ESSAYS ON INFRASTRUCTURE PUBLIC-PRIVATE PARTNERSHIPS

by

Nobuhiko Daito
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Committee:

______________________________  Jonathan L. Gifford, Chair
______________________________  Siona R. Listokin
______________________________  Shanjiang Zhu

                                           Michael J. Garvin, External Reader
______________________________  Kenneth J. Button, Program Director

______________________________  Mark J. Rozell, Dean

Date: ____________________________  Fall Semester 2015
George Mason University
Fairfax, VA
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by

Nobuhiko Daito
Master of Urban and Regional Planning
University of California, Irvine, 2007
Bachelor of Arts
Soka University of America, Aliso Viejo, 2005

Director: Jonathan L. Gifford, Professor
School of Policy, Government, and International Affairs

Fall Semester 2015
George Mason University
Fairfax, VA
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DEDICATION

I dedicate all of my work to my life mentor, Mr. Daisaku Ikeda, who has ceaselessly given me warm encouragement and inspiration, motivating me to fulfill my lifelong mission. I also dedicate this study to my beloved family, Takehiko, Kyoko, Mitsuhiko, Atsuko Muroga, and Terumi Yamashita.
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Views presented in this dissertation do not represent any organizations, and any errors and judgmental mistakes belong to myself.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Tables</td>
<td>vi</td>
</tr>
<tr>
<td>List of Figures</td>
<td>vii</td>
</tr>
<tr>
<td>Abstract</td>
<td>viii</td>
</tr>
<tr>
<td>Chapter 1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>Chapter 3 Evaluating Network Design Decisions of P3 Alternatives: Innovative Investment and Multi-Jurisdictional Perspectives</td>
<td>73</td>
</tr>
<tr>
<td>CHAPTER 4 Comparing P3s and Traditionally Procured Project Contract Prices: An Analysis of the U.S. Highways</td>
<td>146</td>
</tr>
<tr>
<td>CHAPTER 5 Conclusion</td>
<td>189</td>
</tr>
<tr>
<td>Appendix</td>
<td>195</td>
</tr>
<tr>
<td>References</td>
<td>207</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 1 Definitions of Public-Private Partnerships ............................................................... 8
Table 2 Selected P3 Contract Types ....................................................................................... 11
Table 3 Number of U.S. P3 Projects by Sector and Contract Types ..................................... 16
Table 4 Descriptive Statistics of Variables and Their Sources ............................................... 40
Table 5 Correlation of Regressors ......................................................................................... 41
Table 6 Mean and Variance of Candidate Dependent Variables ........................................ 53
Table 7 Comparing DB, P3, and DB+P3 and All States and P3Law States: Fixed Effects Panel Poisson Regressions .............................................................. 56
Table 8 Fixed Effects Negative Binomial Regression of DB&P3 Contract Closes: Governor's Office Years .................................................................................................. 57
Table 9 Fixed Effects Panel Negative Binomial Regression of DB&P3 Project Financial Closes: Republican Governor and Financial Interactions .............................................. 61
Table 10 Fixed Effects Poisson Regressions: DB&P3 and Governors' Office Years and Election Interactions ................................................................................................. 64
Table 11 Cluster Robust Standard Error Fixed Effects OLS Regression of DB&P3 Aggregate Costs: Governors' Office Years and Election Interactions ......................................... 65
Table 12 Functions and Parameter Notations ........................................................................ 100
Table 13 Numerical Results: Base Case Scenarios ................................................................. 123
Table 14 Numerical Results: Multi-jurisdictional Scenarios 1 ................................................... 124
Table 15 Numerical Results: Multi-jurisdictional Scenarios 2 ................................................... 125
Table 16 Sample DB and P3 Highway Projects ...................................................................... 167
Table 17 Descriptive Statistics of Independent Variables ....................................................... 170
Table 18 Estimated Regression Results ................................................................................... 176
Table 19 VIF Tests of Multi-collinearity by Regression Models .............................................. 179
Table 20 Ramsey’s RESET Test of Omitted Variables by Regression Models ...................... 179
Table 21 Breusch-Pagan Test for Heteroskedasticity by Regression Models ......................... 181
Table 22 White’s Test for Heteroskedasticity by Regression Models .................................... 181
Table 23 SK Tests of Residual Normality by Regression Models ........................................... 181
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1 Number of U.S. P3s 1986-2013, by Sector (Public Works Financing)</td>
<td>16</td>
</tr>
<tr>
<td>Figure 2 Cumulative U.S. P3 Investments, 1990-2014 (2009US$BN, Public Works Financing)</td>
<td>18</td>
</tr>
<tr>
<td>Figure 3 P3 Investments and Enabling Legislations of U.S. P3s, 1997-2014 (Public Works Financing, and National Conference of State Legislature)</td>
<td>19</td>
</tr>
<tr>
<td>Figure 4 Network Structure, Multi-jurisdictional Scenarios</td>
<td>108</td>
</tr>
<tr>
<td>Figure 5 The Scale of P3s: Risk Transfer and Private-Sector Involvement (The Canadian Council for Public-Private Partnerships)</td>
<td>148</td>
</tr>
<tr>
<td>Figure 6 Cost Changes through Project Delivery (Gkritza and Labi, 2008)</td>
<td>154</td>
</tr>
<tr>
<td>Figure 7 U.S. Highway Project Cost, 09US$M/lane-mile</td>
<td>174</td>
</tr>
<tr>
<td>Figure 8 U.S. Highway Project Unit Cost, 09US$M/lane-mile</td>
<td>175</td>
</tr>
<tr>
<td>Figure 9 Box Plot of Regression Model Residuals</td>
<td>182</td>
</tr>
</tbody>
</table>
ABSTRACT

ESSAYS ON INFRASTRUCTURE PUBLIC-PRIVATE PARTNERSHIPS

Nobuhiko Daito, Ph.D.

George Mason University, 2015

Dissertation Director: Dr. Jonathan L. Gifford

In pursuit of efficiency gains and overcoming fiscal constraints, public-private partnerships (P3s) have gained popularity as innovative procurement approaches for public agencies to continue providing infrastructure services to their citizens. While academic research on this subject has grown over the years from economic, finance, engineering, and other disciplines, a number of policy relevant questions have yet to be fully addressed. The present study inquires P3s primarily in the highway sector from three distinct but related dimensions. First, the relationship between institutional, political, and financial conditions and the use of innovative procurement contracts of U.S. states was statistically analyzed, finding influence of these factors in insightful ways. Second, alternative procurement models in terms of bundling project components was modeled to theoretically investigate their effect in terms of the use of innovative technologies and aggregate social welfare. The model was then extended to analyze procurement scenarios in the context of cross-border road network link where
neighboring jurisdictions collaborate or compete in designing the network. Third, initial capital costs of large highway projects in the U.S. were statistically compared between procurement types. The results enhanced the understanding regarding how P3 contracts have included risk premiums and potentially innovative investment to minimize lifecycle costs. The results provided lessons for policy makers to effectively employ P3s for their infrastructure investment initiatives. Also, the study pointed to future extensions of these analyses to inquire into these meaningful questions.
CHAPTER 1 INTRODUCTION

Motivated by their tight fiscal conditions and efficient innovations that the private sector is presumed to provide, public agencies in the U.S. are increasing their use of public-private partnerships (P3s) to deliver infrastructure, a critical input to economic development. While the body of knowledge on this phenomenon has been rapidly growing in recent years by scholars of such disciplines as economics, finance, and engineering, there are a number of questions with policy relevance that have not fully been addressed. The objective of the present study is to inform policy-makers regarding factors for successful implementation of P3s and their potential consequences.

In pursuit of this objective, this study will inquire what are the institutional, political, and fiscal environment enable successful close of P3 contracts, and what are the consequences of employing such innovative procurement models. Focusing on the U.S. highway sector, the analysis of the present study consists of three essays that address the following research questions. What institutional, political, and fiscal factors contribute to the use of innovative procurement models by U.S. states for highway projects? How do traditional procurement and innovative contracts for highway network capacity expansion projects differ, with respect to social welfare and private contractor’s operational surplus? Do these differences change when considering competition or collaboration of multiple jurisdictions for a cross border facility? Finally, what are the differences of P3s and
traditionally procured highway projects in terms of their unit construction costs? If any significant differences exist, what do they represent?

Chapter 2 proposes an empirical model of the number of highway construction projects procured through innovative contracts for U.S. states. Underpinned by political business cycle hypothesis, the chapter explores statistical association with the use of P3s and fiscal conditions (e.g., motor fuel tax revenue, debt, and their growths), political environment (e.g., Republican governor, and margin of gubernatorial election victories), political cycle (i.e., the numbers of years in governor’s office), and their interactions.

Chapter 3 presents theoretical models with which various procurement models are examined in the context of highway network design problem, where the decision variables are the capacity and toll on the network link under consideration. Bundling of initial capital construction and operation and maintenance (O&M) are evaluated, while their incentive effects for private contractors to invest in innovative technologies that lower O&M costs at initially higher costs. The models are then extended for a cross-border link context of two neighboring jurisdictions that may compete or collaborate in improving the facility. The consequences of these alternatives in terms of toll, capacity, innovative investment, social welfare, and private contractor’s profit levels are compared to draw insights regarding the use of P3 contracts for highway networks.

Chapter 4 compares unit Design-Build contract prices (ex ante) of large highway construction projects in the U.S. The analysis in Chapter 3 suggests the initial construction costs of P3s would be higher due to the use of innovative technologies to optimize their life cycle costs at higher initial costs. Also, transfer of project risks during
the initial capital delivery, which is another notable feature of P3s, will be considered. The results suggest that these effects might have manifested as higher contract prices of P3 projects compared to more traditionally procured projects, after controlling for various project characteristics. These findings call for lasting analysis of P3s’ performance, so that P3s can continue to be recognized as efficient infrastructure delivery methods through meaningful partnership between public and private partners.

The last chapter will summarize the findings and conclude with directions for analyses in the future.
CHAPTER 2 POLITICAL, FINANCIAL, AND INSTITUTIONAL ENVIRONMENT AND PUBLIC-PRIVATE PARTNERSHIPS: EVIDENCE FROM THE U.S. HIGHWAY PERSPECTIVE

2.1 Introduction

Infrastructure is a critical input for the economy to improve its productivity and to continue development. In many countries, however, investment in infrastructure capital has not kept up with the demand. In the U.S. highway sector, the conventional Highway Trust Fund-based mechanism to build and maintain Interstate assets through gas tax revenues has been struggling, as fuel efficiency improves and construction costs increase. In response, a number of innovative procurement approaches to increase efficiency in asset delivery and to tap into alternative sources of funding has been proposed. In a number of states across the nation, the popularity and use of these approaches have gradually grown over the last two decades. Public-private partnerships (P3s) drastically change the way transportation agencies do their business of providing infrastructure services to citizens. These arrangements also require citizens to adapt to these new business models, such as commercial motivations behind facilities that they use, as well as tolling the roads, which they may be accustomed to pay in other ways such as motor fuel taxes.

Institutional and political environment play critical roles for states and municipalities to facilitate these innovative types of contracts and successfully ensure fulfillment of infrastructure service delivery requirements for particular projects. State
agencies in most cases need authorizations through enabling legislation to engage in these new arrangements and procure through alternative models. States vary considerably with respect to whether a P3 enabling law has been legislated and what provisions are included in these laws (Rall et al., 2010). Furthermore, industry best practices point to the need for policy champions to advocate the use of P3s (NCPPP), while political challenges can easily put P3 projects in jeopardy.

P3s projects are arguably vulnerable to political risks. The risk can materialize in a number of ways: for example, the lack of political consensus at the outset of P3 policy implementation or project delivery is likely to lower the chance of successful completion. Furthermore, the attractiveness of a P3 market or particular projects for private investors could also deteriorate if political support is perceived to be weak. Deye (2015) argues that whether the U.S. P3 market can manifest its full potential depends on three factors: political cycles, especially gubernatorial elections; federal P3 assistance programs, such as loans; and availability of other funding sources, such as renewal of gasoline tax legislations.

While studies on P3s from economic, financial, and engineering perspectives are extensive, attention to their political and institutional aspects have been scarce in the U.S. Body of knowledge on this subject has been substantial in international economic development contexts, but the relevance of these studies to the U.S. context can be limited: e.g., consideration of corruption and rule of law (Moszoro et al, 2015). Employing the frameworks of political economy theories used in understanding public agencies’ spending decisions, this study explores the role of institutional and political
environments behind the employment of P3 contracts. The analysis herein aims to provide insights for public and private decision-makers regarding conditions upon which innovative procurement deals have been closed between public agencies and private contractors. The primary research question to be addressed is: how institutional and political factors affect the use of P3 models for highway projects? A series of empirical models are used to inquire statistical associations between fiscal, political, election, and other factors and the number of P3 deals as well as states’ aggregate investments in highway projects through these innovative contracts.

The remainder of this paper is organized as follows. The next section will provide a short summary of the background of infrastructure P3s. A review of literature relevant to the analysis will follow. After discussing data and empirical models to be used for the analysis, results will be presented. The last section will provide implications of the analysis results and point to the directions of analysis in the future.

2.2 Background

Infrastructure is a key input to economic development and prosperity. This study defines infrastructure rather broadly to encompass transportation facilities (e.g., roads, railways, seaports, airports, etc.), but also utility systems (e.g., power grids and electricity generation plants, water and sewer networks, etc.), facilities for government services (e.g., government offices, educational facilities, and correction facilities), and other relevant systems that have received scholarly attention. While the primary focus of the analysis in this study will be on highways, general discussion on institutional, policy, and financial aspects of the P3s are relevant for other sectors. Hence, the discussions in the
background section and part of theoretical foundations do not exclusively focus on the road sector.

2.2.1 Infrastructure Investment through Innovative Procurement Models

In the last several decades, complex institutional arrangements evolved, whereby the private sector began playing larger roles in delivering infrastructure projects. Alternative project delivery models have emerged for governments to be able to continue investing in the infrastructure to remain competitive in the global economy. One such approach is privatization of the infrastructure services. Privatization has been argued to improve public infrastructure project delivery in terms of service quality, cost efficiency, and overall effectiveness for the following reasons. First, the private sector is considered less bureaucratic and more operationally efficient, thus enabling rapid decision-making regarding resource allocation. Second, budgetary constraints of the government can be overcome with its access to private capital. Third, such an arrangement can take advantage of the technical expertise, management skills, and innovative technologies of private firms. Also, introduction of private competition will remove government monopoly, while market mechanism will incentivize the public organizations to pursue efficiency (Zhang 2005). Full privatization of a public good could, however, lower production to socially unacceptable levels and degrade service quality for profitability. Therefore, public private partnerships (P3s), in which the public sector retains some of the risks and ownership, have become popular in a number of countries instead of privatization.
<table>
<thead>
<tr>
<th>Entities</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S. FHWA</td>
<td>Contractual agreements formed between a public agency and a private sector entity that allow for greater private sector participation in the delivery and financing of transportation projects (FHWA, 2014)</td>
</tr>
<tr>
<td>World Bank</td>
<td>Transactions where the private sector retains a considerable portion of commercial and financial risks associated with a project (PPIAF 2013)</td>
</tr>
<tr>
<td>OECD</td>
<td>An agreement between the government and one or more private partners (which may include the operators and the financiers) according to which the private partners deliver the service in such a manner that the service delivery objectives of the government are aligned with the profit objectives of the private partners and where the effectiveness of the alignment depends on a sufficient transfer of risk to the private partners (ITF and OECD, 2008)</td>
</tr>
<tr>
<td>P3 Canada</td>
<td>A long-term, performance-based approach to procuring public infrastructure that can enhance governments’ ability to hold the private sector accountable for public assets over their expected lifespan. P3s work because they engage the expertise and innovation of the private sector and the discipline and incentives of capital markets to deliver public infrastructure projects. P3s transfer a major share of the risk associated with infrastructure development (such as the costs associated with overruns, schedule delays, unexpected maintenance, and/or latent defects in the assets) to the private sector. This is accomplished by engaging the private sector in a bundled contract for the life of the asset. This contract connects ongoing operations and/or maintenance payments to the quality of the original construction. (PPP Canada)</td>
</tr>
</tbody>
</table>
Scholars have engaged in discussions to evaluate how P3s could be economically justifiable, investigating various dimensions of this approach, including risk allocation, decision making models, and performance evaluation, etc. From a policy perspective, the procurement mechanism has been discussed in the context of governments’ severe fiscal constraints, in a wide range of countries from developed economies, developing countries, and countries with emerging economies. Countries where P3s have been a topic of policy discussions appear to share one commonality: facing the challenge of adding new capacities in areas with growing economies, and efficiently operating and maintaining existing assets. International Transport Forum (ITF), of the Organisation for Economic Co-operation and Development (OECD) views P3s as one of the alternative approaches with which governments can overcome fiscal and other constraints to continue their investment (ITF and OECD, 2008).

Scholars have proposed a variety of definitions of the term public private partnership, reflecting its flexible nature, from which, arguably, its value added can be derived. Any definitions of P3s can therefore be debatable. Hodge et al. (2010) defined the term very loosely as “cooperative institutional arrangements between public and private sector actors.” With respect to commonly observed long-term infrastructure contracts, Campbell defined it as a project that “generally involves the design, construction, financing and maintenance (and in some cases operation) of public infrastructure or a public facility by the private sector under a long term contract” (Campbell, 2001). A number of public entities, such as U.S. Federal Highway Administration (FHWA), Public-Private Infrastructure Advisory Facility (PPIAF) of the
World Bank, and PPP Canada, have also employed respective definitions, which are summarized in Table 1.

While a variety of definitions of the term have been proposed, this study will follow the OECD’s definition and consider that the essential element for being P3s are bundling of multiple project phases and transfer of project risks to a private partner, relative to the traditional procurement model. In this context, public sector is defined as government of all levels (i.e., federal, state and local) and agencies that are governed, fully or in part, by publicly elected or appointed officials, with the objective to maximize social welfare. Private sector, on the other hand, refers to entities that are owned by private individuals and/or entities, whose objective is to maximize profits. It should be noted that the objective function is critical in differentiating one sector from the other. Therefore, while non-profit organizations are legally private entities, the objective they pursue is to provide services to benefit the public (and not necessarily interested in maximizing profit), and hence, arguably, they can be considered as part of this rather loosely defined group of the public sector.

Noticeably, the aforementioned definition of P3s is broad, and a number of contract types falls under this definition, making any scholarly investigations challenging. In the interest of presenting the background of the subject matter in this subsection, Table 2 summarizes various project contract types that are subset of broadly defined P3s, with respective risks allocated to the private contractor.
### Table 2 Selected P3 Contract Types

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>DBFM</td>
<td>Design, build, finance, and maintain</td>
</tr>
<tr>
<td>DBFO</td>
<td>Design, build, finance, and operate</td>
</tr>
<tr>
<td>DBOM</td>
<td>Design, build, operate, and maintain</td>
</tr>
<tr>
<td>DBFOM</td>
<td>Design, build, finance, operate, and maintain</td>
</tr>
<tr>
<td>BLT</td>
<td>Build, lease, and transfer</td>
</tr>
<tr>
<td>BOL</td>
<td>Build, operate, and lease</td>
</tr>
<tr>
<td>BOO</td>
<td>Build, operate, and operate</td>
</tr>
<tr>
<td>BOOR</td>
<td>Build, own, operate, and remove</td>
</tr>
<tr>
<td>BOOT</td>
<td>Build, own, operate, and transfer</td>
</tr>
<tr>
<td>BOT</td>
<td>Build, operate, and transfer</td>
</tr>
<tr>
<td>LROT</td>
<td>Lease, renovate, operate, and transfer</td>
</tr>
<tr>
<td>ROT</td>
<td>Rehabilitate, operate, and transfer</td>
</tr>
</tbody>
</table>

Source: Hodge et al., 2010

Effectively, a project can be referred to as a P3 if the contract deviates from traditional models of procurement in a way that involves transfer of particular project risks to the private firm contracted to deliver the service. In the context of highway capacity expansion projects in the U.S., the traditional procurement model is referred to as Design-Bid-Build model (DBB). A highway construction project consists of multiple phases, such as planning, design, construction, operation, and maintenance. Certain stages of the project will be contracted out to a private firm to do the job, depending on the state: design can be done either by in-house engineers or contracted to an engineering firm; construction will be done by a private contractor; and, the completed highway asset can be maintained by in-house staff or contracted to a private firm specialized in the service.

While this model can ensure accountability of each project stage and achieve transparency, it may not be the best approach to achieve lifecycle cost efficiency, which
is a growing concern under the tight budget conditions of governments. In this traditional un-bundled design-bid-build (DBB) model, contractor for each stage has the incentive to minimize its cost, possibly at the cost of another stage of the project. If there is a discrepancy between design specifications and the actual site condition, the process to reflect the site condition in the blueprints, obtain necessary approvals, redevelop a construction strategy and do the job, could easily lead to cost and schedule overruns. The public owner of the project bears the responsibility under such scenarios.

Design-build contract (DB) evolved to address such design risks: by contracting both design and construction phases together, change-orders may decrease considerably. In this contract, the design risk has been transferred to the private contractor. Thus, some may argue that the DB contract can be considered as a form of P3s (Congressional Budget Office 2012).

By incorporating the project’s maintenance stage to the contract, the cost savings of project bundling can be extended further. When the operation and management stages of the project are bundled to the DB contract (hence, a design-build-operate-maintain, or DBOM, contract), the private partner would be incentivized to optimize the life-cycle cost of the project. For example, the partner may choose a design specification of the asphalt such that the initial construction may be more costly but the life-cycle cost will be more cost efficient.

If the financing arrangement is also bundled into the contract, involving private equity investment to the project, then a design-build-finance-operate-maintain contract (DBFOM) is used. Some have narrowly defined P3s as to only refer to DBFOM contracts
(e.g., Deye, 2015) so as to focus on the aspect of private financing of particular projects. In this case, project finance arrangement is made for the private partner to finance the initial capital investment of the project. Project finance is a financial technique used to finance projects that involve large upfront capital investment (e.g., power plant, water plant, highway). Zhang defined project finance as “the development of a stand-alone project on a nonrecourse or limited recourse financing structure, where debt and equity used to finance the project are paid back from the cash flow generated by the project” (Zhang 2005).

In this model, the initial investment is realized by combining equity investment from companies participating in the project (e.g., contractor, operator, designer, and investor) and debt financing (e.g., bank loans and bonds). Revenues from the project will be used to repay the debt obligation and for operational and maintenance expenses, and the remainder will be the profit, which is equivalent to the return on the equity investment. Multiple private companies form a legally independent project specific entity (special purpose vehicle, or SPV) solely for providing the service defined in the project, such as design-build, operation, and maintenance. Importantly, since the SPVs are legally distinct from participating firms, lenders will make their lending decisions based not on the general credit and firm-wide cash flow but on the conditions specific to the project.

Brealey et al. (1996) explored theoretical justifications of employing project finance techniques for infrastructure projects, and how both the public sponsor and the private partner might benefit from it. They point out that a commonly held notion that the cost of capital might be cheaper for governments could be misleading, since the lower
interest rates merely reflect the risks borne by taxpayers. They argue that the benefit of project finance for infrastructure projects might be found because they allow bringing in the expertise of cost savings and efficient management of certain risks by the private firms, while avoiding the full "privatization." This is so because privatization would entail designing complex new regulatory institutions, which may be inappropriate for certain sectors such as education.

Variations of these contracts include design-build-operate contracts (DBO), design-build-finance (DBF), design-build-maintain (DBM), among others. These capacity expansion projects can be considered as an extension of the traditional construction projects, involving agreed compensation from the public procuring authority to the private partner.

While the above discussion pertains to the use of P3 arrangement particularly for capacity expansion projects ("greenfield" projects), there have also been a number of concession contracts ("brownfield" projects), for existing capacities. Primarily, projects under this category would hand over operation and maintenance of an existing facility that has been operated by a public agency. For example, a revenue generating facility may be leased to a private firm, which would collect user fees and other revenues and be responsible for providing a required level of operation and for maintenance, for an agreed concession term. In contrast to the capacity expansion projects, typically an upfront lump-sum payment from the private partner is made to the asset owner, a public agency.

Adoption of P3 contracts is a growing phenomenon in a number of countries around the world. The following subsections briefly overviews the P3s markets in various
regions and policy issues that have emerged in recent years, focusing on the U.S., OECD nations, and countries with emerging economies.

2.2.2 A Global P3 Market Overview

A global review indicates that P3s are widely used in a variety of countries with respect to their institutional characteristics, their stage of economic development, and other project specific environments. This section will review P3 practices in the U.S., OECD member states, and developing countries, with regard to respective background, history, and on-going issues and debates that will motivate the analysis in this study.

United States

In the U.S., the popularity of the P3s has been increasing, due to the severe public budgetary and financial constraints (Small, 2010), because P3s allow governments to tap the private sector for financing through project equity and debt. Table 3 summarizes the number of P3s that reached financial close between 1986 and 2013 by sector. The total number of financial closes of P3s over the years in all sectors reached 512 by the end of 2013. A large number of transportation projects were built using the DB model. While the discussion here only focuses on highway P3s, the number of military housing lease was notably significant.
## Table 3 Number of U.S. P3 Projects by Sector and Contract Types

<table>
<thead>
<tr>
<th>Contract Type</th>
<th>Building</th>
<th>Transportation</th>
<th>Water</th>
<th>Wastewater</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Military</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BOT, BLT, BTO</td>
<td>7</td>
<td>7</td>
<td>4</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>DB</td>
<td>7</td>
<td>81</td>
<td>8</td>
<td>96</td>
<td></td>
</tr>
<tr>
<td>Private Finance</td>
<td>14</td>
<td>46</td>
<td>15</td>
<td>75</td>
<td></td>
</tr>
<tr>
<td>DBO, DBM, DBOM</td>
<td>6</td>
<td>15</td>
<td>53</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td>Lease, Concession, Asset Sale</td>
<td>18 + 91 military lease</td>
<td>22</td>
<td>20</td>
<td>151</td>
<td></td>
</tr>
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Source: Public Works Financing

![Figure 1 Number of U.S. P3s 1986-2013, by Sector (Public Works Financing)](image)

Figure 1 shows changes in the number of P3s to reach financial close across the U.S. by sector. The number of P3 deals to close increased rapidly during the mid-1990, and has fluctuated since then. The initial increase in the number of P3s that reached its peak in 1998 appears largely due to water sector P3s, whose public sponsors were mostly
municipal water districts or equivalent agencies. The number of financial closes in this sector has decreased since then. In contrast, the number of financial closes in the transportation sector has shown constant increase, despite some years in the 2000s with low numbers. In particular, the number of financial closes has dramatically grown since 2010.

Figure 2 summarizes the cumulative aggregate costs of P3 projects in the U.S. by sector. These costs include procurement of public agencies and investment from private companies (e.g., for concessions). It is notable that in some of the years during the study period, the total investment is driven by the transportation sector: an increase of transportation sector coincides with the increase of total, starting in 2011. An equivalent trend can be found on Figure 1 which only shows the number of projects, but the difference between these two figures highlights the extent to which the transportation sector influence the amount of capital investment.

As for the transportation sector, and specifically the highway sector, the traditional funding model of gasoline tax based Highway Trust Fund (HTF) model has been considered unsustainable. In this model, the revenue from federally imposed gasoline tax (18.3 cents/gallon) is dedicated for the HTF. Without discussing the procedural details of the federal budget system, the fund is allocated to the U.S. states. Typically, these states have their own gasoline tax or equivalent revenue sources, which, together with the federal HTF allocation, are used for new capital construction projects and maintenance of existing assets. The federal gasoline tax is not adjusted to inflation,
and has not been changed since 1997, due to the political climate in which tax increases are highly unlikely.

Figure 2 Cumulative U.S. P3 Investments, 1990-2014 (2009US$BN, Public Works Financing)

The purchasing power of the HTF revenue has been declining, and the fund has been receiving transfer from the general account since 2008. States continue to face demand for expanding capacity in regions with growing economies, while existing assets are deteriorating, and delayed maintenance is pushing up the costs of maintaining the conditions of these assets to satisfactory levels. With the limited prospect for the HTF, states are viewing P3s as one of the innovative approaches to continue investing in the infrastructure (Gifford, 2012).
In the U.S., the use of highways P3s has been relatively limited compared to a number of other countries. Figure 3 shows the amount of highway investments through P3 procurements and concessions through the study period, and the states with P3 enabling legislations as of 2014. The Eno Center for Transportation argued that there are barriers to P3s in the U.S., and claimed, “many states still prohibit P3s and most others have little conception of how to manage one effectively in order to create benefits for both sides” (2014). Critics have pointed to a number of regulatory and legislative barriers at federal, state and local levels. Also, U.S. is unique with respect to the public sector’s capital investment: municipal securities are exempt from federal income tax. This mechanism serves as a disincentive for P3 projects to secure capital in private market (Eno Center for Transportation, 2014).

Figure 3 P3 Investments and Enabling Legislations of U.S. P3s, 1997-2014 (Public Works Financing, and National Conference of State Legislature)
While the number of P3 projects is still small, most of the demand risk toll road P3 projects have been struggling from lower than projected demand level. South Bay Expressway is a notable project that underwent bankruptcy due to low usage. One exception is California State Route 91, which in its years of operation under the P3 was performing financially reasonable. However, the original contract included a non-complete clause, a provision that prohibits the public partner to build facilities that might compete with the express lanes P3. Despite the favorable financial performance, because of policy consideration to alleviate congestion on the general lanes, the government eventually bought back the project to be able to expand the capacity of the general-purpose lanes on the route.

These instances demonstrate the difficulty in hitting a sustainable balance between excessive return for private investors and project bankruptcy. Therefore, it is recommended that a sound P3 enabling legislation should be adopted, including provisions regarding project eligibility, selection process, approval and review requirements, funding regulation, and required contract provisions (Eno Center for Transportation, 2014). Such legislation would provide clarity to possible private partners in making investment decisions in a market. Sound use of this policy tool appears a long way forward.

**OECD member countries**

A number of OECD member nations have used P3s for delivering infrastructure. The interests of policymakers in this procurement approach increased since the financial crisis in 2008, as countries face the need to remain competitive with infrastructure
investment, while overcoming their budget constraints. There are a number of countries with extensive experience with P3s long before the financial crisis, such as the United Kingdom, Australia, and Canada. In these countries, typically P3s were first implemented in the transportation sector (toll road, airport, seaport, and transit), and gradually the use of P3s expanded to other sectors, including water and wastewater management, public utilities, hospital, education facilities, and prisons. This procurement approach will always be a supplementary source of financing infrastructure (e.g., in the U.K., PFI projects account for 10-15% of infrastructure investments in a given year), and not the main approach to dominate the industries.

In reviewing P3 experiences in these countries, one may find that the number and the share of P3 projects that undergo difficulties (e.g., renegotiation of contract terms) are noticeably high. In particular, a number of transportation sector P3s with user fee arrangements have suffered from low facility usage. Shaoul et al. reported, for example, that out of the £90 billion-portfolio of PFI projects in the U.K.’s transport sector, £35 billion worth of projects underwent financial distress, eventually leading to renegotiation. While refinancing and renegotiation are quite possible due to the long durations of these contracts, it is undeniable that such incidents add to the transaction costs of these projects. Hence, if P3s were to be used, the risk should be accounted for in the initial procurement decisions (Shaoul et al., 2012).

The experience of OECD nations with respect to private investment in public infrastructure projects vary, and extensive experiences in these projects are not necessarily associated with better project performance. Considerable proportion of
projects with undesirable outcomes negatively affects private investors, thus continuous development and refinement of P3 institutions is necessary. In turn, from the private investor’s perspective, understanding of the institutional and political aspect of a market is indispensable when evaluating investment opportunities, in addition to market demand and project cost structure.

*Emerging Economies*

Countries with emerging economies need infrastructure that is vital to their economic development, and these governments face significant fiscal constraint in doing so. For example, a study by the World Bank’s Public Private Infrastructure Advisory Facility (PPIAF) reports that Africa has very low infrastructure stock, and to be able to bring up the level of infrastructure asset to a “reasonable” level, it predicted that annual investment of US$93 billion for a decade would be necessary, two-thirds of which would be for capital investment. As the current annual infrastructure investment in the region was US$45 billion, the gap, after accounting for the potential efficiency gains, would reach approximately US$31 billion per year, which is by no means realistic for traditional sources (governments and multilateral organizations) to reach. Private investment is viewed as a potential avenue by which the gap could be bridged at least in part (PPIAF, 2013).

Private firms have been active in delivering these services, as World Bank refers as Private Participation in Infrastructure. A number of issues challenge developing countries’ attempts to successfully develop infrastructure projects through P3 contracts.
From private investors’ point of view, there are particularly three issues for them to access a P3 market in a nation.

First, local financial markets lack the capability to enable large and long-term financial commitments. Keimeier and Versteeg analyzed the potential contribution of project financing for economic development, particularly in the context of low-income countries. Based on the findings from their empirical estimation, they argued that in countries where the financial markets have yet to develop, project financing could serve as a way to ignite economic development by delivering crucial infrastructure while minimizing the risks that prevail in the institutions of these nations (Kleimeier and Versteeg, 2010). Realistically, however, there are a number of issues that have to be addressed to realize project finance arrangements in these countries. Local banks are not large enough to have sufficient resources to provide financing to large projects in the infrastructure sector. Typically they have short loan life of maximum five years due to risky market environment. Furthermore, neither governments nor financial sector have expertise to undertake such complex deals as project finance projects.

Second, perhaps more importantly, critics have suggested that the institutional environment to enable P3s is weak in developing countries. Policy directions, legislations, and regulations that govern P3 deals are typically unclear in these nations. Oftentimes different agencies in the same government as well as different governments have conflicting objectives, and coordination is difficult. Transparency is barely existent with respect to bidding and awarding procurement contracts. All of these serve as serious political and approval risks that deter private investors.
Third, similar to countries at different stages of economic development, the lack of robust project pipeline also detracts private investment in public infrastructure. The PPIAF report on Sub-Saharan African nations suggests that a P3 market is attractive to private investment when a sufficient number of projects which upstream analysis and due diligence demonstrate their commercial viability is available. However, public agencies generally lack the understanding of what P3s are, general timeline of developing a P3 project, necessary appraisal and evaluation techniques, transparent bidding procedures, and fair and reasonable risk allocation. As such, it is unrealistic to assume that a solid pipeline of P3 projects may be available in these countries. As a result, it has been reported that unsolicited projects prevail in developing countries.

PPIAF argues that the prevalence of unsolicited proposals for P3s may not be desirable, as they tend to be based on limited engineering, demand, and cost information, with the hope that the government could be convinced to commit funding for the project. Moreover, unsolicited proposals tend to distract sector-specific investment strategy. Overall, one may conclude that the lack of capacity within public agencies have not only resulted in institutions unfavorable for private investment in public infrastructure, but also in prevalence of P3 projects that may not be desirable with respect to their risks for undesirable outcomes and distraction from long term sector specific investment strategies (PPIAF, 2013).

The review of institutional performances regarding P3s in the U.S., OECD nations, and developing countries demonstrate that challenges continue to exist. As is evident, despite distinct circumstances, the financial constraints appear to have driven the
increasing use of P3s in developing countries, OECD nations, and countries with emerging economies alike. Each project in any countries has unique characteristics, and consideration to these circumstances is essential.

Generally, the lack of capacity within the public sector serves as a factor to deter private investment, and poor performance in cases where private investments have realized. This finding points to the need to comprehensively understand private investment in P3 projects including institutional and political contexts surrounding each project.

2.2.3 Institutional and Political Environment of P3s

One of the reasons that P3s are attractive to policy makers is because P3s could allow access to private capital. The resources for infrastructure investment are ultimately the same: user fees collected by the operator of the particular facility in use, or, tax revenues collected by public agencies at the federal, state, or local level. In principle, therefore, P3s does not add new revenues to the existing mechanisms: privately financed P3 projects merely use private investment as a financing tool to tap into the same revenue source: the users.

In this context, the difference between the two procurement mechanisms, hence the potential benefit of P3s, emerges when the public sector is constrained in tapping into tax or user fee revenues due to legal or budgetary constraints. For example, a number of U.S. states have statutory or constitutional limits on borrowing. Private means (debt or equity) could be used in such cases to invest in capital project, with user charges as the repayment revenue stream, and tax revenues and user fees are equivalent liability to the
state’s economy in any case (Congressional Budget Office 2012). The problem is that private investors participate in a P3 project because of its expected return on their investment. While understanding the financial structure of these arrangements is essential, this study will focus on another important dimension of the investment decisions particularly relevant for P3s, political and institutional environment as well as their risks.

The institutional and political conditions upon which a project could be implemented have considerable influence on public and private decision-makers to invest in the projects through such innovative approaches. The institution refers to the presence of a legal framework for such undertakings as well as how favorable or limiting specific provisions of the legislation are to certain arrangements. Political factors have also been found to considerably influence whether P3s have been successfully implemented.

Guidelines and best practices have been proposed by a number of organizations, such as various industry groups (e.g., Eno Center for Transportation, 2014) and the World Bank. Nevertheless, only a limited number of studies have empirically investigated how or to what extent these factors affect the decisions to be made. This study will fill gap by addressing one of the research questions of the proposed dissertation: how and to what extent institutional and political factors contribute to private investment in infrastructure projects? Building onto an earlier study, this analysis will empirically investigate factors that are associated with the use of innovative procurement approaches for highway capacity expansion projects in the U.S.
One of the critical features of P3s is that they are contracts between a public agency and a private entity that have agreed upon the terms of delivering an infrastructure facility. A variety of factors have been argued to influence these deals, including: market demand for facilities under consideration; costs of supplying the capital and operation, macroeconomic and financial conditions that enables feasible financing arrangements; regulatory and political environment, etc.

Institutional and political factors are critical for successful participation of private firms in infrastructure projects. First, implementing P3s require strong leadership and political commitment. Strong public opposition to specific projects are possible for environmental concerns. In the U.S., P3s are at times perceived in association with tolling, which may be unpopular. Completing an infrastructure facility delivery therefore requires that public decision makers to effectively address these challenges. From the perspective of private partners, in turn, long-term commitment for a project with strong public opposition puts the project in a vulnerable position, hence deterring private investment.

Literature on risk evaluation models for P3 projects without exception discuss the important role of political and institutional risks, and private investors carefully evaluate these factors when deciding whether to enter a P3 market or not. Furthermore, P3s are a unique kind of contracts as the public agency has the right to alter legal environment of a project. Even after a contract has been executed, it may not necessarily be in the interest of private partners to continue their commitment to a project against politically unfavorable environment. For instance, after a project construction has completed and
begun operation, both public and private partners continue to face the risk of contractual renegotiations triggered by the other party. As Guasch demonstrated in his analysis of concession projects in Latin America, government unilaterally initiated 27% of renegotiations, while in 16% cases governments and operators mutually agreed to initiate renegotiations. He attributed these renegotiations fully or partially initiated by governments not honoring the contract provisions (e.g., altering toll regimes for political reasons) or defective regulatory regimes of P3 projects (Guasch, 2004).

These are critical considerations when evaluating private investment alternatives for an infrastructure project, from both public and private partners’ perspectives. Investment decisions of private firms account for these institutional and political risks, while project decisions of public agencies are driven by political motivations and guided by institutional frameworks. Arguably, private investments in public infrastructure projects reveal the level of institutional and political factors, which both sectors can tolerate in collaborating with each other. Understanding these factors is critical for making sound investment decisions for both public agencies and private investors.

