-T* given that the pavement was restored to its original condition at time *T*. The cumulative reliability during the *n*-th PM interval becomes (Ebeling 2004):

$$R_m(t) = R(T)^n R(t-nT) \quad \text{for } nT \le t < (n+1)T \quad n = 0,1,2\ldots \tag{C.5}$$

where $R(t)^n$ is the probability of surviving *n* maintenance intervals and *R*(*t-nT*) is the probability of surviving $t-nt$ time units past the last PM. The original, cumulative, and PM activity reliability curves of pavement under periodic PM are illustrated in Figure C-2.

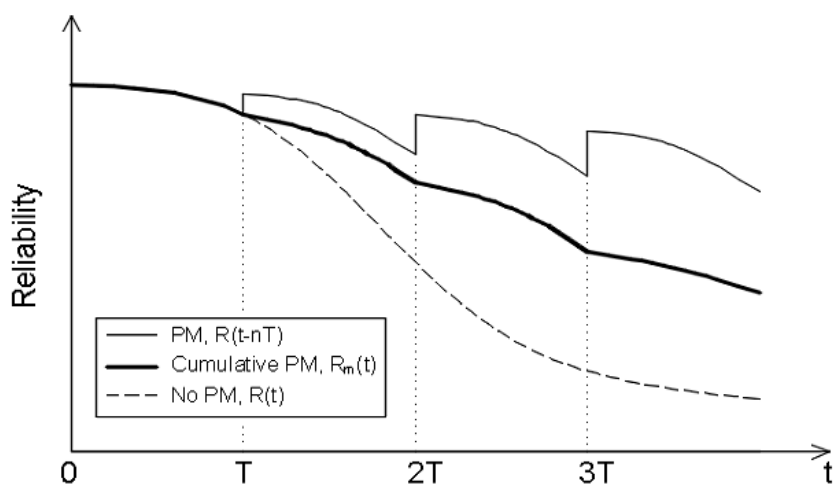

Figure C-2: Pavement Reliability under Periodic PM

It can be observed from Figure C-2 that the original reliability (without PM) decreases with time due to continuous aging and deterioration. However, PM itself is able to restore the pavement reliability to a certain high value. Therefore, the actual reliability of a pavement with PM can be presented by a cumulative curve ($R_m(t)$), which combines the original pavement reliability and the effects of PM treatments. The cumulative reliability curve monotonically decreases with time but much slower than the original reliability without any PM treatments, indicating that PM has cumulative impacts on retarding pavement deterioration. Rehabilitation treatments are needed when the cumulative reliability curve falls below a certain value after several PM cycles.

C.3.4 Optimal PM Interval

PM is a cost-effective approach to extending pavement life and minimizing the life-cycle costs of pavements by efficiently arranging the timing and funding for PM, rehabilitation, and other activities (Geoffroy 1996). The idea of optimal PM intervals comes from the trade-off that, regardless of the pavement PM techniques selected, the cost per unit time (CPUT) of performing PM treatments would be high when a PM treatment is conducted too frequently, i.e., the interval between two consecutive PM treatments is too small. On the other hand, performing PM reduces the probability of pavement failure, which, in turn, decreases the CPUT for risk cost. Risk cost changes over time and is defined as the cost of rehabilitating or restoring the pavement when it fails multiplied by the probability of failure occurrence. In other words, when the PM interval is small, the CPUT for PM is high but the CPUT for risk cost is low. As the interval increases, the CPUT for PM decreases because fewer PM treatments are performed, and the CPUT for risk cost increases since the pavement becomes more susceptible to failures. As a result, the total cost, which is the sum of CPUT for both PM cost and risk cost, should present a “V” shape. The optimal PM interval corresponds to the point which minimizes the total CPUT cost (Levitt 2003). Figure C-3 shows a conceptual illustration of the optimal PM interval.

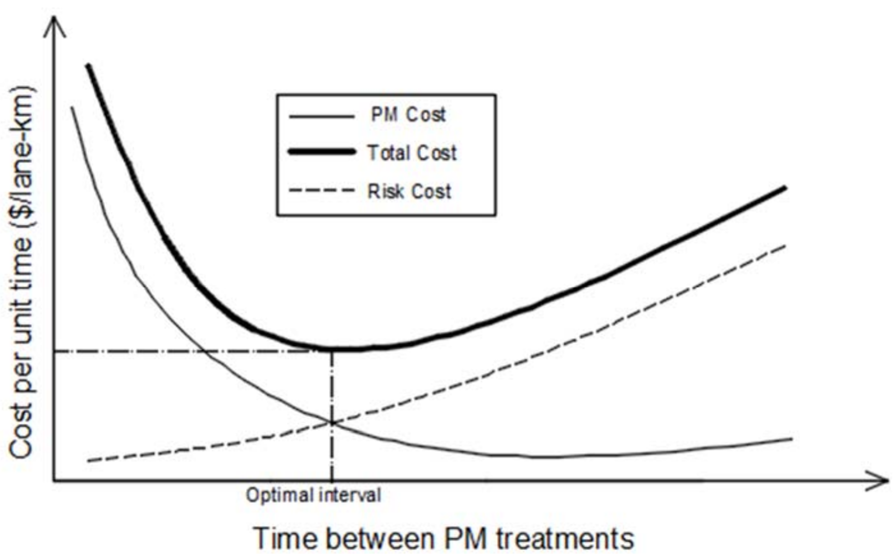

Figure C-3: Conceptual Illustration of Optimal PM Interval

It needs to be pointed out that this paper uses agency CPUT for PM treatment and rehabilitation activities. It does not include user cost because of the variability by project and by application of the state Department of Transportation (Salem and Genaidy 2008).

