Sustainable Infrastructure Finance: Enhancing Transportation Construction Expenditure Management and Exploring Innovative Financing Mechanisms

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Sustainable Infrastructure Finance: Enhancing Transportation Construction Expenditure Management and Exploring Innovative Financing Mechanisms

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To Future.

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SUMMARY

Infrastructure is vital to the daily life of every single person – from the road that people travel to work, to the pipes that deliver clean drinking water, to the electrical grids that deliver electricity to light rooms, no matter in the deep valley or in the New York City. Persistent failure to invest in the aging infrastructure of the United States severely jeopardizes this country: the cumulative documented investment gap in the U.S. infrastructure system is more than $2.6 trillion by 2029, leading to more than $10.3 trillion loss in GDP by 2039. Every household in the U.S. will be expected to suffer an average loss of more than $3,300 per year in disposable income through 2039. Above statistics by American Society of Civil Engineers (ASCE 2021) are tabulated before the outbreak of Coronavirus Disease 2019 (COVID-19), which worsens the situations by shrinking the limited revenue sources. In addition to the rehabilitation of decaying facilities, intensive investment needs in the wake of emerging consensus on constructing sustainable infrastructures due to the challenges such as climate change, urbanization, and the rapid pace of technological advancement, bring additional pressure to infrastructure finance.

The nexus of infrastructure finance and sustainable infrastructure system is more than the financial burden imposed by infrastructure system on finance. Moreover, as the definition of sustainability by ASCE (n.d.) indicates, the financial activities of sustainable infrastructure system should have the capability to maintain and improve quality of life without degrading the quantity, quality, and availability of economic and social resources. People need to finance sustainable infrastructure. Meanwhile, people need to

finance infrastructure sustainably. This thesis describes three studies. Centering around cash flow shortage and default risk of transportation projects, the first two studies use advanced analytics methods to better protect investment by enhancing the risk assessment of P3 projects, and to enable effective use of limited public funding by generating realistic estimate on expenditure cash flow at early phase of project development. The last study aims at helping people apply the innovative financing mechanism originally designed for traditional, large-scale infrastructure projects to sustainable infrastructure projects. Compared to traditional infrastructure projects such as interstate highway, sustainable infrastructure projects are frequently smaller in size. The third study identifies and analyzes the unique challenges of using P3 on smaller infrastructure projects and provides enablers with potentials to overcome the identified challenges.

In the first study, a novel real options model is developed to quantify the risk of cash flow shortage caused by technical uncertainties and market uncertainties in transportation public-private partnerships (P3). As the state-of-art financial engineering instrument which provides evaluation on investment opportunities under uncertain market conditions, real options analysis has been used by many prior researchers to explore various kinds of options in transportation infrastructure investment. Nevertheless, no approach is developed in prior of this study for pricing technical risks, which do not have hands-on market risk premium. Involvement of technical risks enables better approximability of model and higher accuracy in project volatility calculation. The developed model is used to quantify potential refinancing costs due to cash flow shortage, which is a risk receiving litter attention in the literature. In the second study, a new forecasting model which enables reasonably accurate prediction of expenditure cash flow of transportation design-build projects is developed, based on case-based reasoning and genetic algorithm. Lack of complete design and exact quantities for cost estimation make estimating the project payout in pre-award phase difficult. Accurate forecast on construction expenditure cash flow is crucial for state transportation agencies to secure sufficient funding to cover their annual fiscal obligations. However, there is no quantitative model to assist state DOTs in accurately forecasting expenditure cash flows for design-build projects in prior of this study. The third is a conceptual study which identifies the challenges and enabling features of small and medium infrastructure P3. In classic perspective, P3 is exclusively designed for megaprojects. However, drawn upon the transaction cost, a theoretical framework is proposed to explain the features of successful small and medium P3s. The proposed framework is validated by case studies on identified small- to medium- sized P3s in the U.S. The study also reveals the potential of the model as a supplement of existing financing methods in terms of meet ever increasingly complex social needs.

The thesis is ultimately driven by the aspiration of addressing the funding gap of building an economically, environmentally, and socially sustainable infrastructure system. In the age of analytics, infrastructure finance is becoming a multidisciplinary field requiring creative and rigorous combination of advanced analytics, project management and policy analysis. It is hoped that the work presented in this thesis can contribute to the body of knowledge by improving the use efficiency of limited infrastructure funding, by enhancing the risk assessment of infrastructure investment, and finally, by expanding available funding sources of infrastructure development.

CHAPTER 1. INTRODUCTION

1.1 Increasing Importance of Infrastructure Finance

As indicated in the summary, the funding shortage to renovate existing infrastructure facilities and to response climate and technological disruptions are causing daunting loss to every American family. State and local governments are the stewards of majority of infrastructure investment: they own 90 percent of non-defense public infrastructure assets and pay for 75 percent of maintenance and operation cost (CBPP 2019). According to statistics by National Association of State Budget Officers (NASBO 2020), sources of state funding for infrastructure include federal grants, taxes and fees (principally fuel tax and vehicle registration fees for transportation), and bonds. All these three sources are strained: from 1980 to 2015, federal infrastructure investment has fallen by half – from 1 percent to 0.5 percent of GDP (Bernstein 2015). As of 2021, it has been 28 years since the federal gas tax went up. Moreover, the U.S. municipal market is becoming less attractive to investors as a result of low interest rate (Burke and Lipshitz 2018).

Facing the challenges, U.S. government strives to enhance financial management and accountability (e.g., reducing improper payments) and actively explores innovative approaches to finance and deliver projects. For instance, financial management and innovation & the future of transportation are two of the eight identified top management challenges of U.S. Department of Transportation (US DOT 2020) in the fiscal year 2021. As US DOT indicated, financing and project delivery will ultimately transform how transportation agencies carry out their mission, shape their workforce, and deploy resources.

1.2 From Financing Sustainable Infrastructure to Financing Infrastructure Sustainably

There are two layers of meaning of the title. First, sustainable infrastructure finance should have the capability to finance sustainable infrastructure facility projects. Second, as the definition of sustainability by ASCE (n.d.) indicates, the financial activities of sustainable infrastructure system should have the capability to maintain and improve quality of life without degrading the quantity, quality, and availability of economic and social resources.

Together with environmental and social, economical is one of the three pillars constituting sustainable development of infrastructure system (Fischer and Amekudzi 2011). However, in comparison to resulting environmental impacts, less attention has been paid to the economic impact (Jeon and Amekudzi 2005). Economically, sustainable development of infrastructure requires the maintenance of healthy markets without impairing the interests of stakeholders including investors. In addition to the investment from the public sector, there is a track record of using private investment to fund infrastructure in the United States. Nevertheless, the capability of the project to deliver reasonable risk-adjusted returns and the attitudes of elected officers and the public towards private investments are two primary concerns of investors (McKinsey 2017). This opinion is back by a series of recent P3 failure in the United States. Examples include the legal disputes of the Purple Line project in Maryland over millions of dollars in cost overrun (ENR 2020), Skanska's exit of U.S. market for privatized infrastructure development after accumulating large losses on major contracts (Reina et al. 2018), and the termination of Denver airport P3 for unsatisfying cost and schedule performance

(Shaw 2019). Admittedly, private investment, or public-private partnership, is not the only innovative approach to fund infrastructure development in addition to existing funding sources. However, a more thorough and proper risk assessment of P3 will undoubtedly increase the confidence of both the private and the public sectors.

1.3 Dissertation Framing and Structure

Driven by the aspiration of helping address funding gap of sustainable infrastructure development in a sustainable manner, this thesis presents three studies. The three studies contribute to the overarching objective of this thesis from three different but interconnected aspects: (1) enhancing risk assessment regarding cash flow shortage in transportation P3 project, (2) developing an accurate forecasting model of expenditure flow for effective use of limited public funding, and (3) exploiting a novel financing mechanism for sustainable infrastructure facilities.

In Chapter 2, a real options valuation model is developed for pricing the option value of contingent finance support using subjective utility function. The study has three research objectives: (1) quantitatively reveal potential refinancing cost caused by cash flow shortage under uncertain construction cost and toll revenue conditions; (2) critically evaluate the option value of risk-sharing mechanisms in relation to saving refinancing cost and improving the profitability of project; and (3) develop a real options pricing model for risk-sharing mechanisms involving both market risks and technical risks. It is anticipated that the proposed model can help stakeholders better understand and measure the burden of assuring annual debt repayment under uncertain cash flow. The stakeholders can use the proposed model to evaluate the value of the revenue risk-sharing mechanisms on reducing refinancing cost.

In Chapter 3, an expenditure cash flow forecasting model for transportation design-build projects, based on case-based reasoning and genetic algorithm is developed. In prior of this study, there is no quantitative model to assist state DOTs in accurately forecasting expenditure cash flows for design-build projects. This research identifies that, even early at the procurement phase of a design-build project when exact quantities and detailed cost estimates have not been fully developed, the combination of conceptual project information and local construction market indicators offers the capability to predict the future expenditure cash flow of the project through establishing similarities between the project to be awarded and historical design-build projects. The forecasting model will help transportation agencies to avoid underestimating and overestimating the capital needed to build a design-build project during the contract duration. Therefore, limited financial resources of transportation government agencies will be utilized more efficiently and effectively, and likelihood of running into disputes for fund unavailability and cost overruns will be reduced.

In Chapter 4, the challenges and enabling features of small and medium infrastructure P3 are identified by using a framework drawn from the transaction cost. The proposed enabling features are supported by identified small- to medium- sized P3s in the United States. In classical perspective, projects under a certain size are not feasible for P3. However, there is an emerging trend on using P3 to deliver projects which are frequently at small- to medium- size to meet ever increasingly complex social needs, such as enhancing lifecycle performance of existing facilities, designing and building for resilience and sustainability. This study, for the first time, critically examines the enabling features of the P3 model for delivering small and medium infrastructure projects in the United States. This research sheds light on the credibility and viability of small- to medium- sized P3 and increases the confidence in policy makers to promote this model.

Finally, Chapter 5 highlights the contributions of the thesis to the body of knowledge, discusses the limitations of the research works, and foresees some avenues that can expand the use of the developed methodologies and improve the existing methodologies to the next level.

CHAPTER 2. OPTION VALUE OF CONTINGENT FINANCE SUPPORT IN TRANSPORTATION PUBLIC–PRIVATE PARTNERSHIP PROJECTS[1]

2.1 Introduction

Due to the benefits of improving investment efficiency, helping project selection, increasing competition, and extending borrowing constraints, public–private partnership (P3) is attracting governments around world to use it to design, finance, build, operate, and maintain transportation projects. A P3 turnpike project normally has a sizable amount of bank loan in its capital structure (Yescombe 2013), and the project may have the biggest debt repayment pressure at the first few years of operation. This is because the toll revenue, the major income of turnpikes, is positively correlated with the traffic volume which grows in pace with time. Given that typical turnpike projects have relatively small cash flows in the first few years of operation, the fiscal conditions of projects would worsen if the project expenditure increased as a result of commonly seen cost overrun, or the project income decreased as a result of unexpected fluctuation of the traffic volume. Cash flow shortage, a severe problem in some emerging transportation P3 markets like China (Luo and Joanna 2018, Jin and Rial 2019), happens when a project has an insufficient cash flow to serve mature debt repayment obligations. The cash flow shortage does not necessarily lead to project bankruptcy if the project successfully

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conducts a debt refinancing by borrowing a new short-term loan to repay the existing mature debt. Nevertheless, the cash flow shortage inevitably increases the credit and default risk of the project (Caballero and Kurlat 2009). More intuitively, refinancing increases unexpected expenditure and further decreases the profitability of the project. Owing to the immature financial markets in these emerging P3 markets, these projects normally do not have effective financial instruments such as toll revenue bonds for risk hedging. Thus, risk-sharing mechanisms provided by the public sector (i.e., owner) become the principal, sometimes even the only, risk-sharing tools for the private sector (i.e., the concessionaire). It is worthy to note that the risk-sharing mechanisms discussed in this study are instruments of revenue risk concessions. However, another type of concession, availability payments, is gaining ever-increasing popularity in the UK, Australia, Canada, and U.S. markets in recent years.

Public and private information are two distinctive types of information in financial valuation. In financial market, public information refers to the publicly available information which is normally released as required by regulation, such as macroeconomic data. While private information includes knowledge of the quality of a specific firm's product, the management quality and prospects of a specific firm, and the strength and strategies of a firm's potential competitors (Gyntelberg et al. 2009). In the context of highway P3, projected future traffic volume can be classified as public information, and technical risks, such as the probability distribution of construction cost overrun of the general contractor, belong to private information. Stemming from mathematical finance, people use risk neutral valuation to price risk-sharing mechanisms of highway P3. To reflect the risk averseness of the overall market to a specific asset, risk neutral valuation uses market risk premium to adjust the probability of the underlying risks of asset (Luenberger 1998; Hull 2008). However, as the name of market risk premium implies, only the risks falling within the range of public information have corresponding market risk premiums. It is impossible to apply risk neutral approach on the risks falling within the range of private information, by using market risk premium which represents the risk averseness of the overall market.

Therefore, this study has three overarching objectives: (1) quantitatively reveal potential refinancing cost caused by cash flow shortage under uncertain construction cost and toll revenue conditions; (2) critically evaluate the option value of risk-sharing mechanisms in relation to saving refinancing cost and improving the profitability of project; and (3) develop a real options pricing model for risk-sharing mechanisms involving both market risks and technical risks. The refinancing in this study is restricted to necessary actions under cash flow shortage and debt repayment pressure, excluding the exchange of loan agreements aiming at potential savings on debt payments. When the project is successfully completed, refinancing could provide the developer a lower interest rate, and consequently reduce the project's burden on debt repayment.

2.2 Literature Review

This section is comprised of three parts. Each part aims at answering one of the following questions, respectively. The three corresponding questions are: (1) what risk-sharing mechanisms should be included in this study; (2) what is the necessity to develop a new real options model for the research objectives of this study; and (3) what is the potential solution to the development of a new real options model?

2.2.1 Review of Revenue Risk-Sharing Mechanisms

Traffic volume which is significantly lower than that forecasted is found to be one of the principal reasons for the bankruptcy of P3 turnpike projects (Parsons et al. 2016). Studies have shown that traffic and revenue forecast tend to suffer “optimism bias.” The traffic volume is often overestimated because of difficulties in predicting economic conditions, demographic trends, or change in technology (FHWA 2016). Besides the risk of uncertain project revenues, the private sector under a P3 framework predominantly bears the risk of construction cost overrun. That is underscored by the nature of performance based P3 contract (Nguyen et al. 2018). Up to now, there is no sufficient empirical evidence to prove that construction cost overrun, a common risk of transportation projects, has generally vanished in P3 projects. It applies to both developed economies like the United States (Daito and Gifford 2014) and developing economies like India (Rajan et al. 2014). To create a fair business environment and to promote collaboration between the concessionaire and the government, risk-sharing mechanisms were developed for risk sharing. Revenue risk-sharing mechanisms that tend to mitigate cash flow volatility have potentials to incentivize private sector developers and investors (Mostaan and Ashuri 2017).

FHWA generalized common revenue risk-sharing mechanisms used in transportation P3 projects (FHWA 2016). Among the mentioned revenue risk-sharing mechanisms, contingent finance support and minimum revenue guarantee have best overall performance in the aspects of value of money, fiscal impact, financeability, and ease of implementation. Contingent finance support is being tested in the I-77 Express Lanes Project in North Carolina. Minimum revenue guarantee is being implemented in the SH 288 Toll Lanes Project in Texas. Under a contingent finance support mechanism, government provides a guarantee on the repayment of financing instead of a guarantee on revenue. Therefore, there is no refinancing cost under a contingent finance support mechanism and no extra cash flow besides debt repayment will be generated. P3 projects with uncertain cash flow are less attractive to some lenders, compared with other investment alternatives (e.g., bonds), as a result of lacking related knowledge (Carrillo et al. 2008, Chan et al. 2010). Contingent finance support secures the debt repayment and significantly decreases the lenders' risk exposure. Therefore, contingent finance support is taken as an important factor in lenders' decision to lend (Tang et al. 2010). Compared with other revenue risk-sharing mechanisms, the evaluation of contingent finance support receives little attention in literature. Thus, contingent finance support is selected as the risk-sharing mechanisms to be explored in this study.

Rather than directly securing debt repayment, the minimum revenue guarantee is designed for reducing the revenue variability, and it is found to be most applicable to projects with significant revenue volatility (Liu et al. 2017). Under a minimum revenue guarantee, government agency partially retains the revenue risk by guaranteeing toll revenues below a certain negotiated threshold of the forecasted future traffic. Over the life of project, the concessionaire may or may not have the chance to adjust toll rates. It is subject to many factors, such as the renegotiations and specific regulations. Concessionaires may need to pay for the refinancing, if necessary, yet they could expect the mechanism generating extra cash flow to increase the profitability even when there is no gap in debt repayment. Considering the overall performance and popularity, minimum revenue guarantee was selected for benchmarking the option value of contingent finance support.

2.2.2 Review of Existing Real Options Analysis for Highway P3

As the state-of-art financial engineering instrument which provides evaluation on investment opportunities under uncertain market conditions, real options analysis has been used by many prior researchers to explore various kinds of options in transportation infrastructure investment. Real options analysis works for evaluating revenue risk-sharing mechanisms because these mechanisms are essentially options that could be triggered under certain unfavorable market conditions. These mechanisms are options which can bring benefits to the concessionaire.

There is a large body of literature using real options analysis to evaluate revenue risk-sharing mechanisms. By using a binomial lattice model, Ho and Liu simulated traffic volume evolvements and discussed the financial viability of Build–Operate–Transfer projects (Ho and Liu 2002). Ashuri et al. (2012) evaluated the minimum revenue guarantee option by taking a risk neutral method internalizing traffic demands risk. By way of constructing an analytical stochastics model to simulate dynamic traffic volume evolvements, researchers conducted a series of studies to evaluate the option values of revenue risk-sharing mechanisms. Brandao and Saraiva (2008) measured the value of minimum traffic guarantee. Zhao et al. (2004) created a decision-making tool considering different project uncertainties. Garvin and Cheah (2004) explored the strategic value of project deferment. Huang and Chou (2006) performed a compound option pricing to evaluate the option to abandon. Chiara et al. (2007) used European, Bermudan, and Australian options to valuate governmental guarantees. With nine different traffic volume scenarios, Chen et al. (2018) modeled a toll-adjustment mechanism as a real option to assess the value of the flexibility on toll adjustments. Real options analysis was also conducted for other dynamic conditions besides traffic volume. Cheah and Liu (2006) evaluated government guarantees and subsidies. Liu et al. (2014) explored restriction competition in P3 projects. Mirzadeh and Birgisson (2016) used a two-step binomial pyramid as the valuation framework for two risk variables and evaluated the option value of price adjustment clauses.

Existing studies imply two directions for further improvement. First, in addition to the risk of uncertain traffic volume, which could be measured by a market risk premium, some technical risks (e.g., construction cost overrun) do not have hands-on equivalent market risk premiums. In a risk-neutral valuation process, the probabilities of future asset values are first to be adjusted with risk premiums reflecting the decision maker's risk aversion, and then, the option value can be calculated with risk-free rate. Second, there is necessity to develop a model having the capability to include various risks. In contrast to the uncertain traffic volume, which could be described as a time-dependent, stochastic process, some risks should be described as random variables. Examples include uncertain prices of steel (Faghih and Kashani 2018), and potential geotechnical hazards (del Puerto et al. 2017). Therefore, this study proposes using utility function to generate risk-adjusted subjective probabilities for technical risks to incorporate the technical risks. This process is equivalent to the process of generating risk-neutral probabilities using market risk premiums. A model incorporating both market risks and technical risks has better approximability and higher accuracy in calculating project volatility, in comparison to a model merely considering market risks. Accurate calculation of project volatility plays a crucial role in improving binomial lattice real options model (Brandao et al. 2012).