In this study, the focus will be on the environment where both public and private partners can agree upon a complex contractual arrangement. On the public sector’s side, for example, the considerations may include: what factors affect public agencies’ decision makers to sign a contract that authorizes the partner to develop a facility and make profit through operation, sometimes with procurement from the public agencies? In contrast, from private partner’s perspective, what types of regulatory environment,
facilitated by the policy makers, are in or against favor of their decision to attempt to enter a P3 market?

2.3 Literature Review

There is abundant literature that explains behaviors of public agencies in infrastructure investment, while analysis in the specific context of infrastructure P3s has been very limited. The review in this section will first focus on empirical studies on political and institutional factors for P3 projects, primarily from economic development literature and a few studies with similar approaches on the U.S. market. Some of the relevant studies from political economy literature will then be briefly reviewed, as this is the dimension that will serve as value added of the analysis in this study. The section will conclude by pointing to the gap in the literature that this study intends to bridge.

2.3.1 Institutional and Political Determinants of P3s

The literature on infrastructure P3s with respect to their institutional and political environments began emerging in recent years and still is scarce. There have been a number of political economy theories on various aspects of P3s. A notable example is Boardman and Vining (2012), who argued that a sound P3 institution is necessarily limited in terms of private investment favorability. With respect to empirical investigations, one may find several studies in the context of developing countries using the World Bank’s Private Participation in Infrastructure (PPI) database. In this context, following the convention (Hammami et al. 2006), PPI and P3s are used interchangeably (Thomsen, 2005). Scholarly investigations on P3s in developing countries’ with respect
to the institutional, legal and political environment stem from Kirkpatrick et al. (2006), which focused on Foreign Direct Investments (FDI).

As P3s are rather recent phenomena in the modern sense, only in recent years can one find studies of institutional and political determinants of P3 deals. Most of these studies to date focus on developing countries, due to the availability of PPI project information from the World Bank. Shah and Batley (2009) provided a review of this strand of literature. Hammami et al. (2006) proposed empirical models of the number of projects, dollar values of each P3 investment, and the extent of private participation in P3 projects. Their models included variables of macroeconomic conditions, governments’ fiscal constraints, political conditions, institutional quality and legal system, and experiences of P3 deals in the past. The results of energy, telecommunications, transportation, and water between 1990 and 2003 showed that the market conditions (e.g., market size, purchasing power, and exchange rate risk) had the most considerable effect on the use of P3s. Political factors that were included in the empirical model were ethnic fractionalization, established checks-and-balances of government branches, and corruptions had significant effect on P3s. Banerjee et al. (2006) similarly analyzed 40 developing countries between 1990 and 2000 in terms of their divesture revenues, project costs, and private investment. Their results also supported the view that stable and effective economic and legal institutions were associated with higher private investment in infrastructure projects. Economic factors (e.g., macroeconomic stability, exchange rate, GDP growth and GDP per capita) were also found to be associated with greater P3 investments. Notably, corruption was also a significant factor in the use of P3s.
Moszoro et al. conducted a similar analysis with a formalized theoretical model and a refined empirical model for estimation of the same PPI dataset (2015). The authors proposed a theoretical investment model with institutional and political variables that explicitly accounted for discount rate heterogeneity of agents, predicting the institutional quality (e.g., rule of law, freedom from corruption, etc.) would be associated with higher P3s and private investments. Their empirical estimation of moving averages of P3 investments for country year observations showed that P3 investments were sensitive to the regulatory environment variables, as their theoretical model had predicted. With respect to the role of corruption, the authors found cultural factors to influence the appetite for private investment in P3s: low levels of corruption and rule of law were associated with higher greenfield investments. Importantly, government effectiveness and regulation qualities were associated with higher brownfield investments. Overall, in developing countries, facilitation of sound regulatory, legal, and political environment appears to be desirable for private investment in public infrastructure projects.

Other similar studies include Basílio (2011), Sharma (2012), and Mengistu (2013), among others, which conducted equivalent analyses with different empirical models and distinct focuses (e.g., financial liquidity of country markets, legal systems, and public debt). It should be pointed that these studies appear to be primarily driven by data availability. In these cases, the PPI database of the World Bank, which summarizes P3 projects with information on project costs, sector, contract type, and other information. Therefore these findings depend heavily on the quality of available information, and careful consideration of the details in the database is essential.
In the U.S., the experience of public agencies to engage in P3s has only begun in recent years, and the number of projects has been small compared to other nations. Arguably, this is in part due to the well-established municipal bond market. Infrastructure in the U.S. is funded by tax revenue and various financing instruments, such as general obligation bonds (with full faith and credit of the state or municipality) and revenue bonds (backed by a dedicated revenue stream, such as user fees of the facility). These bonds are tax-exempt, and public agencies can benefit from low costs of capital of these vehicles, rather than seeking for more costly private financing (U.S. Department of Treasury, 2014).

Reflecting the short history of P3s in the U.S., only a few studies have investigated factors that contribute to public agencies’ decision to enter into P3 arrangements for specific projects. The P3 markets in the U.S. are still evolving, and facilitation of an institutional environment that allows such investments remains to be of policy relevance. Geddes and Wagner analyzed enabling legislations of P3s in U.S. states and constructed a scale of investment favorability of these legislations to private investments (2013a). The favorability was based on key provisions of these legislations to allow public agencies to close contracts that include such features as: a mix of public and private funds for a project, availability payments, non-competing clauses, and unsolicited proposals. The authors weighted these provisions based on a survey to industry experts, and developed a scale of private investment favorability for each state’s enabling legislation. The authors then conducted an analysis of what political, economic, and other factors affect the decisions of states to enact such laws, and how favorable
these laws are to private investments in P3s. Their empirical results showed P3 legislations were driven primarily by demand-side factors such as states’ traffic levels (travel time index or TTI) as well as their political dispositions (i.e., prevalence of pro-business conservatives). As for the favorability of enabling legislations, the authors showed that the share of Republicans in the state legislature as well as the growth of personal income were associated with higher favorability scores of the state’s enabling legislation. Fiscal conditions were, again, not found to be associated with the favorability of P3 legislation to private investment.

Geddes and Wagner (2013b) also attempted to analyze if the aforementioned favorability scale of P3 enabling legislations were associated with the likelihood of the states to complete P3 projects (as broadly defined to include DB projects), along with other economic and political factors. Their estimation of a linear probability model of a state to complete one or more P3 projects showed that the enabling laws increased the number of P3s undertaken in the states, and their favorability were also associated with more P3s. They found that the states’ bond rating was also significantly associated with P3 projects. The growth in travel demand (as measured by vehicle registration and VMT) was found to be associated with higher DB projects, but not with more complex P3 deals. A highlight of these studies, which resonates with the few other similar studies (e.g., Chen et al., 2014) is that the states’ fiscal conditions were not associated with the use of P3s, which is contrary to the claims often made by policy makers.
2.3.2 Election Cycle and Economic Policy

This subsection will focus on the public choice literature on government’s capital expenditure behaviors. The attention to this line of literature is partly motivated by Boardman and Vining (2012), who argued that the objective function of public decision makers is to maximize votes: P3s can be viewed as a policy tool to maximize votes for reelection. P3s in this view in part compose public agencies’ capital investment for infrastructure services that benefit the economy, with the motivation to augment the voters’ approval of the incumbent policy makers.

It has been well established that election cycles under democratic regimes affect public agencies’ budgeting practices. Initially, the discussion considered not only fiscal but also monetary policies of national governments. The theoretical model of Nordhaus (1975) on maneuvering economic policies for electoral advantage arguably initiated the vast literature on political business cycles. In this model, fiscal and monetary policies would be used to trigger an artificial boom before the election so as to increase the popularity among myopic voters to win in the election. The economic policy and the economy would then contract after the election. The assumption that the voters were repeatedly tricked by the economic policy was criticized, and a rational expectation assumption became a popular view of voters in the models in years that followed (Veiga and Veiga, 2007). Seminal papers by Rogoff (1990) modeled behaviors of politicians using macroeconomic policy variables (e.g., tax, government expenditure, deficits, and monetary policies) and their compositions in a budget package. These studies triggered a large number of studies to explain public agencies’ behaviors for favorable electoral outcomes, at national and subnational levels in the U.S. and elsewhere.
A number of empirical studies addressed the question on the relationship between economic policies and election cycles. Blais and Nadeau investigated expenditures of Canadian provinces between 1951 and 1984, finding that social and road expenditures showed cyclical patterns visible in the year before elections (1992). Khemani analyzed public spending in Indian states and found that the overall public investment increased before elections but the investment contracted after the elections (2004). Veiga and Veiga (2007) analyzed the relationships between budget balances, tax rates, and various types of government expenditure of Portuguese municipalities and election cycles between 1964 and 1982. They found evidence of municipal offices attempting to signal their “competence” to voters through lowering taxes, increasing such “visible” expenditures as road and building constructions in the year or two years prior to mayoral elections.

In recent years, scholars have been addressing the questions of political economic cycles in a manner more sensitive to the complexity of public budgeting and the interactions between policy intervention and electoral turnouts. These questions include various types of economic policy variables, the channels by which electoral cycles might affect policy makers’ behaviors, as well as how these distortionary policies actually affect election outcomes. Drazen and Eslave proposed classifying government expenditures into current and capital expenditures, testing the hypothesis that the political cycle influences not the aggregate spending level but the budget composition. Their empirical estimation of Columbian municipalities found that voters respond to increases in spending for some goods but not others, and that the politicians’ budget manipulation before the elections were not the overall spending but their composition (2010). Schneider also focused on
budget composition in pre-election years in West German states, findings similar results (2010). Katsumi and Sarantides (2012) conducted a national level empirical analysis of 19 member countries of the OECD between 1972 and 1999, finding that in the election years budget composition shifted from capital expenditure to current expenditure. These studies highlight the potential complexities of the relationship between election cycles and economic policy decisions.

Scholars have paid attention to various aspects of political business cycles: heterogeneity of political cycles across countries (e.g., de Haan and Klomp, 2013), debt management strategies of municipalities (Bastida et al., 2013), and the effect the likelihood of re-election to spending levels (Fiva and Natvik, 2012). Relevant to the subject of P3s, Chong et al. investigated the relationship between election cycles and public works procurement of French municipalities between 2005 and 2007 (2014). Their analysis showed that in municipalities where mayors were running for re-election in 2007, public works contracts were more likely to end, supporting the hypothesis that decision makers influence the timing of project delivery with motives related to election cycles. Overall, the view that election cycles affect decision makers’ economic policies has been recognized widely, especially in the context of fiscal policies of subnational government units.

When discussing the relationship between the election cycles and economic policy interventions, understanding of the two-way interaction between the two is critical. Scholars have investigated the effect of economic policy and voters’ response, in terms of the reelection outcomes. Behaviors of voters are complex: scholarly findings on how
voters respond to various economic policies depend on various factors, and the direction of the effect may even be the opposite in different locations. The effect of spending on voter favorability is one such example. Peltzman (1992), Brender and Drazen (2008), Drazen and Eslave (2010), and Balaguer-Coll et al. (2015), among others, showed through various empirical approaches in distinct contexts that deficits and higher spending were unfavorable to voters, decreasing the chance for the incumbent to be reelected. In contrast, Aidt et al. (2011) demonstrated in Brazilian and Portuguese contexts respectively that higher aggregate expenditures were associated with higher likelihood of the incumbents to win re-elections. While the unsettled state of this debate is intriguing on its own right, more relevantly, these studies point to the potential endogeneity issue in conducting empirical investigations on political cycles. Furthermore, inquiries with respect to the economic output (e.g., GDP) almost invariably suffer from endogeneity, as suggested by Moszoro et al. (2015). Therefore, addressing this issue will be indispensable for the analysis in this study.

The manner by which fiscal conditions and political dispositions have been accounted for in the empirical literature may have been insensitive to how these channels could influence the use of P3 contracts. For example, with respect to fiscal conditions, bond ratings, outstanding debt, balance of states’ highway account and other variables used in the analyses to date may give a general idea of the fiscal condition of a state. However, a more careful treatment may be necessary to explicitly account for how specific P3 deals may be formed provided certain fiscal considerations motivate initiation, negotiation, and closing of a deal. Similarly, while political conditions are
intuitively very important in P3 investment decisions, the influence is not as simple as one party supports and the other party opposes. Empirical approaches that are more sensitive to these details may lead to more insightful results regarding the state of P3 markets in the U.S.

The literature review in this section focused on the factors for public agencies and private firms to form a contractual relationship to invest in infrastructure facilities. Assuming that particular sets of attractive conditions would invariably result in private investment in public infrastructure project, the review highlights the political and institutional environments that enable and promote these deals. First, the brief review of the political business cycle literature implied the hypothesis has been tested predominantly for government spending and other economic policy variables. The framework has not yet been extended to P3s either with respect to the number of projects or the size of private/joint investments. Second, the empirical literature on the political and institutional drivers of P3s have been conducted mostly in the developing countries context, and the emphasis is commonly on corruption, political regime, and macroeconomic stability. These considerations are valuable in their own right, but their relevance to the developed countries context may be limited. Finally, the analysis on the U.S. market has been scarce, and the granularity of these empirical models has been questionable at best. These are the gap in the literature that this study attempts to bridge, by estimating an empirical model of the use of innovative contracts.
2.4 Data and Empirical Strategies

This section will present the empirical models and the data employed to test the hypotheses discussed above in the context of U.S. states. Definition of the modeled dependent variable will be discussed first. The second subsection will discuss independent variables of the estimated empirical models, including control variables, states’ financial variables, and political and election cycle variables. The third subsection will present empirical models to be estimated, before proceeding to discuss the results in the next section.

Careful consideration is necessary to define statistically estimable dependent variable to represent states’ activities regarding the use of P3 contracts. In the political business cycle literature, no clear guideline has emerged as to the treatment of P3s in statistically analyzing public capital investments. Among the numerous contract types considered as variants of P3s, DB projects are procured fully by public sponsoring agencies. Therefore, DB was included as one of the dependent variables.

With respect to capital investment amount through P3 projects, in the cases of P3 projects (i.e., not DB contracts), complexities such as private equity investments warrant more thoughtful approach in defining the dependent variable. This study considers total project costs, inclusive of public and private procurement in these projects, as societal capital investments, where right combinations of economic, institutional, and political conditions need to meet to manifest. Similar empirical analyses in the literature also use equivalent approaches (Geddes and Wagner 2013b, Moszoro et al., 2015, Chen et al., 2014).
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<td>6.7080</td>
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<td>816</td>
<td>0.0031</td>
<td>0.0052</td>
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<td>0.0624</td>
<td>U.S. Census Bureau</td>
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<td>MotorFuelTax/GSP</td>
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<td>0.0076</td>
<td>0.0078</td>
<td>0.0002</td>
<td>0.0362</td>
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<td>0.6695</td>
<td>3.6481</td>
<td>-8.0138</td>
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<td>RepGov</td>
<td></td>
<td>867</td>
<td>0.5294</td>
<td>0.4994</td>
<td>0.0000</td>
<td>1.0000</td>
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<td>+</td>
</tr>
<tr>
<td>RepVoteShare</td>
<td></td>
<td>850</td>
<td>0.4915</td>
<td>0.1137</td>
<td>0.1113</td>
<td>0.7917</td>
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*: See discussion in the text.
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<td>Personal Income/Capita</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>L. Personal Income Growth</td>
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<td>1.000</td>
<td></td>
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<tr>
<td>L. VMT Growth</td>
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<td>0.273</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L. Debt/GSP</td>
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<td>0.083</td>
<td>-0.005</td>
<td>1.000</td>
<td></td>
<td></td>
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<tr>
<td>L. Debt Growth</td>
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<td>-0.269</td>
<td>0.113</td>
<td>-0.029</td>
<td>1.000</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>L. Highway Capital Outlay/GSP</td>
<td>0.039</td>
<td>0.114</td>
<td>0.046</td>
<td>0.588</td>
<td>-0.373</td>
<td>1.000</td>
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<td>GasTax/GSP</td>
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<td>0.124</td>
<td>0.058</td>
<td>0.972</td>
<td>0.038</td>
<td>0.053</td>
<td>1.000</td>
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<tr>
<td>L.MGasTax Revenue Growth</td>
<td>-0.037</td>
<td>0.041</td>
<td>0.071</td>
<td>-0.003</td>
<td>0.262</td>
<td>-0.088</td>
<td>0.028</td>
<td>1.000</td>
<td></td>
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<tr>
<td>RepGov</td>
<td>-0.088</td>
<td>0.035</td>
<td>0.066</td>
<td>0.080</td>
<td>-0.030</td>
<td>0.045</td>
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<td>1.000</td>
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</tr>
<tr>
<td>RepVote Share</td>
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<td>0.055</td>
<td>0.113</td>
<td>0.082</td>
<td>0.002</td>
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<td>0.021</td>
<td>0.743</td>
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<tr>
<td>GovVictory Margin</td>
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<td>0.136</td>
<td>-0.027</td>
<td>0.214</td>
<td>-0.072</td>
<td>0.117</td>
<td>0.184</td>
<td>-0.085</td>
<td>0.134</td>
<td>0.209</td>
<td>1.000</td>
</tr>
</tbody>
</table>
Based on these considerations, the empirical models in this study models three classifications of highway P3 projects: DB projects (“DB”); P3 projects that are not DBs (e.g., DBOM, DBFOM, DBF, etc.; “P3”); and DB&P3s, which encompass projects of all innovative contract types. This is due to the nature of available data rather than to any theoretically constructed classification approach, which does not substantively differ from the common approach in the literature, as pointed out in the previous section. The analysis in this study uses P3 project information from Public Works Financing, which is one of the most comprehensive and up-to-date databases that are well respected in the infrastructure industries.

This analysis models: 1) the number of P3 projects, and 2) the aggregate highway P3 costs, for each state in each year during the study period. The data is unbalanced panel data of U.S. states from 1997 to 2013: the study period was determined based on data availability. As the literature review suggested, there are competing views on drivers of P3s (e.g., economic efficiency and fiscal constraints of public agencies), and developing a formal proposition of P3 investments to account for political cycle requires thoughtful analysis. Since the interest here is rather exploratory to understand the U.S. P3 market in these respects, a set of qualitative hypotheses are proposed based on the literature that addressed similar research questions. The following section will describe the data used in the empirical analysis of this study, with discussion on the respective hypothesis to be tested. Descriptive statistics of the independent variables and their sources are summarized on Table 4. Table 5 shows correlation of these independent variables.
2.4.1 Control Variables

In the literature, frequently used control variables for statistically modeling the use of P3s are the size and wealth level of the economies and the demand for automobile trips. With respect to the economy size, Gross Domestic Product is commonly used in the international development literature (e.g., Moszoro et al., 2015), although high collinearity with other variables and the potential endogeneity issue needs to be addressed. Other control variables in similar studies include personal income and median household income. Also, with respect to the demand for automobile trips, the variables commonly used in the literature include Vehicle-Miles-Traveled (VMT) and the number of motor vehicle registrations (Wagner and Geddes, 2013b, Chen et al. 2014). In determining an appropriate set of control variables in this analysis, combinations of these variables and their natural logs were examined. As a result, the following variables were selected primarily on the basis of model fit and co-linearity minimization: natural log of per capita state personal income (Personal_Income/Capita), state personal income growth (Personal_Income_Growth), and growth of vehicle miles traveled (VMTGrowth).

Many of these variables are potentially endogenous to the dependent variables, and unless properly addressed, they are likely to be correlated with the error term, which needs to be addressed. Typically in this line of literature, researchers address this problem by taking the lag of the independent variable (e.g., Moszoro, et al., 2015). This analysis follows these studies in assuming that the P3 deals are closed, affected by events in the previous year (i.e., year t-1: “L.” prior to the variable names). Examination of other lags (e.g., t-2, t-3, etc.) suggested that the one-year lag was the most desirable because of model fit and preserving the number of observations.
As regards the expected effects of these variables, the economy size represents its market size for infrastructure investment, while its growth can be interpreted as the market potential. Therefore, the expected signs of the estimated coefficients of per capita personal income and state personal income growth are positive. VMT growth can also serve as a proxy of the market potential for highway facilities, thus positive coefficient is also expected for empirical estimation.

2.4.2 States’ Financial Conditions

One of the leading arguments regarding the driver of P3s’ popularity is severe fiscal constraint of public agencies, although it should be noted that the plausibility of such claims could be debatable (De Ormijana and Rubio, 2015). Interestingly, many of the estimated coefficients of financial variables in the empirical literature on the U.S. P3 market are statistically insignificant (e.g., Geddes and Wagner, 2013a). To the author’s knowledge, there has been little, if any, convincing analysis as to why this might be the case, other than the intuitive but naïve claim that P3s in the U.S. are indeed motivated by pursuit of economic efficiencies. A more realistic explanation may be that the mechanism by which fiscal constraints influence the decisions to engage in P3 arrangements for highway projects is far more complex than just state debt per capita in the estimated empirical models.

In determining the variables pertaining to financial conditions of states, a number of variables from various sources were examined so as to find a set of variables that is theoretically sound and reasonable with respect to their model fit. Financial variables commonly used in the relevant literature are states’ debt level, bond rating, and capital
expenditure on highways, in the case of the road sector (Geddes and Wagner, 2013, and Moszoro et al., 2015). In addition, other candidate variables include: net balance of state highway accounts and highway indebtedness, such as outstanding or obligation of debt particular to transportation or highway capital investments (Chen et al., 2014). Furthermore, one may hypothesize that motor fuel tax revenue may influence procurement decisions for P3 projects. Finally, growth of these variables may also be important. Among these, the empirical models in this study include the following variables that represent states’ financial conditions: debt per gross state product, or GSP (Debt/GSP), debt growth (DebtGrowth), highway capital outlay per GSP (HighwayCapitalOutlay/GSP), motor fuel tax revenue per GSP (MotorFuelTax/GSP), and motor fuel tax revenue growth (MotorFuelTaxRevenue_Growth). Similar to the control variables, this analysis assumes that these variables in the previous year (i.e., t-1) influences the decisions of P3 deal closes in the present year, so as to avoid the potential endogeneity issue.

Many of these financial variables present difficulty in a priori expecting the signs of empirically estimated coefficients. One example is with respect to the effect of states’ debt levels and debt growths (Debt/GSP and DebtGrowth). On the one hand, states’ aggregate debt and its growth may positively affect the use of P3 models, as public agencies may seek to continue infrastructure investment while circumventing its borrowing capacity limitation (Hodge et al., 2010). On the other hand, debt and debt growth may negatively influence P3 investments, since state contribution to P3 projects
are still indispensable for most projects, and the higher the debt, the less likely that the state has the fiscal or borrowing capacity to make these investments.

Similarly, the effect of highway capital outlay (HighwayCapitalOutlay/GSP) to the number or the amount of P3 deals in a state is not clear. While larger highway capital outlay may indicate the demand for highway infrastructure and hence P3s is also large, it may also suggest that the demand for highways has been addressed without resorting to the P3 models. Furthermore, an increase in gas tax revenue or growth (HighwayCapitalOutlay/GSP and MotorFuelTaxRevenue_Growth) may increase P3s through generating revenues for public contributions to P3s, while it may reduce the need for P3 models should the revenue be committed to traditionally procured projects. Therefore, the expected signs of these variables remain ambiguous, and empirical estimation is necessary to evaluate the relative influence of these effects to the states’ P3 use.

2.4.3 Politics and Election Cycle

Consideration of politics in the context of infrastructure P3s has focused primarily on political risks that, when manifested, present significant challenges to project completion. The intent of the analysis in this study, however, is to explore more in depth, especially in light of election outcomes and political cycle. Three aspects under this category that the empirical models in this study address are: party affiliation of governors, election outcomes, and election cycle.

Political parties have distinct views on the increasing role of private entities in providing public infrastructure services, and empirical studies have employed various
approaches to address this aspect. Wagner and Geddes (2013), for example, hypothesized that strength of unionized public employees would deter P3 investments, since P3 projects are commonly perceived to reduce employment in pursuit of efficiency in service provision. A recent example is the second phase of a $486.9 million Presidio Parkway project (California), which is now moving forward as a DBFOM contract. The project has been challenged in court by the Professional Engineers in California Government (PECG), a labor union of state engineers. Although the court ruled in favor of the P3 approach, the project demonstrated that the political risk could substantially influence the course of candidate P3 projects (Roberts, 2011).

There is also abundant literature on privatization, although it should be noted that P3s refer to a much wider range of infrastructure investment models. The line of literature regrading why and how privatization could achieve societal efficiency, represented by Vickers and Yarrow (1991) is, while extremely important, beyond the scope of the review here. Conventionally, the Republicans are perceived to be more favorable to increasing the roles that private firms play in delivering services conventionally provided by the public sector.

With respect to political philosophies, therefore, the discussion above indicates the following. The strength of labor unions (e.g., number of union members), Democratic governor, and state legislature where the majority is Democrats, are likely to be unfavorable to the use of P3 models for highway projects. In contrast, under a Republican governor and/or a republican majority state legislatures, P3s are more likely to be seriously considered. Based on the model fit and minimization of collinearity with other
independent variables, share of votes of Republican candidates in the gubernatorial election (RepVoteShare) is used in the empirical model for estimation.

With respect to the role of election cycles, competing views have been proposed in the literature. One of these views is that decision makers use capital investments as a means to manipulate voters, as reviewed in the literature review. While the details of this theoretical proposition are beyond the scope of the discussion here, the underlying observation is that public capital expenditure benefits the economy, and that public agencies have limited resources. The decision makers, therefore, strategically determines when to exercise voter-friendly spending such as procurement of capital investment projects (e.g., highways) to maximize the chance of reelection. Empirically, scholars have found that capital spending increases before the election, while other spending shrink (Drazen and Eslava, 2010). Extending this theoretical model and focusing on voter-friendliness of capital spending, decision makers might be inclined to resort to capital spending when facing contestable political conditions, which can be manifested as smaller margin of victory. Facing their limited resources the administration would then be more likely to engage in increased capital spending in years before the elections to raise the chance of re-election. In this context, if P3 projects are perceived as a subset of policy means to invest in public capital, then the number and the amount of P3 investments would be higher before gubernatorial election years, and would be lower in other years.

In contrast, there is a competing school of thought that emphasizes the effect of contestable political climates on the decision makers’ willingness to engage in complex
contractual relationships such as P3s. This view originates from the observation that public agencies are susceptible to political challenges from third party groups for their activities. For example, highway capital investments may be vulnerable to challenges from environmental activists, who may file lawsuits or run political campaigns against particular projects. Supporting this view, it has been empirically found that contracts of public agencies tend to be longer and include more clauses regarding arbitration, litigation, and formalization of renegotiations (Moszoro et al., 2014). While formalizing this theoretical proposition in the particular context of this analysis is reserved for future analyses, such relationship would suggest the following: the smaller the margin of gubernatorial victory, the less likely that the administration engages in politically risky undertakings. P3s are notoriously complex contractual arrangements. Holding the project complexity constant, an increase in political contestability (e.g., more powerful challenger to the incumbent office through smaller margin of gubernatorial election polls) would be associated with lower use of P3s, *ceteris paribus*.

Based on the discussion here, the empirical models in this analysis include margin of victory of gubernatorial elections (GovVictoryMargin), and the years in office GovYear=1, 2, 3, and 4, where the year after the election year is set to take the value of 1. As the above discussion indicates, there are competing views regarding how political conditions and election cycles may affect the use of P3s. Therefore the expected signs of coefficients remain ambiguous, and empirical estimation is necessary to explore the experiences of U.S. states in these regards.
2.4.4 Empirical Estimation Models

In this analysis, two sets of empirical models are employed to model the number of P3 contracts to be closed and the amount of innovative highway P3 investments in the U.S. states between 1997 and 2013. Regarding the models of the number of project contract closes, since the dependent variable is non-negative integer, count data regression models are appropriate. Poisson and negative binomial regression models are commonly used in the literature to model a wide range of economic events such as patents, corporate acquisitions, and insurance claims (Cameron and Trivedi, 2013). A conceivable issue with this approach in the context of highway P3s is that the mere number of closed deals in a state for a particular year may lose sight of rich details behind each project. For example, the cost of each project ranges from several million dollars to multi-billion dollars, and these details seem very important when considering economic, institutional, and political environments.

Count data regression models can be warranted because P3s are notoriously novel for most state transportation authorities, and to close just a single project it takes considerable resources and agency’s commitment, regardless of the project costs (Melehani, 2015). Also, economic theory has suggested that innovative procurement approaches are justifiable when efficiency gains from contract bundling and risk transfers outweigh transaction costs of these deals that are substantial. It is thus reasonable to assume that state agencies undergo equally resource intensive internal effort and procedures to close each P3 deal. In addition, a number of studies in the literature have employed count data regression techniques to model contracts of public agencies, without
regard to their costs (e.g., Hammammi et al., 2006, Dreher et al., 2009). For these reasons, count data regression is one of the approaches employed in the analysis herein.

To shed light on the heterogeneity of highway capital investment amounts, aggregate P3 project costs for each state year was also modeled using OLS estimation, following Moszoro et al. (2015). Nevertheless, this approach suffers from two problems in this particular context. First, unlike in other studies with similar research questions, a large proportion of the dependent variables are zero. This prohibits the use of taking the natural log of dependent variables to address potential non-linearity of the relationships of our interest. Second, variance of the dependent variables is fairly large, and estimated standard errors become extremely large, casting doubts regarding the validity of the estimated empirical models. Therefore, weaknesses can be found in both count data regressions of the numbers of P3 financial closes and OLS regression of project costs. Hence, both approaches are employed so as to allow critical yet more holistic analysis of estimation results.

Presentation of mathematical derivation in the present subsection is based on Cameron and Trivedi (2013), Cameron and Trivedi (2010), and StataCorp. (2013a). The number of highway P3 deals to reach financial close $y_{it}$ in panel data (state $i = 1, ..., N$; year $t = 1, ..., T$) is first assumed to have the Poisson distribution, with the mean of:

$$E(y_{it}|\alpha_i, X_{it}) = exp(\gamma_i + X'_{it}\beta) = \alpha_i exp(X'_{it}\beta)$$  \hspace{1cm} (2.1)

where $\gamma_i = \ln \alpha_i$. $X_{it}$ is assumed to include the state’s own intercept, and is allowed to be correlated with $\alpha_i$. In estimating $\beta$, $\alpha_i$ needs to be eliminated since the data is short panel. Critically, Poisson regression assumes that
\[ E(y_{it}|\alpha_i, X_{it}) = Var(y_{it}|\alpha_i, X_{it}) \] (2.2)

which rarely holds in real world applications. In the literature, however, Poisson models are commonly used even with over-dispersion of the dependent variable, where Negative Binomial models, which are more general approach that relax this assumption, are additionally estimated to compare the results. Unfortunately, estimation of negative binomial models suffered from the lack of convergence in many instances, raising questions whether model estimates can be compared in a sound manner. Furthermore, while the critical issue with the Poisson regression, which commonly triggers the use of the negative binomial regression, is potential violation of the mean-variance equality assumption, the problem may not be serious in this context. Table 6 compares the mean and variance of the dependent variables, for both scenarios where all states are considered and where only state-years with P3 enabling legislations. It should be noted that the dependent variables of a large proportion of the observations were zeros, and jointly with small numbers of dependent variables (e.g., maximum value of 4 for DB&P3 in all states). As a result, both the mean and variance were very close to each other at values close to 0.1. While no formal test has been conducted, it can be reasonably assumed herein that the mean-variance equality assumption of Poisson regression model is not violated. Overall, Poisson regressions are conducted for our analysis with various specifications.

In determining panel count data models, the decision to use random effects, fixed effects, or other panel models rests on the assumptions and the characteristics of independent variables. Cameron and Trivedi (2009) pointed out that time invariant
regressors will be dropped when conducting fixed effect models, since these models take differences of each variable from its mean across the study period. In our research context, all variables are time variant, thus this problem commonly recognized for fixed effects models does not apply. Furthermore, Cameron and Trivedi (2013) suggest that random effect models should be used when observations are randomly drawn samples to draw inferences regarding a larger population. The analysis here is on U.S. states, emphasizing on the unique market characteristics of each state. Therefore, fixed effects models are appropriate and are used in the analysis here.

<table>
<thead>
<tr>
<th>Table 6 Mean and Variance of Candidate Dependent Variables</th>
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<td>States</td>
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<tr>
<td></td>
</tr>
<tr>
<td>Dependent Variables</td>
</tr>
<tr>
<td>Mean</td>
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<tr>
<td>Variance</td>
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</table>

Source: Author’s Calculation

For given $\sum_{t=1}^{T} y_{it}$, the use of conditional maximum likelihood estimator based on a log density for the $i$th state eliminates unobserved heterogeneity among the states. As a result, the first order condition of Poisson Fixed Effects estimator becomes:

$$\sum_{i=1}^{N} \sum_{t=1}^{T} X_{it} \left( y_{it} - \frac{\exp(X'_{it}\beta)}{T-1 \sum_{i} \exp(X'_{it}\beta) \bar{y}_i} \bar{y}_i \right) = 0 \quad (2.3)$$

Cameron and Trivedi (2009) demonstrate that if $E(y_{it}|\alpha_i, X_{i1}, X_{i2}, ..., X_{iT}) = \alpha_i \exp(X'_{it}\beta)$, then the above estimator is consistent, since the left hand side becomes
zero. Thus, this estimator is employed for the fixed effects Poisson regression in the analysis herein.

The Negative Binomial Fixed Effects model assumes negative binomial distribution with two parameters, $\alpha_i \exp(X'_{it}\beta)$, and $\varphi_i$ is an over-dispersion parameter particular to this distribution. $\varphi_i$ is allowed to vary among states. Then, the mean, $E(y_{it}|\alpha_i, X_{it}, \varphi_i) = \alpha_i \exp(X'_{it}\beta)/\varphi_i$, and the variance, $Var(y_{it}|\alpha_i, X_{it}, \varphi_i) = (\alpha_i \exp(X'_{it}\beta)/\varphi_i) \cdot (1 + \alpha_i/\varphi_i)$. The fixed effects estimation uses conditional maximum likelihood estimator of the conditional joint density for state $i$ (Woodridge, 1999),

$$
Pr \left[ y_{i1}, \ldots, y_{iT} \left| \sum_{t=1}^{T} y_{it} \right. \right] = \left( \prod_{t} \frac{\Gamma(\sum_{t} \exp(X'_{it}\beta) + \sum_{t} y_{it})}{\Gamma(\sum_{t} \exp(X'_{it}\beta)) \Gamma(1 + \sum_{t} y_{it})} \right) \cdot \frac{\Gamma(\sum_{t} \exp(X'_{it}\beta)) \Gamma(1 + \sum_{t} y_{it})}{\Gamma(\sum_{t} \exp(X'_{it}\beta) + \sum_{t} y_{it})} \tag{2.4}
$$

It should be noted that in some cases, estimation of the Negative Binomial models did not converge. In these instances, the fixed effects panel Poisson estimator was employed instead. Hence, the mean-variance equality assumption of Poisson regression models could have been violated as a result.

The next sets of empirical specifications model $y_{it}$, the aggregate P3 highways investment in state $i = 1, \ldots, n$ for year $t = 1, \ldots, T$. As already discussed, the dependent variable is assumed to be continuous, hence panel data linear regression models are used for estimation. For the same reasons as the count data regression models, fixed effects models were employed, fitting the following empirical models:
\[ y_{lt} = \alpha_t + X_{lt}\beta + \varepsilon_{lt} \] (2.5)

Here, \( \alpha_t \) is the intercept that is allowed to be correlated with regressors \( X_{lt} \). Also, \( \varepsilon_{lt} \) represents idiosyncratic error, and is assumed to be identically and independently distributed (i.i.d.), i.e., not correlated with \( X_{lt} \). \( \beta \) is the coefficient to be estimated. Due to the large numbers of states and years compared to the number of observations, specification of fixed effects models through dummy variables was not desirable because the degree of freedom would then be exhausted. As such, the following fixed effect specification, which eliminates \( \alpha_t \) by taking the difference of individual means \( \bar{y}_i = X_i'\beta + \varepsilon_i \). As a result, the OLS estimator was used to estimate the following model:

\[ (y_{lt} - \bar{y}_l + \bar{y}) = \alpha + (X_{lt} - \bar{X}_l + \bar{X})'\beta + (\varepsilon_{lt} - \bar{\varepsilon}_l + \bar{\varepsilon}) \] (1.6),

where \( \bar{y}_l = \sum_{t=1}^{T_l} y_{lt}/T_l \) (i.e., individual means), \( \bar{y} = \sum_t \sum_i \bar{y}_i/N \) (i.e., grand mean), \( \bar{X}_l = \sum_{t=1}^{T_l} X_{lt}/T_l \), \( \bar{X} = \sum_t \sum_i \bar{X}_i/N \), \( \bar{\varepsilon} = \sum_{t=1}^{T_l} \varepsilon_{lt}/T_l \), \( \bar{\varepsilon} = \sum_i \sum_t \bar{\varepsilon}_i/N \). Because the i.i.d. assumption of the error term may be too strict, cluster robust standard errors was used for reporting, following Cameron and Trivedi (2009). Assuming \( N \to \infty \) i.e., the asymptotic assumption holds, and that the errors are uncorrelated among states, clustering panel variables leads to consistent robust standard error estimator. Observed sample intercept \( \hat{\alpha} \) and coefficients \( \hat{\beta} \) are used to obtain \( u_i = \bar{y}_l - \hat{\alpha} - \bar{X}_l\hat{\beta} \), which are then be used to report the standard deviation and its correlation with the regressors (Wooldridge, 2013).
<table>
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<td>P3 P3LAW</td>
<td>DB+P3 P3LAW</td>
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<td>P3 All</td>
<td>DB+P3 All</td>
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<td>L.In_Personal Income/capita</td>
<td>5.123 (0.83)</td>
<td>-5.732 (-0.67)</td>
<td>1.916 (0.40)</td>
<td>2.851 (0.49)</td>
<td>-3.471 (-0.46)</td>
<td>1.032 (0.23)</td>
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<tr>
<td>L.Personal Income Growth</td>
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<td>5.005 (0.45)</td>
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<td>-8.420 (-1.35)</td>
<td>-3.378 (-0.45)</td>
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<td>L.VMTGrowth</td>
<td>-0.0851 (-0.97)</td>
<td>-0.107 (-1.27)</td>
<td>-0.103* (-1.75)</td>
<td>-0.0787(-0.92)</td>
<td>-0.119 (-1.42)</td>
<td>-0.104* (-1.82)</td>
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<td>L.In_Debt/GSP</td>
<td>-3.600 (-1.16)</td>
<td>-4.222 (-1.18)</td>
<td>-3.419 (-1.53)</td>
<td>-0.107 (-0.04)</td>
<td>-1.642 (-0.69)</td>
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<td>L.DebtGrowth</td>
<td>-0.220**</td>
<td>-0.149</td>
<td>-0.195**</td>
<td>-0.199*</td>
<td>-0.177</td>
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<td>L.In_GasTaxRev/GSP</td>
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<td>-4.906 (-0.64)</td>
<td>-1.707 (-0.36)</td>
<td>-4.395 (-0.80)</td>
<td>-7.531 (-1.08)</td>
<td>-5.106 (-1.19)</td>
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<td>L.GasTaxRevenue Growth</td>
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<td>0.0534</td>
<td>0.0530</td>
<td>0.107**</td>
<td>0.0513</td>
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Notes. *: p<0.10; **: p<0.05; ***: p<0.01. T statistics in parentheses.
P3LAW: states with P3 enabling legislations. All: all states
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<td>L.In_Population</td>
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<td>-9.149** (-2.05)</td>
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<td>L.DebtGrowth</td>
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</table>

Note. *: p<0.10; **: p<0.05; ***: p<0.01. T statistics in parentheses.
2.5 Results
This section will present the estimation results. Table 7~Table 10 summarize the regressions results on the numbers of P3 projects, and Table 11 shows the OLS estimation results of the fixed effects models of aggregate Highway P3 investments. Stata 13 was used for empirical estimation (StataCorp, 2013b). The following section will discuss interpretation and implications in depth.