C.4 Methodological Framework

The conceptual framework of the proposed methodology is presented in Figure C-4. Variables that affect the strength and stress of a pavement are first defined, and then the corresponding functions representing the strength and stress are mathematically formulated. Based on the formulated functions for the strength and stress, the limit state function is defined, which serves as the basis for determining the reliability of the pavement. With the defined limit state function, the time-dependent failure probability and corresponding reliability of the pavement are defined. Then, the failure probability and corresponding reliability are obtained by employing the method of moments (4M). Using the obtained pavement reliability and identified representative costs for PM treatments and rehabilitation activities, the CPUT function is formulated from which the optimal PM interval can be obtained by searching for the PM interval that yields the lowest CPUT.

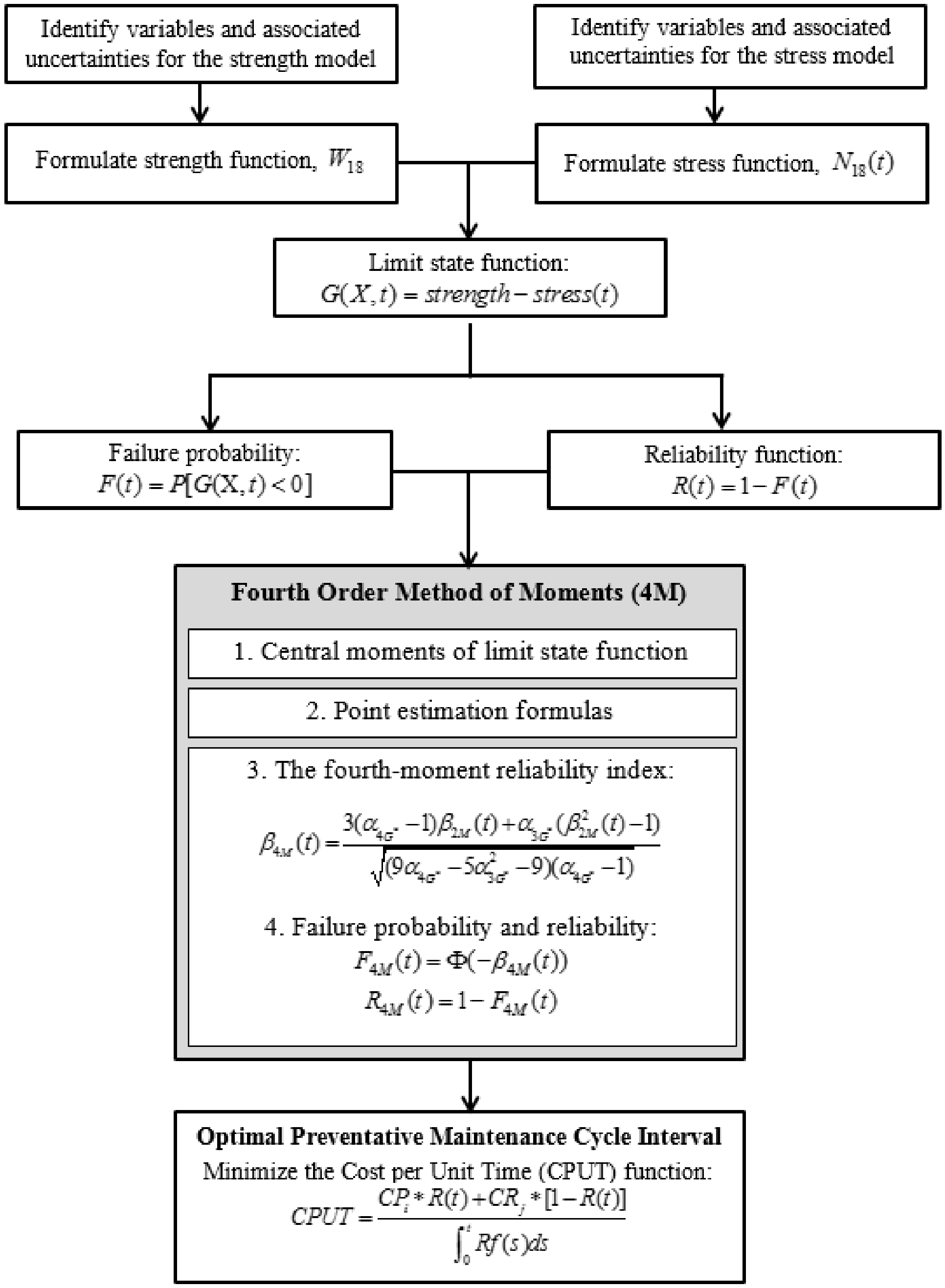

Figure C-4: Conceptual Framework of Proposed Methodology

C.5 Problem Solution

C.5.1 STRENGTH FUNCTION

Although different pavement design approaches have been proposed over years, the AASHTO 1993 Design Method remains one of the most widely used guidelines for designing flexible pavement structures (Grawford 2009). Although the AASHTO 1993

Pavement Design Guide is used in this paper to illustrate the application of the proposed methodology, the proposed methodology can be readily applied to other design guides or models, such as National Cooperative Highway Research Program (NCHRP) or Mechanistic-Empirical Pavement Design Guide (MEPDG) calibrated models.