2.2.3 Review of Subjective Probability and Its Application in Financial Valuation of Construction Projects

In the seminal work *The Foundations of Statistics*, Savage (1972) proposed the concept of subjective probability to describe the personal risk perceptions of decision-makers. The vitality of subjective probability comes from not only individual belief, also the wide existence of real-world risks which are not well delineated, such as "What is the probability that Miami will be underwater because of sea level rise in 2050?". In contrast to the risk analysis methods that are entirely based on inputs from subject matter experts on certain specific issues, the subjective probability proposed by Savage uses a Bayesian approach to incorporate the risk preference of an individual with objective prior probability. The individual risk preference coming from long-term, systematical observation helps contextualize objective, but sometimes generic, prior probability. Subjective expected utility, the combination of subjective probability and individual utility function, can be used to describe the attractiveness of an investment option as perceived by a decision-maker.

Song et al. (2012) proposed a model using alternative dispute-resolution (ADR) implementation insurance as a risk management tool for construction dispute resolution. In the model, Song et al. used subjective probability of expected loss to represent the risk aversion of project participants and to quantify the ADR-implementation costs. In a following work, Song et al. (2014) proposed an advanced model with two more specific insurance limits to help determine the optimal point on the total expected subjective loss curve of the project participants. In the case of this study, the use of subjective probability of technical risk provides decision-makers a reasonable risk premium for risk neutral valuation when there is no available market risk premium. The risk premium represents the strategic attitude and management capacity of the decision-maker towards a specific technical risk.

2.3 Model Development

The proposed model consists of three parts. The first part describes risk-adjusted subjective probability distribution of construction cost overrun and the second part describes uncertainty of future values of annual average daily traffic (AADT). In the third part, a Monte Carlo simulation was performed to characterize concessionaire's risk profile in relation to serving annual debt repayment under uncertain cash flow without revenue risk-sharing mechanisms, with contingent finance support, and with minimum revenue guarantee, respectively. In the section of numerical example, project-specific data will be plugged into the model, such as parameters of variables (e.g., the average growth rate of AADT, parameters of utility function), capital composition, and loan details (e.g., interest rate, loan term, repayment method).

2.3.1 Risk-Adjusted Subjective Probability Distribution for Construction Cost Overrun

As previously mentioned, the best fit probability distribution of construction cost overrun is private information owned by individual practitioners. To generate a best fit probability distribution, it is required to have an available and accessible database. Even though the distribution may vary with project features such as locations, project sizes, and project types, the distributions summarized in the literature could be used for model construction without loss of generality. Love et al. (2015) used the data of road construction projects and identified that the best fit probability distribution of cost overrun is loglogistic distribution. Eq. (3-1) is the probability distribution function of log-logistic distribution with shape parameter α (α>0), scale parameter β (β>0), and location parameter γ (x∈ [γ, +∞)). The mean value of road construction projects' cost overrun rate in Love's et al study is 13.55%, which falls in the range of that value in the literature, i.e., 4% to 14% (Ellis et al. 2007, Odeck 2004, FHWA 2018). This study borrows the values of α, β, and γ from Love's et al study to construct the model.

$$f(x) = \frac{\alpha}{\beta}(\frac{x-\gamma}{\beta})^{\alpha-1}[1 + (\frac{x-\gamma}{\beta})^{\alpha}]^{-2} \qquad \text{Eq. (2-1)}$$

Risk premium, which is frequently seen in investment decision, represents risk aversion of investors. Considering that the probability distribution shown as Eq. (2-1) is generated from objective project data and there is no hands-on market risk premium for the risk of construction cost overrun, utility theory was applied to create risk-adjusted subjective probability distribution. The risk-adjusted subjective probability distribution internalizes the risk preference of decision makers. Dissimilar to the utility functions with variables as input, the input of the utility function of construction expenditure is cash flow because expenditure happens repeatedly over time.

The utility function for cash flow has unique characteristics. Let c_i, c_i' ($c_i < c_i'$) denote two reward scenarios at time i, and let c_j, c_j' ($c_j < c_j'$) denote two reward scenarios at time j ($i \neq j$). (c_i, c_j') denotes the cash flow having c_i and c_j'. Assume there are two portfolios A and B which have the same n payment periods. Portfolio A has equal probability to get reward (c_i, c_j') and (c_i', c_j) while the portfolio B has equal probability to get reward (c_i, c_j) and (c_i', c_j'). The cash flows of portfolio A and B at any time points except i and j are fixed (i.e. $\forall c_k, k \in [1, n], k \neq i, j$)). According to the definition given by Meyer (1972), a multivariate risk-averse investor will always prefer portfolio A over B, even though portfolio A and B have equal marginal probability distribution of each c_t ($t \in [1, n]$). Preference for portfolio A over B reflects the fact that many investors are inclined to smooth cash flows rather than fluctuate cash flows. A proper utility function for construction disbursement should be able to represent multivariate risk aversion. As Fraser (1990) demonstrated, the form of function in Eq. (2-2) is a simple and intuitive way to represent multivariate risk aversion, where $g(\cdot)$ denotes the utility function of the net present value (NPV).

$$u(c_0, c_1, \ldots, c_n) = g(NPV(c_0, c_1, \ldots, c_n)) \qquad \text{Eq. (2-2)}$$

Exponential utility function denoted as $u(x) = (1 - \exp(-ax))/a$ is commonly used in economics to represent risk attitudes, and it is a suitable form for $g(\cdot)$ in Eq. (2-2). In this study, exponential utility is expressed as the simplified form shown in Eq. (2-3), because the linear transformation of utility function does not influence the calculation of risk premium. In Eq. (2-3), ρ denotes the risk tolerance of private sector, and the value of ρ is proportional to the company's equity. The utility function shown as Eq. (2-3) has the capability to express an investor's different utilities towards a same project under different circumstances.

$$g(x) = 1 - exp\,(\frac{x}{\rho}) \qquad \text{Eq. (2-3)}$$

McNamee and Celona (1972) gave an estimation of ρ based on observations across companies in different industries, which is about one sixth of the company equity. This result keeps aligned with the results of a previous studied conducted by Howard (1990), whose data were from a single industry. However, it is worthy to note that one sixth is only a rule of thumb under general conditions. The value could always be updated if there are any studies dedicated to the transportation P3 market. The users of the proposed framework are also encouraged to substitute the value based on their specific experience and information on hand.

As Eq. (2-2) transforms the utility function of cash flow into the utility function of NPV, the certainty equivalent (CE) of expected utility of disbursements can be expresses as follows:

$$-\exp\left(\frac{-CE}{\rho}\right) = -\int \exp\left(\frac{-(1+r_c)x_0}{\rho}\right) \cdot f(r_c) \cdot dr_c \qquad \text{Eq. (2-4)}$$

where r_c = the cost overrun rate with PDF $f(r_c)$ in form of Equation (2-1); x_0 = the estimated construction cost at the time of contract award. Thus, the ratio of risk premium for construction cost overrun p_c is

$$p_c = \frac{CE - x_0}{x_0} \times 100\% \qquad \text{Eq. (2-5)}$$

Risk-adjusted subjective probability distribution of construction cost overrun r_c' which incorporates the risk effects could be denoted as:

$$r_c' = p_c + r_c \qquad \text{Eq. (2-6)}$$

The PDF of r_c and the PDF of r_c' have following relationship, since r_c' is the mathematical artifact generated from r_c.

$$f_{R_c'}(r_c') = f_{R_c}(r_c) \quad \text{Eq. (2-7)}$$

where f_{R_c} = the PDF of r_c; $f_{R_c'}$ = the PDF of r_c'.

2.3.2 Binomial Lattice for Uncertain Future Traffic Volume

Binomial lattice model was applied in this study to describe future traffic volume, with the assumption that traffic volume follows geometric Brownian motion (GBM). GBM assumption frequently appears in real options analysis involving long-term traffic volume forecast (e.g., Ashuri et al. 2012, Brandao and Saraiva 2008, Garvin et al. 2004). The assumption has been justified by researchers from different aspects. For example, Solino and Lara Galera (2012) statistically demonstrated the rationality of the assumption by analyzing the turnpikes in Spain. Afterwards, Lara Galera and Soliño (2010) successfully applied the theory in their real options analysis on highway concessions. Shah and Jammalamadaka (2017) used BMMR, a kind of Brownian models to simulate the future traffic of the Massachusetts Turnpike system and achieved satisfying accuracies. Given that the initial state is known, binomial lattice is a frequently used tool in mathematical finance to demonstrate the state at a certain time of a continuous stochastic process, such as GBM. For any state in the binominal lattice model having value S, there are always two possible values for the following state. The following state has probability p $(0 < p < 1)$ to be $u \cdot S$ and has probability $1 - p$ to be $d \cdot S$. d and u $(d < 1 < u)$ are reciprocals to each other. Even though the binomial lattice model treats a continuous process as if it were discrete, the model will have a good approximation after short periods if the basic period length between adjacent states is short enough (Luenberger 2013). Taking basic period length Δ as one month (i.e., Δ=1/12year), the binomial lattice model can be specified with parameters in Eq. (2-8):

$$u = e^{\sigma\sqrt{\Delta}} \qquad d = e^{-\sigma\sqrt{\Delta}} \qquad p = \frac{1}{2} + \frac{\mu}{2\sigma}\sqrt{\Delta} \qquad \text{Eq. (2-8)}$$

where $\mu = E[\ln(\frac{AADT_{n+1}}{AADT_n})]$; $\sigma = SD\left[\ln\left(\frac{AADT_{n+1}}{AADT_n}\right)\right]$ (i.e., the volatility of AADT); AADT_n = the value of AADT in the nth year.

To internalize the risk of uncertain traffic volume into the binominal lattice model, Ashuri et al. (2011, 2012) suggested to subtract the market risk premium from the revenue growth rate, i.e., the AADT growth rate. In finance, a specific market risk premium could be expressed as the product of the specific risk volatility and Sharpe ratio. Sharpe ratio is defined as the excess return, i.e., risk premium, per unit of deviation in an investment asset. In this paper, the adjusted annual growth rate of AADT a' can be specified as follows:

$$a' = a - \sigma \cdot \frac{r_s}{\sigma_p} \qquad \text{Eq. (2-9)}$$

where $a = \frac{AADT_{n+1}}{AADT_n}$ (i.e., the annual growth rate of AADT); r_s = the cost of capital − risk-free interest rate; $\sigma_p = SD[\ln\left(\frac{PV_1}{PV_0}\right)]$ (i.e., the volatility of the project); PV_i = the present value of project at the end of year i, ($i = 0,1$).

2.3.3 Monte Carlo Simulation

Monte Carlo Simulation helps the authors generate different cost overrun rates and series of random paths in the traffic volume evolution. The cost overrun rates and the random paths of traffic volume evolvement are assumed as statistically independent in the proposed integrated model. The authors characterized the potential refinancing cost and the option value of Contingent Finance Support. The option value of Contingent Finance Support was then compared with that of Minimum Revenue Guarantee. In the ith year of each generated n-year random path, the annual taxable income of the project S_i is expressed as Eq. (2-10)

$$\mathrm{S}_i = \mathrm{OR}_i - \mathrm{OC}_i - \mathrm{LRS}_i - \mathrm{LRL} \qquad i = 1, 2, 3, \dots, n \qquad \text{Eq. (2-10)}$$

where OR_i = operation revenue in the ith year; OC_i = operation cost in the ith year; LRS_i = short-term loan repayment in the ith year; LRL = annual long-term loan repayment. The variables OR_i, OC_i, LRS_i and LRL in Eq. (2-10) can be calculated as follows:

$$\mathrm{OR}_i = \text{Ancillary Revenue} + 365 \cdot \mathrm{AADT}_i \cdot \text{Toll Fee} \qquad \text{Eq. (2-11)}$$

$$\mathrm{OC}_i = \text{Initial Operation Cost} \cdot (1 + \text{Expected Annual Growth Rate})^{i-1}$$

Eq. (2-12)

$$\mathrm{LRS}_i = \begin{cases} (1 + \mathrm{APR}_s)|\mathrm{L}_{i-1} + \mathrm{S}_{i-1}| & \text{if } \mathrm{L}_{i-1} + \mathrm{S}_{i-1} < 0 \\ 0 & otherwise \end{cases}$$

Eq. (2-13)

$$\mathrm{LRL} = \frac{\text{Total Loan} \cdot (1 + r_c{}') \cdot \mathrm{APR}_l \cdot (1 + \mathrm{APR}_l)^n)}{(1 + \mathrm{APR}_l)^n - 1} \qquad \text{Eq. (2-14)}$$

where APR_l = annual percentage rate of long-term loan; APR_s = annual percentage rate of short-term loan; L_i= liquidity available in the ith year. Annual after-tax income is the source of liquidity. The amount of available liquidity is assumed not to exceed the predefined value. In addition, the present value of refinancing cost RC can be calculated as follows:

$$\mathrm{PV(RC)} = \frac{\sum_{i=1}^{n}[(1+\mathrm{MARR})^{n-i} \cdot \mathrm{LRS}_i \cdot \frac{\mathrm{APR}_S}{(1+\mathrm{APR}_S)}]}{(1+r)^{(n-1)}} \quad \text{Eq. (2-15)}$$

where $r =$ risk-free discount rate; MARR= minimum acceptable rate of return. In the case of Minimum Revenue Guarantee is provided, the operation revenue under guarantee OR'_i can be calculated by substituting AADT_i with AADT'_i, and AADT'_i can be calculated as follows:

$$\mathrm{AADT}'_i = \max\,(r_g \cdot \text{ Static Estimation of } \mathrm{AADT}_i, \text{Actual } \mathrm{AADT}_i) \quad \text{Eq. (2-16)}$$

where $r_g =$ the guaranteed rate of traffic volume specified in contract. In case of Contingent Finance Support is provided, the refinancing cost reduces to zero because with such a mechanism, debt repayment is secured by government. The option value of Contingent Finance Support equals to the refinancing cost under cash flow shortage.

2.4 Numerical Example

2.4.1 Project Information

The Capital Beltway of China (Daxing to Tongzhou section) is a 38km highway located at the newly proposed sub-center of Beijing, which aims to accommodate 1.3 million permanent residents by 2035 (China Daily 2020). Expected population and employment growth due to new development are factors with significant impacts on the forecast of future traffic growth rate (Georgia DOT n.d.). A joint venture leading by China Communications Construction Company won the $1.99 billion bid and got a 25-year concession period from the date construction completed (2019-2043). The capital structure of this project is 80% equity and 20% bank loans. Interest payments start at the end of the first construction year, and principal payments start at the end of the first operation year. In this project, APR_l is 5.9% and APR_s of accessible short-term loan (<1 year) is 5.25%. The loan takes an equal payment plan and will mature at the last year of concession period.

The main source of project cash inflows is the anticipated annual toll revenues based on forecasted traffic volume. Expectation of the initial (i.e., 2019) annual average daily traffic (AADT) is 16,715 passenger car unit (pcu). Predictions of expected annual average AADT growth rate are 31.3% from 2019 to 2023, 7.9% from 2024 to 2028, 2.0% from 2029 to 2033, and 0.9% from 2034 to 2038. Moreover, the cap capacity of the highway is 120% of the static estimation. Negotiated toll rate is $0.25/ (pcu·km). Concessionaire can also expect to earn about $0.81 million derived profits from affiliated facilities along the highway (e.g., retail revenues from gas stations) besides toll revenues. The amount of the affiliated facility revenues is expected to increase commensurate with tolls (i.e., traffic). The growth rates of affiliated facility revenues are approximated by the growth rates of traffic. The expenditure of operation and maintenance comes from project cash inflows, which is $23.83 million in 2019 and would grow by 5% in each following year. In addition, the business tax rate is 25%.

For greenfield projects with no historical traffic data, the traffic volatility could be approximated by using macroeconomic indexes such as the volatility of stock market

(Huang and Chou 2006, Banister 2005). Based on the Shanghai Stock Exchange 50 ETF Volatility Index, the annualized value of the volatility of AADT σ is supposed to be 10%. 8%, 20%, and 30% were also substituted into the model as values of the volatility of AADT for sensitivity test. Project discount rate (4.425%) is the sum of risk-free interest (3.835%) and interest spread (0.59%). Concessionaire plans to keep $0.11 million liquidity reserve from 2019 to 2028, and to keep $0.16 million as liquidity from 2029 to 2038. Beijing City Government is considering offering concessionaire one of the two options: (1) Contingent Finance Support; and (2) Minimum Revenue Guarantee from 2019 to 2038, whose guarantee rate is 80%.

2.4.2 Summary of Results

To increase the accuracy of traffic forecasts, some analysts may assume demand "ramp-up" over the first few years of a scheme up to the full modelled demand, such as 50% of the total demand in the first year. However, there are some disagreements on the effects of "ramp-up" in terms of increasing the forecast accuracy. For example, Flyvbjerg (2005) claimed that although ideally studies should take into the demand "ramp-up" over the first few years, there is a lack of empirical evidence supported by statistical analysis, at least not for large-N studies. Comprehensively considering the arguments in literature, the "ramp-up" approach was not adopted in this study.

Plugging in the budgeted construction cost into the applied probability distribution of construction cost overrun rate, the mean value of the potential construction cost overrun of the specific example would be $268.7 million, which is 13.5% of the contract amount. This amount roughly equals to the expected operation profits of the first four years.

The project volatility σ_p is defined as the standard deviation of the project's log-return present value distribution (i.e., $\ln(\mathrm{PV}_1/\mathrm{PV}_0)$). The project's log-return present value is the log-ratio of the concessionaire's first-year present value (i.e., PV_1) to the concessionaire's initial present value (PV_0). In the simulation, both the initial present value and the first-year present value are variable. The initial present value is computed based on the variable construction cost and the constant, most likely forecast of the future traffic. The first-year present value is computed based on the variable construction cost and the generated random paths of future traffic.

According to the simulation results, the standard deviation of the log-return, i.e., $\ln(\mathrm{PV}_1/\mathrm{PV}_0)$, is 52.4%. This is the value of the project volatility of the case, i.e., $\sigma_p =$ 52.4% per year. This value is obtained from the calculation considering two risk factors, i.e., construction cost overrun and uncertain future traffic. The value of project volatility considering only uncertain future traffic is 30.2%. The difference reveals that the project volatility would be obviously underestimated if important uncertain factors, such as construction cost overrun, are not included in the model. As the value of project volatility is used throughout the model, the improvement of the project volatility's accuracy may obviously improve the accuracy of simulation result. This validates the importance of a model's capability to involve various risk factors besides the uncertain future traffic, which is frequently talked about in the literature, such as construction cost overrun.

Although the project is supposed to be able to pay annual debt payment under static measurement, the project has a relatively high cash flow shortage risk in the first

10% (i.e., two years) of the repayment period under dynamic measurement, as shown in Figure 2-1(a). The simulation results show that the project may not encounter the cash flow shortage risk in the later 75% of the repayment period. Ignoring the variability of project expenditure (i.e., cash outflows) and project revenue (i.e., cash inflows) when designing debt schedule may lead to a huge loss. As shown in Figure 1(b), the expectation of loss due to refinancing under cash flow shortage may as high as 6.5% (i.e., 25.827 million USD) of the principal amount of the debt.