2.5.1 Dependent Variable and Sample Determination
Table 7 shows results of panel fixed effects Poisson regressions with base specification (control variables and financial variables) to compare dependent variables and sample states. The regression (1) models the numbers of DB contracts among states with P3 enabling laws; regression (2) models P3s that are not DBs among states with enabling legislations; regression (3) models DBs and P3s among states with P3 laws; and (4)~(6) model the equivalent dependent variables as (1)~(3), among all states. Noticeably, fixed effects models drop all observations whose dependent variables are zero through the study period. The models of states with P3 legislations suffer from small numbers of observations (141-271) compared to models of all states (239-404). In both cases of all states and states with P3 legislations, considerable numbers of observations are dropped when the dependent variable is the number of P3s only. Therefore, modeling the number of P3 contracts only is undesirable as well. Furthermore, comparison of models in terms of estimated coefficients with statistical significance, one may find the relationship $\beta_{DB} + \beta_{P3} = \beta_{DB+P3}$, which is intuitive. While it is likely that statistically significant coefficients are mostly due to DB projects, because the intent of the analysis
here is not to focus on DBs but also P3s, the following analyses will employ empirical models of DB+P3s.

2.5.2 Election Cycle and Political Climate

Table 8 shows the results of fixed effects Negative Binomial regressions that test the hypotheses regarding the effects of election cycles to the number of P3s that reached financial close. Regressions (1)~(4) include the following variables: personal income per capita (natural log), personal income growth (natural log), population (natural log), growth of vehicle miles traveled, debt divided by gross state product (GSP), growth of debt, highway capital outlay divided by GSP (natural log), motor fuel tax revenue divided by GSP (natural log), and growth of gas tax revenue. These variables are considered base specification, and included in all empirical models to follow unless otherwise noted. Additionally, a binary variable of Republican governor (RepGov), margin of victory of gubernatorial elections (GovVictoryMargin), and dummy variables for each of the governors’ year in office (e.g., GovYear1: the first year in governor’s term, or the year after the election) were included in the estimation models.

Estimation results showed statistically significant relationships of some of the base specification variables to the number of DB and P3 financial closes reached, across all models: population (negative at p>0.05), debt growth (negative at p>0.01), and growth of gas tax revenue (positive at p>0.05). Furthermore, margin of gubernatorial election victories was also negatively associated with the dependent variable with statistical significance at p>0.05 level, across all models. As regards the governor’s year in office,
only the model that includes the fourth year in office was significant, with the estimated coefficient of GovYear4 was negative and significant at p>0.05 level.

Count data regression models require careful interpretation, since these models involve exponential conditional mean, \( E(y|x) = \exp(X'\beta) \), which drop subscripts for simplicity. Cameron and Trivedi (2013) derived the marginal effect of a regressor \( j \) at a representative value (MER) as follows:

\[
MER_j = \left. \frac{\partial E(y|x)}{\partial x_j} \right|_{x^*} = \beta_j \exp(x'^*\beta)
\] (2.7)

The problem is that the marginal effect of the regressor to the dependent variable is different across observations, dependent on the value of the regressor. Therefore, the response of the dependent variable for the observation with average value of the regressor can be used in interpreting the results, i.e., marginal effect at the mean (MEM), as derived by Cameron and Trivedi (2013):

\[
MEM_j = \left. \frac{\partial E(y|x)}{\partial x_j} \right|_{\bar{x}} = \beta_j \exp(\bar{x'}\beta)
\] (2.8).

Using GasTaxRevenueGrowth and regression model (1) as an example, \( \beta_{\text{GasTaxRevenueGrowth}} = 0.0768 \) at p>0.05, while \( \overline{\text{GasTaxRevenueGrowth}}' = 0.6664 \). As such, \( MEM_{\text{GasTaxRevenueGrowth}} = 0.0808 \). In other words, one percentage point increase in the growth of gas tax revenue in the previous year was associated on average with 0.0808 unit increase in the number of DB and P3 contracts to close. It should be noted that the marginal effects of this variable differ across observations. Furthermore, the dependent variable is assumed to be a nonnegative integer, and the derived \( MEM_{\text{GasTaxRevenueGrowth}} \) should be considered with caution in this sense.
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<td>(1)</td>
<td>L.ln.DEBT/GSP</td>
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<td>0.0698 (0.17)</td>
<td>1.410 (0.74)</td>
<td>0.101 (0.26)</td>
<td>-0.00357 (-0.04)</td>
<td>0.187 (0.72)</td>
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<td>L.ln.PersonalIncome</td>
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<td>L.ln_VMTGrowth</td>
<td>-0.087 (-0.55)</td>
<td>0.0644 (0.26)</td>
<td>0.068 (0.27)</td>
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<td>L.ln_GasTaxRevenue</td>
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<td></td>
<td>L.ln.PersonalIncome</td>
<td>1.395 (-0.93)</td>
<td>1.332 (-0.92)</td>
<td>1.403 (-0.92)</td>
<td>1.675 (-1.71)</td>
<td>2.21 (-2.63)</td>
<td>0.196 (-0.67)</td>
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</tr>
<tr>
<td></td>
<td>L.ln.Population</td>
<td>-0.6751 (-1.66)</td>
<td>-0.752 (-1.62)</td>
<td>-0.105* (-1.76)</td>
<td>-0.816 (-0.52)</td>
<td>-0.919 (0.58)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L.ln_VMTGrowth</td>
<td>-0.087 (-0.55)</td>
<td>0.0644 (-0.26)</td>
<td>0.068 (-0.27)</td>
<td>-0.858 (-0.52)</td>
<td>0.215*** (2.95)</td>
<td></td>
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<tr>
<td></td>
<td>L.ln_GasTaxRevenue</td>
<td>0.0644 (-0.26)</td>
<td>0.068 (-0.27)</td>
<td>0.0618 (-0.25)</td>
<td>0.215*** (2.95)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>L.ln_GasTaxRevenueGrowth</td>
<td>0.0644 (-0.26)</td>
<td>0.068 (-0.27)</td>
<td>-0.012 (-0.04)</td>
<td>0.187 (-0.72)</td>
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<tr>
<td>(4)</td>
<td>L.ln.DEBT/GSP</td>
<td>-0.418 (-0.23)</td>
<td>0.0698 (0.17)</td>
<td>1.410 (0.74)</td>
<td>0.101 (0.26)</td>
<td>-0.00357 (-0.04)</td>
<td>0.187 (0.72)</td>
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<tr>
<td></td>
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<td>1.332 (-0.92)</td>
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<tr>
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<td>L.ln.Population</td>
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<tr>
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</tr>
<tr>
<td></td>
<td>L.ln_GasTaxRevenue</td>
<td>0.0644 (-0.26)</td>
<td>0.068 (-0.27)</td>
<td>0.0618 (-0.25)</td>
<td>0.215*** (2.95)</td>
<td></td>
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</tr>
<tr>
<td>(5)</td>
<td>L.ln.DEBT/GSP</td>
<td>-0.418 (-0.23)</td>
<td>0.0698 (0.17)</td>
<td>1.410 (0.74)</td>
<td>0.101 (0.26)</td>
<td>-0.00357 (-0.04)</td>
<td>0.187 (0.72)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L.ln.PersonalIncome</td>
<td>1.395 (-0.93)</td>
<td>1.332 (-0.92)</td>
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<td>1.675 (-1.71)</td>
<td>2.21 (-2.63)</td>
<td>0.196 (-0.67)</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>L.ln.Population</td>
<td>-0.6751 (-1.66)</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td></td>
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<td>0.215*** (2.95)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>L.ln_GasTaxRevenue</td>
<td>0.0644 (-0.26)</td>
<td>0.068 (-0.27)</td>
<td>0.0618 (-0.25)</td>
<td>0.215*** (2.95)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: *: p<0.10; **: p<0.05; ***: p<0.01. T statistics in parentheses.
Similarly, on the same regression model, the MEM of DebtGrowth can be derived as follows: the estimated coefficient $\beta_{L, DebtGrowth} = -0.226$ at $p>0.01$, while the mean $DebtGrowth' = 3.969656$. Therefore, $MEM_{L, DebtGrowth} = -0.226 \cdot \exp(3.969656 \cdot -0.226) = -0.09215$. In other words, one percentage point increase in the growth of debt in the previous year is associated on average with 0.09215 unit decrease in the number of DB and P3 contracts to close.

2.5.3 Interaction Effect of Republican Governors and States’ Financial Conditions

The next sets of negative binomial regressions examine the effect of Republican governors, states’ financial condition, and their interactions. Table 9 summarizes the estimation results of models that included, the interaction between the Republican governor (RepGov) and, respectively: Debt/GSP, DebtGrowth, HighwayCapitalOutlay/GSP, GasTaxRevenue/GSP, and GasTaxRevenueGrowth. As was in the case with the previous set of regressions, control and financial variables with statistical significance across all models were VMT growth, debt growth, and gas tax revenue growth. The signs of these estimated coefficients were also the same.

In addition, the estimated coefficient (-0.125) of the interaction of the Republican governor and gas tax revenue growth was statistically significant in the regression (5). The sign of this coefficient was negative. The Republican governor dummy variable in this model was statistically insignificant, while the coefficient of gas tax revenue growth was positive and significant (0.143). As the absolute values of these two coefficients are roughly the same, it can be interpreted that, overall, gas tax revenue growth is positively
associated with the number of DB and P3 contracts to close, but under Republican governors, such association disappears.

2.5.4 Interaction Effect of Governors’ Years in Office and Political Environment

The next sets of regressions examine the interaction effects of binary variables of governors’ years in office and political variables (Republican’s share of gubernatorial election votes and their margin of gubernatorial election victories). Table 10 shows the results of estimating the interaction of political variables and, respectively: GovYear1, GovYear2, GovYear3, GovYear5, and AllGovYears. Fixed effects Poisson regressions were conducted, because Negative Binominal regressions did not converge for some of these regression models. Similar to the specifications discussed above, VMT growth, debt growth, and gas tax revenue growth had statistically significant associations with the dependent variable with the same signs. Also, margin of gubernatorial election victories was also statistically significant and robust across all models. The sign of the estimated coefficients was negative, similar to the regression results on Table 8.

With respect to the interactions, regressions (2) and (5) resulted in statistically significant coefficients of the interactions between governor’s years in office and political variables. The regression model (2) specified the dummy variable for the second year in governor’s term (GovYR2) and its interactions with the share of Republican votes (RepVoteShare) and the margin of gubernatorial election victories. The estimated coefficients of GovYR2 (3.589) and its interaction with RepVoteShare (-6.462) were significant at p>0.01.
<table>
<thead>
<tr>
<th></th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>DBP3 Financial Closes</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L.In_Personal_Income/Growth</td>
<td>1.877</td>
<td>2.093</td>
<td>1.228</td>
<td>0.407</td>
</tr>
<tr>
<td>L.Personal_Income_ Growth</td>
<td>-0.0518</td>
<td>-0.0542</td>
<td>-0.0937</td>
<td>-0.0803</td>
</tr>
<tr>
<td>L.VMTGrowth</td>
<td>-0.110*</td>
<td>-0.0969*</td>
<td>-0.100*</td>
<td>-0.0877</td>
</tr>
<tr>
<td>L.In_Debt/GSP</td>
<td>-0.839(-0.49)</td>
<td>-0.647(-0.38)</td>
<td>-0.984(-0.60)</td>
<td>-0.385(-0.22)</td>
</tr>
<tr>
<td>L.DebtGrowth</td>
<td>-0.184**</td>
<td>-0.190**</td>
<td>-0.231***</td>
<td>-0.193**</td>
</tr>
<tr>
<td>L.In_HWYCapOutlay/GSP</td>
<td>0.128(0.51)</td>
<td>0.00661(0.03)</td>
<td>-0.0510(-0.21)</td>
<td>0.0657(0.25)</td>
</tr>
<tr>
<td>L.In_GasTaxRev/GSP</td>
<td>-5.219(-1.15)</td>
<td>-5.186(-1.18)</td>
<td>-6.053(-1.38)</td>
<td>-6.939(-1.50)</td>
</tr>
<tr>
<td>L.GasTaxRevenue Growth</td>
<td>0.0525(1.40)</td>
<td>0.0778**</td>
<td>0.0792**</td>
<td>0.0707*(1.76)</td>
</tr>
<tr>
<td>RepVoteShare</td>
<td>3.774(1.90)</td>
<td>-0.114(-0.07)</td>
<td>0.625(0.41)</td>
<td>-7.680*(-1.80)</td>
</tr>
<tr>
<td>GovVictoryMargin</td>
<td>-0.0372**</td>
<td>-0.0293*</td>
<td>-0.0299*</td>
<td>-0.285**</td>
</tr>
<tr>
<td>GovYR2</td>
<td>3.589***</td>
<td>(2.77)</td>
<td>-3.164(-1.07)</td>
<td></td>
</tr>
<tr>
<td>GovYR2*RVS</td>
<td>-6.462**</td>
<td>(-2.48)</td>
<td>7.190(1.18)</td>
<td></td>
</tr>
<tr>
<td>GovYR2*GVM</td>
<td>-0.00352(-0.14)</td>
<td></td>
<td>0.299*(1.92)</td>
<td></td>
</tr>
<tr>
<td>GovYR3</td>
<td>-2.016(-1.33)</td>
<td></td>
<td>-7.628**(-2.26)</td>
<td></td>
</tr>
<tr>
<td>GovYR3*RVS</td>
<td>4.835(1.56)</td>
<td></td>
<td>16.07***(2.34)</td>
<td></td>
</tr>
<tr>
<td>GovYR3*GVM</td>
<td>-0.0198(-0.73)</td>
<td></td>
<td>0.330**(2.05)</td>
<td></td>
</tr>
<tr>
<td>GovYR4</td>
<td>-2.857(-0.98)</td>
<td></td>
<td>-11.94*(-1.91)</td>
<td></td>
</tr>
<tr>
<td>GovYR4*RVS</td>
<td>5.527(0.89)</td>
<td></td>
<td>24.38**(1.87)</td>
<td></td>
</tr>
<tr>
<td>GovYR4*GVM</td>
<td>-0.0674(-1.28)</td>
<td></td>
<td>0.490*(1.66)</td>
<td></td>
</tr>
<tr>
<td>RVS*GVM</td>
<td>0.460***</td>
<td>(2.58)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GovYR2* RVS*GVM</td>
<td>-0.589**</td>
<td>(-1.99)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GovYR3* RVS*GVM</td>
<td>-0.655**</td>
<td>(-2.22)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GovYR4* RVS*GVM</td>
<td>-1.098*</td>
<td>(-1.73)</td>
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<tr>
<td><strong>AIC</strong></td>
<td>343.1</td>
<td>348.9</td>
<td>343.5</td>
<td>344.8</td>
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<tr>
<td><strong>N_g</strong></td>
<td>27</td>
<td>27</td>
<td>27</td>
<td>27</td>
</tr>
<tr>
<td><strong>ll</strong></td>
<td>-157.6</td>
<td>-160.5</td>
<td>-157.8</td>
<td>-148.4</td>
</tr>
<tr>
<td><strong>p</strong></td>
<td>0.0000410</td>
<td>0.000230</td>
<td>0.000250</td>
<td>0.000218</td>
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</table>

Note. *: p<0.10; **: p<0.05; ***: p<0.01. T statistics in parentheses. GovYR1 model not included due to insignificance. YR: Year; RVS: RepVoteShare; GVM: Governors’ Victory Margin
Table 11 Cluster Robust Standard Error Fixed Effects OLS Regression of DB&P3 Aggregate Costs: Governors’ Office Years and Election Interactions

<table>
<thead>
<tr>
<th>Regression</th>
<th>(1)</th>
<th>(2)</th>
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<tbody>
<tr>
<td><strong>DepVar:</strong> DBP3 Costs</td>
<td>Control</td>
<td>GovYear2</td>
<td>AllGovYears</td>
</tr>
<tr>
<td>L.In Personal Income/Capita</td>
<td>581.2 (1.04)</td>
<td>711.4 (1.22)</td>
<td>561.0 (0.98)</td>
</tr>
<tr>
<td>L.Personal IncomeGrowth</td>
<td>-11.65 (-1.31)</td>
<td>-10.86 (-1.23)</td>
<td>-6.981 (-0.86)</td>
</tr>
<tr>
<td>L.In Population</td>
<td>417.3 (0.49)</td>
<td>432.8 (0.49)</td>
<td>416.8 (0.46)</td>
</tr>
<tr>
<td>L.VMTGrowth</td>
<td>-15.32** (-2.05)</td>
<td>-15.87** (-2.13)</td>
<td>-15.42* (-2.01)</td>
</tr>
<tr>
<td>L.In_Debt/GSP</td>
<td>-362.2 (-1.13)</td>
<td>-387.8 (-1.21)</td>
<td>-322.0 (-1.04)</td>
</tr>
<tr>
<td>L.DebtGrowth</td>
<td>-45.46** (-2.14)</td>
<td>-49.27** (-2.19)</td>
<td>-48.57** (-2.19)</td>
</tr>
<tr>
<td>L.In_HWYCapOutlay/GSP</td>
<td>-60.78 (-0.85)</td>
<td>-74.63 (-1.02)</td>
<td>-73.14 (-1.06)</td>
</tr>
<tr>
<td>L.In_GasTaxRev/GSP</td>
<td>140.2 (0.30)</td>
<td>215.8 (0.42)</td>
<td>150.2 (0.29)</td>
</tr>
<tr>
<td>L.GasTaxRevenueGrowth</td>
<td>13.33 (1.65)</td>
<td>12.59 (1.48)</td>
<td>12.99 (1.43)</td>
</tr>
<tr>
<td>GVM</td>
<td>-3.457** (-2.32)</td>
<td>-8.773 (-1.29)</td>
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<tr>
<td>RVS</td>
<td>361.7* (1.86)</td>
<td>-291.9 (-0.69)</td>
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<tr>
<td>RVS*GVM</td>
<td>14.39 (1.00)</td>
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<tr>
<td>GovYR2</td>
<td>429.0** (2.22)</td>
<td>226.8 (0.81)</td>
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<tr>
<td>GovYR2*RVS</td>
<td>-973.0** (-2.26)</td>
<td>-413.4 (-0.72)</td>
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<tr>
<td>GovYR2*GVM</td>
<td>4.249 (1.34)</td>
<td>8.033 (0.89)</td>
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<tr>
<td>GovYR2<em>RVS</em>GVM</td>
<td>-11.21 (-0.70)</td>
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<tr>
<td>GovYR3</td>
<td>-466.2 (-1.36)</td>
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<tr>
<td>GovYR3*RVS</td>
<td>1160.9 (1.61)</td>
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</tr>
<tr>
<td>GovYR3*GVM</td>
<td>13.32 (1.38)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GovYR3<em>RVS</em>GVM</td>
<td>-31.80* (-1.74)</td>
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</tr>
<tr>
<td>GovYR4</td>
<td>-914.9 (-1.62)</td>
<td></td>
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</tr>
<tr>
<td>GovYR4*RVS</td>
<td>2139.9* (1.72)</td>
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<td></td>
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<tr>
<td>GovYR4*GVM</td>
<td>22.47 (1.52)</td>
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</tr>
<tr>
<td>GovYR4<em>RVS</em>GVM</td>
<td>-50.81* (-1.73)</td>
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</tr>
<tr>
<td>Constant</td>
<td>-10682.1 (-0.70)</td>
<td>-12461.8 (-0.77)</td>
<td>-10662.6 (-0.64)</td>
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<tr>
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<tr>
<td>AIC</td>
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<td>11332.8</td>
<td>11342.2</td>
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<td>R2_a</td>
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<td>0.0412</td>
<td>0.0391</td>
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<tr>
<td>R2_w</td>
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<td>0.0592</td>
<td>0.0700</td>
</tr>
<tr>
<td>R2_b</td>
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<td>0.393</td>
<td>0.394</td>
</tr>
<tr>
<td>ll</td>
<td>-5656.6</td>
<td>-5651.4</td>
<td>-5647.1</td>
</tr>
<tr>
<td>rho</td>
<td>0.639</td>
<td>0.634</td>
<td>0.614</td>
</tr>
</tbody>
</table>

Note. *: p<0.10; **: p<0.05; ***: p<0.01. T statistics in parentheses. RepGov, GovYear1 GovYear3 and GovYear4 models not shown due to insignificant results. YR: Year; RVS: RepVoteShare; GVM: Governors’ Victory Margin.
These estimates suggest that in the second year, governors tend to close higher numbers of DB and P3 projects, while the higher the share of Republican votes, the effect reverses. Regression (5) indicates even more complex relationships. In the third year of governor’s term, the number of DB and P3 projects contracts to close tend to be lower, but with the higher Republican vote shares, the relationship reverses. Furthermore, in the second and third years in governors’ terms, the higher the Republican’s vote shares and the larger the margin of gubernatorial election victories, the lower the number of DB and P3 projects contracts to close.

2.5.5 Fixed Effects OLS Regression of Project Costs: Governor’s Office Years and Political Interactions

The last sets of regressions model the aggregate investments in highway projects through DB or P3 contracts for each state year. The emphasis of the analysis was the interactions between governors’ years in office and political variables. Regression (1) only includes control and financial variables. In regression (2), RepVoteShare was included instead of RepGov, and also GovYR2, the interaction between GovYR2 and RepVoteShare, and the interaction between GovYR2 and GovVictoryMargin. Regression (3) included dummy and interaction variables of all years.

The estimation results suggest that the margin of gubernatorial election victories was negatively associated with the amount of highway investment through DB and P3 contracts. Also, in the second year, governors tend to close larger aggregate values of DB and P3 contracts of highway projects, but with the higher the shares of Republican votes, the association reversed. Finally, regression (3) shows that the interaction of GovYR3, Republican’s share of votes, and the margin of gubernatorial election victories was
negatively associated with the amount of highway investments through DB and P3 contracts. The interaction of GovYR4 and Republican’s share of votes had positive association with the dependent variable, and the interaction of GovYR4, Republican’s share of votes, and the margin of gubernatorial election victories had negative effects. These associations were rather weak from statistical perspective, as the estimated coefficients were statistically significant only at p>0.1.

2.6 Discussion and Concluding Remarks
U.S. states’ use of innovative procurement models for highway investments demonstrates patterns associated with election cycles, especially in light of political and fiscal conditions surrounding decision makers (i.e., governors). This study investigated the frequencies of DB and P3 highway projects to reach financial close and the aggregate investments in U.S. states between 1997 and 2013. The results suggested that the use of innovative contracting approaches are not only driven by economic reasons to pursue efficiency but also by fiscal constraints of public agencies as predicted in the literature as well as by political factors. While two types of dependent variables were empirically modeled (number of financial close and aggregate investment amount in state-year), the results were qualitatively very similar to each other. The following discussion will focus on the empirical models of the number of DB and P3 projects estimated through the use of count data regressions. Lessons from the aggregate investment amount analyses were, however, integrated into the discussion.

The empirical models on the use and the size of highway projects that employed innovative procurement approaches demonstrated the influence of a number of
macroeconomic, demand, and fiscal factors. The demand side control variables, such as the size of the economy, growth in vehicle miles traveled (VMT) were found to have statistically significant association with the use of innovative contract types. The estimated coefficients were significant only at p>0.1, and became insignificant depending on the specification.

States’ fiscal conditions also demonstrated significant relationships with the use of DB and P3 contracts. The growth of states’ debt was negatively associated with the number of innovative contracts to close for highway projects with statistical significance at p>0.01. This result indicates that the higher the growth of debt in the previous year, on average the lower the number of DB and P3 projects to close. These coefficients were estimated using Fixed Effects Poisson or Negative Binomial estimators. Therefore, heterogeneity of states with respect to debt financing for capital investment, such as constitutional and legal constraints in issuing bonds and bond ratings have been controlled for. It should be noted that many, if not most, of these projects counted in the observations are large projects costing $100 million or more, and they typically require debt financing through bonds or loans. Assuming that the debt capacity of states does not change substantially from one year to the next, if the state debt increased in the previous year, decision makers may be reluctant to exercise their borrowing capacities to fund highway capital investment projects. Many DB projects require public financing of the procured projects. Furthermore, P3 projects may also involve substantial public funding to overcome financial viability for private investors. As such, increase in the debt growth in the previous year may lead to a decrease in contract close of large DB and P3 projects.
The estimated coefficients of gas tax revenue growth leads to similar insights. The positive and significant coefficient estimated across regression models indicate that the revenue increase of motor fuel taxes may provide funding necessary for large capital projects including DB projects, assuming everything else held constant. Overall, these estimation results can arguably be attributed to the dominance of DB projects, funded by sponsoring public agencies. Changes in fiscal conditions of states in terms of debt and motor fuel tax revenue in the previous year affect their usage of innovative contracts such as DB and P3 for the present year.

In light of the literature, these findings present the direct influence states’ fiscal conditions may have on contracting behaviors of states. Bruce et al. (2007) found no statistically significant associations between long-term debt issued or outstanding, motor fuel tax rate, and state per capita highway expenditure. Their analysis on the more widely defined state expenditure for highways found no associations with these debt and gas tax variables. Accordingly, the relationships of growths in debt and gas tax revenues and the number of DB and P3 contracts for highway projects found herein may be attributed to their sizes and their direct impact on states’ financial conditions.

A number of political and election cycle factors were also found to be significantly associated with the numbers of highway projects through innovative approaches for state-years. Most notably, the margin of victory in the last gubernatorial election was consistently and significantly associated with the dependent variables, and the sign of coefficients was negative. Qualitatively, this result indicates that the smaller the margin of victory in the last gubernatorial election (i.e., more politically contestable
environment), the larger the number of innovatively procured highway project contracts is likely to close. This finding is in contrast with the political contestability theory. However, the results are also not exactly in line with the political business cycle theory, which argues that decision-makers attempt to manipulate voters through favorable measures such as capital investment. Implicitly, if such behavior were present, the effect would manifest as an increase in capital investments in the years preceding the elections, and decreases in other years. Cyclical patterns of financial closes, as would have been predicted based on the literature, were not observed in the results herein. Moreover, even if such relationships did exist, the fact that many of these projects require planning and negotiation to extend over years may have undermined our ability to observe statistically significant results. As such, it is premature to claim that these results support the views of political business cycle theory, or, political contestability theory.

Many of the effects of political and election cycle effects were found when these were included in the empirical models as interaction variables. With respect to the number of DB and P3 projects to reach financial close, motor fuel tax revenue growth in a previous year was generally associated with a higher number of deals to close, but under Republican regimes, the effect disappeared. Similarly, the number of DB and P3 highway projects were generally larger in governors’ second year in office, but under Republican governors, this was not quite so. In the third year of governors’ term, the number of DB and P3 highway projects was lower, but under Republican regimes, it tends to be higher.
These complex relationships, while difficult to generalize, suggest at least that these projects do not appear to be used to manipulate voters in a simplistic manner as predicted in the political business cycle framework. Under such a view, the number of projects would increase in the years preceding elections (i.e., third and fourth years in office). Rather, a more probable explanation is that governors have electoral agenda regarding the use of innovative approaches for transportation investments (e.g., the use of P3s) before being elected, and implements once her term begins. It takes a few years to legislate the reform and pass in the legislative branch, and its implementation in projects in the procurement pipeline begins to be reflected in the number of financial closes. Critically, then, a closer examination remains to be necessary to inquire why decision-makers employ innovative procurement models for highway projects. The analysis herein hints at some explanations that are in line with existing theories in the literature (e.g., larger margin of victories associated with smaller numbers of projects), yet further exploration is desirable.

The results herein suffer from a number of limitations inherent in the data and the empirical models employed in the analysis. First and foremost, the use of innovative procurement approaches in the U.S. is still in its infancy although it is growing. Many would agree that most states are still in early stages of implementing P3s in manners suitable for respective conditions. Therefore, a number of factors are likely to be dropped in the present specifications, hence resulting in estimation biases. Also, a unique characteristic of the P3 models is its flexibility: a number of variations of standard contracts have been proposed and implemented. Therefore findings from the empirical
results are precise only to the extent of the vague definition of P3s employed in this study. As regards empirical specifications, as already pointed, a number of potential issues were present, including the prevalence of zeros in the dependent variables as well as the use of bootstrap cluster robust variance in the last set of fixed effects Poisson regressions.

It is the intent of the author to extend the analysis in the following directions. First, based on the exploratory empirical findings, a formal theoretical model needs to be constructed to focus on the public agencies’ use of innovative procurement approaches. While financial implications of specific procurement approaches may be vastly different for public agencies between these innovative procurement models, considerations of political risks may be understood from a distinct perspective.

Second, granted a sound theoretical model has been constructed, empirical models will need to be refined to shed light on the distinct nature of each of the innovative procurement models. Facilitation of an institution favorable for the use of innovative procurement contracts can be assumed as manifestation of considerable commitment of public decision makers. Then logistic or ordered logit regression models can instead be employed for estimation. Statistically testing such behavioral models may be challenging for foreseeable future due to the small number of P3s that are implemented in the U.S. to date. Nevertheless, understanding political and electoral influence on the decision-makers’ behaviors with respect to the use of P3s for highway projects may be beneficial for entities involved in the industry.
CHAPTER 3 EVALUATING NETWORK DESIGN DECISIONS OF P3 ALTERNATIVES: INNOVATIVE INVESTMENT AND MULTI-JURISDICTIONAL PERSPECTIVES

3.1 Introduction

In the United States, public-private partnerships (P3s) have been receiving growing attention as an alternative procurement approach to deliver infrastructure facilities such as highways. From the public sector’s perspective, mainly two considerations motivate the policy debate: pursuit of efficiency in infrastructure provision (i.e., efficient use of limited resources), and overcoming its ever-tightening fiscal constraints. The interstate highway system, which began developing in the 1950s, are rapidly aging today. Road assets require maintenance and renewal, which many states and municipalities have commonly deferred. Urban regions continue to grow, increasing demand on infrastructure systems that are more costly to expand their capacities. In this context, the role and scope of the private sector in providing infrastructure services have become considerably wider than a few decades ago, and a wide range of concerns have arisen with respect to their policy implications.

In the scholarly literature, highway network investment and procurement contracts have rarely been considered simultaneously. On the one hand, there is vast literature on economic theories and engineering models to determine toll levels and capacity of road networks in various contexts with a wide range of emphases. These studies, however, rarely treat alternative procurement models (e.g., bundling project
phases, risk allocation strategies) in explicit manners. On the other hand, in the incomplete contract theory literature, some of the critical assumptions that are commonly included in network design literature, such as monopolistic pricing behaviors of contractors and user equilibrium constraint, are usually ignored. Bridging this gap, this study models these innovative procurement models in the highway network design context, so as to evaluate P3 alternatives for road network projects from a more holistic perspective that is likely to be more relevant for policy makers.

In addition to the cross pollination of network design problems and techniques from incomplete contract literature, complexity of agents’ interaction is slightly augmented in this study. A basic framework to model procurement alternatives in network design problem is then extended to a cross border context where two jurisdictions interact with each other in investing in the project. The roles that private contractor and users of the facility play will be preserved to provide insights into possible consequences of certain policy choices in terms of private profit, aggregate welfare, and other measures. In this sense, this study intends to serve as a foundation to explore disentangling the added complexity of multi-jurisdictional interactions in terms of inherently complex institutional views on highway P3s.

The objective of the study is to develop an analytical framework to gain insights into consideration of procurement alternatives (e.g., bundling project phases) in network design problems, and to apply that to multi-jurisdictional institutional contexts. Specifically, this study will inquire possible consequences of alternative infrastructure delivery models (P3s), and their policy implications when applying the framework to
cross-border contexts. In addressing these questions, this study will develop a set of theoretical models and evaluate procurement alternatives for network investment with respect to travel demand, network capacity, and innovative investments in stylized networks. The analysis will emphasize on developing the foundation in a static model that only accounts for project phase bundling and innovative investments, rather than experimenting with added complexities such as dynamic interactions or risks. Full network applications will also be reserved for future extensions, so that the models will be analytically tractable and that findings will remain straightforward.

The remainder of the paper is organized as follows. The next section will point to the strands of literature that the analysis herein will be based on. The following section will present the analytical models of both base and multi-jurisdictional contexts. After a presentation of numerical analysis of the models, discussions on the results from both analytical and numerical analyses will be provided. The last section will conclude, with policy implications of the findings and directions for further analysis.

### 3.2 Literature Review

Three lines of literature motivate the analytical model proposed in this study. Economic theories of road pricing are essential in understanding the principles in setting toll levels for highway facilities. The literature on network designs to optimize network capacity and toll levels, and models of interactions between operators (e.g., neighboring jurisdictions) are the basis of modeling framework proposed in this study. A few recent studies of the incomplete contract literature on P3s have employed useful approaches to
model alternative procurement strategies. This section provides a review of some of these studies to underpin the analysis in this study.

3.2.1 Road Pricing Principles

Scholars have extensively discussed the subject of governments’ highway investment, often in the context of road pricing principles. The origin of this strand of literature dates back to the early 20th century when economic principles of efficient pricing and supply of public goods and services evolved. Among the studies on pricing, network design, and operational interventions for a wide range of policy contexts, a number of economic and engineering models continue to grow on road pricing.

The origin of the road pricing literature can be traced to the foundational study on the Pigouvian tax (Pigou, 1912). A number of notable studies have extended the application of the concept to various sectors over the decades since then. In the context of highways, Walters constructed a theory of travel demand and argued that marginal cost pricing is a minimum level required to efficiently allocate limited highway space. Claiming the low level of gasoline tax in place at that time, he suggested that a mix of gasoline tax, urban mileage tax and special toll could be suitable to implement the marginal cost pricing (Walters, 1961). Vickrey criticized that urban transportation is priced undesirably low, as congestion had not been accounted for in their prices. He argued that an economic allocation of traffic could be achieved through appropriate levels of “street use pricing” (Vickrey, 1963).

Building on the foundation that the aforementioned studies established, the debate continued on pricing principles to pursue efficiency and suitability of these principles for
various project contexts. Wheaton argued that the levels of road pricing induce the levels of highway investments. Comparing the first-best and second-best investment models of urban highways, he demonstrated that if private prices of road usage are below its social costs, the demand would increase, and the highway capacity would need to be expanded to accommodate the demand. He then argued that, in the U.S., the pricing policy might have led to over-investment of highways (Wheaton, 1978).

In the U.S., each state has its own institutional framework on which roads are built, operated and maintained. Both state and local governments could own these road assets. The source of funding is a mix of state and local revenues (e.g., user fees, taxes, and others), as well as allocations from the federal government (Gifford, 2012).

Pricing principles have been proposed to pursue policy objectives in a variety of project circumstances (Verhoef et al., 2008). In terms of the policy objectives, Button pointed out that road pricing typically is driven by the need for revenue for construction in practice, rather than as a policy tool to achieve efficient allocation of traffic on a given network. Button argued, however, that the policy tool should be designed to pursue efficiency, as congestion on the road network, which adds considerable costs to society, could be optimized through introduction of an appropriate level of pricing (e.g., marginal social cost pricing). As adoption of road pricing has been growing around the world, and congestion pricing could be a powerful means to achieve respective policy objectives (Button, 2004).

Scholars mostly agree that, where possible, road pricing should reflect the marginal external costs of using the road: in additional to the marginal private cost, the
price should reflect the value of time of other drivers sitting in congestion, as well as emission, noise and other externalities not accounted for in the marginal private cost of driving. As a result, as Gross and Garvin contended, the marginal cost pricing serves to maximize throughput under congested traffic conditions, as it is linked to the elasticity of drivers’ demand. However, it should be noted that practicality of such tolling mechanism still needs improvement, despite dramatic improvement in technologies for electronic toll collections systems. While implementation of marginal social cost pricing may still be impractical, scholars have proposed second best pricing solutions (Gross and Garvin, 2011). With respect to these second best pricing principles, although somewhat dated, Lindsey and Verhoef provided a review of literature on second-best pricing mechanism in the 1990s, focusing on such topics as: user heterogeneity, simultaneous existence of multiple externalities, and dynamic constraints on flexible tolling (Verhoef and Lindsey, 2001). In the literature, a number of second-best situations have also been considered, including: distortions in other modes, distortions in other routes, distortions in other sectors, and shadow price of public funds. These models include, for example, modules to correct for the assumed distortions of respective project circumstances (Milne et al., 2000).

There are other pricing principles. One of these alternatives is average cost pricing, which sets toll rates to pay for long-term average cost and a reasonable level of profit for the operator. The implication is that the costs of infrastructure will be accounted when determining the prices to be charged. This principle is applicable in cases of private operation of highways such as P3 arrangements. With this pricing principle, the private
operator has the incentive to achieve lowest operational costs so as to maximize its profit. This would then be equivalent to regulation of natural monopoly for public utility services (Brown and Heal, 1983). As a consequence, this pricing principle may, particularly when the operation term is long, fail to account for uncertainty into the future (Demsetz, 1968).

Revenue-maximizing pricing, in contrast, is based on the drivers’ elasticity of demand but the toll level and congestion levels are decoupled: travel demand is estimated at various toll levels, and the toll is set at the level at which the revenue is maximized (Buchanan, 1956). Revenue maximizing pricing can result in lower traffic levels compared to the marginal cost pricing, unless the demand is unrealistically elastic (Ubbels and Verhoef, 2008).

Research on operationalization of these pricing principles has also been extensive. Milne et al. summarized that modeling approaches can be broadly categorized into conceptual models that are primarily based on economic theories (briefly summarized above), and models for real-world applications, mostly by engineers and mathematicians. There are generally four categories of the real-world models: detailed simulation models, tactical network models, strategic transport models, and geographic models, in the order of microscopic to macroscopic models. In recent years, alternative modeling approaches have been proposed. Agent-based modeling is one of them (L. Zhang and Levinson, 2004). Zhang et al. proposed an agent-based technique to evaluate welfare consequences of alternative pricing scenarios on a complex road network with parallel free and tolled routes and heterogeneous users. They argued that this approach would allow researchers
to account for the decision making, behavioral adjustment, and actual experience of each user and road operator, while accounting for large real-world networks (Zhang et al., 2008).