Based on the AASHTO 1993 pavement design equation, the strength of a pavement is a function of its structural number (SN), reduction in serviceability level (ΔPSI), and subgrade resilient modulus (M_r). The equation for the strength of a flexible pavement is given as:

$$\log W_{18} = Z_R \times S_0 + 9.36\log(SN+1) - 0.20 + \frac{\log(\frac{\Delta PSI}{4.2-1.5})}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32\log M_r - 8.07 \tag{C.6}$$

Where:

W_{18} = allowable number of the equivalent 18-kip single-axle loads ($ESALs$);

Z_R = standard normal deviate;

S_0 = combined standard error of the traffic prediction and performance prediction;

ΔPSI = reduction of the serviceability index;

SN = structural number of the pavement; and

M_r = subgrade resilient modulus (in psi).

The structural number presents the structural strength of a pavement and can be computed as (AASHTO 1993):

$$SN = a_1 \times D_1 + a_2 \times D_2 \times m_2 + a_3 \times D_3 \times m_3 \tag{C.7}$$

Where:

a_1, a_2 and a_3 = layer coefficients of surface, base, and sub-base, respectively;

D_1, D_2 and D_3 = layer thickness of surface, base, and sub-base, respectively (in inches, 1 inch = 2.54 cm); and

m_2 and m_3 = drainage coefficient for the base course and sub-base course, respectively.

These coefficients are indicators of material's relative ability to function as a structural component in an asphalt pavement, their values can be obtained by using empirical equations derived from field experiments.

ΔPSI is the difference between the initial design serviceability index (PSI_i) and the design terminal serviceability index (PSI_t):

$$\Delta PSI = PSI_i - PSI_t \tag{C.8}$$

C.5.2 Stress Function

The stress function can be defined as the accumulated number of 18-kip (80 kN) ESALs during the elapsed time period. According to the AASHTO (1993) pavement design process, the stress function adopted in this paper is a time-dependent function, which includes traffic volume, truck flow, truck factor, traffic growth factor, directional factor, and lane distribution. The stress function is expressed as:

$$N_{18}(t) = (ADT_0)(T)(T_f)(G)(D)(L)(365) \tag{C.9}$$

Where:

$N_{18}(t)$ = the cumulative $ESALs$ applied at year *t*;

ADT_0 = initial average daily traffic on the section of pavement;

T = percentage of trucks;

T_f = truck factor;

G = growth factor;

D = directional factor;

L = lane distribution factor, which is the percentage of vehicles on heaviest loaded lane; and

t = number of years during the analysis.

The traffic growth factor G is a function of growth rate g and are expressed as (AASHTO 1993; Huang 2004):

$$G = \frac{(1+g)^t - 1}{g} \tag{C.10}$$

Where:

g = annual growth rate.

The truck factor T_f can be obtained by the equation:

$$T_f = (\sum_{i=1}^{m} p_i F_i)A \tag{C.11}$$

Where:

p_i = percentage of total repetitions for the *i*th load group;

F_i = equivalent axle load factor for the *i*th load group; and

A = average number of axles per truck.

Once a pavement is constructed, the directional factor D and lane distribution factor L are determined as a fixed value with no variances. Therefore, they are regarded as deterministic values or constants instead of input variables.

C.5.3 Fourth Order Method of Moments (4M)

Upon the definition of strength function (Eq. C.6) and stress function (Eq. C.9), Eq. C.1 can be written as:

$$G(SN, \Delta PSI, M_r, ADT_0, T, T_f, g, t) = strength - stress(t) = \log W_{18} - \log N_{18}(t) \tag{C.12}$$

With further expansion, $G(SN, \Delta PSI, M_r, ADT_0, T, T_f, g, t)$ can be expressed as:

$$G(SN,\Delta PSI,M_r,ADT_0,T,T_f,g,t)=Z_R\times S_0+9.36\log(SN+1)-0.20+\frac{\log(\frac{\Delta PSI}{4.2-1.5})}{0.40+\frac{1094}{(SN+1)^{5.19}}}+2.32\log M_r$$
$$-8.07-\log ADT_0-\log T-\log T_f-\log((1+g)^t-1)+\log g-\log D-\log L-\log 365$$
(C.13)

The failure domain G' is defined as $\{G(SN,\Delta PSI,M_r,ADT_0,T,T_f,g,t)\leq 0\}$. Consequently, the time-dependent probability integral can be defined as:

$$F(t)=\int_{G'}f(SN,\Delta PSI,M_r,ADT_0,T,T_f,g,t)dSN\,d\Delta PSI\,dM_r\,dADT_0\,dT\,dT_f\,dg$$
(C.14)

Where:

$f(SN,\Delta PSI,M_r,ADT_0,T,T_f,g,t)$ is the joint probability density function of $SN,\Delta PSI,M_r,ADT_0,T,T_f$ and g.

Finally, the reliability function becomes:

$$R(t)=1-F(t) \quad \text{(C.15)}$$

In order to obtain solutions Eq. C.14 and Eq. C.15, the central moments of the time-dependent limit state function $G(X,t)$ are used, which can be expressed as (Damnjanovic 2006):

$$\mu_G(X,t)=\int G(X,t)f(X,t)dX \quad \text{(C.16)}$$

$$M_{kG}(X,t)=\int(G(X,t)-\mu_G)^k f(X,t)dX \quad \text{for } k\geq 2 \quad \text{(C.17)}$$

Where:

μ_G and M_{kG} are the mean and the *k*-th central moment of $G(X,t)$.

Since it is too complex to determine an accurate and analytically tractable solution to the integral equations (Eq. C.14), the central moment is introduced by choosing a finite number of points and their corresponding weights (Christian and Baecher 1999; Zhao and Ono 2000 (a)).

$$M_{kX}=\sum_{j=1}^{J}P_j(u_j-\mu_X)^k \quad \text{(C.18)}$$

Where:

u_j represents the *j*-th estimating point and P_j stands for the corresponding weight.