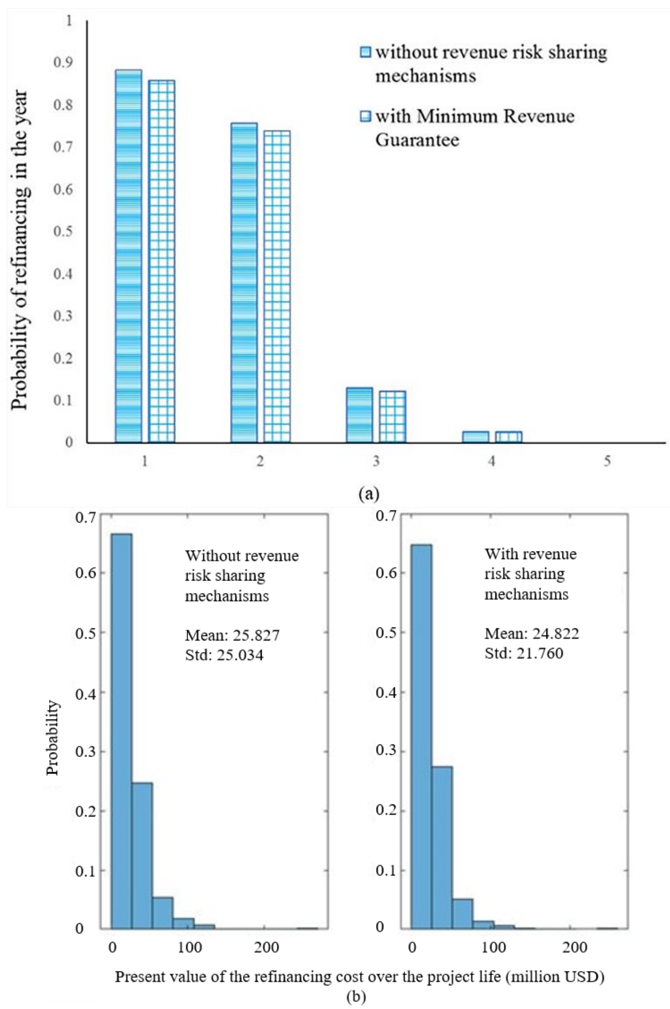


Figure 1 (a) Probability distribution of the year in which the project requires refinancing, and (b) probability distribution of refinancing cost under different conditions.

The difference of Contingent Finance Support and Minimum Revenue Guarantee is clearly revealed by their definitions. As a mechanism designed for securing debt repayment, Contingent Finance Support covers all repayment gaps, and its option value is exactly the probable refinancing cost under cash flow shortage. Contingent Finance Support provides no extra cash inflows as subsidies besides that necessary for debt repayment. On contrast, Minimum Revenue Guarantee, designed for securing minimum revenue, has a modest effect on either reducing the frequency of cash flow shortage risk (Figure 1(a)), or helping save refinancing cost (Figure 1(b)). Nevertheless, Minimum Revenue Guarantee may provide subsidies throughout the contract duration even if the project does not have a debt repayment gap in that year (Figure 2(a) and Figure 2(b)). Table 1 provides a comprehensive comparison on the option values of Contingent Finance Support and Minimum Revenue Guarantee over the project life. The option values were converted to NPV. It is found out that in the above case, Contingent Finance Support is more effective than Minimum Revenue Guarantee in terms of reducing debt repayment burden at the first few years of the repayment period, and Minimum Revenue Guarantee outperforms Contingent Finance Support in overall option value by serving as a profit guarantee.

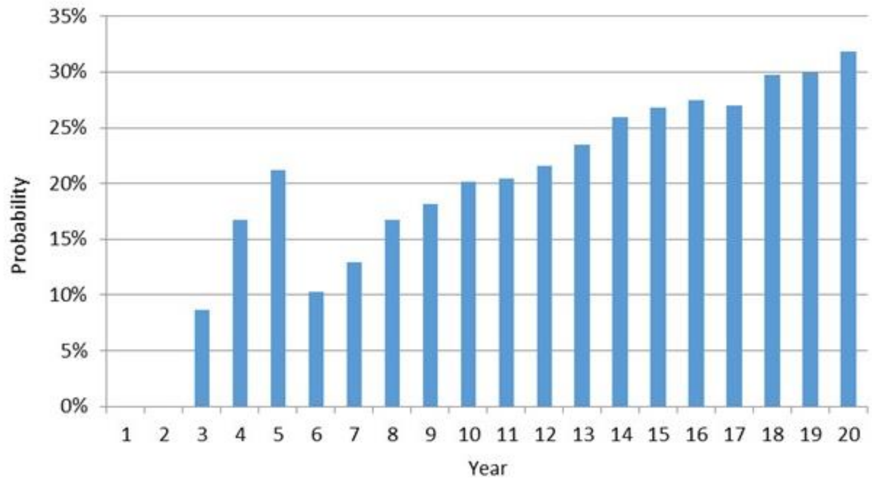
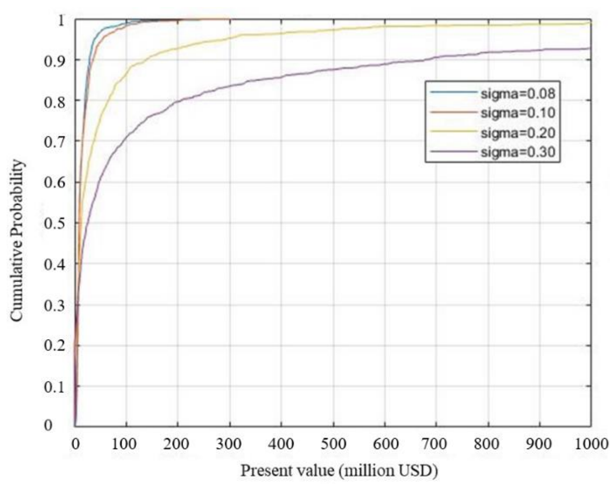


Figure 2 Probability distribution of the year in which minimum revenue guarantee is required and no repayment gap exists.

Table 1. Option value of minimum revenue guarantee and contingent finance support

Revenue risk sharing mechanisms	**Value in saving refinancing cost for debt repayment**	**Value in generating extra cash flow for profit**	**Sum**
Contingent Finance Support	25.827 million USD	0	25.827 million USD
Minimum Revenue Guarantee	1.005 million USD	90.300 million USD	91.305 million USD

Various scenarios were simulated with traffic volatility $\sigma = 8\%$, 20%, and 30% for sensitivity test. The simulation results are shown in Figure 3 and Table 2. Simulation results indicate that higher traffic volatility leads to greater risk in cash flow shortage and higher associated refinancing cost. Static condition is an extreme case where $\sigma = 0$ and the project cash flow would be sufficient for debt repayment. Figure 3 shows the impacts of project volatility on the probability distribution of the refinancing spending which the project may face over the life. As the increase of project volatility, there would be higher refinancing cost when no revenue risk sharing mechanisms is provided (Figure 3(a)). With the Contingent Financial Support, the project would be immune from the refinancing spending. Thus, the project volatility may have no impact on the probability distribution of the refinancing cost, and the refinancing cost would always be zero. With Minimum Revenue Guarantee, the project may have higher refinancing cost as the increase of project volatility. But the impact of the project volatility is much less than its counterpart in the case of no revenue risk sharing mechanisms is provided (Figure 3(b)). The increase in project volatility would improve the option values of both Contingent Finance Support and Minimum Revenue Guarantee with respect to saving refinancing cost.



(a)

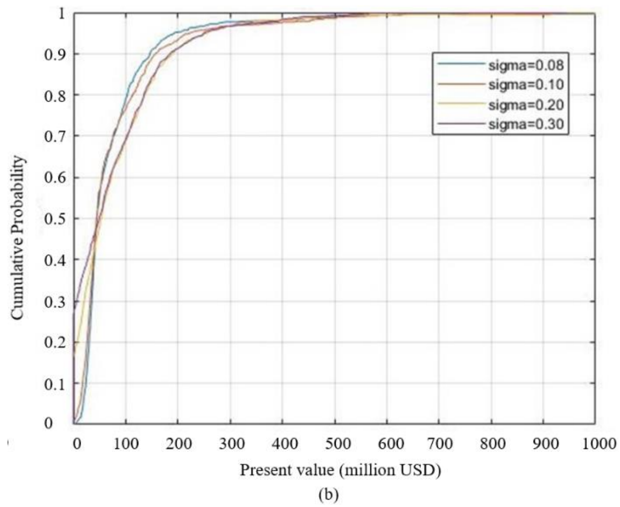


Figure 3 (a) Probability distribution of the refinancing cost under different traffic volatilities (without revenue risk-sharing mechanisms), and (b) probability distribution of the refinancing cost under different traffic volatilities (with minimum revenue guarantee).

Table 2. Expected refinancing cost over the project life under different scenarios (million USD)

Traffic volatility / Risk sharing mechanism	8%	10%	20%	30%
None	19.2	25.8	96.7	170.3
Contingent Finance Support	0	0	0	0
Minimum Revenue Guarantee	23.8	24.8	25.3	26.2

2.5 Conclusions

The beginning phase of a P3 transportation project normally has bigger debt repayment pressure due to comparatively weak revenue cash flow. The debt repayment burden may be even heavier if the project experienced cost overrun. Even though the project was regarded as being capable to service debt repayment under static measurement, the project with uncertain project revenue and uncertain project expenditure is probable to suffer cash flow shortage and has to go refinancing.

Refinancing generates sizable, unexpected expenditure and undermines the profitability of the project. Revenue risk sharing mechanisms stabilize the cash flow and reduce the refinancing cost under unfavorable conditions.

In the specific example of this study, the low initial forecasted traffic, the characteristics of the traffic growth, and the equal debt payment plan collectively contribute to the high cash flow shortage risk at the beginning of the project. The low initial traffic and the high forecasted traffic growth over the first few years imply that the toll revenues at the beginning of the project would be obviously lower than the toll revenue of later years. However, the proposed debt payment schedule is equal across years. The severity of the risk increases as the growth of the project volatility. The project volatility comes from the project's uncertain factors, namely the potential construction cost overrun and the uncertain future traffic in the example. In the case of the example, Minimum Revenue Guarantee, which is originally designed as a profit guarantee, may have limited effects on securing enough cash flow for debt repayment. Even so, Minimum Revenue Guarantee helps to stabilize the potential refinancing cost within a small range as the changes of traffic volatility. On the other hand, as the mechanism dedicated to the mitigation of debt repayment risk, Contingent Finance Support could protect the project from the potential refinancing caused by repayment risk, no matter the project volatility. Despite the disadvantage in the aspect of reducing debt repayment risk, Minimum Revenue Guarantee generally outperforms Contingent Finance Support by providing much more extra cash flow for profits. As the two options have different kinds of strengths, the stakeholders are suggested to make their decisions based on their specific circumstances and concerns.

The contributions of this study are fourfold. First, unlike the previous models mainly focusing on market risks, the proposed integrated real options model provides analysts a decision-making tool involving both market risks which have hands-on market risk premium (e.g., future traffic) and technical risks which do not have hands-on market risk premium (e.g., construction cost overruns). The involved risk factors could be either random processes or random variables; and the involved risk factors could be related to either cash inflows or cash outflows. Second, the proposed model evaluates the potential refinancing risk which receives little attention in literature. The proposed model helps stakeholders have a better understanding on the burden of assuring debt repayment under uncertain conditions. Third, utility theory is involved in the proposed model, which enables the users to specialize their decision-making processes based on their specific conditions. Lastly, the paper comprehensively discusses the option values of Contingent Finance Support and Minimum Revenue Guarantee in terms of saving refinancing cost under uncertainties and improving the profitability of the project. There are almost no prior studies pricing the option value of Contingent Finance Support.

The proposed model contains two uncertain factors, but it would not essentially change the modelling process if more uncertain factors were involved. The potential difficulties of model transfer or model application may lie in properly deciding the coefficients related to technical risks, namely the investor's risk tolerance, the probability distribution of a specific project's construction cost overrun rate, and the volatility of the traffic volume in this case. The values of these coefficients are private information. Thus, historical data and an analyst's experience would play crucial roles in making proper decisions.

The study conducts a primary discussion on the topic of refinancing which has the room for further development. Meeting Debt Service Coverage ratio (DSCR) is a common reason for refinancing, and it should be considered in the future studies. The effect of transaction costs on refinancing should also be considered, without which the refinancing cost might be underestimated. Confined by the word limit, some points are just briefly mentioned in this paper, and they could be further discussed in future. For example, it is necessary to explore the expectations of the discounted cash flows provided by different options. It is also valuable to explore the turning point(s) at which an option outperforms another, by both simulation approach and theoretical approach.

CHAPTER 3. FORECASTING THE CONSTRUCTION EXPENDITURE CASH FLOW FOR TRANSPORTATION DESIGN-BUILD PROJECTS WITH A CASE-BASED REASONING MODEL[2]

3.1 Introduction

Funding availability plays a major role in determining strategic priorities for the long-range statewide transportation development plan. State departments of transportation (state DOTs) have implemented transportation financial plans, such as Transportation Improvement Program (TIP) and Statewide Transportation Improvement Program (STIP), to utilize federal and state transportation funding within at least a four-year horizon, and possibly longer. It is critical for state DOTs to maintain adequate cash balance that helps establish clear transportation plan and program (NASEM 2017). In recent years, a variety of issues, including changing economic conditions, delayed federal transportation reauthorization bills, and the declining value of fuel tax, have affected the ability of state DOTs to provide an adequate budget for building new capacity and performing necessary maintenance on existing infrastructure (Rall et al. 2010, US DOT 2019). Considering significant uncertainty about project cost and construction market conditions, state DOTs have faced great challenges to manage construction expenditure cash flow of transportation projects (Camph 2008). Under these circumstances, an accurate construction expenditure forecasting model would help state DOTs by

[2] This chapter was published as a journal article in ASCE Journal of Construction Engineering and Management with Baabak Ashuri and Mingshu Li as the co-authors. The citation for the journal article is as follows: Liang, Y., *Ashuri, B., and Li, M. "Forecasting Construction Expenditure Flows for Transportation Design-Build Projects through Case-Based Reasoning Approach." ASCE Journal of Construction Engineering and Management, 2021, 147(6): 04021043.

presenting a realistic view of expenditures in a given fiscal period. Driving for an expenditure cash flow model is not the sole justification for this research. The need can be driven by better management of the limited budget of state transportation agencies, not running into disputes for fund unavailability and cost overruns as identified by Poister (2010).

The work on forecasting expenditure cash flow for transportation projects is relatively underrepresented in the literature. Two studies were focused on fitting a mathematical function to model the cash flow of expenditure records of transportation projects. In the first study, Jarrah et al. (2007) classified 245 Texas DOT projects from 2001 to 2003 into 10 groups based on their project types and contract amounts. For each group, Jarrash et al. fitted a single-variable polynomial function to model expenditure cash flows (the single variable was time). In the second study, Liu et al. (2015) fitted several mathematical functions to model the cash flow expenditures of two North Carolina DOT transportation megaprojects, including a linear polynomial model, quadratic polynomial model, cubic polynomial model, quartic polynomial model, exponential model, and rational model. Liu et al. found that, for the two studied megaprojects, quartic polynomial models provided the best fit to model expenditure cash flows.

Linear regression analysis and neural network analysis were also used to estimate the construction expenditure cash flow of transportation projects. Mills and Tasaico (2005) developed two polynomial regression models using time and project attributes, including number of active contracts, size, duration, engineering type, contract type, region and weather, as inputs to estimate monthly payments for 336 transportation projects completed by North Carolina DOT between 2000 and 2002. However, the developed regression models did not show a reasonable accuracy beyond a 12-month forecasting horizon. Chao and Chien (2009) applied neural network analysis to estimate the parameters of polynomial functions that are used to estimate the expenditure curves of six subprojects of the second freeway in Taiwan. Contract amount, duration, type of work, and location were used as the inputs to the neural network models to estimate the coefficients of the developed polynomial functions.

3.2 Problem Statement and Research Objective

At early stage of developing transportation design-build projects, detailed design and quantities are not available. However, transportation agencies still need to program their capital obligations throughout the project duration. This research aims to address the need for developing a forecasting model that can be used by practitioners to estimate the expected expenditure cash flow of transportation design-build projects.

There is no research focused on forecasting expenditure cash flow of transportation design-build projects. Design-build has been increasingly used by state DOTs to expedite project delivery and utilize innovative ideas to improve the project performance (Ashuri et al. 2013). Cash flow estimating models built based on expenditure records of traditional design-bid-build projects are inherently limited for forecasting the expenditure cash flow of design-build projects. Design-build projects include payments for several services that do not exist in design-bid-build projects. Most importantly, a design-build contract includes design fee to complete detailed design services for the project, as the engineer of record is part of the design-build team. Other services, such as design quality management and construction quality assurance services, are also parts of design-build contracts. Also, design and construction tasks are overlapped in design-build projects, which makes the pay-out curve of the design-build project different from that of the design-bid-build project.

The pattern of expenditure is different in design-build projects, as design-builders strive to overlap design and construction services as much as possible, in order to expedite project delivery (i.e., packaging work to facilitate fast-tracking). At the outset of awarding a typical design-build contract, only high-level information is available to develop a conceptual cost estimate for the project. Since design has not been finalized, the exact quantities are not determined to develop a detailed cost estimate for the project. This issue represents a big difference between design-build and design-bid-build projects that makes estimating the project pay-outs more difficult for design-build projects.

Existing models based on design-bid-build projects fit curves for each individual type of projects. However, as transportation owner agencies tend to use design-build to handle project complexity and to transfer risks (Demetracopoulou et al. 2020), a design-build project may consist of tasks of different types, making it hard to classify design-build projects in the way designed for design-bid-build projects. For example, bridge replacement is a project type defined by the Texas DOT, for which Jarrah et al. (2007) fit individual polynomial models to represent. Yet, in addition to the task of bridge replacement, the Northwest Corridor Express Lane project in the State of Georgia, for instance, also includes other types of tasks by definition within the Georgia DOT (GDOT 2015), such as new location roadway, location specific improvement, and widening. Therefore, using expenditure records of design-bid-build projects as inputs to develop a forecasting model for the anticipated expenditure cash flow of a design-build project is not appropriate.

To narrow the gap in the body of knowledge and to help practitioners on transportation budget management, the overarching objective of this study is to develop a new expenditure cash flow forecasting model for modelling pay-out patterns specifically for transportation design-build projects.

3.3 Research Methodology

An approach based on case-based reasoning and genetic algorithm is developed in this research for creating a forecasting model for construction expenditure cash flow of transportation design-build projects. Case-based reasoning is a data mining technique rooted in the notion that the solution of a new problem coming from the experience of solving previous problems in similar situations (Richter and Weber 2013). To generate a forecast for a new case, case-based reasoning retrieves existing cases with the highest similarities to the new case and then integrates the cash flows of the selected existing cases by taking the weighted average. Genetic algorithm is utilized to determine the optimal values of weights. The population of existing cases increases as the completed cases accumulate.