The issue of road pricing has been receiving renewed attention in recent years, since tolling technologies have advanced and the use of P3s has increased its relevance to policy debates underway. Needless to say, tolling policies is an essential aspect of government’s decisions regarding potential partnership with a private contractor to deliver highway facilities. Debate on this subject is active on a global scale. Maffii et al. pointed to a number of possible and likely problems with respect to implementation of social marginal cost pricing for privately financed highways. Primarily, pricing based on the short run marginal costs may not necessarily recover the fixed costs of the project. Furthermore, there is no reason to believe the revenue would be fully captured by the private operator. To alleviate these and more possible issues, they recommended that second best pricing be gradually implemented, rather than haste to achieve marginal social cost pricing across the road system. The marginal cost pricing, in addition, should be employed only for publicly provided projects, and the revenues of such public projects should be reserved for a transportation fund (Maffii et al., 2010).

Macario noted potential issues with employing marginal social cost pricing for privately financed / operated highways. Arguing that the marginal social cost pricing principle should be considered as a long-term policy alternative and not as a project-by-project basis, she recommended that the pricing principle be employed when the policy objective is to incentivize private partners to pursue efficient use of the existing highway
space. The analysis also implied the potential benefit of decoupling compensation for the private partner and revenues from toll charges: such an arrangement may be advantageous to align incentive mechanisms to encourage efficient project delivery (Macário, 2010).

Similarly, Bonnafous asserted that marginal social cost pricing is likely to generate inadequately low revenue levels in cases of privately operated highways. He proposed a set of toll levels depending on the demand: when revenue cannot cover half of the project level, there should be no toll; when the demand is strong enough to cover the total cost, the operator should be given the freedom to set any toll that it sees fit; and when the maximum revenue is between a half and the full cost, the government should set the toll for the operator to maximize the social welfare (Bonnafous, 2010).

Eriksen and Jensen showed that, assuming no inefficiencies with public subsidy, availability payment arrangements were preferable to shadow toll, as they saw no point in allocating the demand risk to the private operator. They further argued that toll should be levied to the road users according to the social marginal cost pricing principle in order to address externalities of using the road capacity, but the revenue stream for the private operator should be decoupled, so as to minimize the risk premium to be required should the project’s demand risk be allocated to the private party (Eriksen and Jensen, 2010). It should be noted that this line of thought is growing in practice: a recent P3 toll road project in Illinois employ an availability payment arrangement so as to retain the demand risk of the project to the public sector. A notable characteristic of this project is that the public sector (the State of Illinois) is arranged to set tolls and collect revenue, while the
availability payment to the private partner of the project will be made (Shields, 2013). One may view this as decoupling the revenue stream and the payment to the private partner, as proposed by Eriksen and Jensen above.

The conceptual models of marginal cost pricing make a number of strong assumptions, while real-world models have traditionally given more emphasis on social, political and engineering goals, rather than on pure economic efficiency. Verhoef and Rouwendal proposed a framework to evaluate such policy alternatives, using a network model where two locations are connected by one free road and one tolled road, and compared the substitutability of these routes under various capacity scenarios (Verhoef and Rouwendal, 2004).

The use of stylized network and models of various project contexts to evaluate policy outcomes have been common. Heterogeneity of travelers, multi-modal system design, consideration of environmental impacts, and short-term and long-term local/regional economic development are only a few of a wide range of concerns that scholars have evaluated.

As the discussion in this section suggests, pricing is an important aspect of road network investment decisions. A number of pricing principles have been proposed, including the social marginal cost pricing, average cost pricing, capital cost recovery pricing, and revenue-maximizing pricing. There are suitable project and policy contexts for these pricing models. In particular, the review in this subsection demonstrated that the social marginal cost pricing is appropriate for public operation where the costs of infrastructure is not under consideration. When the private sector is involved in provision
and/or operation of highway facilities, another principle should be employed: when the cost of infrastructure is accounted for, the average cost pricing may be appropriate.

Theories of road pricing have been discussed in the contexts of achieving optimal design of a road network (i.e., deciding road capacity and toll levels, based on expected travel demand), and the outcomes of project alternatives. Decision-makers need to evaluate potential outcomes of pricing regimes to be employed before making decisions (to grant concession to private partners, in case of private provision), in terms of travel demand, welfare distribution, and economic development.

3.2.2 Road Network Design and Models of Multi-jurisdictional Interactions

A particularly insightful aspect of the literature on road pricing and highway investment is the interaction of governments in making these decisions (Levinson, 2002). Scholarly attention on this matter emerged rather recently in the 2000s. One of the notable features in these studies is its emphasis on the network level analysis of horizontally competing operators (e.g., competition among states). This subsection will provide a rather selective summary of the literature on this subject that is relevant for the analysis in this study.

Strategic pricing and investment decisions of road operators, with possible private operation in mind, was arguably first formalized by De Palma and Lindsey, who investigated the welfare effect of ownership types on parallel links of an origin-destination (OD) pair, using a dynamic congestion bottleneck model (De Palma and Lindsey, 2000, De Borger and Proost, 2012). De Borger et al. conducted an equivalent analysis in the context of two public operators with tolls: parallel links that connect a city
and a suburb were proposed for the analysis. Local traffic and cross-border traffic were 
differentiated, and potential tax competition between the public operators was analyzed. 
While this study led to important policy insights regarding tolling behaviors of 
governments (distinguishing local and through traffic), this study did not address 
highway capacity investments (De Borger et al., 2005).

Since then, a number of studies have investigated, in the context of serial road 
networks, the strategic interaction of public road operators regarding their pricing and 
investment decisions. A typical case of such a network is two links that are connected at 
the border of two abstract regions, such as two uniform jurisdictions, or more 
interestingly, a city and suburb. Several of these studies focused on pricing and 
investment behaviors, as opposed to pricing only. For instance, De Borger et al. proposed 
a game theoretic model of a serial network where two public authorities strategically 
decide road capacity and toll level in a two-stage game. They found a double-
marginalization of cross-border traffic, where public authorities set tolls higher than 
marginal cost pricing levels to extract revenues, disregarding the losses incurred to the 
other public authority. They found that, when one jurisdiction increases the capacity, 
general travel cost decreases, followed by an increase in the traffic level. The other 
jurisdiction then responds by increasing its capacity as well (De Borger et al., 2007). 
While this particular analysis assumed an international context, the framework and 
insights are relevant to the state and municipal levels.

Ubbels and Verhoef analyzed strategic interactions of governments using a 
similar approach, employing Nash and Stackelberg games, which illustrate the effect of
timing of decisions. The results of their analysis suggest that it doesn’t make much difference whether decisions are made simultaneously or sequentially, especially with respect to the welfare effect of alternative policies (Ubbels and Verhoef, 2008). Other studies on two governments’ interactions on strategic road capacity choice on serial network include two reports by Mun and Nakagawa (2008, 2010), De Borger et al. (2008), and De Borger and Pauwels (2010).

There are several ways in which they can be further extended. First, previous studies indicate that the network structures demonstrated larger impacts than other factors, such as the types of games assumed (Ubbels and Verhoef, 2007). In particular, to the author’s knowledge, no studies have analyzed jurisdictional interactions where a network link exclusively served cross-border traffic. Such an extension would be an important step toward understanding the relationships between institutional frameworks and behaviors of decision makers regarding highway capacity investments. Furthermore, one may expect different outcomes of strategic interactions among players, when accounting for different ownership types or more complex procurement models, as they would imply distinct objective functions of players in the game. Another extension to this line of literature could be to generalize the analysis setting to a more complex network that looks like a real road network over multiple jurisdictions. Formulating a full-scale network design problem where jurisdictions with distinct characteristics (e.g., geographic size, wealth levels, travel demand, topography, and even political climate) might enable insightful analysis of various policy scenarios.
In the engineering literature, strategic behavior models and ex ante evaluation of welfare and other outcomes are commonly employed in evaluating various dimensions of P3s as broadly defined. These studies, as far as private operation is concerned, focus primarily on build-operate-transfer (BOT) schemes, where a private firm invests in a facility, maximizes its profit through operation, and reverts the asset back to the public sector as of contract termination. While these approaches provide valuable insights for policy-makers, it should be highlighted that the increasing roles that private firms have been playing in recent years involve much more complex contractual arrangements than BOT projects. Notable characteristics of P3s that have inspired policy debates in recent years include bundling of contracts for multiple stages of project life and allocation of project risks to both public and private parties. Most of the studies discussed in this subsection are not sensitive enough to these details. Hence, the models can be enhanced to account for whether these contractual characteristics have significant impact on the toll and capacity setting behaviors, users’ travel demand, and/or the aggregate welfare. In literature, contract models have been analyzed based on contract theory, industrial organization, and more broadly, new institutional economics literature, which will be reviewed in the following section.

3.2.3 Incomplete Contract Literature

From the economic perspective, public agency’s decision whether to procure a highway project via traditional design-bid-build approach or as a P3 should depend on the relative efficiency of delivering the service over the life cycle of the facility. The differences between these procurement models can be in part attributable to respective
incentive effect for project private partners. There is a tradeoff of economic benefits (i.e., efficiency gains) and drawbacks (i.e., additional costs for transaction and compensations for private risk premium) when making procurement decisions between P3s or traditional model. In this case, for instance, by allocating the design and construction risk, there is incentive for the private partner to optimize design and construction stages of the project so as to minimize delays and inefficiencies. As a result, this contract arrangement can achieve overall efficiency in infrastructure delivery.

Economic analysis of P3 procurement models predominantly deal with transaction costs, risk allocation, and additional consideration on the governmental accounting treatment of P3 financing as well as their macroeconomic implications (Hodge et al., 2010). A number of studies have examined the economic benefit of P3s in terms of their cost-saving and better management of project costs and risks. This subsection will discuss theoretical propositions from a few recent studies on this subject, followed by a review of project evaluation models used in practice.

As discussed already, the two critical components of P3s are bundling of multiple stages of projects’ lifecycle, and transfer of project risks to the party best able to manage them. P3s can be a suitable approach because of the complex nature of the infrastructure services for which P3s have been used, and the incompleteness of contracts for these services as a result of the complexity. In short, the cost of specifying all requirements for the infrastructure service and addressing every single contingency in a contract is prohibitive. Through bundling multiple stages of a project and transferring certain risks to the private partner in the contract, a P3 can incentivize cost saving and service enhancing
effort of the private partner. Hart first applied the incomplete contract framework to the subject of P3 (2003). From the incomplete contract perspective, Hart showed that traditional unbundled procurement is desirable when construction of the building can be well specified while the quality of the service cannot be well specified. P3 procurement may be desirable efficiency-wise when the service quality can be well specified in the contract while the quality of the initial construction cannot be well specified. At the risk of over-simplification, this view would suggest that schools could be suitable for traditional procurement, while hospitals may be suitable for a P3 (Hart, 2003).

Martimort and Pouyet analyzed alternative forms of procurement in terms of service bundling/unbundling choices and of asset ownership (2008). The authors found that an optimal choice of procurement model with respect to efficiency depends not on the form of ownership but on what they referred to as the externality of construction design to the operational costs. Positive externality is present when building specification is such that the operational cost becomes more efficient (e.g., more costly high specification of pavement lowers maintenance costs during the operational phase). Negative externality is situations where the operational costs increase, e.g., luxurious rest area facilities, which only increases operational costs.

The authors argued that when contract can be complete, whereby all contingencies are a priori specified in the contract, there is no difference in terms of efficiency with respect to the decision to bundle multiple phases of a project or the ownership (i.e., public or private ownership). By using fixed fee contract, regardless of whether the contract bundles multiple project delivery stages or not, first-best effort for
quality can be enforced in an efficient manner. When positive externalities are present, however, by bundling the project stages, the private partner can internalize the positive externality and is incentivized to pursue efficiency, hence resulting in efficiency gains. Assuming moral hazard of contractors, unbundled contract may give the contractor disincentive to exert its best effort to deliver quality service, and the low quality of construction may increase the operational costs. For example, the contractor of a highway project may use the pavement of the lowest cost and quality that still satisfies the required specification, but the pavement may be costly during the operational phase of the facility, thus resulting in inefficient lifecycle costs. As such, when positive externality is present, bundling is desirable. Furthermore, if it is costly or impossible to specify every single requirement as for the quality of service to be delivered, the ownership may as well be transferred to the private partner. Then there is incentive for the private partner to exert its best effort to increase the asset value. A P3 is the desirable procurement model. In contrast, when negative externalities are present, the traditional procurement model is preferred (Martimort and Pouyet 2008).

In addition, Benett and Iossa showed that the ownership of the infrastructure facility after the life of the contract also has an important incentive effect on the level of private partner’s effort. Ownership was a critical consideration as it provides the right to make any decisions not specified in the contract. In the case of positive externality of construction quality to the operation costs, ex ante incentive for cost saving and quality service is stronger if after the contract life the asset is to be under the ownership of the private partner. In contrast, such incentive effect will be weaker if the ownership is to be
reverted back to the public agency after the contract is over. As a result, P3 may not be preferable in sectors against which there is strong resistance, political or otherwise, for long-term private ownership (Bennett and Iossa, 2006).

De Bettignies and Ross focused on an important aspect of the modern P3s, private participation in financing of public infrastructure projects. From the industrial organization theory and corporate finance theory, the authors investigated under what conditions public or private financing is preferable in a particular project context. Comparing an infrastructure project with debt financing arrangements through public and private development, the authors analyzed some of the outcomes of private financing. First, the incomplete nature of project contracts leads to inefficiently low level of lending for privately developed projects, for fear of strategic default by the developer. Second, the private developer is only willing to commit to the debt repayment that is smaller than the socially optimal level. This is because of two reasons. First, the private developer maximizes its profit while not considering social surplus, thus achieving lower than socially optimal level of investment. Second, the private developer does not internalize consumer surplus, while extracting its profit from the social surplus, lowering the size of repayments to be committed, hence lowers the level of lending for these projects. The authors claimed that governments could intervene to achieve the socially optimal level of infrastructure investment, by simplifying contract designs (to address contract incompleteness), and by providing direct loan assistance to projects (to substitute for the inefficiently low level of private financing). As regards the publicly financed debt for infrastructure projects, the authors observed that the level of investment would be
different as decision makers try to manipulate voters through its investment, hence leading to ex ante and ex post inefficient levels of investment.

Based on the above findings, de Bettignies and Ross argued that private borrowing might be ex post superior to the public borrowing for infrastructure projects. This is because private developers would be willing to commit to smaller debt and repayment obligations with high expected-returns. Financially unviable projects would not materialize due to the lack of willingness of private developer and lender. Public developer might continue with the investment for other reasons, such as political motives. From a different perspective, projects with smaller expected returns could be financed only through public development, as they do not have the debt commitment problem that the private developers might have (de Bettignies and Ross, 2009).

In this line of thoughts, a key condition for a P3 alternative to be justified for a particular project is whether the transaction costs (i.e., all costs associated with trades attributable to employing the P3 contract, including legal, financial, transportation and other consulting services) are smaller than the efficiency gains, net of transferred risk premiums. Public sector decision makers would make procurement decisions based on the findings from Value For Money (VFM) analysis, which has been developed to compare procurement alternatives in this light (FHWA, 2013).

While the studies reviewed in this subsection provides principles for public agencies in considering alternative procurement strategies for highway investments, there are a few extensions that could further inform decision makers regarding P3s. First, many of these studies focus only on how particular projects are procured, not questioning
whether the projects have been justified on economic basis. With respect to practical implementation, infrastructure investment \textit{per se} is evaluated on benefit-cost basis, and provided an alternative project has been justified on this basis, a procurement strategy is determined through a value-for-money (VFM) analysis. Debate on the specifics of the VFM model is beyond the scope of this study. Nevertheless, some of the models in the incomplete contract literature on P3s (e.g., Blanc-Brude et al., 2009) explicitly assume innovative cost saving and/or quality enhancing technologies that is incentivized in the contract for private contractors to invest. Arguably, these behaviors, while considered one of the bases to warrant P3s under certain circumstances, while not necessarily accounted for in the benefit cost analysis. These are limitations of both benefit cost analysis and value for money analysis, and further refinement of the existing project evaluation frameworks is desirable to account for agents’ behaviors to invest in innovations.

Second, these studies focus on procurement phase of a project, and as such, behaviors of agents that are of critical importance but yet closely related with the innovative investments are considered exogenous, which may not be the case. For instance, a common assumption in these models is perfect competition of bids and hence no profitability of contractors. The assumption is necessary for insightful discussion, but for example monopolistic pricing behaviors after a contractor wins the bid may affect its own behavior on investing in cost saving and quality enhancing innovative technologies. Especially when the objective function of the facility operator is not social welfare maximization, it is naïve to conclude that the efficient marginal social cost pricing or one of the second best pricing strategies would be implemented. Furthermore, the effect of
delivery cost saving and service quality enhancing investment on the optimal toll level is
worth investigating.

Third, while related to the preceding two points, the emphasis of these models are
agents on the supply side of infrastructure facility investment, consideration of facility
users’ behavioral response to alternative policies (e.g., innovative investment) is
exogenous. It is assumed that this is an aspect of project decision process that should be
accounted for at the benefit cost analysis phase (i.e., before the value for money analysis),
there is no clear justification as to why welfare effect of procurement alternatives in terms
of users’ response should not be evaluated simultaneously. Similarly, as based on
financial considerations, the value for money analysis solely considers the project while it
does not view the project in perspective, for example, the network-wide impact of users
for a facility that is part of a larger network, which is mostly the case. As these
procurement models are evaluated with respect to their incentive effects on innovative
investments which are presumed to influence operator’s pricing behaviors and users’
response, it is desirable that these aspects of alternative models to be considered
endogenously.

It is for these reasons that the road privatization literature and incomplete contract
theory models are jointly considered. The analysis in the following section attempts to
build on the foundations of the two strands of literature to address limitations discussed
above.
3.3. Model Formulation

This section lays out the formulation of models to be analyzed analytically and numerically in the subsequent sections. The objective functions of agents will consist of inverse demand function, users’ travel time cost function, facility’s initial cost function, maintenance cost function, and benefit function of service quality due to innovative investment. User demand equilibrium is a condition that plays a critical role in the behavior of the models.

3.3.1 Functions and Assumptions

The analyses will consider a congestible highway network facility. For simplicity, the inverse demand function is assumed to be linearly sloping downwards:

\[ D(v) = d_0 - d_1 v \]  \hspace{1cm} (3.1),

where \( v \) is the number of users using the facility, and \( d_0 \) and \( d_1 \) are exogenously given parameters. As it is sloping downwards, its derivative is negative:

\[ D'(v) = -d_1 < 0 \]  \hspace{1cm} (3.2),

The inverse demand represents users’ willingness to pay in using the facility in terms of the generalized price. It is assumed that there is no income effect. The aggregate utility \( U \), which is equivalent to the Marshallian surplus, is the integral of the inverse demand function:

\[ U = \int_0^v D(v) dv \]  \hspace{1cm} (3.3),

which will be assessed for each demand (market). Usage cost of users \( t \), which encompasses travel time, environmental impact, and other congestible costs of traveling through the facility, is assumed to be a function of the traffic volume and road capacity:
where $v$ is the traffic volume (number of vehicles), $\kappa$ is the capacity of the network link, and $a$ and $b$ are facility specific parameters that represent characteristics of each link. It is assumed that the travel time is monotonically increasing in $v$, and the second derivative is non-negative:

$$\frac{\partial t}{\partial v} = nb \kappa^{-n} v^{n-1} > 0$$

(3.5).

The travel cost is a monotonically decreasing in $\kappa$, and is strictly convex.

$$\frac{\partial t}{\partial \kappa} = -nb \kappa^{-1} v^n < 0$$

(3.6).

These functional forms are pervasive in the literature, including the widely employed Bureau of Public Roads (BPR) model.

In the literature, it is commonly assumed linear capacity supply function, and there is constant economy of scale such that Mohring and Herwitz (1962) self-financing theorem would hold, where toll revenue is sufficient to cover the aggregate, lifecycle capacity costs (e.g., Ubbels and Verhoef, 2006). A typical approach in the network design problem literature is to ignore the maintenance costs as insignificant and to assume away from their decision models (e.g., Chen and Subprasom, 2007). There are different approaches in the literature as to how to consider initial cost and costs in the operation and maintenance phase. Another approach is to consider maintenance costs as a critical component of highway projects’ financial consideration (e.g., project finance). One of the highlights of this study is the effect of innovative investment by private contractors that respond to incentive effects of certain procurement alternatives. To enable such analyses,
the models in this study decompose the capacity cost function into the initial cost and operation and maintenance cost (below referred to as “O&M cost” for brevity) functions. Before discussing the decomposition of the cost function, it is necessary to define innovative investment that is an essential component of the initial and O&M cost functions.

The innovative investment in this context refers to investment in a facility that, for each additional unit: 1) increases initial cost; 2) reduces maintenance costs; and 3) provides better quality infrastructure service to users. Consideration of such components in infrastructure investment is motivated by the incomplete contract theory literature on bundling multiple project phases for P3 procurements (e.g., Hart, 2003, and Blanc-Brude et al., 2009). Various kinds of innovative investments have been envisioned in the literature. For instance, some technologies may allow only lower maintenance costs for additional initial costs. Street lighting bulbs with extended life is an example: assuming equivalent luminosity, Light Emission Diode (LED) consumes lower energy and lasts much longer than traditional light bulbs for a higher initial price. Another type of innovation is higher specification safety feature: for additional costs, users of the facility may enjoy safer travel and possibly more reliable travel time due to lower likelihood of traffic accidents. Intelligent Transportation System (ITS) may also fall under this category, as users will be able to make informed travel route and departure time decisions, which would not have been possible with conventional highway facilities.

These innovative investments would require unique formulations when attempting to model explicitly. For simplicity, nonetheless, the present study will only consider
innovative investments, which, for additional initial investment, reduce maintenance costs and improve the quality of infrastructure service that users would be willing to pay for the premium. An example of this is higher specification pavement material: for a higher initial cost, the pavement achieves lower lifecycle costs and smoother surface (i.e., better roughness index) than other road facilities. This type of innovative investments appears commonly in the literature when discussing P3s as a procurement mechanism to incentivize employment of innovative technologies by private contractors (e.g., Blanc-Brude et al., 2009). Ultimately, it would be desirable and necessary to include such investment in the decision model with a particular technology with empirically estimated and verified parameters in making decisions for real world projects. In this analysis, the innovative investment will be modeled as an abstract variable so as to evaluate its economic impact in a stylized system to draw generalizable insights.

A unit of innovative investment is considered as a variable $\varphi$, and three decision model components are considered as functions of $\varphi$: initial cost, O&M cost, and improved service benefit functions. For analytical tractability, these functions are all assumed to be linear. The initial cost function is $\mathcal{I}(\kappa, \varphi)$, where $\kappa$ represents highway capacity, and $\varphi$ represents the innovative investments. $\mathcal{I}(\kappa, \varphi)$ is linearly increasing in both $\kappa$ and $\varphi$. This analysis assumes the following functional form:

$$\mathcal{I}(\varphi) = s_1 \cdot \kappa + s_2 \cdot \kappa \cdot \varphi \quad (3.7),$$

where it is assumed that $s_1, s_2 > 0$. It follows that,

$$\frac{\partial \mathcal{I}}{\partial \kappa} > 0 \quad (3.8),$$
\[ \frac{\partial I}{\partial \varphi} > 0 \] (3.9),

The O&M cost function is \( M(\kappa, \varphi) \) and is linearly increasing in \( \kappa \) and decreasing in \( \varphi \). The following functional form is assumed:

\[ M(\varphi) = m_1 \cdot \kappa + m_2 \cdot \kappa \cdot \varphi \] (3.10),

where it is assumed that \( m_1 > 0 \) and \( m_2 < 0 \). As such,

\[ \frac{\partial M}{\partial \kappa} > 0 \] (3.11),

\[ \frac{\partial M}{\partial \varphi} < 0 \] (3.12),

A benefit function \( B(\varphi) \) represents the utility gain of users due to the improved quality of infrastructure service accruing from the innovative investment. \( B \) is linearly increasing in \( \varphi \), i.e.,

\[ \frac{\partial B}{\partial \varphi} > 0 \] (3.13).

The service quality improvement due to the innovative investment is included in the analysis as part of the user demand equilibrium condition:

\[ Dv = t(v, \kappa) + \tau - B(\varphi) \] (3.14),

where \( \tau \) represents the toll charged to the traffic using the facility. This section examines the effect of changes in decision to the travel demand. Following van den Berg (2013) and others, the above user equilibrium condition can be rewritten as:

\[ w = Dv - t(v, \kappa) - \tau + B(\varphi) = 0 \] (3.15).

Using the Implicit Function Theorem, the effect of changes in innovative investment to the traffic volume \( v \) can be derived:
\[
\frac{\partial v}{\partial \varphi} = -\frac{\partial w}{\partial \varphi} = -\frac{\partial B}{\partial \varphi} \frac{D'(v)}{D'(v) - \frac{\partial t}{\partial v}},
\]

which is, using (3.2), (3.5), and (3.12),

\[
\frac{\partial v}{\partial \varphi} = \frac{-\partial B}{D'(v) - \frac{\partial t}{\partial v}} > 0
\]

The above result indicates that the traffic volume is increasing in \( \varphi \). Employing the same approach, the effect of changes in the toll to the traffic volume \( v \) is:

\[
\frac{\partial v}{\partial \tau} = -\frac{\partial w}{\partial \tau} = \frac{1}{D'(v) - \frac{\partial t}{\partial v}} < 0
\]

which suggests that the traffic volume is decreasing in the toll, consistent with the literature. With regard to the capacity,

\[
\frac{\partial v}{\partial \kappa} = -\frac{\partial w}{\partial \kappa} = \frac{\partial t}{\partial \kappa} > 0
\]

It follows then that the traffic volume is increasing in the capacity of the facility.

### 3.4 Analytical Results

Based on the functions presented above, this section presents behavioral models of agents and formulation of alternative policy scenarios. The base case scenarios will consider a simple network setting where there is one link that connects an origin and a destination, with a single demand (market), a public agency to sponsor an improvement project, and a private contractor that provides contracted services. Three policy scenarios will be evaluated: a conventional, unbundled procurement; a bundled procurement where
initial construction and maintenance are contracted to the private firm; and a private monopolistic provision. After the discussion of the base case scenarios, the models will be extended to a multi-jurisdictional context that considers a two-link network that connects an urban city and a suburban city, with commuter and urban local markets. Following scenarios will be discussed: global welfare maximization scenario; suburban city sponsored project scenarios (unbundled and bundled procurement); urban city sponsored project scenarios (unbundled and bundled procurement); and a global private monopolistic delivery scenario.

Table 12 Functions and Parameter Notations

<table>
<thead>
<tr>
<th>Variables</th>
<th>Notation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tau)</td>
<td>Toll</td>
</tr>
<tr>
<td>(\kappa)</td>
<td>Capacity</td>
</tr>
<tr>
<td>(\varphi)</td>
<td>Innovative Investment</td>
</tr>
<tr>
<td>(v)</td>
<td>Traffic Volume</td>
</tr>
<tr>
<td>(D(v))</td>
<td>Inverse Demand Function</td>
</tr>
<tr>
<td>(t(\kappa, v))</td>
<td>Congestible Travel Cost Function</td>
</tr>
<tr>
<td>(I(\kappa, \varphi))</td>
<td>Initial Capital Cost Function</td>
</tr>
<tr>
<td>(M(\kappa, \varphi))</td>
<td>O&amp;M cost Function</td>
</tr>
<tr>
<td>(B(\varphi))</td>
<td>Service Quality Benefit Function</td>
</tr>
<tr>
<td>(P(\kappa))</td>
<td>Contract Price Function</td>
</tr>
<tr>
<td>(L)</td>
<td>Urban Local Traffic</td>
</tr>
<tr>
<td>(C)</td>
<td>Suburban Commuter Traffic</td>
</tr>
<tr>
<td>(d)</td>
<td>Parameters of Inverse Demand Function</td>
</tr>
<tr>
<td>(a, b)</td>
<td>Parameters of Travel Cost Function</td>
</tr>
<tr>
<td>(s)</td>
<td>Parameters of Initial Cost Function</td>
</tr>
<tr>
<td>(m)</td>
<td>Parameters of O&amp;M cost Function</td>
</tr>
<tr>
<td>(r)</td>
<td>Parameter of Service Quality Benefit Function</td>
</tr>
</tbody>
</table>
3.4.1 Base Scenarios
This section discusses the objective functions of agents and analysis on their behaviors. The set of models considered in this analysis is static, and it is assumed that all decisions are made long-term. It is also assumed throughout the analysis that at least one interior solution exists for each problem. Corner solutions, which provide less meaningful insights, will be ignored throughout the analysis. It is assumed that only a single modal transportation system exists, and all agents are rational, endowed with complete information. Table 12 summarizes functions and parameter notations.

Unbundled Procurement
The analysis in this study is based on the approaches undertaken in Blanc-Brude et al. (2009) in modeling bundling decisions when procuring an infrastructure project. A two-stage decision making process is considered, where the public sponsor first decides the toll and capacity of the highway link to maximize social welfare, and then the private contractor decides the amount of innovative investment. The objective function of the private contractor is to maximize its own profit $\pi$:

$$\max_{\varphi} \pi^U_P = P(\kappa) - I(\kappa, \varphi)$$

(3.19),

where the superscript $U$ represents the policy scenario “unbundled,” the subscript “P” indicates the decision maker “private contractor,” and $P(\kappa)$ is compensation from the procuring agency, or a private revenue function. The revenue is a function of the capacity that is determined by the public agency, hence is exogenous from the contractor’s perspective. Following Blanc-Brude et al. (2009), a perfect competition is assumed when the project is out for bid, i.e., $P = I$. Therefore, the contractor will make no profit. Hence,
\[
\frac{\partial \pi^U_P}{\partial \varphi} : \varphi^U = 0
\]  \hspace{1cm} (3.20),

which indicates that there is no incentive for the contractor to make innovative investment unless contracted (i.e., accounted for in \( \kappa \)) by the procuring agency.

The public agency determines the optimal levels of toll and capacity an informal backward induction, i.e., to take into consideration the optimal level of innovative investment made by the private contractor (\( \varphi = 0 \)) in its own decision model. Assuming that the private contractor is a member of the same society, the public agency maximizes the social welfare function:

\[
\max_{\tau, \kappa} \pi^U_S = \int_0^V D(v) dv - v \cdot t(\kappa, v) - P(\kappa) + P(\kappa) - I(\kappa, \varphi) - M(\kappa, \varphi)
\]  \hspace{1cm} (3.21),

where the subscript S represents “social.” Toll charges are considered a transfer between members of the same society, and are canceled out. It should also be noted that in this scenario, the public agency is responsible for the maintenance: whether it is contracted out to the same contractor, to another contractor, or to be conducted in-house is outside the concern here. A detailed mathematical discussion is provided in the appendix: only the results will be presented here. As discussed in the Appendix A regarding (A2), taking the first order derivative and setting it to zero, the optimal level of \( \tau \) that maximizes the agency’s objective function is:

\[
\tau^U = v \frac{\partial t}{\partial v}
\]  \hspace{1cm} (3.22).
The optimal toll represents the marginal congestion costs of the traffic volume on the link, as found in a vast body of the literature. As discussed in the Appendix A regarding (A6), the optimal level of $\kappa$, through the same approach, appears as follows:

$$\kappa^{\text{opt}}: \frac{\partial l}{\partial \kappa} + \frac{\partial M}{\partial \kappa} = -v \frac{\partial t}{\partial \kappa} \quad (3.23).$$

It should be noted that this is equivalent to the optimal capacity condition found in the literature (e.g., Ubbels and Verhoef, 2006), provided the initial and O&M costs are considered in aggregate. The sum of initial and O&M costs are set equal to the marginal benefit of the added capacity. It follow that the self-financing theorem of Mohring and Herwitz (1962) is satisfied, assuming that the capacity is a continuous variable, and that there exists constant returns to scale in constructing the facility.

**Bundled Procurement**

One of the essential components of P3 procurements is bundling of multiple project phases into the contract. While another important element is transfer of project risks to the party best able to manage it, the risk consideration will be reserved for a future analysis for the sake of simplicity. In this scenario, the initial construction and maintenance are bundled and procured to a private contractor for a fixed price that is a function of the capacity provided. The private contractor is also able to make innovative investment that reduces O&M costs for additional initial costs. Effectively, this scenario is equivalent with availability payment P3 models where the private contractor is compensated for making the capacity available to the users. The objective function of the private contractor in this context is as follows:

$$\max_{\varphi} \pi_B^p = P(\kappa) - I(\kappa, \varphi) - M(\kappa, \varphi) \quad (3.24),$$
where the superscript B stands for “bundled procurement” scenario.

As in the unbundled procurement scenario analysis, the optimal level of \( \varphi \) in the private contractor’s objective function is first derived, and then the decision rule of the procuring agency is then found, accounting for the private decision on \( \varphi \). As discussed in the Appendix A regarding (A7), taking the first order derivative with respect to \( \varphi \) and setting it to zero:

\[
\varphi^*_B: \frac{\partial I}{\partial \varphi} + \frac{\partial M}{\partial \varphi} = 0 \tag{3.25}
\]

Note that the benefit of improved service quality due to \( \varphi \) is not accounted for in this optimal condition. The contractor makes innovative investment decisions solely based on its own lifecycle cost consideration, since the revenue is determined by the procuring agency and the innovative investment is the only factor it can control. As the discussion regarding (A11) suggests, the level of innovative investment in the bundled procurement scenario is unambiguously larger than in the unbundled procurement scenario.

Denoting optimal level of the innovative investment as \( \varphi^*_B \), the public agency will maximize the social welfare function, accounting for \( \varphi^*_B \) in the user equilibrium constraint. The welfare function appears as follows:

\[
\max_{\tau, \kappa} \pi^B_S = \int_0^v D(v) dv - v \cdot t(v, \kappa) - I(\kappa, \varphi) - M(\kappa, \varphi) + v \cdot B(\varphi) \tag{3.26}
\]

Taking the first order derivative of (3.26) with respect to \( \tau \):

\[
\frac{\partial \pi^B_S}{\partial \tau} = D(v) \frac{\partial v}{\partial \tau} - \frac{\partial v}{\partial \tau} t(\kappa, v) - v \frac{\partial t}{\partial v} \frac{\partial v}{\partial \tau} + \frac{\partial v}{\partial \tau} B(\varphi).
\]
The above can be reduced using the user equilibrium condition (3.14), and as discussed in the appendix regarding (A2):

\[ \tau_B^* = v \frac{\partial t}{\partial v} \]  \hspace{1cm} (3.27),

which consists of the marginal social costs of making the trip. Similarly, the first order derivative of (3.26) with respect to \( \kappa \) is:

\[ \frac{\partial \pi_S^B}{\partial \kappa} = D(v) \frac{\partial v}{\partial \kappa} - \frac{\partial v}{\partial \kappa} t(v, \kappa) - v \frac{\partial t}{\partial v} \frac{\partial v}{\partial \kappa} - v \frac{\partial t}{\partial \kappa} - \frac{\partial l}{\partial \kappa} - \frac{\partial M}{\partial \kappa} + \frac{\partial v}{\partial \kappa} B(\varphi) \]

which can be reduced using the equilibrium condition (3.14):

\[ = \frac{\partial v}{\partial \kappa} \tau - v \frac{\partial t}{\partial v} \frac{\partial v}{\partial \kappa} - v \frac{\partial t}{\partial \kappa} - \frac{\partial l}{\partial \kappa} - \frac{\partial M}{\partial \kappa} \]

The first two terms further cancel out using (3.27). As a result, the optimal condition of (3.26) with respect to \( \kappa \) is:

\[ \frac{\partial l}{\partial \kappa} + \frac{\partial M}{\partial \kappa} = -v \frac{\partial t}{\partial \kappa} \]  \hspace{1cm} (3.28).

This result indicates that the marginal lifecycle cost of capacity investment (i.e., sum of the initial and O&M costs) is equal to the marginal benefit in terms of the congestion cost of that capacity.

**Private Monopolistic Delivery**

Private monopolistic delivery is a scenario in which the private contractor is authorized to set and charge toll for the traffic using the facility. In the bundled procurement scenario, the revenue of private contractor was considered virtually fixed, i.e., revenue risk from the contractor’s perspective was very low. In contract, traffic volume in real world is obviously very difficult to predict, as a number of
macroeconomic as well as project specific factors may affect the demand of potential
users. Since authorizing the private contractor to set and charge tolls would indicate that
their revenue would be dependent on the demand that is unlikely to be fully predictable,
the private monopoly scenario would be equivalent to demand risk P3s. Nevertheless, as
discussed in the preceding section, the analyses in this study will assume deterministic
models and consideration of risks will be in addressed in future extensions.

The private contractor will first contract with the authorizing public agency on the
capacity and toll levels, and then internally determines the innovative investment. The
objective function of the private contractor is:

$$\pi^M_p = v \cdot \tau - I(\kappa, \varphi) - M(\kappa, \varphi)$$ (3.29)

With respect to the toll, the optimal condition is:

$$\tau^{PM*} = v \left[ \frac{\partial t}{\partial v} - D'(v) \right]$$ (3.30).

Here, the first term in the bracket is the marginal social cost of making the trip,
and the second term is the monopolistic markup (Verhoef, 2007).

Similarly, as discussed in the Appendix regarding (A15), the optimal condition of
the private monopolistic delivery scenario with respect to $\kappa$ is:

$$\kappa^{PM*}: \frac{\partial I}{\partial \kappa} + \frac{\partial M}{\partial \kappa} = -v \frac{\partial t}{\partial \kappa}$$ (3.31).

As the discussion regarding (A17) shows, the optimal level of innovative
investment is:

$$\varphi^{PM*} = \frac{\partial I}{\partial \varphi} + \frac{\partial M}{\partial \varphi} = v \frac{\partial B}{\partial \varphi} > 0$$ (3.32).
Comparing the optimal rules of innovative investment for the procurement model alternatives, one may find a few insightful lessons. First, comparing the unbundled and bundled procurement models, there will always be a larger quantity of $\varphi$ in the latter scenario. Furthermore, the optimal level of $\varphi$ in the bundled scenario accounts only for the cost reduction in the O&M costs. In contrast, the optimal rule of $\varphi$ in the private monopolistic delivery scenario also internalizes the users’ benefit of the improved service quality due to the innovative investment. However, due to the monopolistic markups in $\tau$ in this scenario, the traffic volume $v$ will be lower, and the resulting levels of $\kappa$ and $\varphi$ in comparison to the other scenarios will depend on other parameters, notably the slope of the inverse demand curve. However, if, as part of the concession agreement, the toll level was set to maximize the social welfare (i.e., throughput maximizing toll), then $v$ will be larger than the revenue maximizing level. Hence, the level of innovative investment would be larger than in the case of bundled procurement.

Multi-jurisdictional scenarios

Building on the models presented above, this section will extend the analysis by considering interactions of multiple jurisdictions in investing in a highway facility that connects them. As reviewed in the preceding section, a number of studies modeled interactions of multiple jurisdictions in setting highway capacity and tolls, some of which explicitly models private ownership or operation. Theoretical foundation has been well established and proposed approaches of implementation in the real-world road networks have been extensive, including private operation of network links (i.e., privatization). However, consideration of alternative procurement models, especially with respect to
bundling project phases and employing innovative technologies, which are arguably the defining characteristics of p3s, has been sparse. To bridge this gap, this section will evaluate interactions of jurisdictions regarding implementing P3 procurement in terms of setting network design variables and their welfare impacts.