This paper applies a seven-point estimation for a higher level of accuracy when compared to a five-point estimation. The estimation points $u_1,...,u_7$ and their corresponding weights $P_1,...,P_7$ are readily determined and presented in Table C-1 (Zhao and Ono 2000b, Zhao and Ang 2003).

Table C-1: Seven Estimation Points and Corresponding Weights in Standard Normal Space

Point Number (j)	Estimating Point (u_j)	Corresponding Weight (P_j)
1	0	0.4571429
2	1.1544054	0.2401233
3	-1.1544054	0.2401233
4	2.3667594	3.07571×10^{-2}
5	-2.3667594	3.07571×10^{-2}
6	3.7504397	5.48269×10^{-4}
7	-3.7504397	5.48269×10^{-4}

By using Hermit integration and the inverse Rosenblatt transformation, Eq. C.18 can be rewritten as:

$$M_{kX} = \sum_{j=1}^{J} P_j (G[T^{-1}(u_j)] - \mu_X)^k \tag{C.19}$$

Where:

$T^{-1}(u_j) = F^{-1}[\Phi(u_j)]$;

F = the cumulative distribution function of the random variable;

Φ = the cumulative standard normal probability; and

$T^{-1}(u_j)$ = stands for the inverse Rosenblatt transformation at the estimating point u_j.

To solve the computational problem, the approximated limit state function $G^*(X,t)$ can be expressed as (Zhao and Ono 2001):

$$G^*(X,t) = G^* = \sum_{i=1}^{n} (G_i - G_\mu) + G_\mu \tag{C.20}$$

Where:

$G_\mu = G(\mu)$ and $G_i = G[T^{-1}(u)] = G[\mu(i) + \sigma(i)\Phi^{-1}(u)]$, for each $i \in \{SN, \Delta PSI, M_r, ADT_0, T, T_f, g\}$.

G_μ is the original limit state function where all basic variables are equal to their mean values; and G_i employs the inverse Rosenblatt transformation, where all variables are evaluated with the mean values except for the *i*-th variable. Consequently, Eq. C.12 can be approximated as follows:

$$G^*(SN, \Delta PSI, M_r, ADT_0, T, T_f, g, t) = G_{SN} + G_{\Delta PSI} + G_{M_r} + G_{ADT_0} + G_T + G_{T_f} + G_g - 6G_\mu \tag{C.21}$$

According to Zhao and Ono (2000 (b)), the formulas for G_i ($i \in \{SN, \Delta PSI, M_r, ADT_0, T, T_f, g\}$) can be estimated based on the new point estimation technique (Zhao and Ono 2000 (b)).

For example, the point estimation formula for $i = SN$ is:

$$G_{SN} = Z_R \times S_0 + 9.36\log(\mu(SN) + \sigma(SN)\Phi^{-1}(u) + 1) - 0.20 + \frac{\log(\frac{\mu(\Delta PSI)}{4.2 - 1.5})}{0.40 + \frac{1094}{(\mu(SN) + \sigma(SN)\Phi^{-1}(u) + 1)^{5.19}}} +$$

$$2.32\log\mu(M_r) - 8.07 - \log\mu(ADT_0) - \log\mu(T) - \log\mu(T_f) - \log\mu(\text{g}) - \log D - \log L - \log 365 \tag{C.22}$$

With the estimation points $u_1,...,u_7$ and their corresponding weights $P_1,...,P_7$ readily obtainable in Table 1, the first four central moments of G_i ($\mu_{G_i}, \sigma_{G_i}{}^2$, $\alpha_{3G_i}\sigma_{G_i}{}^3$ and $\alpha_{4G_i}\sigma_{G_i}{}^4$ for $i \in \{SN, \Delta PSI, M_r, ADT_0, T, T_f, g\}$) can be evaluated as (Zhang and Damnjanovic 2006):

$$\mu_{G_i} = \sum_{k=1}^{7} P_k G_i[T^{-1}(u_k)] \tag{C.23}$$

$$\sigma_{G_i}{}^2 = \sum_{k=1}^{7} P_k \{G_i[T^{-1}(u_k) - \mu_{G_i}\}^2 \tag{C.24}$$

$$\alpha_{rG_i}\sigma_{G_i}{}^r = \sum_{k=1}^{7} P_k \{G_i[T^{-1}(u_k)] - \mu_{G_i}\}^{\text{r}} \quad \text{for } r = 3,\ 4 \tag{C.25}$$

Subsequently, the first four moments of the approximated function $G^*(SN, \Delta PSI, M_r, ADT_0, T, T_f, g, t)$ are obtained using the first four moments of G_i (Zhao and Ang 2003).