3.3.1 Data

A database of 33 transportation design-build projects completed between April 2007 and January 2020 in the state of Georgia is used as the basis to create the forecasting model. Table 1 provides an overview of 11 project-specific attributes that are available for these Georgia DOT projects at the time that the design-build contracts were awarded. Of these 11 attributes, two variables are numerical attributes, two variables are categorical attributes, and seven variables are binary attributes. A range of possible values for these attributes is also provided in Table 3. These attributes were taken from the fact sheets for these design-build projects. The project-specific attributes, as described in Table 3, are basic conceptual information about the project scope and its major project components at the time the project is getting under contract. According to the GDOT classification (GDOT 2015), transportation projects can include seven major components, bridge replacement, bridge maintenance, interchange reconstruction, location specific improvement, systemic improvement, widening, and new location roadway. A design-build project can include more than one project element. For example, a project may contain intersection reconstruction and traffic signal upgrades along the road (belonging to location specific improvement). The project element attributes are considered as binary attributes in the model.

Table 3. Project-specific attributes

Project-specific attribute	**Description**
Contract amount	Total dollar value of the design-build contract; numerical attribute ranging from \$1,428,267 to \$647,166,673, with mean \$48,113,526
Contract duration	Total duration of the design-build contract; numerical attribute ranging from 234 days to 1763 days, with mean 924 days
Regional district	Categorical attribute: {regional district 1 to regional district 7}, GDOT has 7 district offices throughout the

	State of Georgia.
Procurement method	Method of selecting the design-builder, categorical attribute: {one-phase low bid, two-phase low bid, and best value}. GDOT has used one of these three procurement methods for its design-build projects.
Bridge replacement	Binary attribute, a major project component according to the GDOT classification of project elements
Bridge maintenance	Binary attribute, a major project component according to the GDOT classification of project elements, includes bridge paining, and repair & rehabilitation
Interchange reconstruction	Binary attribute, a major project component according to the GDOT classification of project elements
Location specific improvement	Binary attribute, a major project component according to the GDOT classification of project elements, includes the construction of roundabout & intersections, traffic signals, pedestrian upgrades, lighting, and IT & operational improvements
Systemic improvement	Binary attribute, a major project component according to the GDOT classification of project elements, includes the construction of guardrail & cable barrier, edge line & centerline rumble strips, sharp curve treatments, sign upgrades, railroad crossing safety, and noise wall
Widening	Binary attribute, a major project component according to the GDOT classification of project elements, includes the construction of passing lanes and climbing lanes
New location roadway	Binary attribute, a major project component according to

the GDOT classification of project elements

The major goal in this step is to identify a set of potential factors influencing the cash flow pattern of the project. The project pay-out curve consists of expenditures for major line items, such as asphalt, steel, and concrete pay items, and maintenance of traffic (MOT), that occur throughout the project timeline. These time-stamped expenditures for major line items have significant impacts on the pattern of project expenditure cash flow and therefore, can be used to forecast the project cash flow (Su and Lucko 2015). Potential factors affecting the price of major line items are used as potential attributes with relevance to the cash flow forecasts for the project. For example, earlier studies (Faghih and Kashani 2018; Baek and Ashuri 2019; Shiha et al. 2020) showed that several attributes representing local transportation construction market conditions have significant impacts on submitted bid prices for major line items, such as cement, asphalt, and steel. Using this literature, an initial set of factors is developed as attributes with potential impacts on the project cash flow forecast (as shown in Table 4). Two of these attributes represent how busy the local transportation market is on the same month as the design-build contract is executed, total number of projects and total value of projects awarded by GDOT. The other four attributes represent local transportation market conditions as far as key materials, labor, and equipment: Georgia Fuel Price Index, Georgia Asphalt Cement Price Index (published by the GDOT Office of Materials on a monthly basis), Job Openings and Labor Turnover Index, and Producer Price Index for Construction Machinery Manufacturing (available from the U.S. Bureau of Labor Statistics). Table 4 provides detailed descriptions of these six external attributes that will be used as inputs in our model to forecast expenditure cash flow of design-build projects. All these attributes are numerical: a range of possible values is also provided in Table 4.

Table 4. External attributes

External attribute	Description
Georgia fuel price index	Numerical attribute ranging from $1.73/gal to $3.86/gal, with mean $2.75/gal, an average selling price of fuel that is collected from approved local fuel suppliers as reported in the GDOT's monthly survey
Georgia asphalt cement price index	Numerical attribute ranging from $304/ton to $623/ton, with mean $465/ton, an average selling price of asphalt cement that is collected from approved local asphalt cement suppliers as reported in the GDOT's monthly survey
Producer price index for construction machinery manufacturing	Numerical attribute ranging from 116 to 139, with mean 133, a specific kind of producer price index (PPI) measuring changes in prices received for the output of the construction machinery manufacturing sold to another industries, such as highway and other infrastructure construction
Job openings and labor turnover survey for construction hires (in thousands)	Numerical attribute ranging from 176 to 566, with mean 358, the number of monthly hires (in thousands) in the construction industry
Monthly number of projects awarded in Georgia	Numerical attribute ranging from 5 projects to 110 projects, with mean 30 projects, the total number of projects awarded by GDOT in the same month that the design-build project was awarded
Monthly value of	Numerical attribute ranging from $1,851,745 to $704,899,728,

projects awarded in Georgia	with mean $159,995,719, the total dollar value of projects awarded by GDOT in the same month that the design-build project was awarded

Considering the relatively small number of design-build projects in the dataset, case-based reasoning is selected as an appropriate method to develop a forecasting model for expenditure cash flow. Case-based reasoning is a powerful data mining algorithm for cases with a relatively small number of data points and a relatively large number of attributes describing each data point (Richter and Weber 2013). Case-based reasoning is also found to have flexibility in terms of handling missing data and self-updating with new cases (Arditi and Tokdemir 1999).

3.3.2 Model Development

As Figure 4 shows, the development of the cash flow forecasting model comprises ten steps. Each step is elaborated below.

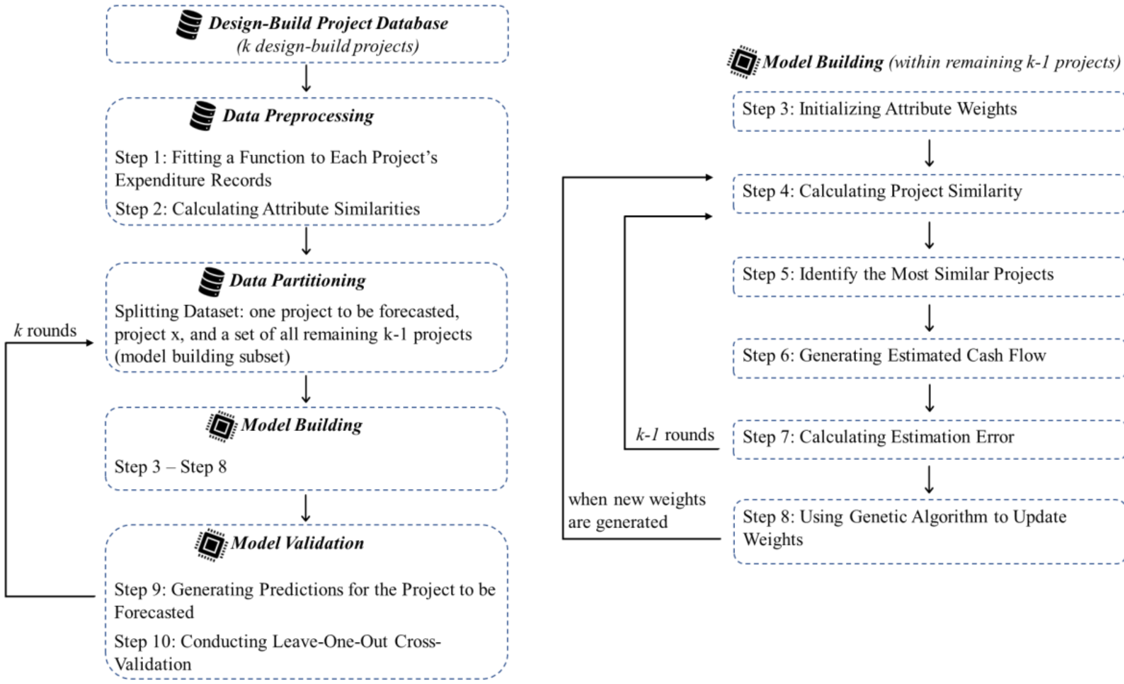


Figure 4. Model development steps

Step 1: Finding an appropriate function that best fits the expenditure records of each design-build project in the dataset

First, the cumulative expenditure records of each design-build project are plotted on a graph where the horizontal axis represents project timeline progress as a percentage of total project duration, and the vertical axis represents the cumulative payment as a percentage of total project price. Figure 5 shows the plotted cumulative expenditure records of four design-build projects in the dataset as examples. The projects are labeled as project #3, #10, #23, and #33. Three types of functions are tried to fit to the cumulative expenditure records of design-build projects in the dataset: cubic polynomial, quartic polynomial, and beta functions. It can be seen that the beta function is overall the best fit for cumulative expenditure records for these projects. In addition to providing a high level of accuracy in fitting the plotted points, the formulation of the beta function satisfies the non-decreasing property of a cumulative expenditure function. The beta function is defined by Eq. 3-1:

$$B(\varphi) = \frac{\int_0^{\varphi} t^{\alpha-1}(1-t)^{\beta-1}\,dt}{\int_0^{1} t^{\alpha-1}(1-t)^{\beta-1}\,dt} \qquad \text{Eq. (3-1)}$$

where α and β are shape parameters that are estimated for each project, φ is the point in the project timeline (measured by percentage of total project duration) for which the cumulative expenditure B(φ) (measured by percentage of total project cost) is calculated by the developed beta function.

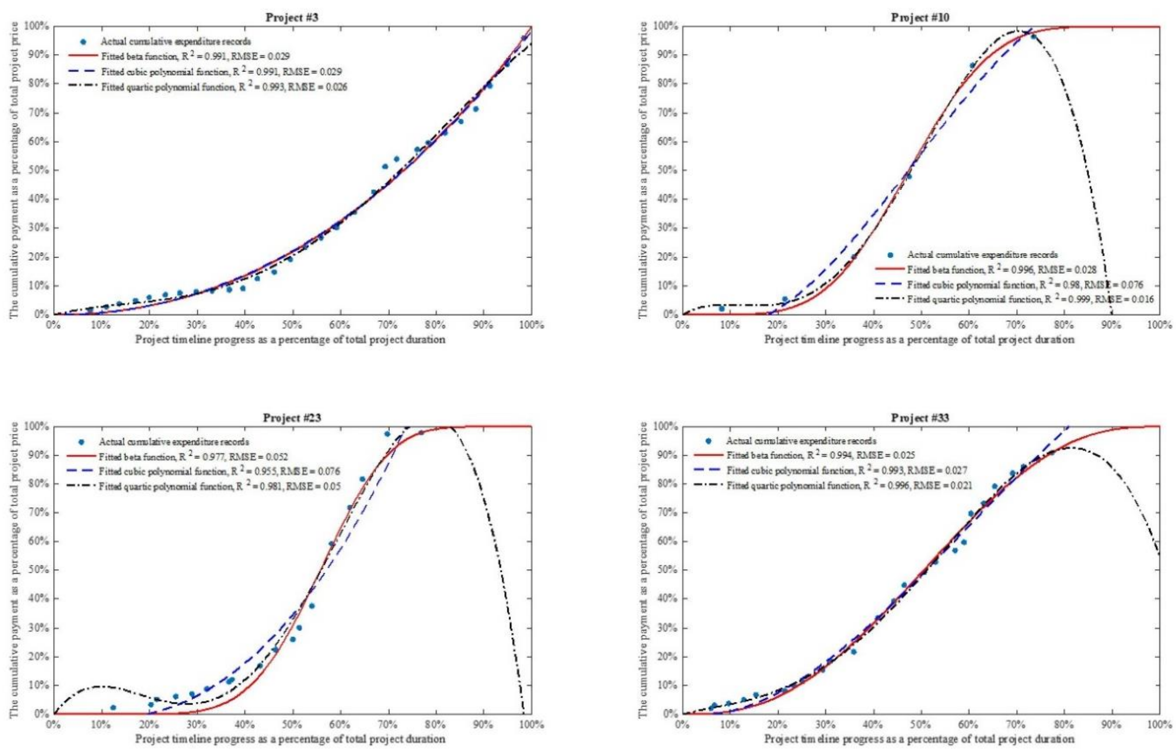


Figure 5. Examples of cumulative expenditure curve fitting for 4 design-build projects

Step 2: Calculating Attribute Similarities

Case-based reasoning algorithm uses the similarity between a project and other projects in the dataset to forecast the expenditure cash flow for the project. Higher project similarities imply higher similarities in cash flows. Project similarity is obtained by taking weighted average of attribute similarity values. Attribute similarities are values ranging from 0 to 100 where a large value indicates high-level similarity. There are two types of project attributes in the model: numerical attributes and categorical attributes (including binary variables). When comparing the similarity of attribute s between project i and project j, the value is defined as Eq. (3-2) if attribute s is numerical, and the value is defined as Eq. (3-3) if attribute s is categorical. Attribute similarities are calculated between each project attribute of any two projects in the dataset.

$$AS_{s,i,j} = \left(1 - \frac{|AV_{s,i} - AV_{s,j}|}{AV_{s,max} - AV_{s,min}}\right) \times 100 \qquad \text{Eq. (3-2)}$$

$$AS_{s,i,j} = \begin{cases} 100 & \text{if } AV_{s,i} = AV_{s,j} \\ 0 & otherwise \end{cases} \qquad \text{Eq. (3-3)}$$

where $AS_{s,i,j}$ = the similarity on attribute s between project i and project j; $AV_{s,i}$ = the value of attribute s in project i; $AV_{s,max}$ = the maximum value of attribute s in all the projects in the dataset; and $AV_{s,min}$ = the minimum value of attribute s in all the projects in the dataset.

Step 3: Initializing Attribute Weights

The overall project similarity is the weighted average of the calculated attribute similarities in the previous step. The computed attribute similarities are rolled up to determine the project similarity using appropriate weights. Finding the right weights is an optimization problem that needs to be solved. The weights are decision variables in this optimization problem. The objective function is to minimize the difference between the predicted expenditure curve and the actual expenditure cash flow curve. The initial sets of attribute weights are randomly generated with values between 0 and 100.

Suppose there are k design-build projects in the dataset. In this step, the k projects are split into two subsets. The first subset contains only one project, denoted by project x hereafter. The second subset contains all the remaining k-1 projects that will be used for building the forecasting model. The second subset is referred to as the model building subset hereafter. The k-1 projects are used to determine an optimal set of attribute weights by which the overall error of cash flow estimating for k-1 projects is minimized. The optimal set of attribute weights will be applied on the project to be forecasted (project x), in order to predict its expenditure cash flow curve.

Step 4: Calculating Project Similarities

Consider a project in the model building subset, project y. Suppose project z is another project in the model building subset. The similarity between projects y and z is defined as Eq. (3-4), i.e., the weighted average of attribute similarities calculated in step 2 with the attribute weights selected in Step 3.

$$PS_{y,z} = \frac{\sum_{s=1}^{m}(w_s \times AS_{s,y,z})}{\sum_{s=1}^{m} w_s} \qquad \text{Eq. (3-4)}$$

where $PS_{y,z}$ = the project similarity between project y and project z; w_s = the weight for attribute s; and m = the total number of project attributes. Using the same set of attribute weights, project similarities are calculated between any two projects in the model building subset.

Step 5: Identifying the Most Similar Projects to Project y in the Model Building Subset

Projects in the model building subset with the highest project similarities to project y are selected to retrieve information for estimating the expenditure cash flow of project y. The top five similar projects with the greatest values of project similarities PS calculated in step 4 are identified. The cumulative expenditure cash flows of these five projects are used to estimate the cumulative cash flow of project y. Choosing top five similar cases in the dataset is a recommended approach in the case-based reasoning literature, as five has been identified as an appropriate number of similar cases for building the prediction model (Ahna et al. 2017). The estimating results will be examined to ensure that selecting the top five similar cases leads to the best possible estimation for cumulative expenditure curves. The retrieval process described in this step is conducted for each of the k-1 projects in the model building subset.

Step 6: Generating Estimated Cumulative Expenditure Flow

The value of cumulative expenditure for project y is calculated at any point of time using the corresponding values of the top similar projects in the model building subset. Calculated project similarities are used as weights applied to the corresponding cumulative expenditure values of the top five similar projects. At any point in time during the project timeline (t), estimated cumulative expenditure for project y, denoted by $CE_{Estimated}^{(t)}$, is calculated using Eq. (3-5).

$$CE_{Estimated}^{(t)} = \frac{\sum_{r=1}^{5}(PS_{y,r} \times CE_r^{(t)})}{\sum_{r=1}^{5} PS_{y,r}} \qquad \text{Eq. (3-5)}$$

where $CE_r^{(t)}$= cumulative expenditure of the cash flow of the r^{th} retrieved project at time (t); $PS_{y,r}$ = the project similarity between project y and the r^{th} retrieved project. The estimating process described in this step is performed on each of the k-1 projects in the model building subset.

Step 7: Calculating Estimation Error

The estimation error for project y is measured by mean absolute value (MAE) using Eq. (3-6).

$$MAE = \int_0^{100\%} \left| CE_{Estimated}^{(t)} - CE_{Actual}^{(t)} \right| dt \qquad \text{Eq. (3-6)}$$

where $CE_{Estimated}^{(t)}$ = cumulative expenditure during the project timeline (t) of the estimated cash flow; and $CE_{Actual}^{(t)}$ = cumulative expenditure during the project timeline (t) of the actual cash flow. The MAE described in this step is calculated for each of the k-1 projects in the model building subset. The overall error of each set of attribute weights is computed by taking the average value of MAEs for all k-1 estimated cash flows.

Step 8: Using Genetic Algorithm to Search for the Optimal Set of Attribute Weights

The space of attribute weights needs to be searched to find an optimal set of attribute weights that provides the lowest reasonable estimation error across all projects in the model building subset. The optimization problem in this step has following features: first, the relationships between the weight attributes and MAE values could not be described by linear transformation. Moreover, the optimal set of attribute weights needs to be updated as soon as possible whenever there are new projects added to the database. A genetic algorithm is used to evolve the initial sets of attribute weights and search for the optimal set of attributes. Genetic algorithm has good capability to handle nonlinear optimization problems within limited time (Eiben and Smith 2015). Stemming from the mechanism of natural selection and genetics, genetic algorithm starts from randomly selecting potential solutions from feasible regions. The solution domain of the genetic algorithm is the sets of attribute weights. The fitness value of each set of attribute weights is its overall estimation error calculated in step 7.

To eliminate unsuitable sets of weights and retain suitable sets of weights, fitness proportionate selection is used as the selection method of genetic algorithm. Compared to non-fitness-based selection method, fitness proportionate selection avoids blind replacement of parent-generation weights and eliminating promising attribute weights. In fitness proportionate selection, the probability of each existing set of attribute weights to breed a new generation of weights is inversely proportional to its overall estimation error. Crossover and mutation are used as the genetic operators of the genetic algorithm to generate new generation of weights. Crossover and mutation rates are set at 0.9 and 0.01, respectively. For each newly generated set of attribute weights, steps 4-7 are repeated. The genetic algorithm stops when the number of maximum generations is reached. In this study, the maximum generation is set as 500, following the rule of thumb given in the literature (Ahmed and Deb 2013; Zhang 2009). Upon completion of this step, an optimal set of attribute weights is found for providing the best estimates for expenditure cash flows of k-1 projects in the model building subset.