![Network Structure, Multi-jurisdictional Scenarios](image)

**Figure 4 Network Structure, Multi-jurisdictional Scenarios**

The network structure used in the analysis here slightly modifies the network considered by Ubbels and Verhoef (2006). There are two types of market demand: local demand of the urban city, and commuter demand from the suburban city to the urban city. Figure 4 shows the structure of the network considered in the multi-jurisdictional scenarios. The link 1 serves exclusively the commuter demand, and the link 2 serves both local and commuter demands. The link 1, which is considered for the investment crosses the jurisdictional border, exclusively serves the cross-border traffic. Unlike Ubbels and Verhoef (2006), the network considered here is asymmetric, and does not include local demand for the suburban jurisdiction. Nevertheless, the motivation of this analysis is the jurisdictions’ interaction in terms of the cross-border facility, rather than focusing on
network demand symmetry. As such, the models in this section resort to using this asymmetric network for tractability of the model and ease of interpreting the results.

The decision variables in this and other multi-jurisdictional scenarios are: capacity and toll of link 1 (stage 1); innovative investment of link 1 (stage 2); and commuter and urban local traffic volume (stage 3). It is assumed that the decision makers have full knowledge of how the travel demand would respond to given sets of toll, capacity, and service quality (innovative investment). It is also assumed that the decision makers have full knowledge on the innovative investment to be made by the private contractor once a contract is executed. Six alternative procurement scenarios will be evaluated: global welfare maximization (unbundled procurement); unbundled and bundled procurement scenarios for welfare maximization of suburban city and urban city, respectively; and global private monopolistic delivery.

Travel time of link 1 is a function of its capacity $\kappa_1$ and commuter traffic $v_C$: $t_1(v_C, \kappa_1)$, and travel time of link 2 is a function of commuter traffic $v_C$ and urban city’s local traffic $v_L$. Following the travel time function in the base case scenarios, the following can be observed. For the sake of analytical tractability, here and in the following analysis, linearity of travel cost function is assumed, i.e., $n = 1$.

\[
\frac{\partial t_1}{\partial v_c} = nb_1 \kappa_1^{-n} v_c^{n-1} > 0 \quad (3.33).
\]

\[
\frac{\partial t_1}{\partial \kappa_1} = -nb_1 \kappa_1^{-n-1} v_c^n < 0 \quad (3.34).
\]

\[
\frac{\partial t_2}{\partial v_c} = nb_1 \kappa_2^{-n} v_c^{n-1} > 0 \quad (3.35).
\]
\[ \frac{\partial t_2}{\partial v_L} = nb_1 \kappa_2^{-n} v_L^{n-1} > 0 \] (3.36).

Each of these objective functions will be constrained by user equilibrium conditions for the commuter and local traffic. The demand of urban city’s local traffic is equal to the travel cost of link 2, which is dependent on the local as well as commuter traffic volume. The capacity of this link is not considered for investment, hence is a variable exogenous to the model. The local user equilibrium condition is as follows:

\[ D(v_L) = t_2(v_L, v_C) \] (3.37),

where \( t_i \) is the travel cost function for link \( i = [1, 2] \), and \( v_j \) denotes traffic of market \( j = [C, L] \). \( C \) indicates the market for commuter travel, and \( L \) represents the market for urban city’s local traffic. Using the same technique as the base case scenarios:

\[ w_1 = D(v_L) - t_2(v_L, v_C) = 0 \] (3.38).

Using the Implicit Function Theorem, the effect of a change in commuter traffic to the local traffic is:

\[ \frac{\partial v_L}{\partial v_C} = - \frac{\partial w_1}{\partial v_C} = \frac{\partial t_2}{\partial v_C} D'(v_L) - \frac{\partial t_2}{\partial v_L} < 0 \] (3.39),

which indicates that an increase in the commuter traffic will reduce local traffic, due to the higher travel cost on link 2 due to congestion. A symmetric result can intuitively be expected: an increase in the local traffic will impose higher travel cost to the commuter traffic on link 2, hence reduces the commuter traffic.
The user equilibrium condition of commuter traffic consists of the travel cost on link 1 and 2, toll charged on link 1, and the utility gains from improved infrastructure service associated with the innovative investment $\varphi$:

$$D(v_c) = t_1(v_c, \kappa_1) + t_2(v_L, v_c) + \tau_1 - B(\varphi_1) \quad (3.40),$$

where $\tau_1$ denotes toll charged on link 1, and $\varphi_1$ denotes innovative investment on link 1. As in the local traffic user equilibrium:

$$w_2 = D(v_c) - t_1(v_c, \kappa_1) - t_2(v_L, v_c) - \tau_1 + B(\varphi) = 0 \quad (3.41).$$

Using the Implicit Function Theorem, the effect of changes in the toll to the commuter traffic is:

$$\frac{\partial v_c}{\partial \tau_1} = \frac{\frac{\partial w_2}{\partial \tau_1}}{\frac{\partial w_2}{\partial v_c}} = \frac{1}{\frac{D'(v_c)}{\partial v_c} - \frac{\partial t_1}{\partial v_c} - \frac{\partial t_2}{\partial v_c}} < 0 \quad (3.42).$$

Therefore, intuitively, an increase in the toll will decrease the commuter traffic.

Similarly, to evaluate the effect of marginal change in the capacity of link 1,

$$\frac{\partial v_c}{\partial \kappa_1} = \frac{\frac{\partial w_2}{\partial \kappa_1}}{\frac{\partial w_2}{\partial v_c}} = \frac{\frac{\partial t_1}{\partial \kappa_1}}{D'(v_c) - \frac{\partial t_1}{\partial v_c} - \frac{\partial t_2}{\partial v_c}} > 0 \quad (3.43).$$

As it is the same as in the base scenario, capacity increase will reduce travel cost on link 1, and results in an increase in the commuter traffic. Finally, marginal increase in the innovative investment is:

$$\frac{\partial v_c}{\partial \varphi_1} = \frac{\frac{\partial w_2}{\partial \varphi_1}}{\frac{\partial w_2}{\partial v_c}} = \frac{\frac{\partial B}{\partial \varphi_1}}{D'(v_c) - \frac{\partial t_1}{\partial v_c} - \frac{\partial t_2}{\partial v_c}} > 0 \quad (3.44),$$
which suggests that, due to the improved service quality, the commuter traffic will increase. Where appropriate, $w_2$ should also be used to analyze the effect of change in $v_C$ to $v_L$:

$$\frac{\partial v_L}{\partial v_C} - \frac{\partial w_2}{\partial v_L} = - \frac{D'(v_C) - \frac{\partial t_1}{\partial v_C} - \frac{\partial t_2}{\partial v_C}}{\frac{\partial t_2}{\partial v_L}} < 0 \quad (3.45)$$

These results on the effect of input variables to the commuter and urban local traffic will be used to analyze behaviors of decision models in the following section.

**Global Welfare Maximization - Unbundled Procurement**

As a benchmark to compare with other scenario, a global welfare maximization scenario is first considered, assuming unbundled procurement with no innovative investment. The social welfare function consists of the following components: utility gains of the commuter and local traffic; travel cost of each link; initial and O&M costs of link 1; and utility gains of infrastructure due to quality improving innovative investments. Similar to the base case scenario, toll charges are considered a transfer between members of the same society, and thus canceled out. The global welfare function is as follows:

$$\max_{\tau, \kappa} \pi^G = \int_0^{v_C} D(v_C)dv + \int_0^{v_L} D(v_L)dv - v_C \cdot [t_1(v_C, \kappa_1) + t_2(v_L, v_C)] - v_L \cdot t_2(v_L, v_C)$$

$$- I(\kappa_1, \varphi_1) - M(\kappa_1, \varphi_1) + v_C \cdot B(\varphi_1) \quad (3.46),$$

where $G$, superscript of $\pi$, denotes global welfare. For the sake of comparison, it is assumed $\varphi_1 = 0$ in this scenario. The optimal condition of $\tau$ is, as derived in the discussion in the appendix regarding (B2):
\[
\tau^*_1 = v_C \left[ \frac{\partial t_1}{\partial v_c} + \frac{\partial t_2}{\partial v_c} + \frac{\partial t_2}{\partial v_L} \frac{\partial v_L}{\partial v_c} \right] + v_L \left[ \frac{\partial t_2}{\partial v_c} + \frac{\partial t_2}{\partial v_L} \frac{\partial v_L}{\partial v_c} \right]
\] (3.47).

This is the marginal social cost pricing, which is consistent with the literature.

Similarly, based on the discussion regarding (B4), the optimal condition of \( \kappa_1 \) is:

\[
\kappa^*_1: \frac{\partial I}{\partial \kappa_1} + \frac{\partial M}{\partial \kappa_1} = -v_C \frac{\partial t_1}{\partial \kappa_1}
\] (3.48).

**Suburban City Welfare Maximization - Unbundled Procurement**

This scenario models a situation where the suburban city serves as the project sponsor to invest in a link that exclusively serves its commuter traffic into the urban city.

Frameworks for modeling jurisdictional competition were developed following Levinson (2002) and, more explicitly, Ubbels and Verhoef (2006). The welfare function consists of the utility gains of commuters (i.e., suburban residents), their travel time, initial and O&M costs, and utility gains due to improved service quality due to the innovative investment. First, as in the base case, the private contractor is compensated with revenue that is a function of the capacity it has been contracted to build. The capacity is determined by the sponsoring agency, and is exogenous to private contractor’s profit maximization problem:

\[
\max_{\varphi} \pi^*_P = P(\kappa_1) - I(\kappa_1, \varphi_1)
\] (3.49),

where the superscript SU denotes suburban unbundled procurement. As discussed in the Appendix B regarding (B5), assuming perfectly competitive bid, the contractor will make no profit. As a result, there is no incentive for the contractor to make innovative investment unless included in the scope of the contract:

\[
\varphi^*_S = 0
\] (3.50).
The public agency decides the capacity and toll on the link 1. The welfare function is as follows:

$$\max_{\tau, \kappa} \pi^{SU}_S = \int_0^{V_C} D(v_C) dv - v_C \cdot t_1(v_C, \kappa_1) - v_C \cdot t_2(v_L, v_C) - I(\kappa_1, \varphi_1) - M(\kappa_1, \varphi_1) + v_C \cdot B(\varphi_1)$$

(3.51).

As discussed regarding (B7), the level of $\tau_1$ that maximizes the objective function is:

$$\tau^{SU*}_1 = v_C \left[ \frac{\partial t_1}{\partial v_C} + \frac{\partial t_2}{\partial v_C} + \frac{\partial t_2}{\partial v_L} \frac{\partial v_L}{\partial v_C} \right]$$

(3.52),

which consists of marginal social cost of the commuter traffic on each of the two links, and its effect on the local traffic on link 2. Similarly, as discussed regarding (B8), the optimality condition of (3.51) with regard to $\kappa_1$ is as follows:

$$\kappa^{SU*}_1 : \frac{\partial I}{\partial \kappa_1} + \frac{\partial M}{\partial \kappa_1} = -v_C \frac{\partial t_1}{\partial \kappa_1}$$

(3.53),

which is the same as in the other scenarios.

Suburban City Welfare Maximization - Bundled Procurement

The unbundled procurement scenario discussed above is then extended to a bundled procurement, where the initial construction and maintenance are procured as one contract. As in the base scenario, in this model the private contractor receives fixed revenue based on the highway capacity of link 1 to be provided to the commuters. The contractor will be responsible for the initial construction and maintenance of the facility. This scenario is equivalent to the availability payment P3 model. The private contractor maximizes its profit:
\[
\max_{\varphi_1} \pi^B_{SB} = P(\kappa) - I(\kappa, \varphi) - M(\kappa, \varphi)
\]  
(3.54)

where the capacity \( \kappa \) is determined by the public agency, hence is exogenous to the contractor. As discussed regarding (B11), the optimal condition with respect to \( \varphi_1 \) is:

\[
\varphi^{SB*}_1 : \frac{\partial I}{\partial \varphi_1} + \frac{\partial M}{\partial \varphi_1} = 0
\]

(3.55),

which can be interpreted as when the marginal cost of innovative investment is equal to the marginal saving that the innovation will achieve. It should be noted again that the private contractor is deciding the optimal level of innovative investment solely based on its lifecycle cost minimization, since the revenue is fixed. The improved service quality for users is not considered. As shown in the appendix in the discussion regarding (B16), the amount of the innovative investment in the bundled procurement scenario is unambiguously larger than in the unbundled procurement scenario, assuming \( s_1, s_2, m_1 > 0 \) and \( m_2 < 0 \).

Provided the optimal level of innovative investment for the contractor, the public agency determines the capacity and toll of the highway link to be invested. The objective function of the suburban city in this scenario is equivalent to the unbundled scenario (3.51). The same conditions of optimality with respect to the toll (3.52) and capacity (3.53) apply in the bundled procurement scenario. The values will be different, however, since in this case the level of innovative investment is non-zero. The welfare outcomes of the two scenarios will depend on the price elasticity of demand, users’ marginal benefit of innovative investment, and other factors.
Urban City Welfare Maximization - Unbundled Procurement

Following Ubbels and Verhoef (2006), this section will consider a situation where the urban city invests in the link 1 so that the commuters from the suburban city can access the urban city for employment, shopping, and so forth. The urban local traffic will not use the facility to be invested: rather, due to the increased congestion on the link 2, excessive investment on link 1 that lowers commuter traffic’s travel costs may impose higher costs on its own residents. There is therefore a tradeoff between the toll revenue from the commuter traffic, which is net positive to the urban community, and the increased congestion costs onto its own residents.

The objective function of the private contractor in this scenario is equivalent to that in the suburban city welfare maximization scenarios. In the unbundled procurement case, the optimal level of innovative investment is zero:

$$\varphi_{1UU}^* = 0$$ (3.56).

The objective function of the urban city consists of the utility gains of local traffic, congestion costs on the link 2, initial and O&M costs of link 1, and toll revenue from the commuter traffic:

$$\max_{\tau, \kappa} \pi_{SU}^{UU} = \int_0^{v_L} D(v_L) dv - v_L \cdot t_2(v_L, v_T) + \tau_1 v_T - I(\kappa_1, \varphi_1) - M(\kappa_1, \varphi_1)$$ (3.57),

where the subscript UU denotes urban city, unbundled procurement.

The optimal toll level is, as derived in the discussion regarding (B21):

$$\tau_{1UU}^* = v_c \frac{\partial t_2}{\partial v_c} + (v_c - v_L) \left[ \frac{\partial t_1}{\partial v_c} - D'(v_c) \right]$$ (3.58).
The above condition indicates that the urban city, when investing and operating the facility to serve inbound traffic, sets tolls in terms of its marginal social cost on the local link and the effect of difference of local and commuter traffic in terms of its marginal social cost on the connecting link and monopolistic markup that is based on the slope of the inverse demand function.

As discussed in the appendix regarding (B23), the optimal condition of urban city’s objective function with respect to $\kappa_1$ is as follows:

$$\frac{\partial M}{\partial \kappa_1} + \frac{\partial I}{\partial \kappa_1} = -v_c \frac{\partial t_1}{\partial \kappa_1}$$ \hspace{1cm} (3.59),

which is equivalent to the other scenarios.

**Urban City Welfare Maximization - Bundled Procurement**

Similar to the suburban welfare maximization scenario, the urban city public agency determines the toll and capacity of link 1, and procures as a bundled project for a fixed compensation. The private contractor then minimizes its lifecycle cost for building and maintaining the capacity contracted by the public authority, by setting an optimal level of the innovative investment. The objective function of the private contractor is the same as the bundled procurement scenario in the suburban city welfare maximization case. As discussed in the appendix regarding (B18):

$$\varphi_P^{UB} : \frac{\partial I_s^{UB}}{\partial \varphi_1} + \frac{\partial M_s^{UB}}{\partial \varphi_1} = 0$$ \hspace{1cm} (3.60).

The optimal capacity and toll set by the urban city follow the same optimal condition as the unbundled procurement case. The level of innovative investment in this
scenario is unambiguously larger than in the unbundled procurement scenario, as discussed in the appendix regarding (B19). Assuming \( s_1, s_2, m_1 > 0 \) and \( m_2 < 0 \):

\[
\varphi_{1B}^* > \varphi_{1U}^* \quad (3.61).
\]

*Global Profit Maximization: Private Monopolistic Delivery*

This scenario examines the procurement scenario where a private contractor is authorized to develop a facility that link the two jurisdictions setting capacity, toll, and innovative investment to maximize its profit. Since it is unlikely that either of the jurisdictions is able to execute a contract with a private entity that affects the other jurisdiction, this scenario can be interpreted that a higher-level jurisdiction is the project sponsor. For example, if the facility crosses a border of two cities, then in this case a state or a bi-city agency is the public sponsor that authorizes the contractor’s undertaking. The objective function of the private contractor is equivalent to the base case private monopolistic scenario, except that the network link that is subject to the investment is explicit. First, a contract that consists of an agreed set of link capacity and toll is executed; then second, the private contractor decides internally on the innovative investment. The objective function of the contractor is as follows:

\[
\max_{\varphi} \pi_{PM} = \tau_1 v_C + -I(\kappa_1, \varphi_1) - M(\kappa_1, \varphi_1) \quad (3.62),
\]

where the optimality condition with respect to the innovative investment is:

\[
\frac{\partial \pi_{PM}}{\partial \varphi_1} = \tau_1 \frac{\partial v_C}{\partial \varphi_1} - \frac{\partial I}{\partial \varphi_1} - \frac{\partial M}{\partial \varphi_1} = 0,
\]

hence,

\[
\varphi_{PM}^*: \frac{\partial I}{\partial \varphi_1} + \frac{\partial M}{\partial \varphi_1} = v_C \frac{\partial B}{\partial \varphi_1} \quad (3.63).
\]
This optimality rule is further discussed in the appendix. In particular, the following observations are made:

$$\varphi_1^{PM*} > \varphi_1^{UU*}$$  \hspace{1cm} (3.64),

$$\varphi_1^{PM*} > \varphi_1^{SU*}$$  \hspace{1cm} (3.65).

In words, the optimal level of innovative investments in the private monopoly is unambiguously larger than in the cases of unbundled procurement procured either by the suburban or urban cities. Comparison of the private monopolistic delivery to bundled procurement is not straightforward, since the higher level of $\tau_1$ will lower traffic level on link 1, and the level of $\varphi_1^{PM*}$ depends on the parameters, especially the slope of the inverse demand curve. However, it should also be noted that if in the concession agreement the toll was set to maximize aggregate welfare (throughput), then the amount of innovative investment would be larger than the bundled procurement scenario.

The above optimality condition with respect to $\varphi$ is then accounted for in optimizing the objective function with respect to $\kappa$ and $\tau$. The optimal toll rule can be derived by taking the first order derivative of the objective function and setting it to zero:

$$\frac{\partial \pi^G}{\partial \tau_1} = v_c + \tau_1 \frac{\partial v_c}{\partial \tau_1} = 0.$$  

After some arrangements:

$$\tau_1^{PM*} = v_c \left[ D'(v_c) - \frac{\partial t_1}{\partial v_c} - \frac{\partial t_2}{\partial v_c} \right]$$  \hspace{1cm} (3.66).

As discussed in the Appendix B regarding (B25), the optimal condition of (3.62) with respect to $\kappa$ is:

119
\[ \kappa_1^{PM^*} \frac{\partial I}{\partial \kappa_1} + \frac{\partial M}{\partial \kappa_1} = -v_c \frac{\partial t_1}{\partial \kappa_1} \]  \hspace{1cm} (3.67).

These conditions are the same as the base case private monopolistic delivery scenario. In determining the innovative investment level, the private contractor accounts not only for optimizing the initial construction and O&M costs but also the user benefit of the improved service quality. In setting the toll, the operator charges the marginal congestion cost on the facility link with monopolistic markup that depends on the slope of the demand curve. The optimal capacity level is where the marginal benefit of adding a unit of capacity is equal to the marginal cost of building and operating it. In the appendix, mathematical details will be provided.

This section summarized analytical results of the models of various procurement alternatives. Two network types were considered: a two-node, one-link, base network case; and a two-node, two-link, multi-jurisdictional case. In the first case, three procurement alternatives were examined: unbundled procurement, bundled procurement (initial construction and maintenance), and private monopolistic delivery. Six alternative procurement models were examined for the multi-jurisdictional, cross-border network case: unbundled, global welfare maximization, unbundled and bundled procurement models where urban city and suburban city each maximizes respective welfare, and, private monopolistic delivery. Assuming at least one global optimum exist for each of these scenarios, optimality conditions were derived.

The analysis showed that when revenue is fixed (bundled procurement), the private contractor makes innovative investments only to optimize its lifecycle cost of delivering the service. Under a private monopolistic delivery, however, the utility gains
of users due to the improved service quality is accounted for in determining the level of
innovative investment. Depending on the parameters assumed with respect to users’
valuation of the improved service quality, the externality can be considerable.

Furthermore, an overall comparison of alternative procurement models requires
additional information in terms of sensitivity of demand to price, initial costs of
innovative technologies invested, their expected cost savings, and so on. These are
parameters that require further project specifics to quantify. As evaluation of these
models in the context of a real world project is beyond the scope of the present study, the
next section will present the results of numerical analysis that use hypothetical functional
forms and parameters.

3.5 Numerical Results
This section presents the results from a series of numerical analyses that have
been conducted to demonstrate how the procurement models proposed in the previous
section could operate in a hypothetical context. The numerical analysis resulted in a
number of insightful findings regarding relationships between the alternative policy
scenarios and model outcomes. As in the analytical models, numerical analyses were
conducted in two project contexts: base case (two-node, one-link, one demand); and
cross-jurisdictional case (three-node, two-link, two demands). The road network assumed
single-directional travel. In conducting the numerical analyses, following assumptions
were made regarding the functional form of each of the functions that consisted objective
functions.
For simplicity of the analysis, the utility gains of users due to improved service quality of innovative investment is also assumed to be a linear function of \( \varphi \):

\[
B(\varphi) = r \cdot \varphi
\]  

(3.68).

### 3.5.1 Base Scenarios

In the base scenarios, a simple network that consists of one link with two nodes with a single demand (market) is assumed. The following section discusses in detail policy scenarios to be evaluated. Exogenous parameters were selected, following Ubbels and Verhoef (2006) with slight adjustment for numerical optimizations: \(d_0 = 140; d_1 = 0.6; a = 20, b = 20; s_1 = 1.2; s_2 = 0.8; m_1 = 3.0; m_2 = 0.8; \) and \( r = 0.5 \). The set of endogenous variables to initialize numerical analyses was: \( \tau = 20; \kappa = 500; \) and \( v = 160 \). The initial equilibrium, which assumes \( \varphi = 0 \), resulted in the aggregate social welfare of 8,396, which includes surplus (toll revenue minus construction and O&M costs) of 1,100. The objective functions of respective policy scenarios were numerically optimized using the interior-point algorithm (Byrd et al., 1999). The parameters and values of the initial endogenous variables are arbitrary, thus resulting values of welfare and other state variables are unit free. These values are by no means meant to represent any realistic situations, evaluated only relative to other policy scenarios to be evaluated in an abstract manner. Table 13, Table 13, and Table 15 summarize the results for the policy alternatives: for ease of comparison, the values in the parenthesis are proportions of respective values to those of the Unbundled Procurement scenario.
### Table 13 Numerical Results: Base Case Scenarios

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Initial</th>
<th>Unbundled</th>
<th>Bundled</th>
<th>Private Monopoly</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau$ (Toll)</td>
<td>20</td>
<td>(0.46)</td>
<td>9.1652</td>
<td>(1.00)</td>
</tr>
<tr>
<td>$\kappa$ (Capacity)</td>
<td>500</td>
<td>(0.74)</td>
<td>369.77</td>
<td>(1.00)</td>
</tr>
<tr>
<td>$\phi$ (Innovative Investment)</td>
<td>0</td>
<td>0</td>
<td>1.125</td>
<td></td>
</tr>
<tr>
<td>$\nu$ (Traffic Volume)</td>
<td>160</td>
<td>(1.06)</td>
<td>169.45</td>
<td>(1.00)</td>
</tr>
<tr>
<td>Welfare</td>
<td>8396</td>
<td>(1.03)</td>
<td>8613.9</td>
<td>(1.00)</td>
</tr>
<tr>
<td>Profit</td>
<td>1100</td>
<td>0</td>
<td>189.58</td>
<td></td>
</tr>
<tr>
<td>Initial Cost</td>
<td>600</td>
<td>(0.74)</td>
<td>443.72</td>
<td>(1.00)</td>
</tr>
<tr>
<td>Maintenance</td>
<td>1500</td>
<td>(0.74)</td>
<td>1109.3</td>
<td>(1.00)</td>
</tr>
<tr>
<td>Lifecycle Cost</td>
<td>2100</td>
<td>(0.74)</td>
<td>1553</td>
<td>(1.00)</td>
</tr>
<tr>
<td>Welfare/Lifecycle Cost</td>
<td>3.9981</td>
<td>(1.39)</td>
<td>5.5466</td>
<td>(1.00)</td>
</tr>
<tr>
<td>Not private utility (net)</td>
<td>2279</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Inside parenthesis ratios against unbundled scenario.

Source: Author's Calculation
<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Initial</th>
<th>First Best (Unbundled)</th>
<th>Suburb Welfare Max Unbundled</th>
<th>Suburb Welfare Max Bundled</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau ) (Toll)</td>
<td>20</td>
<td>27.023 (1.00)</td>
<td>21.063 (0.78)</td>
<td>21.095 (0.78)</td>
</tr>
<tr>
<td>( \kappa ) (Capacity)</td>
<td>500</td>
<td>671.98 (1.00)</td>
<td>692.38 (1.03)</td>
<td>694.2 (1.03)</td>
</tr>
<tr>
<td>( \varphi ) (Innovative Investment)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1.125</td>
</tr>
<tr>
<td>( v_c ) (Commuter Traffic Volume)</td>
<td>160</td>
<td>307.94 (1.00)</td>
<td>317.29 (1.03)</td>
<td>318.12 (1.03)</td>
</tr>
<tr>
<td>( v_L ) (Local Traffic Volume)</td>
<td>100</td>
<td>168.25 (1.00)</td>
<td>167.67 (1.00)</td>
<td>167.62 (1.00)</td>
</tr>
<tr>
<td>Welfare</td>
<td>35020</td>
<td>42440 (1.00)</td>
<td>33977 (0.80)</td>
<td>34155 (0.80)</td>
</tr>
<tr>
<td>Urban Welfare</td>
<td>N/A</td>
<td>8492.8 (1.00)</td>
<td>8433.9 (0.99)</td>
<td>8428.7 (0.99)</td>
</tr>
<tr>
<td>Suburban Welfare</td>
<td>N/A</td>
<td>32227 (1.00)</td>
<td>32078 (1.00)</td>
<td>32240 (1.00)</td>
</tr>
<tr>
<td>Private Profit</td>
<td>N/A</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Initial Cost</td>
<td>600</td>
<td>806.38 (1.00)</td>
<td>830.86 (1.03)</td>
<td>1457.8 (1.81)</td>
</tr>
<tr>
<td>O&amp;M Costs</td>
<td>1500</td>
<td>2015.9 (1.00)</td>
<td>2077.1 (1.03)</td>
<td>1457.8 (0.72)</td>
</tr>
<tr>
<td>Lifecycle Cost</td>
<td>2100</td>
<td>2822.3 (1.00)</td>
<td>2908 (1.03)</td>
<td>2915.6 (1.03)</td>
</tr>
<tr>
<td>Welfare/Life Cycle Cost</td>
<td>16.676</td>
<td>15.037 (1.00)</td>
<td>11.684 (0.78)</td>
<td>11.715 (0.78)</td>
</tr>
</tbody>
</table>

Inside parenthesis ratios against First Best scenario. Source: Author’s Calculation
<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Suburb Welfare Max Bundled</th>
<th>Welfare Max</th>
<th>Urban Welfare Max Bundled</th>
<th>Urban Welfare Max Unbundled</th>
<th>Global Profit Max</th>
<th>Source: Author’s Calculation</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau ) (Toll)</td>
<td>21.501 (0.80)</td>
<td>119.57 (4.42)</td>
<td>119.86 (4.44)</td>
<td>116.25 (4.30)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \kappa ) (Capacity)</td>
<td>726.54 (1.08)</td>
<td>355.17 (0.51)</td>
<td>356.14 (0.53)</td>
<td>366.55 (0.55)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \varphi ) (Innovative Investment)</td>
<td>0</td>
<td>0</td>
<td>1.125</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \nu_C ) (Commuter Traffic Volume)</td>
<td>317.28 (1.03)</td>
<td>162.76 (0.51)</td>
<td>163.2 (0.53)</td>
<td>167.98 (0.55)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \nu_L ) (Local Traffic Volume)</td>
<td>167.67 (1.00)</td>
<td>177.33 (1.06)</td>
<td>177.3 (1.05)</td>
<td>177 (1.05)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Welfare</td>
<td>33970 (0.80)</td>
<td>27404 (0.81)</td>
<td>27496 (0.65)</td>
<td>35948 (0.85)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urban Welfare</td>
<td>8434 (0.99)</td>
<td>27404 (3.25)</td>
<td>27496 (3.24)</td>
<td>9398.9 (1.11)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Suburban Welfare</td>
<td>32071 (1.00)</td>
<td>8042.2 (0.25)</td>
<td>8082.6 (0.25)</td>
<td>8525.4 (0.26)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Private Profit</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>17988</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial Cost</td>
<td>871.84 (1.08)</td>
<td>426.21 (0.51)</td>
<td>747.89 (0.93)</td>
<td>439.91 (0.55)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>O&amp;M Costs</td>
<td>2179.6 (1.08)</td>
<td>1065.5 (0.51)</td>
<td>747.89 (0.37)</td>
<td>1099.6 (0.55)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lifecycle Cost</td>
<td>3051.4 (1.08)</td>
<td>1491.7 (0.51)</td>
<td>1495.8 (0.53)</td>
<td>1539.5 (0.55)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Welfare/Life Cycle Cost</td>
<td>11.132 (0.74)</td>
<td>18.371 (1.57)</td>
<td>18.382 (1.22)</td>
<td>23.35 (1.55)</td>
<td></td>
<td></td>
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<tr>
<td>Not Private Utility (Net)</td>
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<td></td>
<td></td>
<td></td>
<td>17961</td>
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</tr>
</tbody>
</table>

Inside parenthesis ratios against First Best scenario (Table 14).
**Unbundled Procurement**

This scenario envisions a situation in which the public agency makes a long-term decision on the capacity and toll level of the link, procuring the work to a private contractor. As the discussion above regarding the analytical results of the model indicated, there is no investment on innovative technologies that reduce O&M costs and enhances quality of the highway services. The assumption that the public agency has full knowledge of how the users’ travel demand responds to its own decision applies in this situation. It is also assumed, following Blanc-Brude et al., (2009) that the private contractor is hired through perfect competition, hence no profit.

As noted earlier, the life-cycle costs have been disaggregated into the initial cost and O&M cost in this study, unlike many others in the literature. In this situation, the initial cost was 443.72, and the O&M cost was 1109.3: the O&M cost was larger than the initial cost. As the model in this study does not include the time variable to represent duration of public and private (if at all) operations, implicitly it is assumed that the life length of the asset is set at its optimal level. Moreover, the sum of initial and O&M costs is equivalent to the capacity variable considered in the highway network investment literature. The self-financing theorem of Mohring and Herwitz (1962) suggests that, assuming the capacity is a continuous variable, the toll revenue would just cover the aggregate capacity costs when there is constant return to scale (i.e., no economies or diseconomies of scale in providing the highway capacity). The theorem would be applicable in the context of this study if the sum of the initial and O&M costs is considered.
Provided the assumptions discussed above, the above result indicates that the particular asset represented by the set of parameters used for the optimization is characterized by maintenance and operational costs that are larger than the initial capital costs, which some may consider idiosyncratic. A possible interpretation is that this project has a very long life, such that the O&M costs of its life is larger than the initial costs. Since the interest of the study is highway P3s, whose concession term at least in the U.S. commonly extends over 75 years, the findings here can be considered to represent the reality to some extent.

In addition to the state variables commonly used in the literature on numerical highway network design optimization problems, this study evaluates policy alternatives by the ratio of welfare and the asset’s lifecycle costs. The intent behind adding this measure is to shed light on the efficiency dimension in comparing the procurement models. In the unbundled procurement scenario, the measure was 5.5466. The table shows comparison of this scenario and all others with the values and their ratios.

*Bundled Procurement*

This scenario considers a procurement scenario in which the public agency determines the toll and capacity levels of the highway link, procures the project to a private contractor for a fixed cost payment. The compensation is set equal to the sum of initial and O&M costs to provide the capacity. The private contractor in turn determines the level of innovative investments to reduce the O&M costs and enhance service quality of the facility. The toll is charged by the public agency to maximize social benefit. In this formulation, a backward induction is used, whereby the optimal level of phi in terms of
the private contractor’s objective function is first set, and the optimal toll and capacity levels are determined in the public agency’s objective function is set accounting for the innovative investment set in the first stage.

The optimal level of innovative investment was found through the following approach. First, the objective function of the private contractor is a fixed level of revenue that is a function of public agency subtracted by the initial and O&M cost functions whose only decision variable is the cost saving innovative investment. Hence the revenue is an exogenously determined value and can be excluded from decision-models. In the analytical result section, it was found that the private contractor sets the optimal level of \( \varphi \) to be at the level.

This decision rule can be interpreted as to be the level where the marginal costs of the innovative investment and the marginal reduction in O&M costs are equal to each other. In this numerical analysis, for the sake of demonstration, a special case is considered to achieve conversion. This approach first finds a solution of the initial and O&M cost functions where the initial cost is equal to the O&M costs:

\[
I(\varphi) = s_1 \cdot \kappa + s_1 \cdot \kappa \cdot \varphi \quad (3.69),
\]

\[
M(\varphi) = m_1 \cdot \kappa + m_2 \cdot \kappa \cdot \varphi \quad (3.70).
\]

Subtracting \( M(\varphi) \) from \( I(\varphi) \):

\[
(s_1 - m_1) \cdot \kappa + (s_2 + m_2) \cdot \kappa \cdot \varphi = 0
\]

An explicit solution with respect to \( \varphi_1 \) can be found at:

\[
\varphi_1 = \frac{(s_1 - m_1)}{(s_2 + m_2)} \quad (3.71).
\]
When the aforementioned set of exogenous parameters are assumed, the solution is $\varphi_1 = 1.125$. This explicit solution of phi is then used as an input to the numerical optimization of the public agency with respect to $\tau_1$ and $\kappa_1$. It cannot be overemphasized that this assumption is very idiosyncratic and arguably unrealistic: in reality, consideration of specific technologies with empirically estimated parameters are necessary to evaluate procurement alternatives. However, the intent behind the analysis in this section is to demonstrate how the economic model can be integrated with engineering consideration of specific technologies in evaluating policy alternatives.

With these assumptions, at the equilibrium the initial cost and O&M costs were both 772.22: compared with the unbundled procurement scenario, the initial cost increased by 74%, while the O&M cost decreased by 30%. As a result of 1.125 unit innovative investment, the lifecycle costs decreased by 1%, and the welfare-lifecycle cost ratio also decreased by 1%. This result indicates that the life cycle cost of providing the infrastructure decreased, but also with decrease in the aggregate welfare, consisting of users’ utility of making trips and operational profit, if at all. The optimal toll level, which is the sum of marginal social cost and marginal benefit of the enhanced quality of the facility, increased by 12% from the unbundled procurement scenario, while the capacity and the traffic volume that responds to the decision variables decreased slightly. Overall, at least with the particular set of exogenously given parameters, the reduction in lifecycle costs of delivering facility coincided with modest welfare decrease, when the user demand equilibrium was taken into consideration.
Private Monopolistic Delivery

This scenario is equivalent to the Build-Operate-Transfer (BOT) schemes where a for-profit entity is authorized to invest in building and operating a facility for a given concession period. Again, the model in this study assumes away the concession length as a decision variable to be set at the life length of the asset (i.e., first best, Nie and Zhang, 2013). In this scenario, the private contractor determines toll, capacity, and innovative investment to maximize its profit, and the road users responds so that the generalized travel price is equal to the utility of making the trip (i.e., user equilibrium condition).

Because of the linearity of initial and O&M cost functions with respect to the innovative investment, the analysis employs an approach similar to the Bundled Procurement scenario discussed above.

An explicit solution to the innovative investment variable was first found, and then it was plugged into the objective function of the private contractor to maximize its profit. Specifically, the decision rule for an optimal level of $\varphi$ is:

$$s_2 - m_2 = \tau \cdot \frac{\partial B}{\partial \varphi} D'(v) - \frac{\partial t}{\partial v}$$

$$= \tau \cdot \frac{r}{-d_2 - n \cdot b \cdot \kappa^{-n} \cdot v^{n-1}}$$

(3.72),

while the optimal condition of $\kappa$ is:

$$s_1 + s_2 \cdot \varphi + m_1 - m_2 \cdot \varphi = \tau \cdot \frac{\partial t}{\partial \kappa} D'(v) - \frac{\partial t}{\partial v}$$

$$= \tau \cdot \frac{n \cdot b \cdot \kappa^{-n-1} \cdot v^n}{-d_1 - n \cdot b \cdot \kappa^{-n} \cdot v^{n-1}} - m_1 - s_1$$
\[
\varphi = \left( \frac{1}{s_2 - m_2} \right) \left( \tau \cdot \frac{n \cdot b \cdot \kappa^{-n-1} \cdot v^n}{-d_2 - n \cdot b \cdot \kappa^{-n} \cdot v^{n-1} - s_1 - m_1} \right) \tag{3.73}.
\]

Substituting \( s_2 - m_2 \) in (3.84) with the condition in (3.83), an explicit optimizing rule of \( \varphi \) after some manipulations, becomes:

\[
\varphi = \left( \frac{\kappa}{v \cdot r} \right) (n \cdot b \cdot \kappa^{-n-1} \cdot v^{n+1} - s_1 - m_1) \tag{3.74}.
\]

Resonating with the similar analyses of private monopolistic operation of highway links (Verhoef, 2007), the optimal toll is considerably higher at 6.35 than the unbundled (1.00) and bundled procurement (1.12) scenarios. This is mostly due to the monopolistic markup that was added to the marginal social costs of making the trip, as suggested in the analytical results section. The optimal capacity level was smaller (0.39) than in other scenarios (unbundled procurement: 1.00; and bundled procurement: 0.99).

The optimal level of innovative investment was 2.366, which is larger than the other scenarios (unbundled procurement: 0; and bundled procurement: 1.125). The initial cost was virtually equal to that of the unbundled scenario (unbundled procurement: 1.00; and private monopoly: 1.00), while, O&M costs were much lower than that of the unbundled scenario (1.00: unbundled procurement; and 0.14: private monopoly). Lifecycle cost of the private monopolistic scenario, which accounts for the lower capacity and higher innovative investment, was in aggregate 60% lower than in the unbundled scenario. The traffic volume, in response to the higher toll as well as the better quality of the infrastructure service, decreased from the unbundled scenario by approximately 50%.

The aggregate welfare was approximately 24% lower than the unbundled procurement scenario. Of the 6,534.6 unit of the aggregate welfare, the operational profit of the private
contractor was 4,356.4. The net utility of users (i.e., utility of making the trip and the improved service minus travel time and toll, or, welfare that does not fall into the private contractor’s profit) was 2,279. The welfare-lifecycle cost ratio increased to 10.8 compared to the unbundled scenario (5.54), while it should be noted that a considerable share of the welfare was due to the private contractor’s profit. The non-private utility of users making the trip and the improved infrastructure service appears to have decreased due primarily to the smaller travel demand, resulting from the higher toll and smaller capacity.