$$\mu_{G^*} = \sum_{i \in \{SN, \Delta PSI, M_r, ADT_0, T, T_f, \text{g}\}} (\mu_{G_i} - G_\mu) + G_\mu \tag{C.26}$$

$$\sigma^2{}_{G^*} = \sum_{i \in \{SN, \Delta PSI, M_r, ADT_0, T, T_f, \text{g}\}} \sigma_{G_i}{}^2 \tag{C.27}$$

$$\alpha_{3G^*}\sigma_{G^*}{}^3 = \sum_{i \in \{SN, \Delta PSI, M_r, ADT_0, T, T_f, \text{g}\}} \alpha_{3G_i}\sigma_{G_i}{}^3 \tag{C.28}$$

$$\alpha_{4G^*}\sigma_{G^*}{}^4 = \sum_{i\in\{SN,\Delta PSI,M_r,ADT_0,T,T_f,g\}} \alpha_{4G_i}\sigma_{G_i}{}^4 + 6(\sigma_{G_{SN}}{}^2\sigma_{G_{\Delta PSI}}{}^2 + \sigma_{G_{SN}}{}^2\sigma_{G_{M_r}}{}^2 + \sigma_{G_{SN}}{}^2\sigma_{G_{ADT_0}}{}^2$$
$$+\sigma_{G_{SN}}{}^2\sigma_{G_T}{}^2 + \sigma_{G_{SN}}{}^2\sigma_{G_{T_f}}{}^2 + \sigma_{G_{SN}}{}^2\sigma_{G_g}{}^2 + \sigma_{G_{\Delta PSI}}{}^2\sigma_{G_{M_r}}{}^2 + \sigma_{G_{\Delta PSI}}{}^2\sigma_{G_{ADT_0}}{}^2 + \sigma_{G_{\Delta PSI}}{}^2\sigma_{G_T}{}^2$$
$$+\sigma_{G_{\Delta PSI}}{}^2\sigma_{G_{T_f}}{}^2 + \sigma_{G_{\Delta PSI}}{}^2\sigma_{G_g}{}^2 + \sigma_{G_{M_r}}{}^2\sigma_{G_{ADT_0}}{}^2 + \sigma_{G_{M_r}}{}^2\sigma_{G_T}{}^2 + \sigma_{G_{M_r}}{}^2\sigma_{G_{T_f}}{}^2 + \sigma_{G_{M_r}}{}^2\sigma_{G_g}{}^2$$
$$+\sigma_{G_{ADT_0}}{}^2\sigma_{G_T}{}^2 + \sigma_{G_{ADT_0}}{}^2\sigma_{G_{T_f}}{}^2 + \sigma_{G_{ADT_0}}{}^2\sigma_{G_g}{}^2 + \sigma_{G_T}{}^2\sigma_{G_{T_f}}{}^2 + \sigma_{G_T}{}^2\sigma_{G_g}{}^2 + \sigma_{G_{T_f}}{}^2\sigma_{G_g}{}^2) \quad \text{(C.29)}$$

Where:

μ_i and σ_i are the mean and standard deviation of G_i; α_{3i} and α_{4i} are the third and fourth dimensionless central moments, i.e., the skewness and kurtosis of G_i.

According to Zhao and Ono (2001), the failure probability and the reliability index based on the 4M are (Zhao and Ono 2001):

$$\beta_{4M}(t) = \frac{3(\alpha_{4G^*}-1)\beta_{2M}(t) + \alpha_{3G^*}(\beta^2{}_{2M}(t)-1)}{\sqrt{(9\alpha_{4G^*} - 5\alpha^2{}_{3G^*} - 9)(\alpha_{4G^*}-1)}} \quad \text{(C.30)}$$

$$F_{4M}(t) = \Phi(-\beta_{4M}(t)) \quad \text{(C.31)}$$

$$R_{4M}(t) = 1 - F_{4M}(t) \quad \text{(C.32)}$$

Where:

$$\beta_{2M}(t) = \frac{\mu_{G^*(SN,\Delta PSI,M_r,ADT_0,T,T_f,g,t)}}{\sigma_{G^*(SN,\Delta PSI,M_r,ADT_0,T,T_f,g,t)}} = \frac{\mu_{G^*}}{\sigma_{G^*}}$$

C.5.4 COST PER UNIT TIME (CPUT) FUNCTION

With the time-dependent pavement reliability obtained by employing 4M, the CPUT concept is used to determine the optimal PM interval. The mathematical formulation of the CPUT function is expressed as (Dodson 1994):

$$CPUT(t) = \frac{Total\ Expected\ PM\ Treatment\ and\ Risk\ Costs\ per\ Cycle}{Expected\ Cycle\ Length}$$
$$= \frac{CP_i\int_t^\infty f(s)ds + CR_j\int_0^t f(s)ds}{t\int_t^\infty f(s)ds + \int_0^t sf(s)ds} \quad \text{(C.33)}$$
$$= \frac{CP_i * R(t) + CR_j * [1-R(t)]}{\int_0^t R(s)ds}$$

Where:

CP_i = estimated unit cost of a PM treatment with technique *i* (USD per lane-kilometer, or \$/ln-km);

CR_j = estimated unit cost for rehabilitating or restoring the pavement with technique j when it fails ($/ln-km);

$R(t)$ = reliability of the pavement at time t;

$f(s)$ = probability density function (pdf) of pavement failure; and

t = time between PM treatments (years).

The numerator of Eq. C.33 represents the average cost for a single treatment action. The first portion of the cost is the PM treatment cost on conditions that the pavement has survived to the time when the PM treatment is applied, whereas the second portion of the cost is the cost for rehabilitating or restoring the pavement on condition that the pavement has failed before the PM treatment can be applied. The denominator represents the average PM cycle length, i.e., the time between two PM treatments. As shown in Eq. C.33, the cycle length is composed of two terms: $t\int_t^\infty f(s)ds$ is the cycle length on condition that the pavement has survived until the scheduled PM treatment; $\int_0^t sf(s)ds$ is the cycle length on condition that the pavement has failed before the scheduled PM treatment. Consequently, the optimal PM interval t is the interval which minimizes the CPUT function (Eq. C.33).