Step 9: Applying the Optimal Weights to Predict the Expenditure Curve of Project x

The optimal set of attribute weights obtained in step 8 is used to forecast the cash flow expenditure curve of project x. The optimal weights are used to calculate the project similarities between project x and each of the k-1 projects in the model building subset using Eq. (3-4). The top five similar projects to project x are identified based on the greatest values of project similarities, and the value of cumulative expenditure for project x is calculated at any point in time using the corresponding values of these similar projects in the model building subset. The MAE measure described in Eq. (3-5) is used to calculate the error of forecasting the cash flow expenditure of project x.

Step 10: Conducting Leave-One-Out Cross-Validation

A leave-one-out cross-validation (LOOCV) method is used to assess the accuracy of the developed case-based reasoning model. Completion of steps 3-9 results in the forecasted expenditure cash flow of one project in the dataset, project x. The same steps 3-9 will be repeated to forecast cash flow expenditure curves of other k-1 projects in the dataset. In all, k rounds of the developed partitioning-training-forecasting process are conducted to predict expenditure cash flows of all projects in the dataset.

3.4 Results

3.4.1 Illustrative Example

In this section, one of the 33 examined projects (Project #6) is selected as an example to demonstrate how the cumulative expenditure flow of the design-build project can be estimated using the actual expenditure records of the other 32 projects in the dataset. The selected project is a local specific improvement project which worth $30,954,797 and lasts for 863 days. All the other information of the project is summarized in Table 5.

Following are detailed steps showing how to use the remaining 32 projects to generate an optimal set of attribute weights for forecasting Project #6: first, several sets of random attribute weights between 0 and 100 are generated (Step 3). Then, for each set of attribute weights, project similarities between any two of the 32 projects are calculated by multiplying attribute similarity matrix and attribute weight matrix using Eq.4 (Step 4). For each of the 32 projects, the five projects with highest similarities are identified (Step 5). For each of the 32 projects, the forecasted cash flow is calculated by taking weighted average of the cash flows of the five retrieved projects. For instance, if the accumulative expenditure at timeline (t) of the five retrieved projects listed in Table 3-5 are c1, c2, c3, c4, and c5, respectively, then the forecasted cash flow of the project to be predicted at the same timeline is 0.216c1+0.215c2+0.200c3+0.187c4+0.182c5 (Step 6). The MAEs of 32 forecasted cash flows and corresponding actual cash flows are calculated using Eq. (6) (Step 7). The mean value of 32 obtained MAE values is the fitness of the corresponding set of attribute weights used in calculation. The population of sets of attribute weights is evolved by Step 8, and the final optimal attribute weights are listed in Table 6.

The profiles of the five projects retrieved for forecasting Project #6 are listed in Table 7, including their corresponding project similarities with Project #6. The calculation process is the same as the process of step 4 mentioned above using Eq. 4.

The forecasted cumulative expenditure cash flow of Project #6 and corresponding MAE are shown in Figure 6. The calculation processes are the same as the processes of step 6 and step 7 mentioned above, using Eq. 5 and Eq. 6. The MAE value indicates that the overall average deviation of the forecast from the actual value is less than 5%.

Table 5. Project information of the illustrative example

Project	Description
#6	Contract amount = $30,954,797; Contract duration = 863 days; Regional district = 7; Procurement method = two-phase low bid; Types of tasks = location specific improvement; Georgia fuel price index = $2.99/gal; Georgia asphalt cement price index = $460/ton; PPI for construction machinery = 124.7; Job openings and labor turnover = 250; Monthly number of projects awarded = 5; Monthly value of projects awarded = $1,851,745.37

Table 6. Optimal attribute weights for the illustrative project

Attribute	Weight	Attribute	Weight
Contract amount	0.0013	Widening	0.0251
Contract duration	0.0229	New location roadway	0.0123
Regional district	0.0243	Georgia fuel price index	0.0022

Procurement method	0.0190	Georgia asphalt cement price index	0.0022
Bridge replacement	0.0004	PPI for construction machinery	0.0163
Bridge Maintenance	0.0141	Job openings and labor turnover	0.0101
Interchange reconstruction	0.0005	Monthly number of projects awarded	0.0088
Location specific improvement	0.0004	Monthly value of projects awarded	0.0053
Systemic improvement	0.0018		

Table 7. Retrieved projects for constructing forecasted cumulative expenditure flow

Project (similarity score)	**Project profile**					
	Contract amount	Contract duration	Regional district	Proc. method	Types of tasks*	GA fuel index
#12 (92.93)	$9,268,236	960 days	7	two-phase low bid	BR; IR; LSI	$3.276/gal
#7 (92.21)	$21,423,500	900 days	7	two-phase low bid	BR; IR; LSI	$3.862/gal
#3 (86.18)	$17,128,865	938 days	7	two-phase low bid	BR; IR; W	$1.729/gal
#15 (80.43)	$1,428,267	596 days	7	one-phase low bid	LSI	$3.293/gal
#14 (78.07)	$24,066,000	940 days	2	two-phase low bid	BR	$3.221/gal
Project	**Project profile**					

(weight)	GA asphalt cement index	PPI for construction machinery	Job openings and labor turnover	Monthly number of projects awarded	Monthly value of projects awarded
#12 (0.216)	$568/ton	133.1	176	10	$91,380,891
#7 (0.215)	$604/ton	126.6	497	22	$124,098,761
#3 (0.200)	$522/ton	121.8	204	27	$75,445,350
#15 (0.187)	$563/ton	135.4	268	9	$54,288,689
#14 (0.182)	$565/ton	133.9	233	15	$49,025,722

*BR = bridge replacement; IR = intersection reconstruction; LSI = location specific improvement; W = 356 widening

3.4.2 Validation Results

The construction expenditure cash flow curve of each design-build project in the dataset is forecasted using information from the other 32 design-build projects in the dataset. Thirty-three forecasts are made using the developed case-based reasoning model, in order to evaluate the accuracy of the forecasting method. Figure 6 shows forecasted cumulative expenditure cash flow for four design-build projects in the dataset. The values of shape parameters α and β are specified for each forecasted beta function in the graph. The forecasted error term, i.e., MAE, is also identified for each predicted cumulative expenditure curve.

Figure 7 shows the distributions of MAE values of all predictions and associated minimum value, maximum value, and standard deviation.

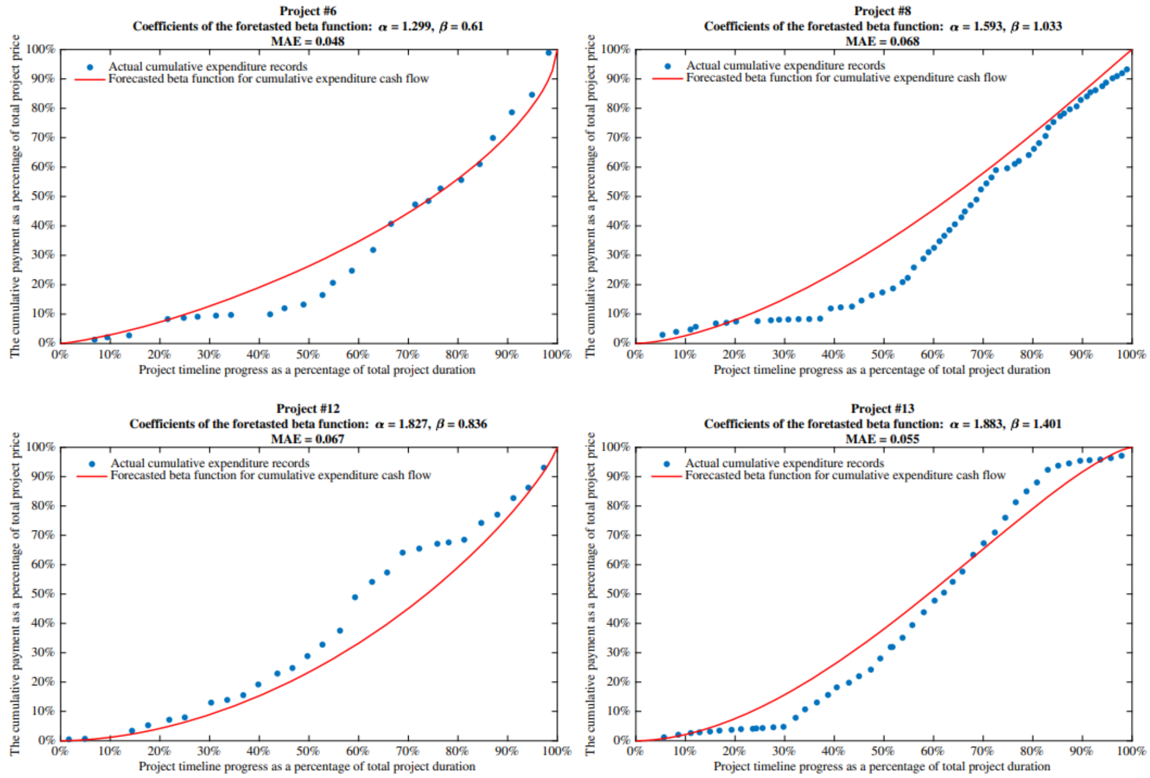


Figure 6. Examples of forecasted cumulative expenditure cash flow for four design-build projects.

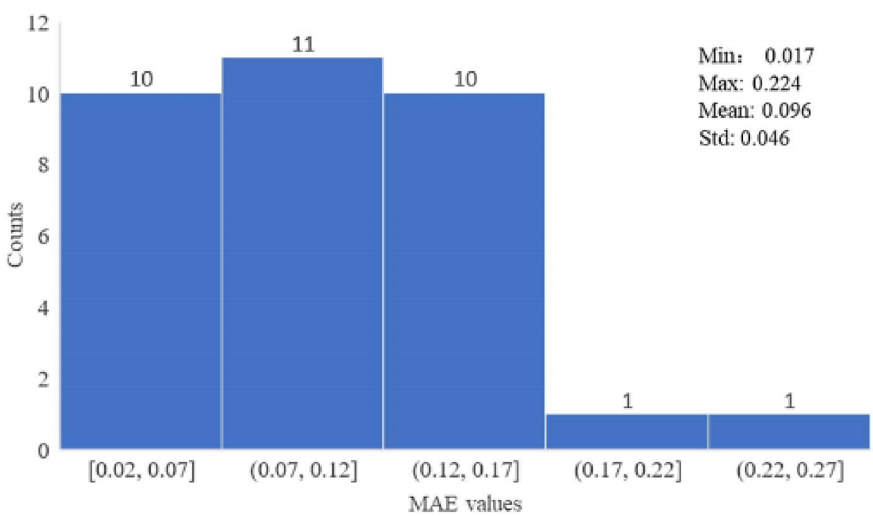


Figure 7. Distribution of MAE values of predictions.

Other configurations can be examined to assess how changes in the number of similar projects may impact the accuracy of the proposed forecasting model. Table 8 summarizes the accuracy level of the forecasting method under different scenarios for configurations of similar projects, i.e., using top three, five, seven, and nine similar projects for predicting the cash flow. The results show that the mean value of MAE is higher when the top seven or nine similar projects are used for forecasting. The accuracy levels of the top three or five similar projects are fairly close to each other, but the accuracy range for the top five is lower than that for the top three. Therefore, five is considered as the appropriate number of similar projects in the developed case-based reasoning method for cash flow forecasting. This number is consistent with some other applications of case-based reasoning method in the literature (Ahn et al. 2017, Kwon et al. 2019).

Table 8. Comparison of different retrieval configurations

Retrieval configuration	Maximum MAE	Minimum MAE	Mean MAE	Standard deviation of MAE
3 similar projects	0.240	0.015	0.095	0.052
5 similar projects	0.224	0.017	0.096	0.046
7 similar projects	0.223	0.024	0.111	0.038
9 similar projects	0.225	0.029	0.119	0.038

3.5 Conclusions

This research for the first time created a forecasting model to estimate the expenditure cash flow of transportation design-build projects. A forecasting model based on case-based reasoning and genetic algorithm was developed for predicting expenditure cash flow of transportation design-build projects. The proposed model has the capability to provide accurate forecasts for cash flows of design-build projects using a number of project-specific attributes and external factors representing market conditions. The applicability of the proposed model was shown on the dataset of 33 transportation design-build projects delivered by Georgia Department of Transportation from April 2007 to January 2020. The results showed great accuracy in forecasting the expenditure cash flow for these design-build projects.

This research has potential to elevate the state of practice from four aspects. First, at early stage of developing transportation design-build projects, detailed design and quantities are not available. However, transportation agencies still need to program their capital obligations throughout the project duration. Since 2013, accompanying with the enactment of Moving Ahead for Progress in the 21st Century Act (MAP-21), enhancing budget internal controls to protect federal investments is always among the top management challenges of U.S. DOT (U.S. DOT n.d.). This research bridges this gap and shows how high-level information items about the design-build project concept can be used to develop a forecasting model for expected expenditure cash flow of transportation design-build projects. Second, design-build projects have diverse project features, which brings challenges to project managers in budgeting adequate fund throughout the project timeline. The proposed model is capable to capture the inherent similarities between seemingly unrelated design-build projects. Third, compared with traditional design-bid-build projects, there are relatively fewer completed design-build projects, which makes it challenging to apply the data-intensive expenditure flow models developed for design-bid-build projects. The ability of the proposed model to reliably forecast expenditure cash flow in conditions with limited dataset considerably enhances the model's applicability. Moreover, the proposed model is implemented in consideration of projects with common project attributes. Thus, it is expected that the model accuracy would increase as data on similar completed projects get accumulated. It helps to tackle the challenges in ever-evolving, rapidly expanding design-build market.

This research contributes to the body of knowledge in two aspects. First, this research for the first time identifies an appropriate combination of conceptual project information available at the early stage of project development and several transportation market indicators that has potential for characterizing the expenditure cash flow of transportation design-build projects. The identification of these factors as leading indicators of design-build project cash flow was not known before. Second, this research creates a novel forecasting model that uses the identified variables as inputs to a case-based reasoning algorithm, in order to predict the future cash flow expenditure of the design-build project using the quantified similarities between the identified attributes of the project and those of other design-build projects in the dataset. This new case-based reasoning model did not exist before to help transportation agencies estimate their financial obligations throughout the design-build project timeline with a reasonable accuracy.

CHAPTER 4. CHALLENGES AND ENABLING FEATURES OF SMALL AND MEDIUM INFRASTRUCTURE PUBLIC–PRIVATE PARTNERSHIPS: CASE STUDY OF THE U.S. P3 INFRASTRUCTURE MARKET[3]

4.1 Introduction

In the popular belief, Public-Private Partnership (P3) is normally mobilized for infrastructure projects with large contract amount (Maltin 2019; Rocca 2017). According to a research by U.S. Federal Transit Administration, an infrastructure P3 is designated as small or medium with respect to financial impact if its capital cost is less than $150M (National Academies 2017). Besides U.S., administration authorities around the world give rules of thumb on the lower limit of recommended P3 size (Table 1). For instance, HM Treasury examined the Public Finance Initiative (PFI) projects of less than £20M ($25.1M). PFI is a scheme where a private sector organization provides upfront capital for a public sector infrastructure project. The upfront cost is then recouped through a long-term lease or concession with the public sector on the developed assets. The results show that although the project performance of small projects is in line with the results of large projects, small projects normally have similar transaction and bid cost as major capital schemes. The disproportionately high transaction cost puts small projects in an unfavourable position in attracting bidders.

[3] This chapter was published as a journal article in the Journal of Engineering, Construction, and Architectural Management with Baabak Ashuri as the co-author. The citation for the journal article is as follows: Liang, Y., and Ashuri, B. “Challenges and enabling features of small and medium infrastructure public-private partnerships: a case study of the U.S. P3 infrastructure market.” Engineering, Construction, and Architectural Management, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/ECAM-09-2020-0720

Among the authorities listed in Table 9, only UK provides justifications for the recommended threshold. It is also worthy to note that these thresholds are general and are given without indicating specific sectors. However, different sectors may have different typical project sizes: a small highway project can be a medium or even large building project in terms of contract amount. These two issues on prevailing definitions of small to medium size P3 reflect the primitive status of studies on small and medium P3, as well as the necessity of clarifying the application scope of P3 model. Nevertheless, these thresholds would still be used for defining small- to medium- sized projects in corresponding countries hereinafter, since they are the state-of-practice definitions.

Table 9. Rules of thumb on the lower limit of recommended P3 size

Jurisdiction	Value	Administration authority
UN	$30M	Department of Economics and Social Affairs (Bond 2012)
USA	$150M	National Academies (2017)
UK	£20M ($25.1M)	Her Majesty (HM) Treasury (2003)
Netherlands	€60M ($67.3M)	Ministry of Finance of Netherlands (2014)
Denmark	kr.100M ($15M)	Danish Enterprise and Construction Authority (2005)
Canada	Can$60M ($46.3M)	Conference Board of Canada (2013)
Australia	AU$50M ($34.8M)	Department of Infrastructure and Regional Development (2015)

However, paradox emerges between the popular belief and the practice. Although it is regarded as unfavourable, small- to medium- sized P3 is not rare across the world, as shown in Table 10. The United States also witnesses a growth in relatively smaller P3 in a two-year period. According to the statistics by Buckberg et al. (2018), the proportion of small and medium P3 has jumped from 13.16% between 2006-2014 to 18.44% between 2015-2017. Obviously, the contradiction could not be easily explained by random chance. It is worthy to critically examine the cases and explore the question of how the model worked for these small and medium P3s.

Understanding the rationale of small- to medium- sized P3 has significant implication on facilitating the U.S. infrastructure development. The United States is plagued by aging infrastructure system. As of 2019, about 55.7% of the highway bridges across the United States are in poor or mediocre condition (U.S. DOT 2019). Merely the investment gap in surface transportation sector is expected to cause $1.167T losses to the national economy from 2016-2025 (ASCE 2016). Historically, state and local governments have been responsible for the majority of infrastructure spending. Statistics by Congressional Research Service (2018) show that, from 1956 to 2017, state and local governments pay for 77.8% of public spending on transportation and water infrastructure. Moreover, the statistics show that federal investment constantly decreases, and it is almost the lowest since 1998. Typically, taxes and fees account for around 60% of state and local government spending on infrastructure, and the rest 40% is traditionally financed by bonds and debts (NASBO 2020). In recent years, changing economic conditions motivate state and local governments to actively explore alternative financing tools, including P3, to supplement existing financing methods. Nested within state structures, local governments have restricted authority to raise revenue through taxes and fees and limited ability to freely spend those raised funds. As an emerging mechanism, P3 is considering to be a potential available tool for local governments to fund infrastructures, which are frequently in small- to medium- size (NLC 2016, Bay Area Council Economic Institute 2018).

Besides the potential application on local infrastructure rehabilitation, small and medium P3 may also benefit the diffusion of technologies, especially when complementary infrastructures are required for the commercialization of the technologies. An example is electric vehicle (EV) and charging piles. Studies show that the availability of public EV charging is an important factor in decisions on EV purchases in the United States (Hardman et al. 2018). However, some studies suggest a "chicken and egg" problem, in which more public EV charging infrastructures are required for growth in EV sales and more EV sales are required for growth in public EV charging infrastructures (Mixson 2015). The partnership between the public and private may help break the tie and result in a win–win–win situation for consumers, governments, and private enterprises; consumers benefit through improved access to modern energy services, governments advance social and economic development objectives, and private enterprises expand business opportunities (Balachandra et al. 2010).