3.5.2 Multi-jurisdictional Scenarios

Multi-jurisdictional scenarios consider a stylized network consisting of two links that connects two jurisdictions, urban and suburban cities. This section will discuss in detail the policy scenarios to be evaluated. The same functions consist the objective functions of the agents modeled in the analysis. There are two inverse demand functions that represent the two markets:

Commuter travel demand: \( Dv_C = d_{c0} - d_{c1} \cdot v_C \) \hspace{1cm} (3.75)

Urban local travel demand: \( Dv_L = d_{l0} - d_{l1} \cdot v_L \) \hspace{1cm} (3.76)

Users’ travel time functions are modeled for the two links:

\[ t_1 = a_1 - b_1 \cdot \left(\frac{v_C}{\kappa_1}\right)^n \] \hspace{1cm} (3.77)

\[ t_2 = a_2 - b_2 \cdot \left(\frac{v_C + v_L}{\kappa_2}\right)^n \] \hspace{1cm} (3.78).

It should be noted that kappa2 represents the capacity of the link in the urban city, which already exists at the time of the consideration of the cross-border link, thus is not a
variable endogenous in the models considered here. As in the preceding sections, linearity of the user travel time function is assumed, hence \( n = 1 \). The multi-jurisdictional analysis assumes the same functional forms as the base scenarios, with respect to the initial and O&M cost functions as well as the benefit function of the innovative investments.

The exogenous parameters were selected in a similar manner as in the base scenarios: \( d_{L0} = 140; d_{L1} = 0.6; d_{c0} = 280; d_{c1} = 0.6; a_1 = a_2 = 20; b_1 = b_1 = 20; s_1 = 1.2; s_2 = 0.8; m_1 = 3.0; m_2 = 0.8, \kappa_2 = 500; \) and \( r = 0.5 \). No toll was assumed for the link 2. The set of endogenous variables used to initialize the numerical optimizations was: \( \tau_1 = 20; \kappa_1 = 500; \nu_c = 160; \) and \( \nu_L = 100. \) The initial equilibrium, which assumed \( \varphi_1 = 0 \), resulted in the aggregate social welfare of 35,020. The same algorithm as in the base scenarios was used to numerically optimize the objective functions of the multi-jurisdictional scenarios. The following sections will discuss the results in detail.

**Global Welfare Maximization**

In this scenario, the aggregate welfare of both jurisdictions is maximized so as to compare with other procurement models. The values in parentheses of all state variables under all scenarios are their ratios with the values of this scenario. The optimal level of \( \varphi_1 \) was derived to maximize the global welfare function, by first taking the derivative with respect to \( \varphi_1 \), and plugging the condition into the derivative of the global welfare function with respect to \( \kappa_1 \), which explicitly include \( \varphi_1 \). After some manipulations, the following optimal level of phi was used when numerically optimizing the objective function:
$$\varphi_1 = \left( \frac{K_1}{T} \right) \cdot (n \cdot b_1 \kappa_1^{-n-1} v_c^n + s_1 - m_1) \quad (3.79).$$

The resulting toll level of the link 1 was 27.0, and the capacity was 672.0. The optimal level of phi was virtually equal to zero. The commuter traffic volume was 307.9, while that of the local traffic of the urban city was 168.3. The highway capacity investment solely benefits the commuters of the suburban city, the suburban city was assumed to incur the entire cost of construction. As a result, the welfare of the urban city was 8492.8, while that of the suburban city was 32,227. In aggregate, the system-wide welfare was 42,440. The total lifecycle cost was 2,822.3, which could be decomposed to the initial cost of 806.4 and the O&M costs of 2016.0. The aggregate welfare to lifecycle cost ratio was 15.037. As in the discussion of the base scenarios, the table shows the ratio of the results in each scenario and the unbundled procurement scenario for each variable to ease comparison.

**Suburban City Welfare Maximization, Unbundled Procurement**

This scenario assumes that the suburban city maximizes the welfare of its residents (i.e., commuters) by choosing the optimal levels of capacity and toll for the link that exclusively serves the commuters. Since the procurement will be unbundled, \( \varphi_1 = 0 \) is assumed. Compared to the unbundled global welfare maximization scenario, the optimal toll was lower (0.78), while the capacity was slightly higher (1.03), and the commuter traffic slightly increased. The effect of the increased commuter traffic to the local traffic of the urban city was marginally negative. Initial cost, O&M cost, and hence the lifecycle costs increased slightly (1.03), while the total welfare decreased by 20%, due to the fact that no innovative investments to enhance the welfare was made. As a
result, the welfare to lifecycle cost ratio decreased by 22%. The welfare of the suburban city was notably larger (32,227) than the urban city (8,492.8). This is because the utility gains resulting from the highway capacity investment is accrued by the commuters of the suburban city who travel to the urban city.

\textit{Suburban City Welfare Maximization, Bundled Procurement}

In this scenario, the welfare function of the suburban city, which consists of the utility gains of suburban commuters, their travel time costs, the initial and O&M costs of the infrastructure facility, and service improvements. The optimal level of innovative investment was derived in the same manner as the bundled procurement scenario of the base case. Assuming the unique case where the initial and O&M costs are equivalent, 

$$\varphi_1 = \frac{m_1-s_1}{s_2+m_2}$$

was derived by applying the optimal rule of phi to the optimal rule of the capacity, which explicitly includes phi. The results were mostly equivalent to the unbundled procurement scenario. Compared to the global welfare maximization scenario, the optimal toll decreased (0.78), while the capacity increased slightly (1.03). The optimal value of phi was 1.125, and the traffic volumes of both suburban and urban cities were virtually the same as the unbundled suburban city welfare maximization scenario. The initial construction cost was higher than the global welfare maximization by 81%, while the O&M costs decreased by 28%. The lifecycle cost of the project, however, increased by 3%, which was equivalent to the unbundled procurement scenario. The welfare to lifecycle cost ratio also decreased by 22%, the same degree as the unbundled scenario. Arguably, the similarity of the bundled and bundled scenarios of the suburban welfare maximization problem reflects is due to the small size of the innovative
investment relative to the size of capacity. Also, the assumption in both scenarios that the
effect of improved service quality was internalized in the objective functions likely to
have contributed to this result.

*Urban City Welfare Maximization, Unbundled Procurement*

The urban city welfare maximization scenarios assume that the urban city
becomes the owner and sponsor of the link 1, which connects the two jurisdictions and
serve the inbound commuters from the suburban city. The initial construction and
maintenance are procured separately, and there is no incentive for the private contractors
to make innovative investments to lower lifecycle costs or improve infrastructure service
quality, unless explicitly included in the contract. The urban city bears the entire costs of
delivering the project, and charges toll to the commuters who are not its residents. The
utility of urban residents making trip on their local link is included in the objective
function. As found in the analytical results section, the more inbound commuters, the
higher the travel costs of local travelers, hence it is expected that the lower the traffic
volume would result. As it is an unbundled procurement scenario, $\varphi_1 = 0$ was assumed.

The results strongly showed the tax-exporting behavior (Levinson, 2002, Verhoef
and Ubbels, 2006) of the urban city. The optimal toll level relative to the global welfare
maximum scenario was 4.42, while the optimal capacity was 0.51. The commuter traffic
decreased by 49%, while the local traffic increased by 6%. The welfare of the urban city
more than a tripped of the global welfare maximization scenario to 3.24 in relative term,
while the welfare of the urban city dropped by 73%. In aggregate, the global welfare was
19% lower than the global welfare maximization scenario. Both the initial and O&M costs decreased by 49%. The welfare to lifecycle cost ratio was 57% higher.

**Urban City Welfare Maximization, Bundled Procurement**

This scenario makes the same set of assumptions and that the innovative investment is made only to optimize the initial and O&M costs (i.e., not to account for the users’ benefit due to improved service quality). Specifically, similar to the bundled procurement scenarios already discussed above, it was assumed that:

\[ \varphi_1 = \frac{m_1 - s_1}{s_2 + m_2}. \]

As in the suburban welfare maximization scenarios, the results of the bundled procurement was very similar to that of the unbundled procurement scenario, in part due to the small size of innovative investment (1.125) compared to the capacity. Demonstrating the tax exporting behavior, toll was higher (4.44), while the capacity was lower (0.53), and the commuter traffic dropped significantly (0.53), while the urban local traveler increased (1.05).

The urban city’s welfare considerably grew (3.24), whereas the welfare of the suburban city was 75% lower than the global welfare maximization scenario. The initial cost slightly decreased to 0.93, while the O&M cost decreased considerably to 0.37, and the lifecycle cost was 47% lower than that of the global welfare maximization scenario. The welfare to lifecycle cost ratio was 22% higher than that of the global welfare maximization case.
Global Profit Maximization

This scenario assumes complete private delivery to maximize its operational profit: the objective function consists of a revenue function of toll charged to commuter traffic and the initial and O&M cost functions. This scenario was included for the sake of comparison with the other scenarios. The optimal level of innovative investment was derived similar to the private monopolistic delivery model in the base case scenario: the decision rule of the objective function with respect to \( \varphi_1 \) was applied to the optimal condition regarding the capacity, which explicitly includes the innovative investment variable. Specifically:

\[
\varphi_1 = \frac{n \cdot b_2 \cdot \kappa_1^{-n} v_C^n - s_1 - m_1}{v_C \cdot \kappa_1 \cdot r}
\]  

(3.80)

The results were similar to the tax-exporting urban welfare maximization scenarios, except that the welfare increases to the urban city was replaced with private profit. The optimal toll was 4.30, and the capacity was 0.55, respectively relative to the global welfare maximization scenario. Since the optimal level of innovative investment accounts for the benefit of improved service quality to the users, the optimal level of \( \varphi_1 \) was very close to zero. The commuter traffic volume was 45% lower than that of the global welfare maximization scenario, while the local traffic of the urban city was 5% higher.

The welfare of the urban city was 11% higher, while that of the suburban city was 74% lower: in aggregate, the system-wide welfare was 15% lower than that of the global maximization scenario. The private profit was 17,988, which was obviously higher than all the other scenarios which assumed/resulted in zero profit. The net welfare to the non-
private sector, which consists of travelers’ utility, welfare gains due to improved service quality, and travel time cost, was 17,961. Both the initial and O&M costs were 45% lower than the global welfare maximization scenario. The welfare to lifecycle cost ratio was 1.55, which was one of the highest of all scenarios.

3.6 Discussion

Through analytical derivation and numerical simulation, the present study investigated the effect of various procurement scenarios for road network expansion projects, in terms of toll, capacity, innovative investment, traffic levels, and aggregate welfare. The analysis led to a few insights relevant for policy debates regarding the use of P3s for highway investments. First, the procurement models considered under the wide definition of P3s are vastly different from each other in terms of behavioral responses of agents involved in deals, depending on the procurement approaches employed for the project. This is particularly so when considering toll pricing principles and cost saving and quality improving innovations that the private sector is expected to bring in to justify the procurement models.

Second, fixed payment contracts may constrain private partners’ investments on welfare-enhancing innovations. Although the models in this analysis did not explicitly account for project risks, the demand risk implicitly is allocated to the public partner, whereas the private contractor is effectively taking the lifecycle cost risk in delivering the facility. In the private monopolistic delivery case, however, implicitly the demand risk is on the private contractor. In the fixed price contract cases, the private contractor is taking lower risk for limited prospect of return on their investments. The results in this study
showed that the results are similar with respect to the efficiency gains due to innovative investments: the efficiency gains would also be constrained in the cases of fixed price contracts. This result adds to the findings of Martimort and Pouyet (2008) who suggested conditions where a P3 procurement may be preferred (i.e., when cost saving positive externalities of the innovative investment is present), in terms of to what extent these investments could be made.

In the U.S., application of availability payment models appears to be growing, in part due to the materialization of demand risks amid the financial crisis for a number of demand risk projects, and the taste for risk taking investment appears to have drastically shrunk (De la Peña, 2015). The increase in the use of availability payment P3s indicates the supposed efficiency gains through P3 project deliveries may be diminishing. It is necessary for policy makers to be fully informed of these tradeoffs in terms of risk exposure and efficiency gains, together with other financial and economic considerations in making project procurement decisions.

Ultimately, the analysis suggests that when P3s are possible alternatives in delivering an infrastructure, earlier considerations of these models, with possible involvement of private contractors, are essential in optimizing the costs and efficiency gains. Currently, the recommended practice is to first conduct a benefit cost analysis, and then to determine a procurement strategy through risk evaluation, value for money analysis, and financial feasibility test (FHWA, 2013). In practice, states with experiences appear to conduct VFM repetitively at various stages of candidate project evaluation (Virginia Office of Public Private Partnerships, 2014). This is in a way desirable to reach
fair results while controlling various project risks, but this approach comes at a cost. The framework in this study leans rather on the philosophy to integrate VFM and BCA, resonating with the ongoing effort to extend VFM and/or BCA to address limitations that have been pointed in the literature (DeCorla-Souza et al 2014). Further research may be necessary to improve the practice of P3 implementation across nation.

The results also point to a few weaknesses of the analytical framework. The numerical simulation is subject to the parameters assumed for the extensive form functions. Particularly with respect to the bundled procurement scenarios in both the base and multi-jurisdictional cases, when assuming the rather idiosyncratic case of equal initial and O&M costs, the magnitude of optimal $\phi_1$ was very small compared to the optimal capacities. The effect of alternative procurement models in terms of welfare and other variables may appear small in terms of these numbers that are not intended to reflect anything in reality. Nevertheless, the relative sizes of each variable between particular sets of procurement models may lead to insights on the effect of employing alternative P3 models for particular project contexts. This is not uncommon to studies that employ similar approach: procurement decisions should, indeed, be made based on the specifics and details of each candidate project.

Second, the analysis assumes static models, and there is no consideration of value of time or dynamic behavior of agents. This is a very restrictive assumption especially when considering the financial aspect of the problem. However, the emphasis in this analysis is long-term project decisions at the contract. Furthermore, renegotiation of these contracts and any changes to the underlying characteristics of the environment or of the
project are not the focus. These questions are reserved for future extension of the framework proposed in this study.

Third, similar to the above point, the models in this analysis are deterministic, and no stochastic properties were assumed for the parameters. While consideration of project risks requires stochastic models, as it will be pointed in the conclusion, risk consideration will be part of the future extension of the analytical framework proposed in this study.

Also, the linearity assumption of initial cost, O&M cost, and innovative investment benefit functions require resorting to mathematical manipulation to enable convergence of the optimization. The equality of initial cost and aggregate O&M costs in terms of the innovative investment is obviously very restrictive, and needs to be relaxed in future extensions. Desirably, a set of specific innovative technologies can be considered, and empirically estimated parameters should be used for more realistic application of these models.

3.6 Conclusion
The roles that private firms have played in delivering highway projects in the U.S. have grown over the past decades. Today, when large capital projects are considered, P3s are frequently viewed as an alternative to pursue efficiency and overcome budgetary constraints. The existing literature has considered P3 alternatives with particular emphases, two of which were the basis for the analytical framework proposed in this study: incomplete contract literature and network design and privatization literature. These studies emphasized either procurement alternatives or profit maximizing operation of roadways, and not both simultaneously. The present study inquired consequences of
considering these alternative models, especially when interaction of multiple jurisdictions for cross-border facilities were concerned. This study proposes an analytical framework to evaluate highway capacity expansion projects, simultaneously accounting for procurement alternatives (bundling multiple project phases or not) and network design decisions of operators as well as responding users’ travel behaviors.

While lessons for policy makers from the analysis results are summarized in the preceding section, it is worth highlighting that project partners’ project decisions and welfare outcomes have intricate relationships. Separating project decisions (i.e., benefit cost analysis) and procurement decisions (i.e., value for money analysis) may result in biased estimation of welfare outcomes regarding project components critical to justifying a contract model over another. In this sense, the practice of some of the U.S. states to repetitively conduct value for money analysis throughout the planning process appears appropriate, albeit perhaps costly. Further research is needed to refine the existing decision models to materialize presumed efficiency gains of P3 models.

This study presents only a foundational framework to evaluate outcomes of P3 alternatives: there are a few considered future extensions, some of which are underway. First of all, it is critical for the analytical models to account for various project risks. Consideration of risk allocation is critical when discussing welfare and efficiency outcomes of P3s. By allocating specific project risks (e.g., demand risk, construction risk, and design risk) to the party best able to manage them, there is an incentive for both public and private partners to exert the best effort to minimize costs and hence achieve efficiency. By extending the currently deterministic model to include stochastic terms in
order to explicitly model allocation of various project risks, the analytical framework can be further refined to represent agents’ behavior in various project contexts.

Second, the linearity assumption of the initial cost, O&M cost, and the service quality function with respect to the innovative investment can be relaxed to assume nonlinearity to allow more realistic analysis. Such extension might enable consideration of specific sets of innovative technologies that are available in the market but have not yet implemented in the context of Interstate class assets development. Such extension could allow decision makers to evaluate project alternatives, accounting for the life cycle costs of the facility and service quality of the facility, which may not have been thoroughly done to date.

Third, the static theoretical models in this analysis can be extended to dynamic models to address more policy relevant questions. Due to their long contractual lives, renegotiations of initially agreed contracts have been recognized as important. Project environment (e.g., macroeconomic conditions, travel demand, performance of contractors, policy changes, etc.) can change considerably over the years. Also, valuation of future cash flows may change as project progresses from design, construction, and to operational phases, as risk profile of each project changes. Such valuations are likely to be distinct between sponsoring public agencies and private contractors. A number of important policy questions can be addressed by extending the analysis herein in this direction.

Finally, the analytical model can be extended to a network-wide evaluation, where the impact of P3 development can be evaluated at the system level. Obviously,
change in the service quality of a single link in a network affects users’ travel behaviors at the local and regional scales. A possible approach is to develop an algorithm whereby, a certain user equilibrium allocation model is assumed, and travelers’ behavioral responses for alternative P3 models are evaluated. Such extension would allow policy-makers to consider P3 alternatives with a more comprehensive understanding of their impact, and it would be especially appropriate for multi-jurisdictional contexts.
CHAPTER 4 COMPARING P3S AND TRADITIONALLY PROCURED PROJECT CONTRACT PRICES: AN ANALYSIS OF THE U.S. HIGHWAYS

4.1 Introduction

Responding to the growing needs for improved capacity expansion and renewal project delivery despite ever-tightening fiscal conditions, public-private partnerships (P3s) are considered as a useful procurement approach for public agencies to continue investing in highway facilities (Congressional Budget Office, 2012). These new procurement models not only enable private financing of highway projects but also incentivize the pursuit of lifecycle cost efficiency through innovative investment and know-hows that private firms are endowed with. A growing number of U.S. states are implementing policy initiatives to authorize public agencies to procure projects through P3s in various sectors, such as highways, railways, seaports, schools, correction facilities, water and wastewater treatment facilities, and general government buildings.

While advocates emphasize advantages of the P3 models over the conventional design-bid-build (DBB) approach for highway construction projects, these claims have been supported mostly by business cases with limited counterfactuals (Hodge and Greve, 2009). Empirically, little evidence has been found to support these claims to date. Around the world, the list of successful P3 projects has grown over the last several decades. Yet, there are persistent criticisms that may threaten the generally supportive sentiment toward P3s. Notably, commentators have urged their calls to address the limited transparency of
P3 project performance, which hinders benchmarking against traditional procurement approaches (Siemiatycki, 2012).

Because P3s are a new phenomenon and they have long contractual lives extending to as long as 99 years, cost comparison between P3s and traditionally procured highways over their full lifecycle will not be possible for another several decades. Nevertheless, there have been a few exploratory comparisons of the initial project delivery costs between the two procurement models. To the author’s knowledge, such analyses have been conducted in Europe and in some other countries, but not in the U.S. This remains as a gap in the literature.

In this context, the present study will empirically analyze the difference of highway P3s and traditionally procured highway construction projects in terms of their unit design-build costs as of contract award. The objective of the study is to inform policy makers on the implication of using a P3 contract for a project and their actual performance in terms of cost differences. The analysis will address the research question: what have been the differences of highway P3s and traditionally procured highway projects in terms of their costs, and what are the sources of the difference? After a theoretical discussion on the attributes of cost differences between the procurement models, the present study will empirically estimate the unit costs of large highway projects in the U.S. that were procured using design-build or P3 contracts. The findings will provide valuable insights for policy makers and the public regarding the desired benefits of P3s and the actual outcomes to date in the U.S. context, and help to underscore the need for continuing analysis of existing P3s.
The remainder of the chapter is structured as follows. The next section will provide the background of the study with a review of relevant literature. The subsequent section will present the data and models used for the empirical analysis, followed by the results. The last section will discuss the findings, their policy implications, limitations of the analysis, and directions for further research in the future.

4.2 Background
This section will present the background of the analysis in this study. Review of relevant literature and discussion of theoretical propositions regarding how P3s should be different from traditionally procured infrastructure projects will motivate the empirical analysis in the subsequent sections.

Figure 5 The Scale of P3s: Risk Transfer and Private-Sector Involvement (The Canadian Council for Public-Private Partnerships)
Notable characteristics of P3s that drive economic efficiency of public infrastructure delivery are bundling of project phases and allocation of substantial project risks to private contractors (Välilä, 2005). A variety of P3 contract types have been proposed and employed with different degrees of private firms’ involvement in taking financing and other project risks. Figure 5 is a scale of some of these P3 contract types summarized in Siemiatycki (2012). It should be noted that the design-build (DB) contract has longer history than P3 models, and involved project risk transfers are relatively limited. Today, therefore, the DB contract is sometimes considered as one of the conventional public procurement models. P3s are variations of project contracts between DB and full privatization, and the present study also follows this definition.

These characteristics incentivize innovative investments of private contractors that enhance efficiency (i.e., cost saving) and improve service quality that enhances the welfare gains through provision of the facility (Välilä, 2005). Since the effect of P3 contracts to incentivize innovative investments is discussed extensively in the previous chapter, the discussion herein will briefly touch on this subject and mainly focus on the project risk allocation. Because the analysis in the present study concerns the initial capital investment of highway projects, the emphasis here is mostly on design and construction risks: what they are; why they occur; and how significant they have been, as found in the empirical literature to date. P3s’ financial aspect, demand risk, and risks during operational phases regarding maintenance are, while equally important, beyond the scope of the discussion here. The use of alternative technical concepts (ATC) has increased in some states over the last decade (e.g., Jolley and Garvin, 2014). Where
legally allowed, the ATCs effectively alter project scopes from the original public tender, in pursuit of cost saving innovation and financial viability for private concessionaires (De Ormijana and Rubio, 2015). To the author’s knowledge, theoretical discussion to discuss whether scope changes of highway projects via ATCs are a form of “design and construction risk” manifestation has not evolved yet. As such, explicit treatment of ATCs is also beyond the scope of this study.

4.2.1 Welfare-Enhancing Innovative Investment

A P3 contract, which bundles multiple project phases, incentivizes private contractors’ investment in innovative technologies, not explicitly contracted, to save costs and/or improves service quality. Underpinned by Williamson (1979), Hart (1995) constructed a theoretical framework that considers infrastructure P3s from the perspective of incomplete contracts for services characterized by asset specificity. Depending on the characteristics of the infrastructure, Hart (2003) argued that, depending on the extent to which service quality can be monitored, P3 contracts incentivize the use of technologies that improves service quality and/or reduces costs of delivering the service. As such, certain sectors are more suitable to contract in bundles than others. Ownership, private equity investments, and private financing for the contracted project also encourages private contractors to exert their effort to maximize revenue through improving service quality and minimize costs (Bennett and Iossa, 2006; Martimort and Pouyet, 2008; and De Bettignies and Ross, 2009). A recent theoretical proposition by Iossa and Martimort provides a comprehensive framework with which to consider welfare implications of P3 contracts (2015). They argued that P3s are desirable when: improved quality of the
facility reduces life-cycle delivery costs; service demand and maintenance costs are sensitive to the quality of the facility; and the demand is stable and easy to forecast. Overall, the incentive effect of contracts with respect to investment in innovative technologies has clearly been a critical component in scholarly consideration of P3s.

With respect to the implication of contract types (i.e., P3s or conventional design-bid-build, or DBB, procurement) for empirically observable differences of project delivery models with respect to their costs, Blanc-Brude et al. tested the following hypothesis (2009). Bundling construction and operational phases of a facility gives incentive for a private contractor to invest in innovative technologies that, for additional costs, minimize the aggregate costs of the three project phases. An example of such innovative technology is high-quality pavement materials that achieve low lifecycle costs for a higher initial cost. In this context, because P3 projects have long contract terms (e.g., 25~99 years) and most existing P3s in the U.S. today will not complete for a several more decades, statistical lifecycle cost comparison is not possible yet. What is observable is the difference of contract prices and construction costs, although the latter is commercially sensitive and is unavailable in the public domain. The hypothesis suggests that the unit initial construction cost (e.g., design-build contract price) of P3 projects is higher than traditionally procured projects, ceteris paribus.

4.2.2 P3 Project Risk Allocation
Risk allocation of P3 projects is a critical component in considering the performance of P3s, as the premium of project risks transferred to private contractors typically drive value for money analysis results that support the use of P3 procurement
Siemiętcki and Farooqi, 2012). Defining risks in broad term as “uncertainty of outcomes, whether positive opportunity or negative threat, of actions and events” (p.263), Monteiro distinguishes risks from different disciplinary approaches (2010). In project management context, risk is “an event that may or may not occur and can lead to cost overruns, delays in project completion, or failure to satisfy some project requirements.” From economics and finance perspectives, in contrast, risk is “having an upside and a downside: a party facing risk suffers from negative events, but may also benefit from positive events,” which implies its incentive effects for agents to exert their effort managing negative outcomes. This distinction indicates that in understanding risks of P3 projects, one needs to consider what risks P3 projects face, and how contracts can be used as a means to pursue efficiency by managing these risks. There is growing evidence that public infrastructure projects of especially large magnitudes are often subject to considerable cost and schedule overruns (Flyvbjerg, 2014). As is commonly argued (Väilälä, 2005; Blanc-Brude et al., 2009; Monteiro, 2010), the principle of risk allocation in P3s is that risks should be allocated to the party best able to manage them, with premiums compensated if transferred to a private contractor. The risks are then managed more effectively than in the case of traditionally procured projects, and hence the P3 schemes may be able to lower the costs associated with manifestation of certain project risks. This subsection will discuss in detail what risks infrastructure P3 projects face during the delivery, theories as to why they occur, empirical literature as to how serious they have been, and how P3s have performed to date.
Construction Risks of Large Infrastructure Projects

Infrastructure projects are subject to a number of risks during the planning, design, and construction phases. It is rather frequent that infrastructure projects experience cost and schedule overruns (Van Wee, 2007). These risks refer to situations where an estimate of design and construction costs are used in determining to proceed with the project and/or to close a deal with a contractor, but by the time the construction completes and the facility begins operation, the costs have gone over the initial estimates. Figure 6 shows the process by which estimates of project costs change as the project evolves (Gkritza and Labi, 2008). The construction cost risk generally refers to the difference between the last two phases, project cost at the contract award phase and at the final construction phase. It should be noted that this depends on contract types: e.g., design-build contract, where contract award takes place before the design phase.

Manifestation of construction risks is problematic, as Flyvbjerg points out, because systematic underestimation of project costs (and overestimation of benefits) in benefit cost analysis (BCA) leads to falsely high benefit-cost ratios, justifying projects that might have been unviable economically or financially (2014). Project cost overruns also deprive public agencies’ budget or debt capacity that could otherwise have been allocated to other projects, resulting in Pareto inefficient, wasteful resource allocation from the public sector’s perspective.

A number of studies discussed factors that might cause construction cost and schedule overruns. Shane et al. (2009) classified construction cost escalation factors into internal and external sources. Internal factors include: analysts’ bias, procurement approach, project schedule changes, engineering and construction complexities, scope
changes, scope creep, poor estimating, inconsistent application of contingencies, faulty execution, ambiguous contract provisions, and contract document conflicts. External factors are: local concerns and requirements, effects of inflation, scope changes, scope creep, market conditions, unforeseen events, and unforeseen conditions. It follows then that understanding these factors allows public agencies to mitigate the risk of cost overruns by being better prepared (Shane et al., 2009).

Besides the rather technical-oriented view discussed above, some have instead considered the issue from a broader institutional perspective on their root causes. Flyvbjerg (2009) proposes three explanations of project cost and schedule overruns: technical, psychological, and political-economic. Technical explanation refers to genuine

Figure 6 Cost Changes through Project Delivery (Gkritza and Labi, 2008)
technical limitations in developing project cost estimates, including estimation model limitations, inadequate data, honest mistakes, lack of experience, and limitations inherent in forecasting future events (Thomas et al., 2006; Adams, 2006; Lind and Borg, 2010). In particular, Lind and Brunes argue that the lack of competence on the public agency prevails in public construction projects (2015).

Psychological explanations refers to optimism bias and planning fallacy, where decision makers base their project decisions on delusional optimism rather than rational expectations in terms of possible benefits, costs, and their associated probabilities. In this explanation, decision makers, though not voluntarily, overlook potential mistakes and unfavorable information while focusing only on hopeful success scenario, resulting in pursuing a project alternative that is doomed to fail due to cost underestimation. This can be attributable to cognitive biases where decision makers’ minds make errors in processing information (Odeck, 2004; Flyvbjerg, 2009; Flyvbjerg, 2014).

Political economic explanation claims that decision makers strategically manipulate cost and benefit estimates, by overemphasizing benefits and covering up the potential for failures, so that the project is approved. When competing for limited resources or seeking project approvals for personal gains (e.g., to increase voter support in cases of elected officials, and to boost professional reputation in the case of public agency career staff), such strategic behaviors may rather be a rational choice. Because the costs are underestimated, once approved and pursued the project is likely to experience cost overruns (Nijkamp and Ubbels, 1999; Odeck, 2004; van Wee, 2007). Because project alternatives with biased forecasts tend to be approved, less resource is committed
to other, genuinely beneficial, infrastructure projects. Flyvbjerg (2009) claimed the current implementation of project decision making processes allows “survival of the unfittest” (p.344), provoking scholarly and policy debate on this subject.

A few notes should be made regarding these explanations. Cantareli et al. differentiates these explanations into technical, psychological, economic, and political, and organized formal theories that they could be embedded into (2010). These theoretical models have various sets of assumptions, sector focuses, and approaches in modeling, but all explain risks associated with construction projects. While these modeling approaches are important, the details are beyond the scope of this analysis, since they mostly agree with each other in terms of their propositions with respect to their impact on project costs. Also, Siemiatycki sheds light on the differences of conclusions between various types of reports. His findings suggest that auditor reports of government agencies tend to emphasize technical issues and professional incompetency as the leading cause of cost overruns. In contrast, scholarly literature, where economics, public administration, and urban planning dominate, tend to focus on political economy consideration of infrastructure project outcomes (2009). Overall, various propositions have been made in explaining construction risks of infrastructure projects, but consideration of their relative importance appears to have been qualitative, as quantification of some of these factors is challenging.

It is generally acknowledged that increasing roles of private firms in infrastructure delivery may be effective in managing some of these risks. Notably, inclusion of private capital at risk has been recognized as a means to incentivize analysts and decision-makers
to exert their best effort when conducting *ex ante* evaluation of project alternatives.

Theoretically, De Bettignies and Ross (2009) proposed that private financing would screen out financially unviable projects, with which arguments of Flyvbjerg et al. (2004) resonate. Van Wee (2007) argued that inclusion of private risk capital would improve forecast quality while reducing the cost escalation risk once a project decision has been made, although, unlike Flyvbjerg et al. (2004), they also point out the advantage may not be unconditional.

### 4.2.3 Empirical Studies on Construction Risks

In the literature, one may find a few empirical studies on construction risks of public infrastructure projects (i.e., cost and schedule overruns) in recent years. Flyvbjerg et al. (2003) presented a series of descriptive statistics of large-scale public infrastructure projects to demonstrate the existence of these risks. They estimated the ratio of actual construction costs to the budgeted or estimated cost at the time of decision to build, of 258 infrastructure construction projects (58 rail, 33 bridges and tunnels, and 167 motorway projects) around the world. They found that, across all sectors: 86% of projects experienced cost overruns; the average cost overruns was 28%; and its standard deviation was 39%. Their analysis of 24 U.S. road construction projects revealed that the average cost escalation was 8.4% with standard deviation of 49.4%. In Europe, 143 road projects resulted in on average 22.4% cost overruns with standard deviation of 24.9%. They asserted that cost estimates for large infrastructure projects were systematically and significantly deceptive, biasing the benefit-cost analysis used to justify these societal investments.
Extending the above study, Flyvbjerg et al. (2004) statistically investigated associations between the cost overruns and various project factors. They found that the length of project execution was highly associated with cost overruns, while the monetary size of the projects in the road sector demonstrated significant association with cost overruns only in bridge and tunnel projects but not in rail and road projects. Interestingly, contrary to the claims often made, their results indicated that the ownership structure (i.e., public, private, or state-owned enterprises) did not show any difference in terms of cost overruns.

Triggered by the provocative findings of Flyvbjerg and his colleagues, a number of studies followed in inquiring the magnitude of construction risks and factors associated with the cost overruns, some of which employed more sophisticated statistical models than others. Gkritza and Labi (2008) analyzed discrepancies of project contract amounts and final costs of 1,957 highway construction contracts in Indiana between 1996 and 2001. They found that the longer the contract period, the more overruns the projects were likely to experience. The relationship between the contract amount and cost discrepancies was nonlinear: for small projects smaller than 2001 US$6 million, the larger the project cost, the larger the cost overruns; for projects over $6 million, the relationship reversed. Thus, the authors concluded that the project complexity influenced the manifestation of construction risks. It should be noted that the samples in this analysis are DBB contracts of both construction and maintenance works, and the mean contract amount was 2001 US$1.01 million. These samples are very different from the samples evaluated in Flyvbjerg et al. (2004), which dealt with much larger, so-called mega projects.
More recently, Bhargava et al. proposed a more sophisticated econometric model to estimate factors that contribute to construction risk manifestation (2010). Assuming separate and independent functions for cost overrun and schedule overrun, the authors proposed a three-stage least squares model to address potentially endogenous relationship between time and cost overruns of highway construction projects. Estimation of 1,862 highway construction project samples between 1995 and 2001 procured by Indiana Department of Transportation (INDOT) showed a statistically significant relationship between overruns and contract size, project duration, and weather conditions. Also, they found a simultaneous relationship between cost and schedule overruns, suggesting the need to address this endogeneity issue when conducting empirical analyses on these two types of construction risks.

Empirical literature on public infrastructure projects’ construction risks has developed considerably in recent years, and growing data availability has enabled analyses of a variety of project types in different countries. A few notable studies include: transportation projects in the Netherlands (Cantarelli et al., 2012); highway projects in Slovenia (Makovšek et al., 2012; Makovšek, 2013); and a cross sector analysis worldwide (Blanc-Brude and Makovšek, 2013). These analyses employ slightly different definitions for referenced costs and cost overruns, and estimation results of these studies all vary widely depending on project types and geographic contexts. These studies therefore indicate the difficulty in empirically evaluating the performance of public works, each of which is complex and idiosyncratic such that statistically robust analyses are challenging.
The need to improve *ex ante* project evaluation procedures has been well recognized (van Wee, 2007). Recommendations made to address these issues have mostly been with respect to technical aspect as well as institutional and regulatory approaches. On the technical side, Trujillo et al. advocated using state of the art models in estimating project forecasts, while addressing the potential of strategic behaviors of decision-makers to bias the results (2002). A number of scholars, for example Odeck (2004), called for the need to include consideration of risks and uncertainties when evaluating project alternatives.

The literature that makes recommendations on the institutional and regulatory aspects of project decision-making has been extensive. For instance, Bruzelius et al. proposed principles of adequate project decision process to include: transparency, introduction of performance specification in the contract, explicit formulation the regulatory institution to manage political risks, and inclusion of private capital at risk (2002). Flyvbjerg et al. called for transparency and public sector accountability, specifically recommending the following, among others: independent peer review of estimates; the use of “reference forecasting model” in alternative evaluation; inclusion of private risk capital; holding financially responsible for decision makers for forecast manipulations (2004).

*Performance Comparison of Procurement Models*

Reflecting the technical difficulty, limited data availability, and the interest in the subject being only a recent phenomenon, limited evaluation of infrastructure projects that compares procurement models has been made to date. A few studies compared the
magnitude of construction cost overruns between procurement models. In the U.S. context, Shrestha et al. empirically compared performance of 16 DBB and six DB highway projects, mostly in Texas, costing over 2010 US$50 million and completed between 1990 and 2010 with respect to their cost and schedule overruns and change orders (2012). Their input-output comparison of sample projects suggested that DB and DBB projects were not statistically different in terms of cost related metrics, but that DB projects were delivered faster than DBB projects. Similar studies include: highway construction risks in Australia (Raisbeck et al., 2010), road projects in India (Rajan et al., 2013), and military buildings in U.S. (Hale, 2009).

More relevantly to this study, Chasey et al. estimated cost and schedule overruns of large (over US$90 million) 12 highway P3s in the U.S. The analysis result showed that the success ratio of DBFOM projects to complete on time and on budget was over 80%. The authors attributed the cost performance of P3s mostly to the DB component of the projects rather than their financing and operation and management (O&M) components, while their schedule performance could be due to the financing arrangements. In other words, project finance arrangements of P3 projects incentivize early completion of construction works to begin operation (i.e., revenue generation) in pursuit of favorable project cash flow (Chasey et al., 2012).

Focusing on the effectiveness of project finance arrangements in controlling construction risks, Blanc-Brude and Makovšek (2013) analyzed cost overruns of 75 project finance projects worldwide that reached financial close between 1993 and 2010, in various sectors such as transportation, energy, and telecommunications. Their
estimation supported the view that project finance projects demonstrated effective management of construction risks with the expected cost overruns of zero, while project specific risks were idiosyncratic and hence diversifiable.

The review of literature herein addressed mostly on construction risks in public works projects, and a clear synthesis emerges: large infrastructure projects have experienced considerable cost and schedule overruns. These are risks to the public agencies that procure these projects, and the emergence of alternative procurement models is arguably a response to control these risks, which present serious fiscal, economic, and political ramifications.

While the most relevant and critical question is whether P3s have been effective in achieving this objective, as the literature review below suggests, evidence has been scarce at best. Blanc-Brude et al. compared *ex ante* project costs as of contract award of 227 motorway projects that received funding from the European Investment Bank between 1990 and 2005 (2009). Their OLS estimation found that on average the unit costs of P3 highway projects were 24% higher than the traditionally procured projects. The authors interpreted this difference to be the construction risk allocated to private contractors, as it was equivalent to the construction cost overrun estimated by Flybjerg (2002). This interpretation would imply that there was no innovative investment to optimize their life-cycle costs at higher initial construction costs.