In practice, the average unit cost for PM (CP_i) and the average unit cost for rehabilitation or restoration (CR_j) can be estimated by pavement engineers based on the specific treatment techniques applied to roadways with similar characteristics.

C.6 Numerical Study

A numerical study was conducted based on a newly built two-lane flexible roadway in Texas to demonstrate the application of the proposed methodology. The pavement structure parameters and traffic characteristics were obtained by consulting pavement engineers and related experts in Texas in addition to information gathered from published research studies (AASHTO 1993; Piepmeyer 2005; Zhang and Damnjanovic 2006). Considering the booming economy and future land use in Texas, the annual traffic growth rate was set at 3 percent. Because of variations associated the construction process, most of the design variables are asscociated with certain levels of variabilities. Therefore, a coefficient of variation (CV) was assigned to each of the variables to capture such uncertainties. By changing the CV of each input variable, the proposed methodology is able to cover different distributions of the variables and thus to handle different levels of uncertainties. The input variables and theirs corresponding values are presented in Table C-2; these values and their validity were verified by pavement design experts in Texas.

Table C-2: Input Variables Verified by Texas Pavement Design Experts

Strength Model

Variable	Mean (μ)	CV (%)
S_0	0.4	n/a
Z_R	-1.282	n/a
a_1	0.44	5
a_2	0.14	5
a_3	0.11	5
D_1	2 inches (5.1 cm)	5
D_2	12 inches (30.48 cm)	5
D_3	6 inches (15.24 cm)	5
m_2	1	5
m_3	1	5
M_r	7,500	5
PSI_i	4.5	5
PSI_t	2.5	n/a
W	12 ft (3.7m)	n/a
Y	20	n/a

Stress Model

Variable	Mean (μ)	CV (%)
ADT_0	8,000	10
T	0.15	10
T_f	0.21	10
g	0.03	10
D	0.5	n/a
L	1	n/a

***SN* and Δ*PSI* Based on Strength Model**

Variable	Mean (μ)	Std. Dev. (σ)
SN	3.22	0.17
ΔPSI	2.0	0.225

Where: W = lane width; and
Y = design life of the pavement (years).

Based on strength model information from Table C-2, the mean and standard deviation of SN and ΔPSI were obtained by applying Taylor's expansion to Eq. C.7 and Eq. C.8.

With all input variables well defined, the probability of failure for the pavement, i.e., the probability that the stress (N_{18}) is greater than the strength (W_{18}) is computed for each of the 20-year design life with the 4M procedure discussed earlier; then, based on the probability of failure, the reliability of the pavement was obtained. Figure C-5 shows how the reliability changes over the 20-year analysis period or design life.

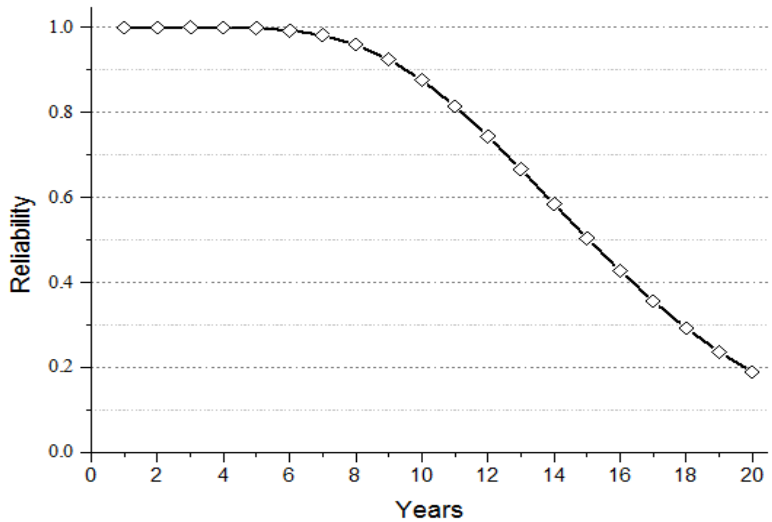

Figure C-5: Pavement Reliability Obtained with 4M

According to the final reports published by Montana Department of Transportation (DOT) (2006) and Pennsylvania DOT (2011), the cost of a PM treatment ranges from \$1,243 to \$24,855 per lane-km, depending on the specific treatment technique (MDOT 2006). In addition, the cost of the same PM treatment technique changes with time and varies from state to state due to different costs of material and labor. Based on the input parameters and practice in Texas, microsurfacing is a typical PM treatment suggested by the pavement engineering due to the ability to fill minor rutting, seal cracks, and improve skid resistance. Table C-3 summarizes costs of microsurfacing reported by various studies (Wade *et al.* 2001, Temple *et al.* 2002, Cuelho *et al.* 2006, Labi *et al.* 2006).

Table C-3: Microsurfacing Costs Reported by Various Studies

Cost for 12-ft (3.7m) lane width pavement in \$/ln-km	Location	Year Data Taken
3,107-4,350	TN	1995
4,350-6,214	MI, MS, MO, NC, OH	1995
6,214-9,321	ID, TX, WI, IN	1995
9,321-15,534	KS, VA	1995
16,653	IN	2006
7,456-21,189	LA	1995-1996
5,468-8,761	OH	1997
3,728-8,823	OK	1983-1991

Note: listed cost unit has been converted from English System Units into SI Units.

Considering that the data for Texas in Table C-3 were taken in 1995, \$15,534 per lane-km was suggested as the average unit microsurfacing cost for current practice in Texas, which reflects the inflation and includes labor costs.