Table 10. Small and medium P3s in UK, Canada, and low- to middle- income countries

Data source	Region	Data as of year	Number of projects in the database	Number of small/ medium projects in the database	Proportion of small and medium projects	Suggested minimum size for P3
WBPPI[1]	139 low- and middle-income countries	2019	7,201	2,263	31.43%	$30M
GOV.UK[2]	UK	2018	715	192	26.85%	£20M ($25.1M)
CCPPP[3]	Canada	2019	243	41	16.87%	Can$60M ($46.3M)

[1]World Bank - Private Participation in Infrastructure

[2]The web portal operated by UK government for releasing news, statistics, and consultations.

[3]Canadian Council for Public-Private Partnerships

The research question of this study is: in the context of U.S., what features of those small- to medium- sized P3s with successful formation records enable the selection of P3 as delivery method. This study departs from the literature related to the challenges of implementing small and medium P3 and attempts to provide theoretical justifications to better understand the reasons why small- and medium-size P3 infrastructure projects are sound and can make sense in specific situations.

4.2 Literatures on the Challenges of Implementing Small and Medium P3

To identify the challenges of implementing small and medium P3 in literature, the authors review publications including peer-reviewed journals, conference proceedings, working papers, technical reports, government press release, and books. Almost no peer-reviewed paper is found dedicating to small and medium P3. This finding is in line with the finding of literature review on the lower limit of recommended size for P3: all administration authorities except UK give the values of threshold without providing empirical evidence. As an alternative, the authors start from technical reports on small and medium P3 published by influential research institutes, such as World Bank and Transportation Research Board, and then go back to peer-reviewed papers with the keywords found in the technical reports (e.g., transaction cost). Moreover, the authors search peer-review papers in relation to public-private partnerships with keywords "barriers", "constraints", "challenges", and "obstacles". Only the ones in relation to the size of P3 would be considered. The search of peer-reviewed papers was performed in academic databases including Science Direct, American Society of Civil Engineers (ASCE) Library, Taylor and Francis Online, and Emerald Insight.

Challenges identified in the literatures related to the implementation of small and medium P3s are mainly in three areas: (a) disproportionately high bid preparation cost; (b) impediments from the financial sector; and (c) legislative restrictions. The first challenge is the disproportionately high bid preparation cost which undermines the value for money of the project and decreases the private sector's willingness to bid. For many small and medium P3s, the identical development, appraisal, approval, and procurement processes with large projects make small and medium P3s require similar efforts for bid preparation and have overall higher bid reparation/procurement cost relative to the size of the projects (Bond 2012). Without separate processes and standardized documents, small and medium P3s face lengthy procurement processes, complex legal and technical documentations similar to those for large projects in most jurisdictions (World Bank 2014). This is supported by the results of a UK-based statistical analysis (Dudkin and Välilä 2006), a survey based in Belgium (De Schepper et al. 2014), and a survey based in the United States (Mostaan and Ashuri 2017).

Small and medium P3 also faces impediments from the financial sector. Special purpose vehicles (SPVs) of small and medium P3s do not always get funded by non-recourse loans with viable risk premium (Bond 2012). As the typical type of loan used by P3, non-recourse loan is secured by collateral, which is usually property. The non-recourse lender cannot pursue compensation beyond collateral if the borrower defaults. In that case, lenders rely on the asset pledged on the loan and the stability of project's future cash flow for debt repayment to make their decisions. As a result of lack of precedents, a small and medium P3 which passes the financial scrutiny may still not get financed if the project does not have credible sponsors (Yescombe 2013). The small business normally has to demonstrate the borrower its financial viability and at the same time, has credible sponsors on board in order to get financed.

Appropriate legislative frameworks are critical for the success of P3 (Geddes and Wagner 2013). To implement P3 smoothly, two prerequisites must be met: 1) the government agency is authorized to implement P3; and 2) P3 is authorized in the sector. Compared to typical P3, small and medium P3 is more frequently granted by local governments and is distributed in diverse industries (ICMA 2018). State agencies would not be able to use P3 in a non-transportation project if the state P3 legislation is restricted to transportation projects only. A local government would not be able to use P3 to delivery its projects if the state P3 legislation does not apply to local governments (ICMA 2018). According to a summary synthesized by FHWA (2018), 36 out of 50 states in the United States have authorized P3 in at least one primary sector as of 2018. However, among the 36 P3 states, only 17 states have authorized the use of P3 in non-transportation sectors; 26 states explicitly allow municipal or local governments to implement P3 (ASA et al. 2018); and only 16 states fall in the convergence (Table 11). The legislative environment is generally more unfavourable for local and non-transportation projects.

Table 11. P3 State Laws (as of August 2018)

Type of state legislation	**States**
P3 is authorized for state agencies on transportation projects only	Arizona, Delaware, Maine, Massachusetts, Ohio, Oregon, South Carolina, Washington, West Virginia
P3 is authorized in both transportation and non-transportation sectors, but only for state agencies	Maryland
P3 is authorized for both state and local agencies, but only in transportation sector	Alabama, Colorado, Illinois, Iowa, Louisiana, Minnesota, Mississippi, New Hampshire, Pennsylvania, Tennessee
P3 is authorized for state and local agencies on both transportation and non-transportation projects	Arkansas, California, Florida, Georgia, Indiana, Kentucky, Michigan, Missouri, Nevada, New Jersey North Carolina, North Dakota, Oklahoma, Texas, Utah, Virginia

4.3 Theoretical Basis and Hypothesis Development

Before developing hypothesis on enabling features of small- to medium- sized P3, the authors first review the enablers in the literature. Since enablers/critical success factors is a common topic in the field of P3, the authors only review the ones related to the challenges summarized above. As shown in Table 12, even though previous studies have generated numerous enablers, they are not seamlessly connected with the summarized challenges of small and medium P3. For instance, developing project portfolios (project bundling) was proposed to reduce the transaction cost for both the private and public sector (Mostaan and Ashuri 2017). However, bundled projects are not essentially small- to medium- sized projects. Additionally, it is not always possible to find several similar small- to medium- sized projects under a certain temporal and spatial condition for bundling. Moreover, the enablers identified in the literatures are generic, and thus it is hard to project them into the space of small- to medium-sized projects. For instance, favorable legal framework was repeatedly mentioned in the literature. But it is awaiting to explore the specific meaning of favorable legal framework in the context of U.S. small and medium P3 market. Therefore, it is necessary to analyze the summarized challenges systematically and contextually and to specifically proposed corresponding enabling features.

Table 12. Enablers/critical success factors in the literature

Challenges	Related enablers/critical success factors in the literature
Disproportionately high	Appropriate PPP arrangement and tender preparation (Liu et

bid preparation cost	al. 2015); Developing project portfolios (Mostaan and Ashuri 2017)
Impediments from the financial sector	Suitable and adequate financial market (Chan et al. 2010; Chou et al. 2012); Utilizing conduit bond issuing entities and escrow accounts mechanism (Mostaan and Ashuri 2017); Financed focused programs (Mahalingam 2010); Financial capabilities of the private sector (Osei-Kyei and Chan 2015; Owolabi et al. 2020); Sound financial package (Zhang 2005)
Legislative restrictions	Favorable legal framework (Abdel Aziz 2007; Chan et al. 2010; Dulaimi 2010; Chou et al. 2012; Hwang et al. 2013; Osei-Kyei and Chan 2015)

As mentioned above, UK sets lower limit of recommended size of P3 based on empirical findings that small P3 projects are frequently plagued by disproportionately high transaction cost. Transaction cost is the cost in making any economic trade when participating in a market. The idea of transaction cost has been successfully used in prior literatures in relation to the feasibility of P3 model (Dudkin and Välilä 2006, Soliño and de Santos 2010, Carbonara et al. 2016, Soliño and de Santos 2016). Therefore, the authors of this study try to use the perspective of transaction cost to examine the challenges summarized above. The authors further put five propositions grounded in the perspective of transaction cost to answer the question: why those successful small- to medium- sized P3 are not blocked by disproportionately high transaction cost. It should be noted that the concept of transaction cost in this study is different from another term with similar wording in literature, that is, transaction cost economic (TCE), which focuses on governance structure, bounded rationality, and opportunistic behaviours (Ho et al. 2015).

Following Dudkin and Välilä (2006), transaction cost in the context of this study encompasses (1) legal, financial, and technical advisory costs incurred by both public and private sectors in the procurement and operational phases of a project; (2) costs for organizing and participating in the bidding process; (3) costs for negotiating the contract between the public sector and the winning bidder; and (4) monitoring the private sector partner's compliance with the contract and also renegotiating the contract during its life cycle. By this definition, most challenges identified in existing literatures, i.e., disproportionate bid preparation efforts, lack of viable financing, and unfavorably legislative environment, could be categorized under the transaction cost framework (Figure 4-1). Building upon the transaction cost framework, this study tries to explain under what circumstances P3 is a viable model for small- to medium- sized projects by proposing five enabling features as the critical enablers of U.S. small- to medium- sized infrastructure P3s. The five proposed enabling features are mapped into two dimensions (i.e., higher tolerance enabler or cost reduction enablers) as shown in Figure 8.

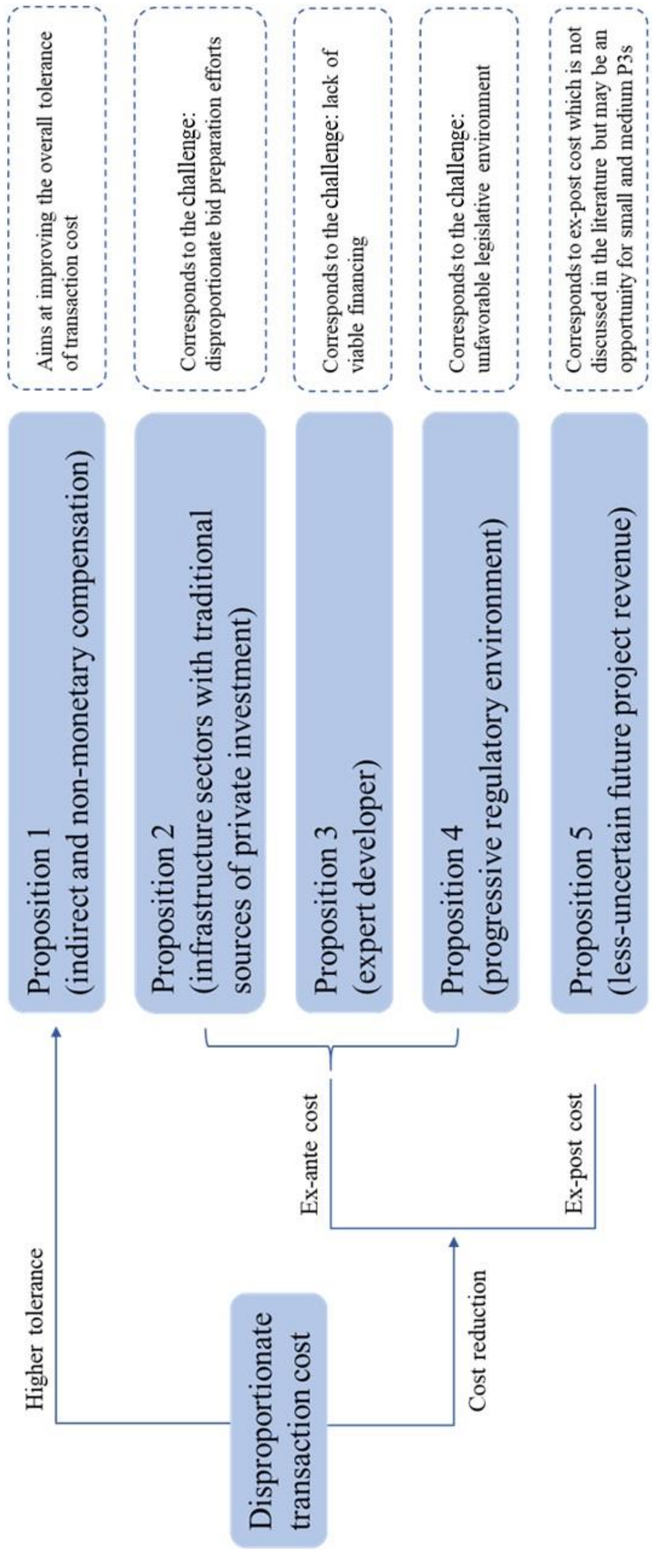


Figure 8. Proposed Enabling Features of U.S. Small- to Medium- sized P3s

No matter the project size, P3 generally tends to have higher transaction cost compared to traditional project delivery and contracting methods (Blanc-Brude et al. 2006). Based on a research led by World Bank (2016), a survey among 35 U.S. State Department of Transportation (DOT) (Ashuri and Mostaan 2015), a case study on nine U.S. P3 projects (Bolanos et al. 2019), and a survey among 46 respondents from 42 different academic/industrial organizations (Zhang 2006), saving the cost for project delivery is not among the greatest concerns of the public sector to mobilize private financing (Table 13). Those results are in line with a research by Hodge and Greve (2013), which says that besides cost concerns, dimensions related to project delivery, economic, policy, and governance are important as well.

Table 13. Objectives for Utilizing Private Financing in Literature

Checklist of objectives	Source
(i) Introducing innovation and improving efficiency; (ii) Improving project cost and time performance; (iii) Imposing budgetary certainty in terms of life-cycle cost; (iv) Utilizing local firms; (v) Transferring skills to the private sector and giving a boost to economy; (vi) Supplementing public sector capabilities in providing infrastructures; and (vii) Transferring risk to private sector and extracting long-term value-for-money.	World Bank
(i) Developing delayed projects; (ii) Expediting contract award and overcoming fiscal constraints; (iii) Improving project time performance and project quality; (iv)	A survey by Ashuri and Mostaan among U.S. State DOTs

Incentivizing innovation; (v) Enhancing agency's image; and (vi) Saving project life-cycle cost.	
(i) Accessing private-sector financing; (ii) Accessing private-sector expertise and innovation; (iii) Accelerating project delivery; (iv) Increasing certainty about project cost, schedule, and quality; (v) Transferring and managing risk; and (vi) Improving transit and development opportunities.	A case study by Bolano et al. on nine U.S. P3 projects
(i) Exploring private finance initiatives for enhanced infrastructure development; (ii) Improving construction engineering and management process; (iii) Utilizing private sector technologies and managerial skills for innovative and cost-effective project procurement; and (iv) Improving the scope for private sector participation to promote the development of priority and other needed projects.	A survey by Zhang among 46 respondents coming from 42 different academic/industrial organizations

Moreover, the statistics on all the 16 Canadian small P3s having reached financial close as of 2019 show that, in spite of the higher transaction cost, the economic benefits incurred by reduced infrastructure project delay bring average 19.85% value of money savings (CANCEA 2016). After investigating the small P3s in UK, Germany, and Italy, Koch and Jensen (2009) proposed that protecting first experiments to enable learning and focusing on user-driven innovation might be enabling conditions for small P3. Building upon the work by prior scholars, this study complements prior work by proposing Proposition 1 as one of the critical enablers of U.S. small and medium P3s:

Proposition 1 (indirect and non-monetary compensation): The use of P3 could expedite project delivery, thereby satisfying the expectations of the stakeholders on *indirect financial compensation and/or non-monetary compensation brought by the completion of project.*

Indirect financial and non-monetary compensation look beyond the direct revenue generated by the project, such as toll fee. Some examples are socioeconomic benefits, such as the application of new technologies, the creation of new government revenue source, the creation of new jobs, and the innovation of local governance (Peter 2012, Blackburn et al. 2020).

Transaction cost could be classified into ex-ante transaction cost and ex-post transaction cost by the time of occurrence. Ex-ante transaction cost incurred in searching information, making appraisal, bargaining and drawing up an acceptable contract. As discussed above, the three identified challenges fall into the category of ex-ante transaction cost. This study proposes Proposition 2, 3, and 4 corresponding to the three challenges identified in the literature:

Proposition 2 (infrastructure sectors with traditional sources of private investments): P3 could be a viable approach for delivering small- to medium- sized projects in sectors where private investments traditionally play crucial roles.

As result of relatively high private sector involvement, the partnership or concession would not be taken as alternative delivery methods. Both the public sector and the private sector may have more experience and lessons learned in the procurement and the operation of concession. Therefore, fewer efforts would be required in collecting information and preparing acceptable contracts, which implies lower ex-ante transaction costs (Kululanga and McCaffer 2001).

Proposition 3 (expert developers): Small and medium P3s require developers with expertise in infrastructure finance, in order to get viable project financing plans.

The credibility and the financing pipelines of infrastructure developers could remedy the disadvantages of small and medium P3 in terms of attracting viable financing, because the expertise of the developers is of great importance for the investors to make investment decisions (Yescombe 2013). This proposition complements and contextualizes the 'financial capabilities of the private sector' critical success factor in the literature (Osei-Kyei and Chan 2015; Owolabi et al. 2020).

Proposition 4 (progressive regulatory environment): Small and medium P3s could first appear in the states having favorable enabling law and greater P3 experience.

In the United States, the use of P3 to deliver small- to medium-sized infrastructure projects is at its early phase. The jurisdictions which have generally favourable P3 environment and greater experience have higher probability to become the pilot districts. The lack of favourable environment and P3 experience may be challenges for government agencies to pledge enough commitments and possess sufficient capabilities, which are crucial in shaping the willingness of the public sector to turn to P3 (Geddes and Reeves 2017). This proposition complements and contextualizes the 'favorable legal framework' critical success factor in the literature (Abdel Aziz 2007; Chan et al. 2010; Dulaimi 2010; Chou et al. 2012; Hwang et al. 2013; Osei-Kyei and Chan 2015).

In contrast to the ex-ante transaction cost, ex-post transaction cost is mostly a result of incomplete contract. Ex-post transaction cost is the cost of ensuring the other party fulfilling the terms of the contract and the cost of taking appropriate actions if not

(Soliño and de Santos 2010). Neglect of offering explicit duties and responsibilities for every possible "state of the world" is a typical source of incompleteness (Soliño and de Santos 2016). Benefited from smaller size of projects, small and medium P3s tend to have less project complexity and uncertainties. These features may help reduce the ex-post transaction cost incurred in contract enforcement, renegotiation, and related litigation. Hence, it is plausible that:

Proposition 5 (less-uncertain future project revenue): Small and medium P3s normally have comparatively more straightforward and less uncertain payment mechanisms, such as availability payments.

In case of availability payment mechanism or its equivalents, the private sector receives a fixed remuneration that generally budget financed and payable at regular intervals, based on specific service level agreements (Weber et al. 2016). The payment mechanism allocates most general risks which are not directly relevant to the projects, such as market risk, to the public sector, and the private sector could focus on managing project-specific risks, such as construction and operations risk. This arrangement helps private sector by reducing the required efforts on risk mitigation and consequently reducing the ex-post transaction cost.

4.4 Research Approach

To examine the proposed propositions and to explain the rationale for development of small- to medium- sized P3 in the context of these propositions, the authors conduct a thorough analysis of important documentation of twelve small and medium P3 infrastructure projects in the U.S., including contracts, project websites, request for proposals, and public hearing minutes. The records of these twelve projects are found in the following three databases: (a) Public Works Financing (PWF) Newsletter; (b) U.S. Federal Highway Administration Office of Innovative Program Delivery; and (c) Inframation Global Transaction Database. These three databases are identified as the principal databases for U.S. P3 market (Daito 2014). These 12 projects represent all P3 projects found in these databases that are small and medium P3 projects having reached financial closure as of 2018 in the U.S. Although P3 is a long-term contract during which complexities and uncertainties would gradually reveal, financial closure represents an important "moment of truth" in which the amount of private investments is finally stated by the contract (World Bank 2017). The degree of private commitment captures the attractiveness of the P3 proposal and the degree of success from a public perspective, reflecting the capacity of public institutions to build up an appealing negotiation. (Panayides et al. 2015). Moreover, since the challenges and enablers of small and medium P3 centre around the delivery process, using financial closure as the indicator is appropriate and consistent. Nevertheless, the enablers proposed in this study are necessary to be re-examined as life-cycle assessment of P3 is available in future.