Makovšek (2013), while agreeing that P3 contracts should be more costly than traditionally procured projects, suggested the above finding reinterpreted: that the cost differences also accounted for distinct reference points of *ex ante* project costs between
there is a difference between the “decision to build” (Flyvbjerg, 2002) and *ex ante* construction cost (Blanc-Brude, et al., 2009). As projects progresses toward construction completion, the scope and design become clearer, and cost overruns decreases. Here, decision-to-build and contractual commitment serve as distinct reference points in terms of project scope definition in terms of their contract types, such as traditionally procured projects, design-build projects, and P3 projects. The price differences among design-build, P3s, and traditionally procured projects would reflect transfer of these risks to private contractors with respective magnitudes.

This debate effectively reflects contrasting views among scholars regarding whether P3 projects have really incentivized life-cycle cost saving innovative investments. Makovšek (2013) argued that the presence of innovative investment in P3s could not be rejected, while Blanc-Brude et al. (2009) cast doubt to this proposition from empirical results. Lind and Borg (2010) suggested that, to the extent they observe from experience in Sweden, the presence life-cycle cost minimizing innovations was questionable. Also, Roumboutsos and Saussier (2014) argued innovative investment of P3s has been “diverse” (p. 359) at best. Siemiatycki (2012) went so far to argue that P3s could limit innovation and long-term flexibility of designs as private contractors aim at minimizing project risks and upfront construction costs. This is due to the fact that the common assumptions made in theoretical models of procurement models have been violated if contract length is different from the asset life or the concession right (i.e., project equity shares) is sold in the secondary market, which is not uncommon. The incentive effect of P3 procurement regarding lifecycle cost minimization is not
immediately clear from the empirical perspective. Daito and Gifford empirically compared project costs of U.S. highways between procurement models and found statistically significant differences between DBFOM and DB models (2013). However, the results suffer from small sample size of 53 projects, while only project length, number of lanes, construction duration were included as independent variables besides procurement dummy variables. These weaknesses, as well as the use of aggregate values for both dependent and independent variables, as opposed to using per unit values (Blanc-Brude et al., 2009), motivate the need to further refine the data and estimation models, which is one of the motivations of the present study.

4.2.4 Literature Gap
The discussion herein portrays the state of knowledge regarding the theoretical underpinnings to differentiate highway project costs as well as empirical understanding as for the performance of these projects. Since the observations are extremely complex engineering products with complicated institutional procedures through implementation, scholarly analyses have faced challenges in gathering data, conduct sound analyses, and provide meaningful interpretation. Hodge and Greve (2009) suggest that evaluating the extent to which P3s have fulfilled their promises is challenging, and the outcomes to date widely differ. Hence, the state of literature warrants continuing evaluation on these projects. While cost comparison of highway projects between procurement models have been conducted in Europe, India, and a few other geographic contexts, to the author’s knowledge, analysis in the U.S. context has only been done with significant room for improvement. In particular, the analysis in Daito and Gifford (2013) and the discussions
therein were primarily underpinned by the effect of contract types in terms of cost saving innovative investments, and not by design and construction risk perspectives. This is the gap in the literature that the present study intends to fill as an exploratory step.

Specifically, the analysis in the following section will conduct an analysis equivalent to Blanc-Brude et al. (2009), with slight modification, regarding highway projects in the U.S. The next section will present data and estimated empirical model.

4.3 Data and Empirical Strategy

The present study will evaluate the performance of highway P3s in terms of their unit cost differences with traditionally procured highway projects. The analysis will employ the framework used in Blanc-Brude et al. (2009) but analysing data from U.S. highway projects. Underpinned by Hart’s theoretical model of cost differences between traditionally procured highway projects and highway P3s discussed above, Blanc-Brude et al. proposed the following reduced-form empirical model of unit project cost $y_i$ per lane-mile of project $i$:

$$y_i = \beta_0 + \beta_1 D_{PPP} + \sum_j \beta_j X_j + \epsilon_i$$

(3.1)

where, $D_{PPP}$ is a binary variable that denotes whether the project was procured with non-P3 contract types, or as a P3, $X_j$ is a set of variables pertaining to other project characteristics, and $\epsilon_i$ represents random noise.

The observations are tolled and non-tolled highway capacity expansion projects. There are numerous contract types under the umbrella of P3s, but projects that do not include design and construction of highway new capacity, such as operation and
maintenance contracts, leases, concessions with no capacity expansion, were excluded. Highway projects whose main components are bridges or tunnels were also excluded, as these projects require very different engineering specifications and are likely to have distinct cost structure. Following Blanc-Brude et al. (2009), only those projects with costs larger than 50 million 2009 U.S. dollars were included. This is because of the insight that P3s are suitable for projects with substantial costs because of their considerable transaction costs (e.g., legal experts, financial advisors, project management consultant, etc.). This definition is also in line with the proposition of Välilä, who proposed a threshold of €50 million as the minimum cost of highway projects suitable for P3 procurement (2005). Although the exchange rate of U.S. dollars and Euros constantly change over time, we considered 50 million U.S. dollars would be reasonable for our analysis. The number of projects satisfying these criteria was 69 (summarized in Table 16). It should be noted that the data source Public Works Finance Project Database is a fairly comprehensive database that is well respected in the industry, and their coverage of infrastructure projects is likely to be impartial. However, there will always be the risk that projects satisfying the aforementioned criteria may be missing in this database, and there are projects with missing independent variables and thus dropped from the analysis. Therefore, in this analysis observations are assumed to be samples, and because the size is rather smaller than the ideal, the results will be cautiously interpreted, conducting relevant statistical tests.
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<tr>
<td>GA</td>
<td>I-75/ I-575 Managed Lanes, Atlanta</td>
<td>TX</td>
<td>SH 71 Express Project, Austin</td>
</tr>
<tr>
<td>IL</td>
<td>Elgin-O'Hare Western Access (EOWA)</td>
<td>TX</td>
<td>SH 99/Grand Pkwy, F1, F2, G, Houston</td>
</tr>
<tr>
<td>IN</td>
<td>I-69, Section 5 Upgrade</td>
<td>TX</td>
<td>Lp 1604 Western Extension, San Antonio</td>
</tr>
<tr>
<td>MA</td>
<td>Route 3 North Widening</td>
<td>TX</td>
<td>SH 601, Liberty Expressway, El Paso</td>
</tr>
<tr>
<td>MD</td>
<td>Intercounty Connector (ICC)</td>
<td>TX</td>
<td>US 77 Upgrade, Kingsville-Driscoll</td>
</tr>
<tr>
<td>MN</td>
<td>Highway 212 (new section)</td>
<td>UT</td>
<td>I-15 New Ogden Weber Expansion (NOW)</td>
</tr>
<tr>
<td>MN</td>
<td>I-494 (Hennepin County) Widening</td>
<td>UT</td>
<td>I-15, Utah County (I-Core)</td>
</tr>
<tr>
<td>MN</td>
<td>ROC 52</td>
<td>VA</td>
<td>495 Express Lanes, Capital Beltway</td>
</tr>
<tr>
<td>MO</td>
<td>I-64 Reconstruction</td>
<td>VA</td>
<td>95 Express Lanes</td>
</tr>
<tr>
<td>NC</td>
<td>Triangle Expressway, Raleigh-Durham</td>
<td>VA</td>
<td>Pocahontas Parkway and Connector, I-895</td>
</tr>
<tr>
<td>NC</td>
<td>Knightdale Bypass US 64</td>
<td>VA</td>
<td>Jamestown Corridor</td>
</tr>
<tr>
<td>NC</td>
<td>U.S. 17 Washington Bypass</td>
<td>VA</td>
<td>Route 288</td>
</tr>
<tr>
<td>NC</td>
<td>I-540, Western Wake Freeway</td>
<td>VA</td>
<td>Route 58, Phase 2, Hillsville Bypass</td>
</tr>
<tr>
<td>NC</td>
<td>I-485, Charlotte Outer Loop</td>
<td>VA</td>
<td>I-5 Everett HOV Lanes</td>
</tr>
<tr>
<td>NC</td>
<td>I-77 Rehab, Surry &amp; Yadkin Counties</td>
<td>VA</td>
<td>I-5 Everett HOV Lanes</td>
</tr>
</tbody>
</table>

Source: Public Works Financing
The dependent variable of the empirical model is the unit DB contract price per lane-mile as contract awarded to a private contractor, in 2009 U.S. dollars, deflated using GDP deflator of the U.S. Bureau of Economic Analysis. These costs do not include all other costs borne by the public authority, such as the costs to purchase project right-of-way, financing, operation and maintenance, and so forth. For projects with DBFOM contracts, design build contract price was used for estimation. For instance, while the project cost of Presidio Parkway P3 in California, which began operation in July 2015, was $365 million, the project’s design-build contract price of $254 million (Public Works Financing) was used in the analysis. Similarly, while the project cost of I-95 Express Lanes project was $940 million, the design build contract price of $618 million (Public Works Financing) was used for estimation. Unlike Blanc-Brude et al. (2009), however, some of the project cost elements that may have been included in the officially announced estimates such as taxes and fees would be included in our analysis, due primarily to the aggregate nature of available project information.

In applying such conceptual definitions to the context of empirical investigations, previous studies have emphasized different dimensions of these projects. For instance, Blanc-Brude et al. (2009) as well as Chasey et al. (2012) defined P3s as projects that bundle all of design, build, finance, operate, and maintain components, and classified projects with all other contract types as non-P3s. In this study, P3 dummy variables with various combinations of contract types are used to differentiate the procurement models. Specifically, the analysis will compare empirical models with the dummy variables defined with the following contract types: 1) DBFOM, DBM, and DBF; 2) DBFOM and
DBF; 3) DBFOM and DBM; and 4) DBFOM only. These definitions correspond with what project components constitute P3, in addition to design-build: 1) any one of finance, operation, or maintain (DBF, DBM, and DBFOM); 2) finance (DBF&DBFOM); 3) maintain (DBM&DBFOM); and 4) all finance, operate, and maintain (DBFOM). It should be noted that the project samples used for our empirical analysis only include these P3s and Design-Build projects. As a result, Design-Bid-Build (DBB) projects are not included in the analysis.

This is primarily because our interest is, to the extent that is possible, in comparing projects on an equal footing. The traditional DBB model would only procure the construction stage, after the project design has been completed within the public authority or by a design firm. While this would considerably change the cost structure of these projects, it would not be in our interest to explicitly investigate this cost difference. Furthermore, conducting sound statistical analysis involving DBB projects to compare against projects procured through other contract types is challenging, since DBB projects are generally divided into smaller procurement packages to give business opportunities for more contractors (Shrestha et al., 2012). Hence, the traditional projects in our analysis is defined as DB projects with all other projects that are not defined as P3s in respective scenarios.

Table 17 summarizes descriptive statistics of the variables included in the empirical models, as well as their descriptive statistics. LN_LANE is the number of lanes, while LN_MILE is the length of the facility in mile. These data were gathered from Public Works Financing database, states’ official announcements regarding each.
project, and FHWA Office of Innovative Program Delivery Project Profile database. Information was crosschecked for validity.

The number of lanes is also included as an independent variable because the structural complexity of a motorway considerably changes as the number of lanes increases. This variable is included as a numerical variable, as opposed to dummy variables like in Blanc-Brude et al. (2009), since in the U.S. there appears to be larger variation: in the E.U., 227 samples were mostly two-, four-, or six-lane facilities, while in the U.S. 69 samples showed minimum of two, maximum of 24, and mean of 7.28. Potential linearity was addressed by taking the natural log. Hence, considering the small sample size, the use of dummy variables to account for the number of lanes is not appropriate. Assuming that the facilities with larger number of lanes require more complexities in terms of designing and constructing, the expected sign of this variable is positive.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>LN_LANE</td>
<td>1.848</td>
<td>0.513</td>
<td>0.693</td>
<td>3.178</td>
</tr>
<tr>
<td>LN_MILE</td>
<td>2.454</td>
<td>0.932</td>
<td>0</td>
<td>4.771</td>
</tr>
<tr>
<td>LN_UDURATION</td>
<td>-3.069</td>
<td>0.888</td>
<td>-5.004</td>
<td>-1.186</td>
</tr>
<tr>
<td>INTERSTATE</td>
<td>0.3571</td>
<td>0.483</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>TOLLED</td>
<td>0.429</td>
<td>0.498</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>TIMELAPSE</td>
<td>10.586</td>
<td>4.974</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
<td>CA</td>
<td>0.071</td>
<td>0.259</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>FL</td>
<td>0.171</td>
<td>0.380</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>TX</td>
<td>0.257</td>
<td>0.440</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>NC</td>
<td>0.086</td>
<td>0.282</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>VA</td>
<td>0.086</td>
<td>0.282</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>DBFOM</td>
<td>0.186</td>
<td>0.392</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Note: N=69. Author’s Calculation
The length of the facilities is included in natural log (LN_MILE) to account for potential economy of scale. Blanc-Brude et al. (2009) points out that because the dependent variable is in unit term (per lane-mile), this variable only captures scale economies. Hence this study follows in expecting the sign of the variable to be negative. Also, the samples herein are similar to the European analysis in terms of the uniformity of project types i.e., fixed link facilities (bridges and tunnels) maintenance contract, rest area rehabilitation, and other types of projects were excluded. Therefore it is unnecessary to account for these variations.

Another variable included in the empirical model herein is construction duration per lane-mile in natural log (LN_UDURATION). Construction duration has been included as a control variable in the empirical models of some of the studies in relevant literature (e.g., Meduri and Annamalai, 2013; Bhargava et al., 2010). In the literature, this variable is used to account for per unit complexity of works involved in the construction beyond binary distinction of project types. For example, Menduri and Annamalai (2013), in estimating the unit cost of P3 highways in India, included binary variables of bridges and tunnels while also including the construction length. Blanc-Brude et al. (2009), in contrast, included percentage of bridges and tunnels in the observation. While, it is not clear how this percentage is defined, the model of Blanc-Brude et al. accounted for the presence of project components with complex engineering structures and their magnitude in a sensitive manner. The model of Menduri and Annamalai, in contrast, accounted for these structurally complex facilities only as dummy variables, but had no way to account for their magnitude. Hence the construction duration appears to have accounted for the
unit structural complexity of each observation. Because the samples exclude bridges and tunnels, there is no need to include dummy variables to differentiate for these facilities. In addition, construction duration, expected as of the signing of the contracts, was included as the number of years per unit lane-mile in natural log to control for such variations of the projects. The expected sign of coefficient is positive, as it reflects the engineering complexity of the samples projects.

Geographic cost variation is another important component in empirically modeling construction projects. Various cost components of highway construction projects, such as labor, fuel, materials, and material shipping, are likely to vary across states. In Blanc-Brude et al. (2009), labor cost was included, and country dummy variables were also included to account for unspecified effects including political, institutional, and others. The European empirical estimation resulted in statistically significant coefficients of the labor costs and some of the country dummy variables. On the contrary, the empirical estimations in this study resulted in insignificant coefficient of the labor costs, with various specifications, once state dummy variables are included. Therefore, it is likely that the effect of labor cost geographic variations was absorbed to state dummy variables once they are included. Hence, it is assumed in this study that the geographic cost variations were all accounted for by the state variables. It should be noted that some states in the U.S. have closed very small number of project contracts that meet the criteria. In consideration of degree of freedom in this empirical estimation, dummy variables of only the following states with sufficient number of projects were included: California, Florida, North Carolina, Texas, and Virginia.
The year in which the project is implemented is also an important consideration. Flyvbjerg et al. (2004) analyzed project cost overruns with respect to their samples’ completion years, hypothesizing that should there have been any learning by the public agencies, projects in later years would demonstrate smaller construction cost overruns. Meduri and Annamalai (2013) also used year in which contracts were awarded to private contractors to investigate any learning curve of agents involved in highway P3 projects in India in terms of cost saving. Following these studies, the variable TIMELAPSE was included in the empirical models, defined as: \( \text{TIMELAPSE} = \text{year} - 1997 \), such that sample projects whose contracts were closed in the first year in the study period (1998) would take the value of 1, and values of the following years would incrementally increase by one.

Several binary variables are also included in the empirical model to account for distinct characteristics of some of the projects. INTERSTATE and TOLLED are dummy variables that, respectively, take the values of 1 if the facility is Interstate Freeway asset and 0 if not, and 1 if tolled and 0 if not. Intuitively, Interstate facilities have design standards distinct from other classes of road assets e.g., lane width, safety features, and so on. Also, tolled motorways require additional facilities such as toll booths or, more likely in recent years, electronic tolling systems with sophisticated information and communication technologies (ICT), both of which would increase the initial construction costs.

Figure 7 is a box plot of the project cost by contract type in 2009 U.S. million dollars, while Figure 8 is a box plot of unit project cost in 2009 U.S. million dollars per
lane mile. These figures indicate that DBFOM projects had project costs and unit costs that were higher than projects with other contracts, while there are a number of DB outlier observations with large project costs.

Figure 7 U.S. Highway Project Cost, 09US$M/lane-mile

The analysis will follow Blanc-Brude et al. (2009) in assuming that the procurement model choice can be considered exogenous when investigating a single sector i.e., highways. The referenced study points out that the procurement decision is a function of various factors including asset specificity, disaggregation of large projects to multiple phases, monitorability of service quality, and project risks and their
manageability. These are likely to be heterogeneous when considering across multiple sectors, but the institutional environment especially of road sector in this regard is homogenous across nation. Therefore, it is assumed that the scoping of a single sector effectively serves as a control for the potential endogeneity of procurement model decisions.

Figure 8 U.S. Highway Project Unit Cost, 09US$M/lane-mile
### Table 18 Estimated Regression Results

<table>
<thead>
<tr>
<th>Model</th>
<th>Control</th>
<th>DBF&amp;DBFOM</th>
<th>DBM&amp;DBFOM</th>
<th>DBFOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>LN_LANE</td>
<td>0.733***</td>
<td>0.704***</td>
<td>0.674***</td>
<td>0.645***</td>
</tr>
<tr>
<td></td>
<td>(4.16)</td>
<td>(3.84)</td>
<td>(3.71)</td>
<td>(3.51)</td>
</tr>
<tr>
<td>LN_MILE</td>
<td>0.629***</td>
<td>0.599***</td>
<td>0.574***</td>
<td>0.548***</td>
</tr>
<tr>
<td></td>
<td>(3.99)</td>
<td>(3.68)</td>
<td>(3.46)</td>
<td>(3.35)</td>
</tr>
<tr>
<td>LN_UDURATION</td>
<td>1.295***</td>
<td>1.262***</td>
<td>1.253***</td>
<td>1.210***</td>
</tr>
<tr>
<td></td>
<td>(7.09)</td>
<td>(6.70)</td>
<td>(6.76)</td>
<td>(6.35)</td>
</tr>
<tr>
<td>INTERSTATE</td>
<td>0.542***</td>
<td>0.511***</td>
<td>0.495***</td>
<td>0.439**</td>
</tr>
<tr>
<td></td>
<td>(3.43)</td>
<td>(3.12)</td>
<td>(3.17)</td>
<td>(2.66)</td>
</tr>
<tr>
<td>TOLLED</td>
<td>0.495***</td>
<td>0.496***</td>
<td>0.494***</td>
<td>0.456***</td>
</tr>
<tr>
<td></td>
<td>(3.30)</td>
<td>(3.22)</td>
<td>(3.23)</td>
<td>(2.94)</td>
</tr>
<tr>
<td>TIMELAPSE</td>
<td>-0.00456</td>
<td>-0.00594</td>
<td>-0.00329</td>
<td>-0.00443</td>
</tr>
<tr>
<td></td>
<td>(-0.28)</td>
<td>(-0.35)</td>
<td>(-0.20)</td>
<td>(-0.27)</td>
</tr>
<tr>
<td>CA</td>
<td>0.504* (1.82)</td>
<td>0.469* (1.75)</td>
<td>0.447* (1.72)</td>
<td>0.385 (1.52)</td>
</tr>
<tr>
<td>FL</td>
<td>-0.573**</td>
<td>-0.655***</td>
<td>-0.563**</td>
<td>-0.556**</td>
</tr>
<tr>
<td></td>
<td>(-2.64)</td>
<td>(-2.84)</td>
<td>(-2.58)</td>
<td>(-2.54)</td>
</tr>
<tr>
<td>NC</td>
<td>-0.445**</td>
<td>-0.439**</td>
<td>-0.420**</td>
<td>-0.398**</td>
</tr>
<tr>
<td></td>
<td>(-2.43)</td>
<td>(-2.26)</td>
<td>(-2.23)</td>
<td>(-2.13)</td>
</tr>
<tr>
<td>TX</td>
<td>0.202 (1.09)</td>
<td>0.176 (0.91)</td>
<td>0.162 (0.87)</td>
<td>0.141 (0.74)</td>
</tr>
<tr>
<td>VA</td>
<td>-0.326 (-1.22)</td>
<td>-0.348 (-1.32)</td>
<td>-0.386 (-1.47)</td>
<td>-0.390 (-1.49)</td>
</tr>
<tr>
<td>DBF&amp;DBFOM</td>
<td>0.133 (0.86)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DBM&amp;DBFOM</td>
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<td>0.168 (1.09)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DBFOM</td>
<td></td>
<td></td>
<td>0.325* (1.75)</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>2.376***</td>
<td>2.401***</td>
<td>2.469***</td>
<td>2.487***</td>
</tr>
<tr>
<td></td>
<td>(6.31)</td>
<td>(6.33)</td>
<td>(6.40)</td>
<td>(6.64)</td>
</tr>
<tr>
<td>N</td>
<td>69</td>
<td>69</td>
<td>69</td>
<td>69</td>
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<td>df_m</td>
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<td>12</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>RSS</td>
<td>15.56</td>
<td>15.40</td>
<td>15.31</td>
<td>14.77</td>
</tr>
<tr>
<td>Adjusted R2</td>
<td>0.592</td>
<td>0.589</td>
<td>0.591</td>
<td>0.606</td>
</tr>
<tr>
<td>F</td>
<td>10.79</td>
<td>10.18</td>
<td>9.650</td>
<td>10.94</td>
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<tr>
<td>AIC</td>
<td>117.1</td>
<td>118.3</td>
<td>117.9</td>
<td>115.4</td>
</tr>
</tbody>
</table>

Dependent Variable: LN_RCCPLM (Natural log of project cost per lane-mile)

Note: t statistics in parentheses. *: p<0.1; **: p<0.05; ***: p<0.01.
4.4 Results

Table 18 summarizes the estimation results of the regression models. Estimated coefficients of the number of lanes, length of the facility, construction duration per lane-mile, Interstate facility, and tolled motorway are statistically significant. While the signs of most of the estimated coefficients were in accordance with the pre-estimation expectations, the estimated sign of LN_MILE was positive, contrary to the initial hypothesis. This outcome suggests that sample highway projects demonstrate diseconomies of scale: the longer the facility, the higher the unit construction costs. This may be due to engineering characteristics particular to large highway projects that were unaccounted for in the estimated models.

The result also suggested that there was no time trend of the unit construction cost, since the estimated coefficient of TIMELAPSE was not statistically significant. This result is contrary to the findings of Meduri and Annamalai (2013), in which the coefficient in the estimation of P3s and traditionally procured projects in India was positive and statistically significant. It should be pointed out that highway construction projects require input materials with price levels that may change over the years, aside from taking the real dollar values. While there may have also been other variations, this result does not indicate the presence of the learning effect of public agencies in the U.S. as far as the unit cost of highway projects is concerned.

Dummy variables of CA, FL, NC, TX and VA were included to account for unobserved state-specific effects compared to projects in all other states. Therefore, these states are compared against all other states of the samples, i.e., Arizona, Colorado, Georgia, Illinois, Indiana, Massachusetts, Maryland, Minnesota, Missouri, New Mexico,
Nevada, New York, South Carolina, Utah, and Washington. Estimated coefficients of some of the states’ dummy variables were statistically significant: California, Florida, and North Carolina. Most of these state dummies were significant across all models, and the signs of the estimated coefficients were robust with no changes among models. The coefficient of California was positive, while that of North Carolina was negative.

With respect to contract types i.e., the main variable of interest here, the coefficient of the DBFOM model was statistically significant at 10%. The estimated coefficient was 0.325: to interpret, one needs to take the anti-log of the coefficient, subtract 1, and multiply 100. In this case, the result suggests that the difference of design-build contract cost per lane-mile was approximately 38% higher than all other projects, ceteris paribus. While all positive, the estimated coefficients of the other two models (DBF&DBFOM and DBM&DBFOM) were not statistically significant.

Table 19 through Table 23 report the results of the statistical tests of these estimations. Because the statistical tests per se are not the focus here, mathematical details of these tests are beyond the scope of discussion here. Hence this section will only provide the results and references for each of the tests presented herein. First, multicollinearity of independent variables was tested using Variance Inflation Factors (VIF), as reported on Table 19. Following Gujarati and Porter (2009), there appears no collinearity issue in the estimated models. Following the convention in the literature, robust standard errors are reported so as to minimize the potential of estimation biases.
Table 19 VIF Tests of Multi-collinearity by Regression Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Control</th>
<th>DBF&amp;DBFOM</th>
<th>DBM&amp;DBFOM</th>
<th>DBFOM</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>VIF</td>
<td>1/VIF</td>
<td>VIF</td>
<td>1/VIF</td>
</tr>
<tr>
<td>LN_LANE</td>
<td>2.37</td>
<td>0.422</td>
<td>2.46</td>
<td>0.4063</td>
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<tr>
<td>LN_MILE</td>
<td>5.87</td>
<td>0.170</td>
<td>6.19</td>
<td>0.1616</td>
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<tr>
<td>LN_UDURATION</td>
<td>6.22</td>
<td>0.161</td>
<td>6.59</td>
<td>0.1518</td>
</tr>
<tr>
<td>INTERSTATE</td>
<td>1.69</td>
<td>0.592</td>
<td>1.78</td>
<td>0.5616</td>
</tr>
<tr>
<td>TOLLED</td>
<td>1.51</td>
<td>0.661</td>
<td>1.51</td>
<td>0.6613</td>
</tr>
<tr>
<td>TIMELAPSE</td>
<td>1.71</td>
<td>0.586</td>
<td>1.73</td>
<td>0.5793</td>
</tr>
<tr>
<td>CA</td>
<td>1.35</td>
<td>0.741</td>
<td>1.38</td>
<td>0.7228</td>
</tr>
<tr>
<td>FL</td>
<td>1.66</td>
<td>0.603</td>
<td>2.06</td>
<td>0.4855</td>
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<tr>
<td>NC</td>
<td>1.24</td>
<td>0.807</td>
<td>1.24</td>
<td>0.8064</td>
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<td>TX</td>
<td>1.84</td>
<td>0.543</td>
<td>1.89</td>
<td>0.5286</td>
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<tr>
<td>VA</td>
<td>1.29</td>
<td>0.775</td>
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<td>0.7665</td>
</tr>
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<td>Proc. model</td>
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<td>1.68</td>
<td>0.5947</td>
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</tr>
<tr>
<td>Mean VIF</td>
<td>2.43</td>
<td>2.48</td>
<td>2.48</td>
<td>2.48</td>
</tr>
</tbody>
</table>

Table 20 Ramsey’s RESET Test of Omitted Variables by Regression Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Control</th>
<th>DBF&amp;DBFOM</th>
<th>DBM&amp;DBFOM</th>
<th>DBFOM</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>F(d.f.)</td>
<td>Prob&gt;F</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F(d.f.)</td>
<td>0.52 (3, 54)</td>
<td>0.6728</td>
<td>0.75 (3, 53)</td>
<td>0.5291</td>
</tr>
<tr>
<td>Prob&gt;F</td>
<td>1.21 (3, 53)</td>
<td>0.3144</td>
<td>1.04 (3, 53)</td>
<td>0.3813</td>
</tr>
</tbody>
</table>

Note: Tests using powers of the fitted values of Dependent Variable: LN_RCCPLM.

The empirical models estimated herein are arguably very simplistic, considering the complexity of large construction projects. While these models accounted for unobserved state-specific determinants through including dummy variables for some states, year specific effects (e.g., sudden and temporary change in material price) were not accounted for in the estimated models. This is due to the tradeoff between the small number of observations and the number of regressors acceptable to ensure sufficient degrees of freedom. Furthermore, there may have been other possible determinants that
were not included in the models. For example, Blanc-Brude et al. (2009) included dummy variables for urban and mountainous terrains where projects are located. These variables, while important, require theoretically sound definitions and careful determination of values for each observation, and not sufficient information across all observations was available to include such variables into the estimated models. For example, the U.S. 36 High Occupancy Toll Lanes project is an intercity link between Denver and Boulder, CO, and necessarily the project passes through both urban and rural areas, however defined. Unfortunately, the author has not found a theoretically sound and empirically meaningful guideline to determine whether this project is an urban project or not. Instead of using such questionable data, estimation results were tested using a post-estimation test for omitted variables. Table 20 reports the outcome of regression specification error test (RESET) proposed by Ramsey (1969). The null hypothesis of this test is that the model has no omitted variables. The test statistics of the regression models failed to reject the null hypothesis. Hence, concluding that potential systematic bias due to missing variables is statistically insignificant, further inquiry into this potential is reserved for future.

Also, Breusch and Pagan’s Test (1979) and White’s Test (1980) were conducted to examine the potential of heteroskedasticity in the estimated results. The former tests the null hypothesis of constant variance of the estimation results, while the latter tests the null hypothesis of homoscedasticity. As Table 21 and Table 22 show, neither tests for all regression models failed to reject the null hypothesis.
Table 21 Breusch-Pagan Test for Heteroskedasticity by Regression Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Control</th>
<th>DBF&amp;DBFOM</th>
<th>DBM&amp;DBFOM</th>
<th>DBFOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chi² (d.f.)</td>
<td>0.43 (1)</td>
<td>0.19 (1)</td>
<td>0.06 (1)</td>
<td>0.03 (1)</td>
</tr>
<tr>
<td>Prob&gt;chi²</td>
<td>0.5139</td>
<td>0.6669</td>
<td>0.8101</td>
<td>0.8693</td>
</tr>
</tbody>
</table>

Table 22 White’s Test for Heteroskedasticity by Regression Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Control</th>
<th>DBF&amp;DBFOM</th>
<th>DBM&amp;DBFOM</th>
<th>DBFOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chi² (d.f.)</td>
<td>54.39 (56)</td>
<td>68.62 (65)</td>
<td>67.67 (65)</td>
<td>67.4 (64)</td>
</tr>
<tr>
<td>Prob&gt;Chi²</td>
<td>0.5359</td>
<td>0.3558</td>
<td>0.3861</td>
<td>0.3617</td>
</tr>
</tbody>
</table>

Finally, following Blanc-Brude et al. (2009), normality of estimated residuals was inspected. Figure 9 is a box plot of distribution of estimated residuals so as to visually inspect the residuals. It appears that the residuals are normally distributed with means not considerably different from zero. Skewness-Kurtosis Tests was conducted to formally examine the normality of estimated residuals (Hamilton, 2008). The null hypothesis tested was normality of residuals, and the results reported on Table 23 show that the test failed to reject the null hypothesis for all regression models.

Table 23 SK Tests of Residual Normality by Regression Models

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>DBF&amp;DBFOM</th>
<th>DBM&amp;DBFOM</th>
<th>DBFOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pr(Skewness)</td>
<td>0.2689</td>
<td>0.3523</td>
<td>0.4556</td>
<td>0.6949</td>
</tr>
<tr>
<td>Pr(Kurtosis)</td>
<td>0.3803</td>
<td>0.311</td>
<td>0.3203</td>
<td>0.3819</td>
</tr>
<tr>
<td>Adj. Chi² (d.f.)</td>
<td>2.07 (2)</td>
<td>1.96 (2)</td>
<td>1.6 (2)</td>
<td>0.96 (2)</td>
</tr>
<tr>
<td>Prob&gt;Chi²</td>
<td>0.3556</td>
<td>0.3748</td>
<td>0.4496</td>
<td>0.6236</td>
</tr>
</tbody>
</table>

Note: N=69.
Overall, the fit of the estimated empirical models ranged between 0.59 and 0.61, which is comparable to other similar studies, whose equivalent figures range from 0.42 (Meduri and Annamalai, 2013) to 0.79 (Blanc-Brude et al. 2009). It is notable that the model fit was almost equivalent among all estimated empirical models, showing no significant difference from each other. Table 18 also reports Akaike Information Criteria (AIC) of each of the estimated models. While the model with the DBFOM only dummy variable shows the lowest result (115.4), the differences with those of other models (117.1-118.3) are very small. Nevertheless, only the DBFOM model shows any statistical difference of P3s with other projects, hence is the preferred model in this analysis.
4.5 Discussion and Concluding Remarks

Public-Private Partnerships have become a popular procurement model for U.S. states to continue investing in infrastructure, a critical input to their economies, while pursuing efficiency and overcoming their fiscal constraints. Claims often made regarding their cost saving and innovative features, however, have not been verified in a rigorous manner, and critics have called for close scrutiny of the performance of existing P3 projects. Because of their long contractual lives and the fact that they began being implemented only in the last two decades, full lifecycle *ex post* analysis is still not possible. In this context, the aim of this study has been to serve as one of the early studies to compare highway P3s and traditionally procured highway projects with regard to their design and construction costs. P3s remain one of the contentious political issues in a number of countries, such as in Canada (Syemiatycki, 2015). Therefore, the need for objective analysis of their performance and unbiased communication of their advantages and disadvantages cannot be overemphasized.

In this study, construction costs (i.e., design-build contract prices) per lane mile of highway projects was empirically specified as a function of various project features (e.g., the number of lanes, Interstate facilities, etc.) and institutional environments (i.e., state dummies). The difference of unit construction costs due to contract types was specified as dummy variables following the approach commonly employed in the literature. The results indicated statistically significant differences of, on average, 32.5%, between DBFOM projects and highway projects with all other contract types. The 32.5% difference can be qualitatively attributed to a mix of the three sources described in the
preceding sections, although, as in Blanc-Brude et al. (2009) noted, quantification of the effect of each of these sources is challenging.

In interpreting this result, the discussion herein is based on Blanc-Brude et al. (2009) and Makovšek (2013). The construction cost of P3s is likely to be higher than traditionally procured projects due to three sources. First, the DBFOM contracts require private contractor to operate and maintain the facility through the life of the facility, while, supposedly, giving them the freedom to design and construct so that the lifecycle costs of providing the facility can be minimized. Second, by bundling these project phases, DBFOM contract effectively allocates the construction risks to the private contractor, so that the sponsoring public agency will not incur the costly construction risks. The contractor will charge premiums for the risks transferred to them. Schedule and cost overruns have long been problematic in public works. Critics have warned that the project decision-making processes that give approval to large-scale infrastructure projects could cause Pareto inefficient allocation of scarce resources in society. Allocation of this risk to the private contractor and inclusion of private capital at risk in project financing arrangement have been considered as an effective approach to incentivize the contractor to exert its effort in managing this risk.

The contract price (project design and construction) can be different as the timing of contract award may serve as distinct reference point in the process of project delivery. Makovšek (2013) pointed out that, while cost estimates at the time of decision-to-build might still be subject to the construction cost overruns, by the time of contractual commitment, cost overrun would have decreased considerably, if not dissipated. Hence,
Makovšek suggested that the unit cost difference between highway P3s and traditionally procured highway projects should have been larger than the 24% estimated in Blanc-Brude et al. (2009), which had initially been interpreted as to have been dominated by the premiums of construction risk transferred to private contractors.

The analysis herein only includes Design-Build and P3 projects. In the context of the above discussion, the estimated unit cost differences control for the different reference points of cost overruns, since DBB projects are excluded. Therefore, the above discussion suggests that the innovative investments to optimize the lifecycle costs of the facility, as estimated in this analysis, appears to be larger than non-existence, as suggested by Blanc-Brude et al. (2009). In this regard, the finding from this analysis resonates with the view presented by Makovšek. However, per Roumboutsos and Saussier (2014), who questioned private contractors had really made innovative investments for life cycle cost optimization, a closer scrutiny is necessary to identify these innovations and quantify their cost and efficiency implications.

The analysis faces a number of limitations that warrant exercising cautions in interpreting the results. First, the scope of the analysis is only the *ex ante* cost of delivery at the time of contract award. Actual construction costs (i.e., *ex post*) is not accounted, let alone the lifecycle cost comparison. It would have been insightful if benchmarking with construction cost overrun estimates from other studies was possible. Unfortunately, this study compares DB and P3 contract prices, while to the author’s knowledge no studies have explicitly estimated the difference of *ex post* construction costs between them. Therefore, directly comparing the estimates herein and those in the literature can be
misleading. Relevance of the findings with respect to the policy debate on the overall P3 models is therefore limited. Second, the data used for the empirical estimation were all from public domain. If any of the projects have private information that influences our understanding of their cost structures, the true estimates of the empirical models might be different.

More importantly, there is a possibility that P3 contract models have been used for projects with particular characteristics, such as complex projects with sophisticated engineering designs. If such were the case, then the estimated coefficients would have been biased. Nevertheless, as Table 18 shows, both P3 and DB contracts were used for highway mega-projects (e.g., over US$1 billion), which are likely to involve engineering complexities particular to mega-projects. Besides, as suggested by Flyvbjerg’s discussion on the history of infrastructure projects, (2003, these mega-projects existed even before the emergence of P3 models. Therefore, the assertion that DBFOM projects have particular characteristics that differentiates its unit cost structure would be arguable. Similarly, private firms bidding for P3 projects are likely to have more degrees of freedom of bidding with respect to scopes of work, investment strategies, etc. The reference point of these decisions for P3 projects can be very different from those for Design-Build projects. The differences in reference points in this regard may not be fully controlled for. This remains as potential limitation of the estimation results. At any rate, closer scrutiny regarding the innovative investments employed in particular P3 projects should continue to deepen our understanding the effectiveness of innovative procurement models.
From a broader perspective on P3s as a policy subject, the discussion thus far depicts the poor state of knowledge regarding the performance of value for money that P3s have been presumed to provide in the existing infrastructure delivery regime. The result of the present analysis only deals with contractual commitment stage of highway projects i.e., \textit{ex ante} estimations as of contractual commitment, and it says nothing about the actual performance of design and construction phases of highway P3s. Moreover, the finding from this analysis does not include maintenance and operation phases of these projects. In this respect, Lind and Borg suggested that, as far as operation and maintenance activities are concerned, no significant difference has been found between P3s and publicly operated and maintained highway assets (2010). This aspect also requires further investigation. Overall, the value-for-money propositions that are used to justify the business cases of P3 projects have hardly been validated from the empirical standpoint. The critics’ call for more and continuing information disclosure to evaluate the performance are still relevant, and perhaps their importance is growing, since now the use of the procurement models is no longer considered exceptional in the U.S.

Besides the need for continuous evaluation of P3s’ performance, there are a few directions for future extensions of the present study. First, the limitations of the analysis need to be addressed to minimize the potential bias. These include accounting for geographic and time variations of projects inputs (e.g., labor, material, and shipping costs) instead of using the state dummy variables. Also, contrary to some studies in the literature, (e.g., Flyvbjerg et al., 2004), the year in which project contracts were awarded did not result in statistically significant associations with the unit project costs. Inclusion
of the variable may be questionable. Second, more samples should be added to strengthen the statistical properties of the results, since the current sample size (69) is not necessarily sufficient to ensure asymptotic assumptions of the empirical models and statistical tests are satisfied. Also, granularity of the data should be enhanced to enable closer scrutiny of the scope and costs of works involved in the delivery of sample projects.