In terms of the rehabilitation treatment, the costs range from \$62,137 to over \$559,236 per lane-km, depending on the technique selected (Piepmeyer 2005; Caltrans 2013; PATH-P 2016). Based on engineering practices in Texas, milling and replacing with hot mixed asphalt (MRHMA) is commonly performed as a rehabilitation technique. This technique was therefore recommended as a representative rehabilitation treatment with its cost set as \$186,412 per lane-km.

Since only one PM treatment and one rehabilitation action were used for conducting this case study, it means that $CP_i = \$15{,}534$/ln-km and $CR_j = \$186{,}412$ /ln-km, where i = microsurfacing and j = MRHMA. With the 4M reliability index obtained, the CPUT values over the 20-year design life were calculated using Eq. C.33. The results are presented in Figure C-6.

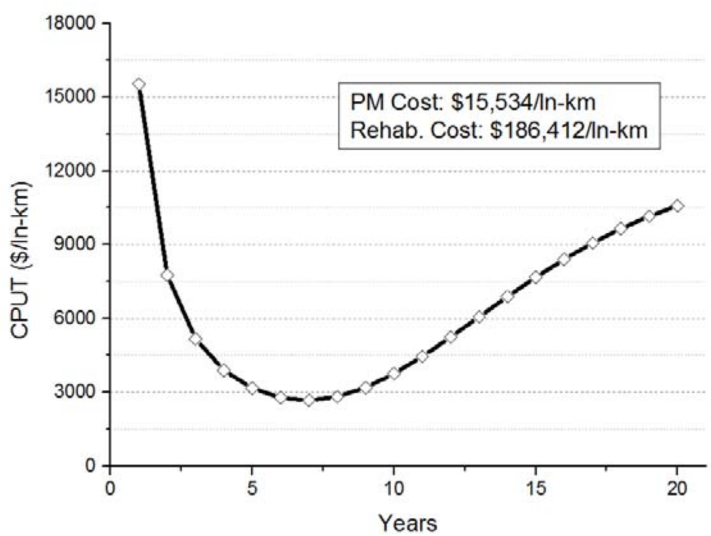

Figure C-6: The CPUT Values over Pavement Design Life Using 4M Reliability Index

The CPUT curve shown in Figure C-6 shows an expected “V” trend. The CPUT value decreases with time at first and then increases. More specifically, the CPUT values decrease from \$15,534 per lane-km at Year 1 to \$2,677 per lane-km at Year 7; then it increases from Year 7 to Year 20. The minimum CPUT value is \$2,677 per lane-km which corresponds to Year 7. In other words, if microsurfacing (cost: \$15,534 /lane-km) is chosen as the PM treatment and MRHMA (cost: \$186,412 /lane-km) as the rehabilitation action, the optimal interval to perform the PM treatment is 7 years. This result is very close to that obtained by running Flexible Pavement Design System (FPS 19W) software using the same parameters, which is currently used by Texas Department of Transportation (TxDOT).

C.7 Sensitivity Analysis

A sensitivity analysis was undertaken to explore how the change in PM and rehabilitation costs would affect the optimal PM interval.

C.7.1 Impact of PM Cost on Optimal Interval

In order to explore the impact of PM cost on the optimal PM interval, the PM cost is set to \$1,553, \$6,214, \$15,534, and \$31,069 per lane-km while the rehabilitation cost remains at \$186,412 per lane-km. The CPUT values are calculated and presented in Figure C-7.

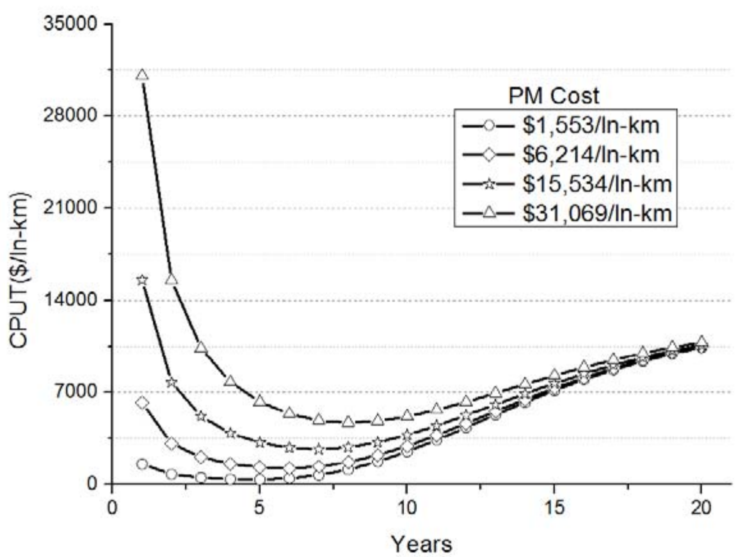

Figure C-7: Impact of PM Cost on Optimal PM Interval

As it can be seen from Figure C-7, the trend of corresponding CPUTs all exhibits the general “V” shape for different PM costs. The optimal intervals were calculated for each of the PM costs and presented in Table C-4.

Table C-4: Impact of PM Cost on CPUT and Optimal PM Interval

PM Cost in $/ln-km	CPUT Value in $/ln-km	Optimal Interval in years
1,553	365	4.7
6,214	1,215	5.8
15,534	2,677	7.0
31,069	4,634	8.0

It can be seen from Table C-4 that, when the rehabilitation cost is fixed, both the CPUT value and optimal PM interval increase as PM cost increases. The results indicate that when a more costly PM treatment is chosen (e.g., thin overlay, cold in-place recycling), the maintenance agency should accordingly perform PM treatment less frequently. It is intuitive that the agency would perform PM treatment more frequently to preserve the roadway when a relatively cheap treatment is chosen (e.g., fog seal).