Project selection process is shown as Figure 9. The criteria of project selection are twofold. First, the selected projects should meet the definition of P3 by National Council for Public-Private Partnerships (NCPPP 2018), which says "a contractual arrangement that is formed between a public or governmental agency and a private company that can include a variety of activities that involve the private company in the development, financing, ownership and/or operation of a public facility or service. In such a partnership, public and private resources are pooled and responsibilities divided so that the partners' efforts complement one another." Second, the project size should be less than $150M, as suggested by the National Academies (2017), in order to be qualified as small- to medium-sized P3. Although this study is supported by FTA, it covers projects from various sectors, including transportation, real estate, communication, and energy. Table 14 provides an overview of the twelve investigated projects.

A multiple-case study approach is selected for this study for three reasons. First, this study aims at exploring the enabling features of completed projects, and case study is an appropriate analysis and interpretation method for inductive, exploratory inquiries (Yin 2014). Second, multiple-case design represents a rationale derived from the prior hypothesizing of different conditions and the desire to have cases covering each condition (Yin 2014). Moreover, multiple-case design applies replication logic, and the evidence from multiple cases is often considered more compelling (Herriott and Firestone 1983). Considering the fact that the number of small and medium P3 projects having reached financial closure in the United States is very limited, all projects in the above-mentioned database meeting the two selection criteria are included, and no sampling is involved.

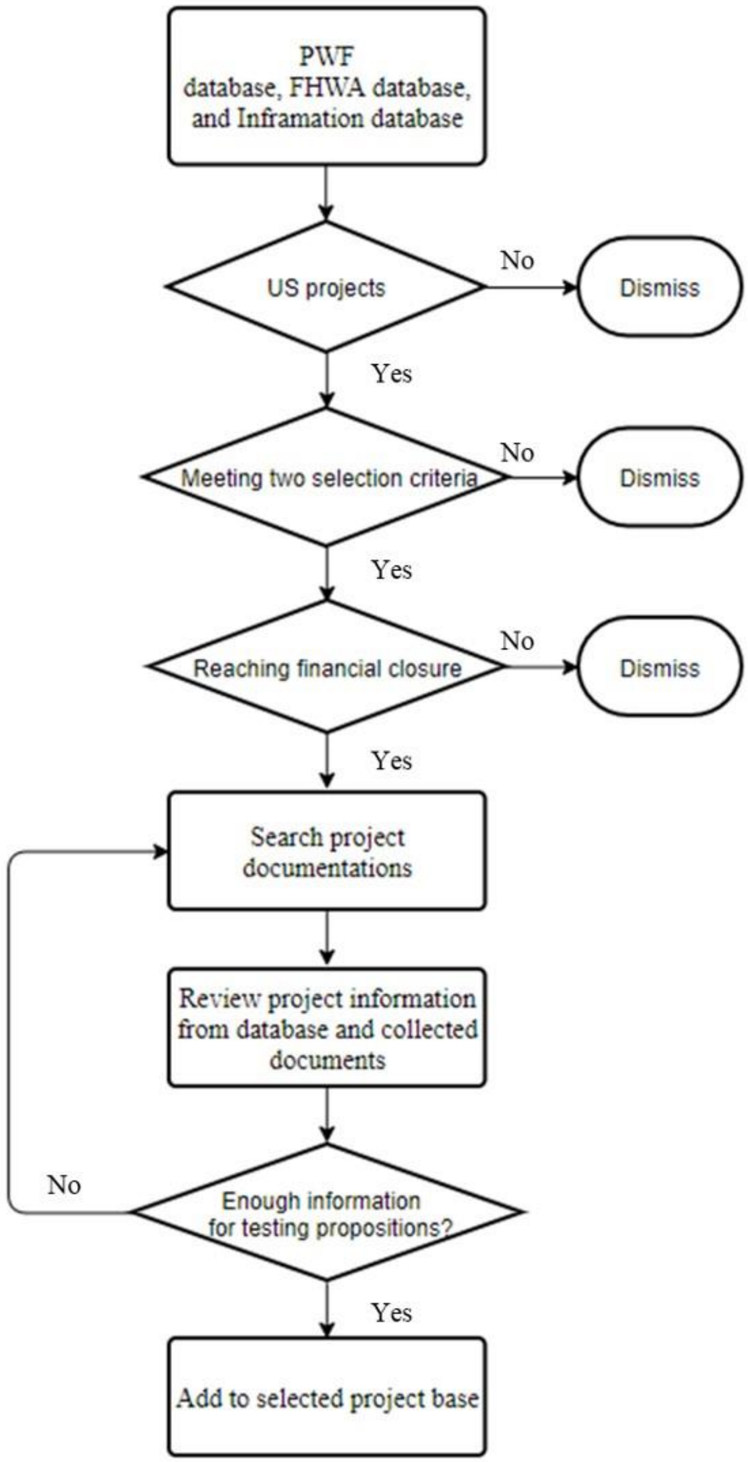


Figure 9. Project Selection Process

Table 14. Small and Medium P3 in the United States

Jurisdiction	Sector	Delivery model	Payment mechanism	Value (USD)
Pennsylvania	Water/wastewater	DBFOM	Availability payment	$50M
Pennsylvania	Energy	DBFOM	Revenue risk	$84.5M
Connecticut	Commercial facilities	DBFOM	Asset lease	$105M
Michigan	Educational facilities	DBFOM	Asset lease	$55M
Maryland	Governmental building	DBFOM	Availability payment	$137M
Maryland	Commercial facilities	DBFOM	Asset lease	$56M
Michigan	Energy	DBFOM	Availability payment	$50M
Indiana	Educational facilities	DBFOM	Availability payment	$125M
California	Water/wastewater	DBFOM	Revenue risk	$125.5M
Indiana	Transportation	DBFOM	Availability payment	$70.6M
Texas	Educational facilities	DBFO	Revenue risk	$54M
Colorado	Transportation	DBFOM	Revenue risk	$120M

Project	Grantor	Grantor type
Chester Storm Water Runoff System P3	Chester Stormwater Authority	Local
Compressed Natural Gas (CNG) Fueling Stations	Pennsylvania DOT	State DOT
Connecticut Service Plazas Acquisition	Connecticut DOT	State DOT
Maryland Courthouse P3 (Howard County)	Eastern Michigan University	University
Maryland I-95 Travel Plazas Redevelopment	Howard County	Local
Michigan Freeway Lighting	Maryland DOT	State DOT
Michigan Freeway Lighting	Michigan DOT	State DOT
Purdue University Student Housing P3	Purdue University	University
Santa Paula Water Concession	Santa Paula City Council	Local
State Street Redevelopment P3	City of West Lafayette, Purdue University	Local& University
University of Texas at Dallas - Northside Phase 1	The University of Texas at Dallas	University
U.S. 36 P3	High Performance Transportation Enterprise	State DOT

Concession duration	Greenfield/ Brownfield	Debt& Bond profile (USD)
30 years	Greenfield	N/A
20 years	Greenfield	N/A
35 years	Brownfield	Senior secured term loan $110M; Senior secured letter of credit $5M
35 years	Brownfield	N/A
30 years	Greenfield	Senior secured term loan $78M
35 years	Brownfield	N/A
15 years	Greenfield	Asset backed bond $44M
65 years	Greenfield	Private placement $115M
30 years	Greenfield	N/A
22 years	Greenfield	Senior secured amortizing loan $25.17M
61 years	Greenfield	N/A
50 years	Greenfield	Subordinated term loan $20.6M; Asset backed bond $20.36M; Transportation Infrastructure Finance and Innovation Act (TIFIA) $60M

Financial close	Investor(s)
2017	Corvias Solutions
2016	Trillium CNG
2016	John Laing Infrastructure Fund
2018	Preston Hollow Capital
2018	Edgemoor Infrastructure and Real Estate; Star America Infrastructure Fund
2012	Acquiror Areas USA
2015	Aldridge Electric; Star America Infrastructure Fund
2018	Plenary (North America)
2008	Alinda Infrastructure Fund II; PERC Water
2016	Plenary (North America)
2015	Balfour Beatty Communities, LLC; Wynne /Jackson Inc; Star America Infrastructure Fund
2014	Plenary (North America)

Table 15. Indirect financial and/or non-monetary compensation objectives of the identified projects

No.	Project	Goals and objectives
1	Chester Storm Water Runoff System P3	This project helps minimize flooding and eliminate sewage into the Delaware River by separating stormwater and household wastewater. The project creates jobs for residents via high requirements on utilizing local and disadvantaged business.
2	Compressed Natural Gas (CNG) Fueling Stations	This project helps capitalize the abundance of natural gas in Pennsylvania. DOT could reduce greenhouse gas emission and save long-term operating cost via this project. P3 leverages the expertise of CNG industry in operations and management.
3	Connecticut Service Plazas Acquisition	P3 revives the obsolete assets, creates jobs, and brings long-term revenue to DOT without using government capital and human resources.
4	Eastern Michigan University Parking P3 Acquisition	P3 monetizes the asset of university and provides needed capital improvements to the university.
5	Maryland Courthouse P3 (Howard County)	P3 transfers the risk of operations and maintenance entirely to the private sector, which has plagued the asset owner for decades.
6	Maryland I-95 Travel Plazas Redevelopment	The project partially transfers the contamination remediation risk to the private sector. P3 revives the obsolete assets, creates jobs, and brings long-term revenue to DOT without using government capital and human resources.
7	Michigan Freeway Lighting	The P3 transfers the risk of using new technologies and theft prevention liability to the private sector.

		DOT could expect significant energy cost saving. DOT staff could shift focus on other electrical infrastructure.
8	Purdue University Student Housing P3	P3 helps the project achieve the accelerated project schedule. It enables the use of innovative, prefabricated components and improves project safety by minimizing on-site work.
9	Santa Paula Water Concession	P3 helps the project meet strict time and budget constraints. The city faced fines of over $8M if the new wastewater treatment facility could not be completed from scratch in three years.
10	State Street Redevelopment P3	The project is created to be catalytic to the planned development of a large-scale live-work-play technology hub on the western end of the University.
11	University of Texas at Dallas - Northside Phase 1	P3 leverages the expertise of developer in design, build, and operation of an on-campus mixed-use housing and retail complex.
12	U.S. 36 P3	P3 dramatically accelerates construction on projects that would take decades to build without private funding.

4.4 Results

In the following, the authors describe the results of analysis on the documentation of twelve identified small and medium P3 infrastructure projects. In support of the proposed enabling features, findings are grouped and analyzed within the framework of the five propositions on enabling features.

Major objectives of using the P3 model in development of the 12 small and medium projects – related to Proposition 1 indirect/non-monetary compensation

The analysis begins with the first proposition, that is whether the objectives of using P3 imply higher tolerance towards transaction cost. The goals and objectives of the identified projects related to indirect financial compensation and/or non-monetary compensation are summarized in Table 15.

The goals and objectives of five projects, projects #2, #3, #5 #6, and #7, are further elaborated here. The Connecticut Service Plaza project (Project #3) was awarded to a project company with most of members based in Connecticut to upgrade, operate and maintain all 23 existing highway service plazas in Connecticut. These service plazas were built in the 1940s–1950s and have had no significant capital investment since the1990s. Based on the concession, there is no upfront payment between the private sector and Connecticut DOT, and Connecticut DOT is supposed to receive $500M in economic benefits over the full term (Reinhardt, 2012). Similarly, the Maryland Service Plaza project (project #6) was awarded to a project company which promises a disadvantage business enterprises (DBEs) goal higher than the state requirements to upgrade, operate and maintain two service plazas along I-95. The concession has no upfront payment and revenue sharing agreement. The concession is supposed to support 400 construction and 575 operating jobs and will bring in more than $400M to the State over the agreement (MD DOT, n.d.). The above two projects have one distinguished feature in common, that is they are not the major public services provided by State DOTs. Outsourcing as P3 could benefit State DOTs by maximizing the value and use of transportation-owned or managed properties, by generating new sources of revenue for transportation projects, by creating job opportunities and without adding State DOTs' administrative burdens.

Prior to initiate the freeway lighting P3, the Detroit metro area was plagued by the dysfunctional freeway lights along the major interstate corridors: 30% of the failure rate, ongoing incidents of copper theft, and high operation cost for running outdated high-pressure sodium lights (FHWA, n.d.). By entering P3 (Project #7), Michigan DOT avoided the burden of significant upfront cost required to improve the existing system and share the risk related to the uncertainty of new technologies, theft, operation and maintenance with the private sector. The energy saving payment under the P3 mechanism incentivized the project company to provide energy efficient equipment. Compressed Natural Gas (CNG) Fueling Stations (Project #2) is another small and medium P3 let by State DOT in the energy sector. Pennsylvania has the second largest natural gas proved reserves as of 2018 (US EIA, 2019) and Pennsylvania DOT intended to capitalize on the abundance resources by building CNG stations to supply gas to more than 1,600 CNG public transit buses. The change of fleet from gasoline powered vehicles to CNG powered vehicles could help Pennsylvania DOT save $100M fuel cost in ten years and reduce 20 million pounds of carbon dioxide emissions. As the market demand expands and more individuals turn to CNG vehicles, CNG stations are supposed to provide Pennsylvania DOT a new long-term revenue source. The use of P3 allows Pennsylvania DOT taking advantage of CNG stations faster than the use of traditional procurement while transferring the risk on operation and management to the private partner. In the above two cases, P3 mechanism offers at least two opportunities besides reduction in overall project cost and risk transfer, that is technological advancements and important public policy advancements (e.g., mitigation of existing environmental impacts).

Howard County Courthouse (Project #5) was opened in 1843. It was periodically renovated and was last expanded in 1983. The latest engineering studies show that the existing building could no longer be future renovated to provide extra spaces and to accommodate latest IT facilities, which are urgently required by the owner. Prior to P3, the renovation work had been delayed many times over twenty years. That deferred maintenance experience makes the owner decide to go for a solution including high quality, long-term maintenance service.

It is important to note that expectations on indirect financial compensation and/or nonmonetary compensation facilitate the formation of P3. However, its effectiveness is not yet fully proved as these projects are still early in concession. Private Finance 2 (PF2) in UK getting terminated six years after initiation reminds worldwide practitioners of critically examining goal achievement of P3s (Cheng et al., 2020).

Sectors of the twelve small and medium P3 projects – related to Proposition 2 infrastructure sectors with traditional sources of private investments

Among the twelve identified projects, the gas station project (Project #2) and highway service plaza projects (Project #3 and Project #6) are in a sector with a long history of private capital involvements. In the US, gas station and service plaza is categorized as a subsector of retail business, which is predominantly run by private investors. The well-established tradition using private investment matches the features described by the second proposition.

P3 could be a successful delivery model for small and medium-sized projects in social infrastructure sector too (Project #4, Project #8, Project #10, and Project #11). In recent years, public universities have increasing use of alternative delivery methods for constructing projects to service their student population, with tight deadlines and compacted or accelerated schedules (Shrestha and Fernane, 2017). According to Tan (2008), early in 1960s, to respond the large-scale urban renewal and acute housing shortage, public universities in the US started to use P3 to meet their funding requirements. The value of investment in public university social infrastructure spiked dramatically since 2008 and there is at least $16.4B investment from 2006 to 2016 (Levey et al., 2020). Decades of practice accumulates experience for both the owners and the contractors with respect to project evaluation, contract negotiation, and project financing. Some empirical studies on student housing projects (Audit Scotland, 2002; Audit Commission, 2003, and Mehra, 2005) show that small P3 projects have higher probability to achieve success because they normally have better-defined scope, lower transaction cost, and easier access to financing and higher occupancy levels. However, as mentioned above, these social housing projects are waiting for re-examination when the specific definition of small and medium US social housing projects are available.

Water/wastewater is another example of growing P3 market in the US Water/wastewater is a sector with significant private investments. Kopaskie (2016) analyzed the data published by US Environmental Protection Agency (US EPA) and found out that 12% of the national population is served by private community water systems. According to statistics on projects with a value greater than $50M from 1991 to 2016, there are $3.3B worthy of projects use private financing (CBO, 2020). Benefiting from the wealth of practical experience and the support of US EPA, the water/wastewater sector sets about to develop Community-Based P3 models to address the unique challenges faced by the sector (US EPA, 2015). Project #1 is an example. It involves a community-based advisory board besides the owner and developer to ensure the benefits of local communities: it is set forth in contract that nearly a third of work hours should be performed by local subcontractors.

Types of developers behind the twelve small and medium P3 projects – related to Proposition 3 expert developers

As shown in Table 14, four out of the six projects with debt/bond have dedicated infrastructure funds as their P3 developers and equity investors. The other two have dedicated infrastructure funds as co-equity investors. Compared to traditional construction firms, these funds are dedicated to the P3 market, and have stronger investor base including institutional investors. For example, the John Laing Group is a specialist equity stakeholder partnering with public sectors across the world to deliver local and national infrastructure projects. As at July 9 2020, John Laing is valued at £1.147B ($1.42B) on the London Stock Exchange. In addition, Plenary Group is a P3 specialist having a portfolio of 69 assets under management worth more than $42B (Plenary, 2020). This observed evidence is in line with the feature described by the third proposition. It is noteworthy to recognize that private sector developers of these P3 projects are international firms with several decades of experience in the international infrastructure finance market. These international players have a large portfolio of infrastructure projects across the globe that helps them capture and deploy lessons learned and manage financing risks more effectively.

Enabling legal environment for the twelve small and medium P3 projects – related to Proposition 4 progressive regulatory environment

The twelve observed projects distribute in eight states, PA, CT, MI, MD, IN, CA, TX, and CO and all these states have enabling legislations (Table 11). Five of the twelve projects were delivered by state DOTs, and the other seven were delivered by local governments/universities. As shown in Table 16, all the local/university grantors except Howard County get their authority from state legislations. Compared with getting authority from home rule, getting authority from state legislation enables local government to use P3 without passing local ordinance. As Maryland does not authorize local government to use P3, Howard County passed a specific bill for the project as a home rule county (Howard County, 2018).

Casady et al. (2019) analyzed the P3 projects having reached financial close or still being in procurement from 2015 to 2018. Casady et al. classified 50 US states into five categories based on their amount of P3 transactions (i.e., 10+, 6–10, 3–5, 1–2, and 0). All the eight states with observed small and medium P3s are at the top two ranks (i.e., 10+or 6–10). These facts match the features described by the fourth proposition.

Payment mechanisms used in the twelve small and medium P3 projects – related to Proposition 5 less-uncertain future project revenue

The twelve identified projects consist of nine greenfield projects and three brownfield projects. Concessions of brownfield projects normally use asset lease, where the concept of payment mechanism is not applicable. For greenfield projects, there are two common payment mechanisms, that is revenue risk and availability payment. As shown in Figure 10, the number of greenfield projects using availability payment approach is more than the number of greenfield projects using revenue risk approach. There is a clear trend of shifting to the use of availability payment. In the four greenfield projects using revenue risk approach, three projects have assured future demand (minimum revenue guarantee). The CNG fueling stations project is supported by more than 1,600 public-transit buses at 29 cities in Pennsylvania. The Santa Paula concession was endorsed by the mission of increasing the quality of the discharging wastewater with limited time. The University of Texas at Dallas' student housing project is supported by the steadily growing student population. Thus, there are five out of nine greenfield projects have features which rigorously match the description of the fifth proposition (i.e., availability payment), and there are eight out of nine greenfield projects have features which broadly match the description of the fifth proposition (i.e., secured revenue).