Furthermore, as pointed earlier, the present study does not add to the knowledge regarding the difference between highway P3s and traditionally procured highway projects with respect to their operational and maintenance activities. Therefore, analysis of ongoing highway P3s and public operation and maintenance of highway facilities is also a critical addition to the body of knowledge on P3s as a policy subject. In summary, advocates of P3s should be reminded that their claims have yet to be founded empirically, and continuous research activities is necessary to truly evaluate their performance and validity of these arguments.
CHAPTER 5 CONCLUSION

The present study has inquired various dimensions of infrastructure public-private partnerships (P3s) that are relevant for policy makers but have not been fully addressed in the scholarly literature. The three essays improve the understanding of highway P3s in several respects. First, in statistically analyzing the associations between various factors of U.S. states and their use of P3s, Chapter 2 extended the body of knowledge by considering not just political factors (e.g., Republican governor, and margin of election victory) but also the election cycle. From the perspective of political business cycle literature, this study adds to the understanding of state behaviors by explicitly considering the use of innovative contract models (P3s) for economic infrastructure investment. Furthermore, while empirical consideration of political and institutional drivers of P3s has been mostly in the context of developing world, this study extended the framework to the U.S. context. Results of the empirical model estimated in the analysis raise a number of insights as well as questions regarding the use of P3s. Fiscal conditions were associated with the number of projects to reach contract closes: the larger the debt growth in the previous year, the smaller the number of contracts to close, while the larger the gas tax revenue in the previous year, the larger the number of P3 contracts. Also, the use of P3s appeared to have been driven neither to avoid taking political risks when margin of election victories is small (political contestability theory) nor to manipulate voters.
through boosting infrastructure investment in years prior to the elections (political business cycle theory). The decisions were more nuanced, although election cycles and political conditions did appear to influence the use of P3 contracts. These findings are insightful for private contractors in making investment decisions for particular projects, since these large-scale infrastructure projects typically costs millions of dollars just to bid. The results are also relevant for policy makers, since facilitation of institutional environment favorable for private investment is desirable, since ironically some U.S. states are beginning to be recognized as a politically risky markets, through experiences where well-known P3 candidate projects faced considerable political challenges.

Based on the theoretical models of road network design and incomplete contract literature, Chapter 3 evaluated procurement models (unbundled, bundled, and private monopolistic deliveries) for an abstract toll road project, with respect to social welfare and other state variables. Unbundled procurement scenario, which is equivalent to the conventional design-bid-build (DBB) procurement by the public agency, was found to have no incentive effect for private contractors to invest in innovative technologies to optimize lifecycle of the facility, unless explicitly contracted. Bundled procurement, equivalent to design-build-operate-maintain (DBOM) where the private contractor is responsible for providing the facility for fixed payments through the project life, incentivizes innovative investment only to the extent the technology minimizes the facility’s lifecycle costs. Under private monopolistic delivery, the contractor will also account for the benefit of the innovative technology to the users in setting the level of innovative technology investment. If in the concession agreement the toll is set to
maximize social welfare (i.e., as opposed to maximize private contractor’s profit), then the level of innovative technology investment is unambiguously larger than the other procurement models. Otherwise, comparative statics would depend on the slope of the demand curve. The results suggested that the project decision making procedures employed commonly by U.S. states, where Benefit Cost Analysis and Value for Money analysis are conducted separately, may result in biased results. Consideration of welfare effects of alternative procurement models at earlier stage, or in a repetitive manner, may be desirable to enable policy makers to make informed decisions.

In Chapter 4, unit design-build (DB) contract price of large highway projects were statistically compared among contract types. The chapter inquired whether the ex ante contract prices of P3 projects, which include, in addition to DB, maintenance (DBM), finance (DBF), or both (DBFOM), is significantly different from traditionally procured DB projects at contract award. In addition to the theoretical findings in Chapter 3, P3 contract prices would also include premium of construction risks transferred to the private contractor. The empirical analysis tested the hypothesis that the DB contract prices of P3s would be higher than the traditionally procured DB projects. The estimation results indeed supported this hypothesis, and suggested that the prices were likely to have reflected not only the construction risk premiums but also innovative investments for lifecycle cost optimization.

These findings lead to a few insights relevant for policy makers. First, the complex and nuanced relationships between political conditions and the use of P3s suggest that private contractors may face uncertain political risks when considering
bidding for P3s in a particular state in a particular year. While some, primarily from political economy literature, have argued undeniable relationships between states’ economic infrastructure investment behaviors and the political climate the decision-makers face, theories that underpin the use of P3s are based mostly on economic and financial considerations. P3s are complex undertakings that require substantial investment for private contractors just to bid for a project. Political risks, if significant, may deter private contractors to consider entering a particular state’s P3 market. Establishing institutional frameworks where the influence of politics can be limited may encourage private investment in participating in the state’s P3 market, and further, theorized efficiency gains of the innovative procurement models can fully manifest. While in the relevant literature that focuses on developing countries context necessarily need to consider aspects such as the rule of law, corruption levels, and other factors that are considered influential for private investment, in the U.S. this findings may have more specific implications. Legal challenges are rather common in large infrastructure projects in the U.S. Political challenges are not uncommon, coming from the legislative branches or even from the executive branches when a new governor replaces the incumbent. The discussion warrants continuing exploration of an institutional design that balances democratic decision making and efficient project delivery.

Also, while theories strongly predict private contractors are incentivized to invest in innovative technologies to optimize the lifecycle costs of delivering an infrastructure project, most of P3s at least in the U.S. began operation only in recent years. With decades remaining for their contractual relationships to complete, their theorized
advantages have not been empirically supported by any means. Even if initial capital was designed and constructed with the aim to optimize the lifecycle costs, the lifecycle cost efficiency will not manifest if private partners conduct O&M activities in poor manners. It will be desirable if continuous monitoring and scrutiny by sponsoring public agency are possible to ensure sound performance of private contractors in terms of fulfilling their contractual obligations through the contractual lives. Further inquiry into the performance of ongoing P3s will be necessary.

The analyses herein points to a few directions for future inquiry. Regarding Chapter 2, the next step will be to construct a formal theoretical model to explicitly model the use of P3s to evaluate the relationships between unique features of innovative contracts and their political risks that affect decisions of policy makers. The theoretical model can be used to refine the empirical models of institutions favorable for the use of innovative procurement contracts. Logistic or ordered logit regressions can be employed in addition to the regression models used in the analysis herein, depending on the assumptions of the mechanisms of innovative procurement decision making. While empirically testing such models can be challenging in the U.S. context due to small number of P3s to date, findings from such theoretical analyses can be meaningful to various entities involved in the P3 industry.

The theoretical models in Chapter 3 can be significantly enhanced to be more relevant to network and procurement problems in the real project context. First, consideration of various project risks (e.g., revenue risk, construction risk, and risks during the O&M phases) will be essential to be able to underpin empirical analyses as in
Chapter 4. The current deterministic models can be extended by including stochastic terms to explicitly model risk allocation of contract types, and various policy scenarios can be examined to understand behaviors of agents. Also, the current static models can be extended to be dynamic, where agents adjust their strategic decisions responding to changes in the system. A number of policy relevant questions can be addressed, including: renegotiations of contractual arrangements in response to changes in project environment; and examination of multi-phase development strategies, initiated from public or private partners. Finally, the model can be extended to a full scale network to evaluate various network capacity expansion scenarios, which will then allow consideration of competing facilities to candidate projects for private investment.

The analysis in Chapter 5 will need to be improved as regards the empirical models: explicit inclusion of project components in the cost function is desirable to account for their geographic variations, rather than the rather ad hoc approach to use state dummies. Also, more samples will need to be included to ensure the asymptotic assumption of the OLS estimation is not violated. Relatedly, the potential differences in the reference points of private contractors’ bidding decisions (e.g., scope of work, investment strategies, etc.) between P3s and Design-Build projects need to be accounted for, desirably with more refined data. Comparison of O&M costs between conventional and innovative procurement models will also be meaningful for policy makers. Infrastructure P3s remains a subject relevant to policy makers, and continuing scholarly inquiry is desirable to ensure this policy instrument is value-creating for society.
Appendix A: Chapter 3 Base Case Scenarios

This appendix presents detailed mathematical discussions on the base case scenarios of the model in Chapter 3. It is assumed that at least one global optimum exists for each of the scenarios analyzed in this section.

Unbundled Procurement Scenario

The first order derivative of \((3.21)\) with respect to \(\tau\) is as follows:

\[
\frac{\partial \pi^U_S}{\partial \tau} = \frac{\partial v}{\partial \tau} D(v) - \frac{\partial v}{\partial \tau} t(v, \kappa) - v \frac{\partial t}{\partial v} \frac{\partial v}{\partial \tau}
\]

Because of the user equilibrium condition \((3.14)\), the first two terms cancel out to equal \(\tau\):

\[
\frac{\partial \pi^U_S}{\partial \tau} = \frac{\partial v}{\partial \tau} - v \frac{\partial t}{\partial v} \frac{\partial v}{\partial \tau}
\]  

(A1).

The optimal toll level is:

\[
\tau^* = v \frac{\partial t}{\partial v}
\]  

(A2).

The first order derivative of \((3.21)\) with respect to \(\kappa\) is as follows:

\[
\frac{\partial \pi^U_S}{\partial \kappa} = \frac{\partial v}{\partial \kappa} D(v) - \frac{\partial v}{\partial \kappa} t(v, \kappa) - v \frac{\partial t}{\partial v} \frac{\partial v}{\partial \kappa} - v \frac{\partial t}{\partial \kappa} - \frac{\partial l}{\partial \kappa} - \frac{\partial M}{\partial \kappa}
\]  

(A3).

Using the demand equilibrium condition \((3.14)\), the above reduces to:

\[
= \frac{\partial v}{\partial \kappa} \left[ \tau - v \frac{\partial t}{\partial v} \right] - v \frac{\partial t}{\partial \kappa} - \frac{\partial l}{\partial \kappa} - \frac{\partial M}{\partial \kappa}
\]  

(A4).
Inside the bracket cancels out using (A1),

\[
\frac{\partial \pi_U^S}{\partial \kappa} = -v \frac{\partial t}{\partial \kappa} - \frac{\partial I}{\partial \kappa} - \frac{\partial M}{\partial \kappa}
\]

(A5).

The optimal capacity rule is therefore:

\[
\kappa^{U^*} \cdot \frac{\partial I}{\partial \kappa} + \frac{\partial M}{\partial \kappa} = -v \frac{\partial t}{\partial \kappa}
\]

(A6).

**Bundled Procurement Scenario**

The remainder of the analysis assumes the existence of an interior solution for each of the base case scenarios. In this scenario, the private contractor’s objective function is (3.24), the optimal condition with respect to \( \varphi \) is:

\[
\varphi^{B^*} \cdot \frac{\partial I}{\partial \varphi} + \frac{\partial M}{\partial \varphi} = 0
\]

(A7).

Since linearity is assumed of the objective functions with respect to \( \varphi_1 \), a special case is considered here in which the above condition, equivalence of the initial investment and lifecycle O&M cost savings, is met. The following functional forms are assumed:

\[
I(\varphi) = s_1 \cdot \kappa + s_2 \cdot \kappa \cdot \varphi
\]

(3.7),

\[
M(\varphi) = m_1 \cdot \kappa + m_2 \cdot \kappa \cdot \varphi
\]

(3.10),

Subtracting \( M(\varphi) \) from \( I(\varphi) \):

\[
(s_1 - m_1) \cdot \kappa + (s_2 + m_2) \cdot \kappa \cdot \varphi = 0
\]

(A8)

An explicit solution with respect to \( \varphi_1 \) can be found at:

\[
\varphi^{B^*} = \frac{(m_1 - s_1)}{(s_2 + m_2)}
\]

(A9).

Assuming \( m_1 > s_1 \) and \( s_2 > -m_2 \),
\begin{equation}
\varphi^{B^*} > 0 \tag{A10}
\end{equation}

As shown in the previous subsection, \( \varphi_1 \) does not influence the decision of public agencies with respect to \( \tau_1 \) and \( \kappa_1 \). Furthermore, based on the discussion regarding (3.20),

\begin{equation}
\varphi^{B^*} > \varphi^{U^*} = 0 \tag{A11}.
\end{equation}

**Private Monopolistic Delivery Scenario**

Following the main text, the optimal level of innovative investment is derived, and using backward induction, the optimal levels of capacity and toll are determined.

The first order derivative of (3.29) with respect to \( \tau \) is as follows:

\begin{equation}
\frac{\partial \pi^{PM}}{\partial \tau} = v + \tau \frac{\partial v}{\partial \tau} \tag{A12}.
\end{equation}

The optimal level of \( \tau \) is therefore:

\begin{equation}
\tau^{PM^*} = v \left[ \frac{\partial t}{\partial v} - D'(v) \right] \tag{A13}.
\end{equation}

The first order derivative of (3.29) with respect to \( \kappa \) is as follows:

\begin{equation}
\frac{\partial \pi^{PM}}{\partial \kappa} = \frac{\partial v}{\partial \kappa} \tau - \frac{\partial I}{\partial \kappa} - \frac{\partial M}{\partial \kappa} \tag{A14}.
\end{equation}

The optimal capacity rule is therefore as follows:

\begin{equation}
\frac{\partial I}{\partial \kappa} + \frac{\partial M}{\partial \kappa} = \frac{\partial v}{\partial \kappa} \tau
\end{equation}

\begin{equation}
= \frac{\partial t}{\partial \kappa} D'(v) - \frac{\partial t}{\partial v} v \left[ \frac{\partial t}{\partial v} - D'(v) \right]
\end{equation}

\begin{equation}
\kappa^{PM^*} : \frac{\partial I}{\partial \kappa} - \frac{\partial M}{\partial \kappa} = -v \frac{\partial t}{\partial \kappa} \tag{A15}.
\end{equation}
The first order derivative of (3.29) with respect to $\varphi$ is as follows:

$$\frac{\partial \pi^{PM}}{\partial \varphi} = \frac{\partial v}{\partial \varphi} \tau - \frac{\partial l}{\partial \varphi} - \frac{\partial M}{\partial \varphi}$$  \hspace{1cm} (A16).$$

The optimal condition of $\varphi$ is therefore:

$$\frac{\partial l}{\partial \varphi} + \frac{\partial M}{\partial \varphi} = \frac{\partial v}{\partial \varphi} \tau$$

$$= -\frac{\partial B}{\partial \varphi} D'(v) - \frac{\partial t}{\partial v} \left[ \frac{\partial t}{\partial v} - D'(v) \right]$$

$$\varphi^* = \frac{\partial l}{\partial \varphi} + \frac{\partial M}{\partial \varphi} = v \frac{\partial B}{\partial \varphi} > 0$$  \hspace{1cm} (A17).$$

**APPENDIX B Chapter 3 Multi-jurisdictional Case Scenarios**

**Global Welfare Maximization**

For the sake of comparison, it is assumed $\varphi_1 = 0$ in this scenario. The first order derivative of (3.46) with respect to $\tau_1$ is as follows:

$$\frac{\partial \pi^G}{\partial \tau_1} = D(v_C) \frac{\partial v_C}{\partial \tau_1} + D(v_L) \frac{\partial v_L}{\partial \tau_1} - \frac{\partial v_C}{\partial \tau_1} t_1(v_C, \kappa_1) - v_C \frac{\partial t_1}{\partial \tau_1} \frac{\partial v_C}{\partial \tau_1} t_2(v_C, v_L)$$

$$- v_C \frac{\partial t_2}{\partial \tau_1} \frac{\partial v_C}{\partial \tau_1} - \frac{\partial v_L}{\partial \tau_1} \frac{\partial v_C}{\partial \tau_1} t_2(v_C, v_L) - v_L \frac{\partial t_2}{\partial \tau_1} \frac{\partial v_C}{\partial \tau_1} + \frac{\partial v_C}{\partial \tau_1} B(\varphi_1)$$  \hspace{1cm} (B1).$$

Using the user equilibrium conditions (3.38) and (3.40):

$$\frac{\partial v_C}{\partial \tau_1} [D(v_C) - t_1(v_C, \kappa_1) - t_2(v_C, v_L) + B(\varphi_1)] = \frac{\partial v_C}{\partial \tau_1} \tau_1$$

$$\frac{\partial v_L}{\partial \tau_1} [D(v_L) - t_2(v_C, v_L)] = 0.$$

As a result,
\[
\frac{\partial \pi^G}{\partial \tau_1} = \frac{\partial v_c}{\partial \tau_1} \tau_1 - v_c \frac{\partial t_1}{\partial v_c} \frac{\partial v_c}{\partial \tau_1} - v_c \frac{\partial t_2}{\partial v_c} \frac{\partial v_c}{\partial \tau_1} - v_c \frac{\partial t_2}{\partial v_L} \frac{\partial v_c}{\partial \tau_1} - v_L \frac{\partial t_2}{\partial v_c} \frac{\partial v_c}{\partial \tau_1}
\]

After rearranging, the level of \( \tau_1 \) that maximizes (3.46) is:

\[
\tau_1^* = v_c \left[ \frac{\partial t_1}{\partial v_c} + \frac{\partial t_2}{\partial v_c} \frac{\partial v_c}{\partial \tau_1} + v_L \frac{\partial t_2}{\partial v_L} \frac{\partial v_c}{\partial \tau_1} \right] \quad \text{(B2)}.
\]

The first order derivative of (46) with respect to \( \kappa_1 \) is as follows:

\[
\frac{\partial \pi^G}{\partial \kappa_1} = D(v_c) \frac{\partial v_c}{\partial \kappa_1} + D(v_L) \frac{\partial v_L}{\partial \kappa_1} - \frac{\partial v_c}{\partial v_c} \frac{\partial \tau_1}{\partial \kappa_1} \tau_1(v_c, \kappa_1) - \frac{\partial v_c}{\partial v_c} \frac{\partial t_2}{\partial v_L} \frac{\partial v_c}{\partial \kappa_1} - v_c \frac{\partial t_1}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1}
\]

\[
- v_c \frac{\partial t_2}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1} - v_c \frac{\partial t_2}{\partial v_L} \frac{\partial v_c}{\partial \kappa_1} - v_c \frac{\partial v_L}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1} - \frac{\partial v_m}{\partial v_c} \frac{\partial \tau_1}{\partial \kappa_1} t_2(v_c, v_L)
\]

\[
- v_L \frac{\partial t_2}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1} - v_L \frac{\partial t_2}{\partial v_L} \frac{\partial v_c}{\partial \kappa_1} - \frac{\partial L}{\partial \kappa_1} - \frac{\partial M}{\partial \kappa_1} + B(\varphi_1) \quad \text{(B3)}.
\]

Using the user equilibrium conditions (38) and (40):

\[
\frac{\partial v_c}{\partial \kappa_1} [D(v_c) - t_1(v_c, \kappa_1) - t_2(v_c, v_L) + B(\varphi_1)] = \frac{\partial v_c}{\partial \kappa_1} \tau_1
\]

\[
\frac{\partial v_L}{\partial \kappa_1} [D(v_L) - t_2(v_c, v_L)] = 0
\]

As a result,

\[
\frac{\partial \pi^G}{\partial \kappa_1} = \frac{\partial v_c}{\partial \kappa_1} \tau_1 - v_c \frac{\partial t_1}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1} - v_c \frac{\partial t_1}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1} - v_c \frac{\partial t_2}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1} - v_c \frac{\partial t_2}{\partial v_L} \frac{\partial v_c}{\partial \kappa_1} - v_L \frac{\partial t_2}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1}
\]

\[
- v_L \frac{\partial t_2}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1} - \frac{\partial L}{\partial \kappa_1} - \frac{\partial M}{\partial \kappa_1}.
\]

The optimizing capacity rule is therefore as follows:
\[
\frac{\partial l}{\partial \kappa_1} + \frac{\partial M}{\partial \kappa_1} = -v_c \frac{\partial t_1}{\partial \kappa_1} + v_c \left[ t_1 - v_c \left( \frac{\partial t_1}{\partial v_c} - \frac{\partial t_2}{\partial v_c} - \frac{\partial t_2}{\partial v_L \partial v_c} \right) - v_L \left( \frac{\partial t_2}{\partial v_c} - \frac{\partial t_2}{\partial v_L \partial v_c} \right) \right],
\]

which can be rearranged as:

\[
= -v_c \frac{\partial t_1}{\partial \kappa_1} + v_c \left[ v_c \left( \frac{\partial t_1}{\partial v_c} + \frac{\partial t_2}{\partial v_c} + \frac{\partial t_2}{\partial v_L \partial v_c} \right) + v_L \left( \frac{\partial t_2}{\partial v_c} + \frac{\partial t_2}{\partial v_L \partial v_c} \right) \right] - v_c \left( \frac{\partial t_1}{\partial v_c} + \frac{\partial t_2}{\partial v_L \partial v_c} \right) - v_c \left( \frac{\partial t_2}{\partial v_L \partial v_c} - \frac{\partial t_2}{\partial v_L \partial v_c} \right)
\]

\[
\kappa_1^*: \frac{\partial l}{\partial \kappa_1} + \frac{\partial M}{\partial \kappa_1} = -v_c \frac{\partial t_1}{\partial \kappa_1} \quad (B4)
\]

**Suburban City Welfare Maximization, Unbundled Procurement**

The optimal level of private contractor’s investments in innovative technologies that maximizes the objective function of private contractor (3.49) is as follows:

\[
\varphi_1^{SU} = 0 \quad (B5).
\]

The public agency optimizes its decision model, accounting for the above. The first order derivative of (3.51) with respect to \( \tau_1 \) is as follows:

\[
\frac{\partial \pi_1^{SU}}{\partial \tau_1} = D v_c \frac{\partial v_c}{\partial \tau_1} - v_c \frac{\partial v_c}{\partial \tau_1} t_1(v_c, \kappa_1) - v_c \frac{\partial t_1}{\partial v_c} \frac{\partial v_c}{\partial \tau_1} - v_c \frac{\partial t_2}{\partial v_c} \frac{\partial v_c}{\partial \tau_1} - v_c \frac{\partial t_2}{\partial v_c} \frac{\partial v_c}{\partial \tau_1} - v_c \frac{\partial t_2}{\partial v_c} \frac{\partial v_c}{\partial \tau_1}
\]

\[
- v_c \frac{\partial t_2}{\partial v_L} \frac{\partial v_c}{\partial \tau_1} + v_c \frac{\partial v_c}{\partial \tau_1} B(\varphi_1) \quad (B6).
\]

Using the (3.40), the above reduces to:

\[
\frac{\partial \pi_1^{SU}}{\partial \tau_1} = \frac{\partial v_c}{\partial \tau_1} t_1 - v_c \frac{\partial t_1}{\partial \tau_1} \frac{\partial v_c}{\partial \tau_1} - v_c \frac{\partial t_2}{\partial \tau_1} \frac{\partial v_c}{\partial \tau_1} - v_c \frac{\partial t_2}{\partial \tau_1} \frac{\partial v_c}{\partial \tau_1} - v_c \frac{\partial t_2}{\partial \tau_1} \frac{\partial v_c}{\partial \tau_1}
\]

The optimal toll level in this scenario is therefore:

\[
\tau_1^{SU} = v_c \left[ \frac{\partial t_1}{\partial \tau_1} + \frac{\partial t_2}{\partial \tau_1} + \frac{\partial t_2}{\partial \tau_1} \right] \quad (B7).
\]
The first order derivative of (3.51) with respect to $\kappa_1$ is as follows:

$$
\frac{\partial \pi^{SU}}{\partial \kappa_1} = D(v_c) \frac{\partial v_c}{\partial \kappa_1} - \frac{\partial v_c}{\partial \kappa_1} t_1(v_c, \kappa_1) - v_c \frac{\partial t_1}{\partial \kappa_1} - v_c \frac{\partial t_2}{\partial \kappa_1} \frac{\partial v_c}{\partial \kappa_1} - t_2(v_c, v_L)
$$

$$
- v_c \frac{\partial t_2}{\partial \kappa_1} - v_c \frac{\partial t_2}{\partial \kappa_1} \frac{\partial v_c}{\partial \kappa_1} - \frac{\partial l}{\partial \kappa_1} - \frac{\partial M}{\partial \kappa_1} + \frac{\partial v_c}{\partial \kappa_1} B(\varphi_1) \quad (B8).
$$

Using (3.40), the above reduces to:

$$
\frac{\partial \pi^{SU}}{\partial \kappa_1} = \frac{\partial v_c}{\partial \kappa_1} \tau_1 - v_c \frac{\partial t_1}{\partial \kappa_1} - v_c \frac{\partial t_2}{\partial \kappa_1} \frac{\partial v_c}{\partial \kappa_1} - v_c \frac{\partial t_2}{\partial \kappa_1} \frac{\partial v_L}{\partial \kappa_1} - v_c \frac{\partial t_2}{\partial \kappa_1} \frac{\partial v_c}{\partial \kappa_1} \frac{\partial v_c}{\partial \kappa_1}
$$

$$
- \frac{\partial M}{\partial \kappa_1}
$$

(B9).

Rearranging the optimal capacity rule:

$$
\frac{\partial l}{\partial \kappa} + \frac{\partial M}{\partial \kappa} = \frac{\partial v_c}{\partial \kappa} \tau_1 - v_c \frac{\partial t_1}{\partial \kappa} - v_c \frac{\partial t_2}{\partial \kappa} \frac{\partial v_c}{\partial \kappa} - v_c \frac{\partial t_2}{\partial \kappa} \frac{\partial v_L}{\partial \kappa} - v_c \frac{\partial t_2}{\partial \kappa} \frac{\partial v_c}{\partial \kappa} \frac{\partial v_c}{\partial \kappa}
$$

$$
= -v_c \frac{\partial t_1}{\partial \kappa} + \frac{\partial v_c}{\partial \kappa} \left[ \tau_1 - v_c \left( \frac{\partial t_1}{\partial v_c} + \frac{\partial t_2}{\partial v_c} + \frac{\partial t_2}{\partial v_L} \frac{\partial v_c}{\partial v_c} \right) \right]
$$

$$
= -v_c \frac{\partial t_1}{\partial \kappa} + \frac{\partial v_c}{\partial \kappa} \left[ v_c \left( \frac{\partial t_1}{\partial v_c} + \frac{\partial t_2}{\partial v_c} + \frac{\partial t_2}{\partial v_L} \frac{\partial v_c}{\partial v_c} \right) - v_c \left( \frac{\partial t_1}{\partial v_c} + \frac{\partial t_2}{\partial v_c} + \frac{\partial t_2}{\partial v_L} \frac{\partial v_c}{\partial v_c} \right) \right]
$$

$$
\kappa^{SU}_{1*} : \frac{\partial l}{\partial \kappa_1} + \frac{\partial M}{\partial \kappa_1} = -v_c \frac{\partial t_1}{\partial \kappa_1} \quad (B10).
$$

**Suburban City Welfare Maximization, Bundled Procurement**

The level of $\varphi_1$ that maximizes the private contractor’s objective function in this scenario (3.54), which is derived by taking the first order derivative and setting it to zero, is as follows:

$$
\varphi^{SB}_{1*} : \frac{\partial l}{\partial \varphi_1} + \frac{\partial M}{\partial \varphi_1} = 0 \quad (B11).
$$
Since linearity is assumed of the objective functions with respect to $\varphi_1$, a special case is considered here in which the above condition, equivalence of the initial investment and lifecycle O&M cost savings, is met. The following functional forms are assumed:

\[ I(\varphi_1) = s_1 \cdot \kappa_1 + s_2 \cdot \kappa_1 \cdot \varphi_1 \]  
\[ M(\varphi_1) = m_1 \cdot \kappa_1 + m_2 \cdot \kappa_1 \cdot \varphi_1 \]

where it is assumed that $s_1, s_2, m_1 > 0$ and $m_2 < 0$.

Subtracting $M(\varphi_1)$ from $I(\varphi_1)$:

\[(s_1 - m_1) \cdot \kappa_1 + (s_2 + m_2) \cdot \kappa_1 \cdot \varphi_1 = 0\]

An explicit solution with respect to $\varphi_1$ can be found at:

\[ \varphi_1^{SB*} = \frac{(m_1 - s_1)}{(s_2 + m_2)} \]  

Assuming $m_1 > s_1$ and $s_2 > -m_2$,

\[ \varphi_1^{SB*} > 0 \]

As shown in the previous subsection, $\varphi_1$ does not influence the decision of public agencies with respect to $\tau_1$ and $\kappa_1$. Furthermore, the private contractor’s decision on $\varphi_1$ is equivalent in the scenarios where the urban city is the procuring agency.

\[ \varphi_1^{SB*} > \varphi_1^{SU*} \]  

**Urban City Welfare Maximization**

The optimal level of private contractor’s investments in innovative technologies in the unbundled procurement scenario, when the urban city is the procuring agency, is as follows:
\[ \varphi_{1u^*} = 0 \quad (B17), \]

which is equivalent to the case where the suburban city is the public partner.

When the contract is bundled, as was in the case of (B7),

\[ \varphi_{1u^b} \cdot \frac{\partial l}{\partial \varphi_1} + \frac{\partial M}{\partial \varphi_1} = 0 \quad (B18). \]

Assuming \( s_1, s_2, m_1 > 0 \) and \( m_2 < 0 \):

\[ \varphi_{1u^b}^* = \frac{(m_1-s_1)}{(s_2 + m_2)} > 0 = \varphi_{1u^*} \quad (B19). \]

The first order derivative of (3.57), urban city’s objective function, with respect to \( \tau_1 \) is as follows:

\[
\frac{\partial \pi_{S U U}}{\partial \tau_1} = D v_L \frac{\partial v_c}{\partial \tau_1} \frac{\partial v_c}{\partial \tau_1} t_2(v_L, v_C) - v_L \frac{\partial t_2}{\partial v_C} \frac{\partial v_C}{\partial \tau_1} - v_C \frac{\partial t_2}{\partial v_C} \frac{\partial v_C}{\partial \tau_1} + \frac{\partial v_C}{\partial \tau_1} + \tau_1 \frac{\partial v_C}{\partial \tau_1} \quad (B20). \]

The first two terms cancel out due to the user equilibrium condition (3.40), hence:

\[
\frac{\partial \pi_{S U U}}{\partial \tau_1} = -v_L \frac{\partial t_2}{\partial v_C} \frac{\partial v_C}{\partial \tau_1} - v_C \frac{\partial t_2}{\partial v_C} + \frac{\partial v_C}{\partial \tau_1} + \tau_1 \frac{\partial v_C}{\partial \tau_1} \]

The toll level that maximizes this objective function is as follows:

\[ \tau_{1u^*} = -v_C \left[ D'(v_c) - \frac{\partial t_1}{\partial v_C} - \frac{\partial t_2}{\partial v_C} \right] + v_L \left[ \frac{\partial t_2}{\partial v_L} \frac{D'(v_c)}{\partial v_C} - \frac{\partial t_1}{\partial v_C} \frac{\partial t_2}{\partial v_L} \frac{\partial v_C}{\partial \tau_1} + \frac{\partial t_2}{\partial v_C} \frac{\partial v_C}{\partial \tau_1} \right] \]

\[ \tau_{1u^*} = v_L \left[ \frac{\partial t_2}{\partial v_L} \frac{D'(v_c)}{\partial v_C} - \frac{\partial t_1}{\partial v_C} \frac{\partial t_2}{\partial v_L} \frac{\partial v_C}{\partial \tau_1} + \frac{\partial t_2}{\partial v_C} \frac{\partial v_C}{\partial \tau_1} \right] \]

\[ \tau_{1u^*} = v_C \frac{\partial t_2}{\partial v_C} + (v_C - v_L) \left[ \frac{\partial t_1}{\partial v_C} - D'(v_c) \right] \quad (B21). \]
The first order derivative of (3.57) with respect to $\kappa_1$ is as follows:

$$
\frac{\partial \pi^{uu}}{\partial \kappa_1} = D v_L \frac{\partial v_L}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1} - \frac{\partial v_L}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1} t_2(v_L, v_T) - v_L \frac{\partial t_2}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1} - v_L \frac{\partial t_2}{\partial v_L} \frac{\partial v_L}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1} + \tau_1 \frac{\partial v_C}{\partial \kappa_1}
$$

$$
- \frac{\partial M}{\partial \kappa_1} - \frac{\partial l}{\partial \kappa_1}
$$

(B22).

The first two terms cancel out due to the user equilibrium condition (3.40), hence:

$$
\frac{\partial \pi^{uu}}{\partial \kappa_1} = - v_L \frac{\partial t_2}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1} - v_L \frac{\partial t_2}{\partial v_L} \frac{\partial v_L}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1} + \tau_1 \frac{\partial v_C}{\partial \kappa_1}
$$

The optimal condition of $\kappa_1$ is:

$$
\frac{\partial M}{\partial \kappa_1} + \frac{\partial l}{\partial \kappa_1} = \frac{\partial v_C}{\partial \kappa_1} \tau_1 - v_L \frac{\partial t_2}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1} - v_L \frac{\partial t_2}{\partial v_L} \frac{\partial v_L}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1}
$$

Plugging in (B21),

$$
= \frac{\partial v_C}{\partial \kappa_1} \left[ -v_c \left( D'(v_c) - \frac{\partial t_1}{\partial v_c} - \frac{\partial t_2}{\partial v_c} \right) + v_L \left( D'(v_c) - \frac{\partial t_1}{\partial v_c} \right) \right] - v_L \frac{\partial t_2}{\partial v_L} \frac{\partial v_L}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1} \left[ 1 + \frac{\partial v_L}{\partial v_c} \right]
$$

$$
= \frac{\partial v_C}{\partial \kappa_1} \left[ -v_c \left( D'(v_c) - \frac{\partial t_1}{\partial v_c} - \frac{\partial t_2}{\partial v_c} \right) + v_L \left( D'(v_c) - \frac{\partial t_1}{\partial v_c} \right) \right]
$$

$$
= \frac{\partial v_C}{\partial \kappa_1} \left[ -v_L \left( \frac{\partial t_2}{\partial v_c} + \frac{\partial t_2}{\partial v_L} \frac{\partial v_L}{\partial v_c} \frac{\partial v_c}{\partial \kappa_1} \right) \right],
$$

which can be rearranged to:

$$
= \frac{\partial v_C}{\partial \kappa_1} \left[ -v_c \left( D'(v_c) - \frac{\partial t_1}{\partial v_c} - \frac{\partial t_2}{\partial v_c} \right) + v_L \left( D'(v_c) - \frac{\partial t_1}{\partial v_c} \right) \right]
$$

$$
= -v_c \frac{\partial v_C}{\partial \kappa_1} \left[ D'(v_c) - \frac{\partial t_1}{\partial v_c} - \frac{\partial t_2}{\partial v_c} \right].
$$

204
Using (3.43),

\[
\frac{\partial M}{\partial \kappa_1} + \frac{\partial I}{\partial \kappa_1} = -\nu_c \frac{\partial t_1}{\partial \kappa_1}
\]  \hspace{1cm} (B23).\]

**Global Profit Maximization**

The first order condition of (3.62) with respect to \( \tau_1 \) is as follows.

\[
\frac{\partial \pi^G_F}{\partial \tau_1} = \nu_c + \tau_1 \frac{\partial v_c}{\partial \tau_1} = 0.
\]

After rearranging, the optimal toll for the private contractor is as follows:

\[
\tau_1^{PM*} = \nu_c \left[ \frac{\partial t_1}{\partial v_c} + \frac{\partial t_2}{\partial v_c} - D'(v_c) \right] \hspace{1cm} (B24).
\]

The first order condition of (3.62) with respect to \( \kappa_1 \) is as follows:

\[
\frac{\partial \pi^G_F}{\partial \kappa_1} = \tau_1 \frac{\partial v_c}{\partial \kappa_1} - \frac{\partial I}{\partial \kappa_1} - \frac{\partial M}{\partial \kappa_1} = 0
\]

After rearranging, the optimal rule becomes:

\[
\frac{\partial I}{\partial \kappa_1} + \frac{\partial M}{\partial \kappa_1} = \tau_1 \frac{\partial v_c}{\partial \kappa_1}
\]

\[
= \nu_c \left[ \frac{\partial t_1}{\partial v_c} + \frac{\partial t_2}{\partial v_c} - D'(v_c) \right] \frac{\partial v_c}{\partial \kappa_1}
\]

\[
= -\nu_c \frac{\partial t_1}{\partial \kappa_1} D'(v_c) - \frac{\partial t_1}{\partial v_c} - \frac{\partial t_2}{\partial v_c}.
\]

Therefore, the optimal capacity rule in this scenario is:

\[
\kappa_1^{PM*}: \frac{\partial I}{\partial \kappa_1} + \frac{\partial M}{\partial \kappa_1} = -\nu_c \frac{\partial t_1}{\partial \kappa_1}
\]  \hspace{1cm} (B25),
which is equivalent to the other scenarios. However, due to the higher level of \( \tau_1 \),
the traffic level is smaller, and hence the capacity will also depend on the parameters.
Numerical analysis that follows will demonstrate this point.

The first order condition of (3.62) with respect to \( \varphi_1 \) is as follows:

\[
\frac{\partial \pi^F}{\partial \varphi_1} = \tau_1 \frac{\partial v_c}{\partial \varphi_1} - \frac{\partial l}{\partial \varphi_1} - \frac{\partial M}{\partial \varphi_1}
\]  
(B26).

After rearranging,

\[
\frac{\partial l}{\partial \varphi_1} + \frac{\partial M}{\partial \varphi_1} = v_c \left[ \frac{\partial t_1}{\partial v_c} + \frac{\partial t_2}{\partial v_c} - D'(v_c) \right] \frac{\partial v_c}{\partial \varphi_1}
\]

Using (3.44),

\[
\frac{\partial l}{\partial \varphi_1} + \frac{\partial M}{\partial \varphi_1} = v_c \left[ \frac{\partial t_1}{\partial v_c} + \frac{\partial t_2}{\partial v_c} - D'(v_c) \right] \frac{-\frac{\partial B}{\partial \varphi_1}}{D'(v_c)} \frac{\partial t_1}{\partial v_c} - \frac{\partial t_2}{\partial v_c}
\]

\[
\varphi_1^{PM*}: \frac{\partial l}{\partial \varphi_1} + \frac{\partial M}{\partial \varphi_1} = v_c \frac{\partial B}{\partial \varphi_1}
\]  
(B27).

Using (3.19),

\[
\varphi_1^{PM*} > \varphi_1^{UU*}
\]  
(B28),

and,

\[
\varphi_1^{PM*} > \varphi_1^{SU*}
\]  
(B29).
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BIOGRAPHY

Nobuhiko Daito holds a B.A. degree in Liberal Arts from Soka University of America, Aliso Viejo and a Master’s degree in Urban and Regional Planning from University of California, Irvine. His research interests include municipal finance, transportation economics, regional science, and infrastructure public-private partnerships.

During his doctoral career, Nobuhiko received John E. Petersen Memorial Scholarship in Public Finance Policy Endowed Scholarship and George Mason University Provost’s Doctoral Dissertation Completion Grant. He was also named as an International Road Federation Road Scholar Fellow in 2013.

Nobuhiko’s recent research has been published in Transport Reviews, Journal of the Transportation Research Forum, Managerial Finance, Applied Economics Letters, and Case Studies on Transport Policy. His recent study was also published as part of the OECD International Transport Forum’s Roundtable on Public Private Partnerships for Transport Infrastructure: Renegotiations, How to Approach Them and Economic Outcomes.