C.7.2 Impact of Rehabilitation Cost on Optimal Interval

Similarly, in order to investigate the impact of rehabilitation cost on optimal PM interval, the rehabilitation cost is set to $62,137, $186,412, $372,824, and $559,235 per lane-km while the PM cost remains $15,534 per lane-km. The CPUT values were calculated and presented in Figure C-8.

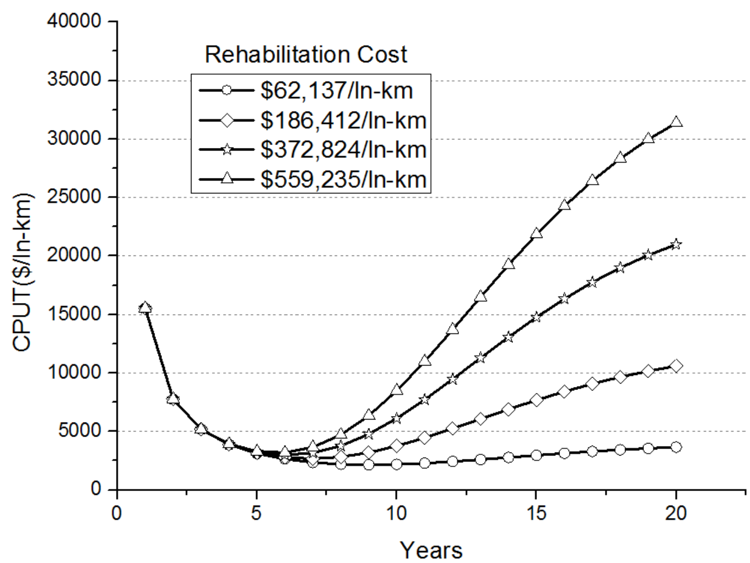

Figure C-8: Impact of Rehabilitation Cost on CPUT and Optimal PM Interval

As it can be observed from Figure C-8, the CPUT values drop to the minimum point and then increase with time. The CPUT and optimal PM interval in corresponding to each of the rehabilitation costs were calculated and presented in Table C-5.

Table C-5: Impact of Rehabilitation Cost on CPUT and Optimal PM Interval

Rehabilitation Cost in $/ln-km	CPUT Value in $/ln-km	Optimal Interval in years
62,137	2,115	9.0
186,412	2,677	7.0
372,824	2,938	6.1
559,235	3,116	5.7

Table C-5 shows that when the PM cost is fixed, with the increase of rehabilitation cost, the CPUT value increases and the optimal PM interval decreases. The results suggest that if the cost for rehabilitating or restoring the pavement when it fails is high, the maintenance agency should accordingly perform the PM treatment more frequently. This is because that a higher rehabilitation cost implies a higher risk cost when the pavement fails.

C.8 Conclusions and Discussion

This paper provides a reliability-based comprehensive framework to optimize PM interval for highway pavements. Closed-form solutions are obtained by evaluating the time-dependent multidimensional probability integral using the Fourth Order Method of Moments (4M). In addition to the existing basic random variables describing the mathematical relation to the failure event, the formulation of the limit state can be extended to allow for the explicit consideration of epistemic uncertainty. The feasibility and applicability of the proposed methodology is illustrated by a numerical case study where the CPUT values are calculated and the optimal PM interval is determined. The sensitive analysis shows the impact of PM and rehabilitation costs on the optimal PM interval, providing insight information to the maintenance agencies in terms of making the most-cost-effective PM treatment decisions. To summarize, the following conclusions and recommendations can be drawn:

- Based on the stress and strength model, the Fourth Order Method of Moments (4M) proves to be a viable approach to estimating the pavement reliability and determining the optimal PM interval when it is combined with the CPUT concept;
- For transportation infrastructure like highway pavements where there are a large number of various uncertainties associated with the input variables, the 4M reliability approach is capable of returning a closed-form solution. More importantly, for variables associated with uncertainties, the 4M approach does not require that the exact distribution for each variable be specified, making it more applicable to real-world engineering problems when compared with other methods such as Monte Carlo Simulation where the exact distribution for each variable under consideration must be clearly defined;

- Besides pavement reliability, the CPUT concept and corresponding formulation takes the PM and rehabilitation techniques, as well as their corresponding costs, into consideration when analyzing optimal PM intervals. The proposed methodology can help maintenance agency develop more cost-effective maintenance strategies for highway pavements;
- Sensitivity analyses can provide valuable insights to pavement maintenance agencies in terms of the effect of PM and rehabilitation costs on the optimal PM interval. More specifically, when the PM cost is fixed, with the increase of the rehabilitation cost, the optimal PM interval should be reduced; when the rehabilitation cost is fixed, as the PM cost increases, the optimal PM interval should be increased. Finally, even though this paper demonstrated the applicability of the proposed methodology only with a flexible pavement, it is obvious it can be applied to other types of pavements as well as other types of infrastructure systems.

The proposed framework works in conjunction with other traffic prediction models. For pavement design methods (i.e. MEPDG) where the design equations are more complex with more input variables, certain adjustments should be made to apply the proposed framework. For example, the computational complexity can be reduced by analyzing the key contributing variables and main uncertainty sources. Besides this, the methodology can serve as a basis for future research. There are a few directions on which future research can embark and improve the presented framework and corresponding results, including: directly take the discount rate and user cost into consideration by choosing appropriate models; and incorporate salvage value models, pavement performance models, and increased service life concepts to ameliorate the proposed scheme.

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