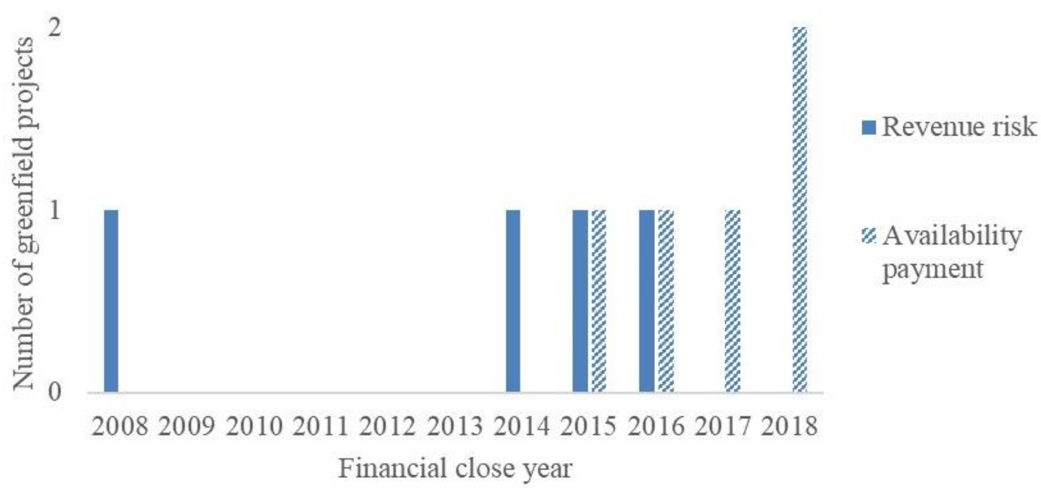


Figure 10. Payment mechanisms of greenfield small and medium US P3 projects

Table 16. Authority source of the local/university grantors

Jurisdiction	Number of local/university let P3 projects	State P3 legislation applies to local governments
Pennsylvania	1	Yes
Michigan	1	Yes
Maryland	1	No (Home rule applies)
Indiana	2	Yes
California	1	Yes
Indiana	1	Yes
Texas	1	Yes

4.5 Policy Implications and Recommendations

As a typical mature market economy, much of the U.S. infrastructure is several decades old and reaching the end of its useful life (Scott et al., 2019). From 2016–2025, there is a $2T gap in infrastructure investment to maintain existing infrastructure facilities (ASCE, 2017). This does not include the necessary investment on technologies for increasing automation, improving communication, and self-monitoring in wake of the Fourth Industrial revolution. Furthermore, massive resistance of taxpayers to increase in taxes and unstable economic conditions pose another type of challenge in financing infrastructure projects. The ongoing COVID-19 pandemic makes the difficult situation worse by significantly reducing a sizable funding source of infrastructure, that is, user-generated revenue (ASCE, 2020). Partnering with private entities that control or can leverage private resources has long been an instrument of government entities in face of the above challenges (Scott et al., 2019). Therefore, the authors suggest policy makers to consider offering explicit authorization to local government, especially for home-rule states. Among the three challenges mentioned in the study, the one related to legislation is the one hardest (almost impossible) to circumvent. Despite the complexity and diversity of legislative processes and political environment across the United States, there are some feasible actions could reduce legislative barriers without substantially changing status quo. An inspiring example is the Howard County Courthouse Project discussed in the study. Existing state law and regulations of Maryland neither prohibit nor authorize local government using P3. As a home rule state, local governments in Maryland could use P3 by passing local ordinance. If state legislation explicitly authorizes local government, the counties of Maryland could avoid time-consuming legislative procedures without materially changing existing conditions. Entering into P3 is a risky decision for private sector. P3 is an alternative delivery method, whose name implies that it is not a viable model for all projects. Some projects are structurally flawed and do not become viable via a P3 model (McCarthy et al., 2020). Besides project features, it is worthy to note that P3 is not an attractive and doable business for all companies: while some world-leading contractor is existing US P3 market after years of less-satisfying practice (Reina et al., 2018), some dedicated infrastructure investor is expanding P3 business in the US (John Laing, 2020). This study characterizes some features of viable projects (e.g., proposition 2 and proposition 5) and competent developers (proposition 3). Private sector is recommended to consider these factors before entering P3. To summarize and visualize the above recommendations, a pathway for both the private and public sectors are shown in Figure 11. The pathway represents executable recommendations drawn upon the theoretical framework developed in this study.

The traditional belief on the availability of P3 deprives any opportunities of small and medium projects using P3, without giving clear definitions or sound justifications. The analysis and reflection on US small and medium P3s presented in this study shed light on the credibility and viability of small- to medium- sized P3 by successfully identifying the features enabling the selection of P3 as delivery method. It is anticipated that the findings of this study could increase the confidence in policy makers to apply P3 on small- to medium- projects by outlining the contour of applicable field. Experience in the US has persuasively proved that suitability assessments of alternative project delivery method could facilitate the legislative transformation and alternative delivery adoption (Vanmeter, 2018). The findings of this study are expected to benefit private sector at making P3-entry related decisions by offering a pattern of successful small and medium P3s for reference.

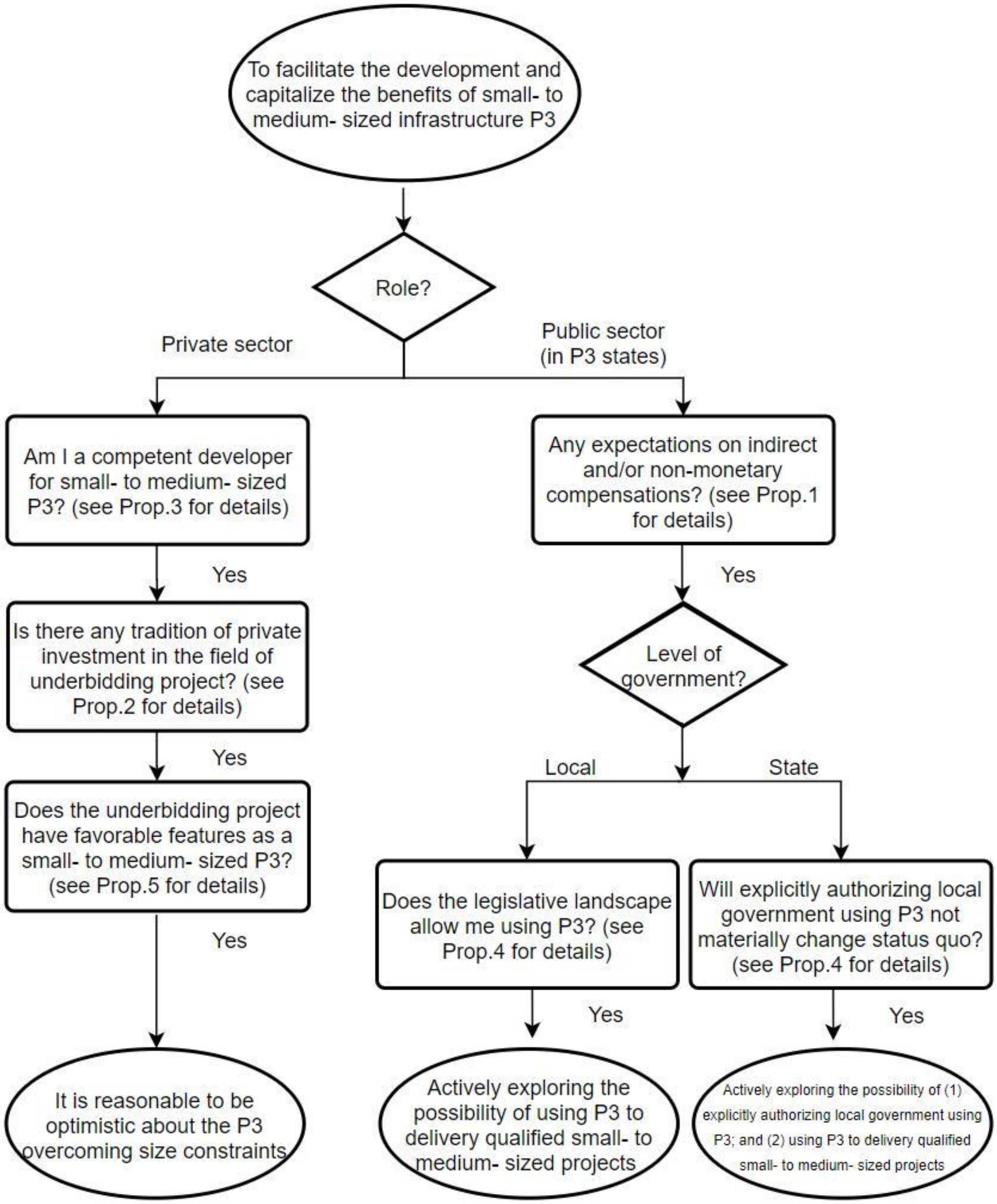


Figure 11. Recommended pathway of facilitating small- to medium- sized infrastructure P3

4.6 Conclusion

Public–private partnership is traditionally taken as an alternative delivery method exclusively for large megaprojects. However, the authors use the statistics to show that the existence of small and medium P3s is not just an accident in developed economies, such as the United States. The authors critically review the opinions related to the challenges of implementing small and medium P3s in the literature, and then employed a framework drawn from the transaction cost to categorize the challenges summarized from the literature. Based on the analysis of summarized challenges, the authors provide two sets of propositions as potential enabling features of US small and medium P3s. First, small and medium-sized infrastructure P3 projects could have higher tolerance on transaction cost because of expectations on indirect financial compensation or non-monetary compensation brought by the completion of project. Second, small and medium-sized infrastructure P3 projects could have the following features to enable lower transaction cost: (1) being in the sectors which have well-established traditions on using private investments; (2) having developers with expertise on infrastructure finance; (3) being in the jurisdictions with favorable legislation environment and (4) having less uncertain payment mechanisms. The proposed enabling factors were supported by the analysis of twelve identified US small- to medium- sized P3 projects reaching financial closure as of 2018. The results show how the identified enabling features in these cases contribute to enhancing the viability of P3 model in infrastructure market.

The major contributions of this research are: (1) the categorization and analysis of challenges of implementing small- and medium-sized infrastructure P3 in the US; (2) the development of a theoretical framework consisting of five distinct propositions that are used to explain why P3 can be a viable model for small- and medium-sized infrastructure projects and (3) the identification of enabling features as growth opportunities for small and medium P3 market. This study distinguishes itself by providing specific and contextualized analysis on the challenges and enabling features of US small to medium infrastructure P3. For instance, even though favorable legislation environment is an enabling feature mentioned in prior studies, the authors further specify it as being widely authorized beyond transportation sector and being explicitly authorized for local government by state legislative branch. This corresponds to the reality that P3 is primarily used for transportation projects in the United States and the unique US federalism.

This study shows that under the specific conditions suggested by the identified enabling features, P3, even at small- to medium- sized level, could help meet local infrastructure needs, promote technology adoption (e.g., EV and LED road lights), create jobs, achieve public policy advancement (e.g., greenhouse gas emission reduction), reduce life-cycle operations and maintenance cost and outsource non-public services provided by the government without adding administrative burdens. In future, quantitative empirical studies should be conducted on individual small to medium P3 projects to examine if the proposed enablers could mitigate the encountering challenges.

CHAPTER 5. CONTRIBUTION AND FUTURE WORK

By the time I put together this thesis, Biden Administration declares a "once-in-a-generation investment" to boost the infrastructure system of the United States. The $2 trillion plan covers transportation, power, water, internet, and social infrastructure, with aims to not only rehabilitating decaying facilities, also achieving sustainability, fostering innovation, and promoting social equity. The research works presented in this thesis fit well in this background, despite that they were conducted in prior of the new infrastructure investment plan. Below, I will summarize how each research work contributes to the body of knowledge, discuss their limitations, and project future works that can expand the use of the developed methodologies. The approaches which may further improve the existing methodologies will also be introduced.

In the environment of Public-Private Partnership, risk-sharing mechanisms create safe buffer for enormous infrastructure investments by offering managerial decision flexibility. Creation of risk-neutral measure is at the center of correctly pricing the options on real assets in relation to managerial decision flexibility. Investors are typically risk-averse and demand returns for bearing uncertainty. Existing studies mostly use Sharpe ratio, i.e., the quotient of market risk premium and project volatility, for risk-neutral valuation (Ashuri et al. 2012). This approach only applies to the uncertainties with trackable, equivalent market risk premium, such as future traffic volume. In contrast, during the development of sustainable and resilient infrastructure system, there are a lot of technical risks without equivalent market risk premium threatening infrastructure investment. Examples include the increased cost of pavement maintenance due to climate change, and the change of traffic volume due to pandemic. In light of that, Chapter 2 proposes an approach using subjective probability and utility theory to calculate the constant equivalent of technical risks for risk-neutral valuation. Other contributions of the study in Chapter 2 include the exploration on a seldomly discussed topic – cash flow shortage risk, and the exploration on a seldomly discussed risk sharing mechanism – contingent finance support.

The uncertainties involved in the study – uncertain future traffic volume and potential construction cost overrun – represent two distinctly different types of risk. Uncertain traffic volume is a market risk, and potential construction cost overrun is a technical risk. Uncertain traffic volume is a non-stationary risk which changes constantly as time evolves. Commonly used modeling approaches of non-stationary risks include stochastic processes or the method used in this study, i.e., multinomial lattice. Potential construction cost overrun is a kind of stationary risk which can be described using statistical modeling, e.g., the method used in this study – probability distribution fitting. The way of handling the two risks in this study can be applied to other specific risks in the future without substantial revisions.

It is worthy to note that the statistical model and the utility function used in this study to describe construction cost overrun and to describe people's risk preference are not necessarily the best. It is more of a showcase exhibiting the methodology – how to generate equivalent risk premium using utility function, and how to incorporate risk premium into a statistical model. Normally there are numerous statistical models for a single technical risk, such as construction cost overrun or excess expenditure on pavement maintenance due to climate change. The choice of most appropriate model is subject to spatial factor, temporal factor, the features of the project, the features of the developer, and more. Similarly, even though the format of utility function is relatively stable. The values of parameters vary from case to case. They are pertinent on the timing of decision-making, the contents of decision-making, and the features of decision-makers. In face of future uncertainties, owners want robustness while keep flexibility – avoid high upfront investment. This is a trade-off. Real options thinking is fundamental to creating a robust and flexible investment plan for investors. Also, options thinking is important for design of flexible infrastructure systems that are more resilient.

Owners can use the developed model to determine the equilibrium of their specific situations, by adjusting statistical models and utility functions. For instance, owners always face such a decision: either spending more resources to secure a better capital structure right now or saving the resources for future in case of any fiscal difficulties happen. By plugging in different parameters, one may determine to modify the current capital structure because he/she finds out that the risk portfolio of the project in future is higher than the resources needed to modify existing capital structure. Another person may determine the other way around – due to opposite results obtained from the model. In addition to the timing of investment (e.g., multi-stage investment), real options can help owner via multi-scale investments. The sizing of investment can also be a decision variable, to get a better risk profile (minimize upfront risky and costly investment in situation where investment is happening in a volatile environment). An example is determining the sizing (also timing) of investment in solar power for buildings, under demand uncertainties. Panel sizes and timing of panel installation can both change in order to get better a risk profile (Gahrooei et al. 2016).

Known unknown (identified risk) and unknown unknown (unidentified risk) are two types of risk that may jeopardize infrastructure project management (Kim 2012). The developed real options model can only be applied to known unknows. For unknown unknowns, which are believed to be impossible to find or image in advance, real options model can hardly help. When such a risk becomes reality, it is suggested to be improvised. Understanding the root cause of the issue and detailed documentation can help the risk turn to known unknown in the future.

Having realistic estimate on future periodical fiscal obligations can significantly reduce the risk of cash flow shortage and debt default at the early stage of project development. However, the forecasting task is not easy, especially for the projects delivered via alternative delivery methods. Alternative delivery methods, including design-build (DB), design-build-finance (DBF), and design-bid-finance-operate-maintain (DBFOM) provide significant opportunities for transportation agencies to enhance their financing capabilities for delivering transportation infrastructure. In addition, alternative delivery methods are also excelling in incubating innovation that can help overcome resource constraints, address energy and environmental considerations, and promote efficiencies in program delivery (FHWA n.d. (b)). However, there is no complete design, exact quantity, and detailed schedule for the estimate of construction expenditure at the time of project awarding since alternative delivery methods partially overlap design and construction. The study presented in Chapter 3 focuses on design-build projects – the basic, also the most popular alternative delivery method – and develops an accurate construction expenditure cash flow forecasting model. The model is the first construction expenditure cash flow forecasting model for transportation projects delivered through alternative methods. The model uses high-level project attributes and works well with small dataset. From the theoretical aspect of construction management, the study proves the rationality and feasibility to generate accurate expenditure cash flow estimate early in the planning phase of project development, using a combination of project attributes and external indicators representing local construction market.

It worthy to note that the composition of attributes involved in the current model is not necessarily the best. As the increase of people's knowledge on the impacts of attributes on shaping the pattern of expenditure cash flow, the list of attributes involved can be future improved. The improvement can also be achieved when more data are available, that is, there are sufficient data that some insights can be obtained using data mining techniques.

Another thing worthy to note is that the use of genetic algorithm to generate optimal attribute weights is a heuristic, rather than classic approach for optimization problems. Genetic algorithm provides "good enough" solutions instead of universally and absolutely optimal solutions. The model validation has proved that the use of genetic algorithm can lead to satisfyingly accurate forecasts. Considering that the identification of optimal attribute values is a part of the entire model, and the identification process needs to be repeated whenever the database has an update, the choice of a heuristic method is reasonable and necessary. A classic but sophisticated optimization algorithm does not add much value when the currently available data are limited, and the database is expected to have obvious changes. In future, more work can be done in relation to the optimization process if there is a higher expectation on forecasting accuracy, or there is a relatively stable and well-established database.

Compared to traditional, large-size infrastructure projects, sustainable or smart infrastructure facility projects are frequently smaller in size. A lot of these projects are delivered by local governments, such as the Southeast Atlanta Green Infrastructure Initiative and the US-33 Smart Mobility Corridor in Ohio. The development of these sustainable/ smart infrastructure projects requires expertise that is not commonly possessed by governmental agencies. The partnerships between public sectors and private sectors not only address the difficulty of fundraising, but also introduce the indispensable expertise of private sectors to the project. Centering around transaction cost, popular belief deprives the possibility of small- to medium- sized projects using public-private partnerships (P3). For the first time, the study presented in Chapter 4 demonstrates the discrepancy between the empirical records and popular belief. Stemming from the concept of transaction cost, the study proposes a theoretical framework featuring the circumstances where P3 could be a viable choice for small- to medium- sized infrastructure projects. The framework is validated by all identified projects reaching financial closure in the United States.

In addition to the specific challenges and enablers, this study, as one of the first research of its kind, suggests a novel perspective on the theory of infrastructure finance. That is, by applying certain constraints to the project and developer, P3 can be a viable approach for infrastructure projects even at small- to medium- size. Even though the current study takes the United States as the context of interest, the perspective can be applied to other countries and domains. In future, more work can be done to examine the generalizability of the perspective proposed in this study, using the same methodology but cases from other countries.

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