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Capital Program Cost Optimization through Contract Aggregation Process

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16. Abstract

An earlier study (SPR-3702) indicated that INDOT's practice of grouping (or bundling) projects into multiple-project contracts (MPCs) usually resulted in lower unit costs. This follow-up study (SPR-4156) takes advantage of INDOT's increased use of project bundling and the data that have been assembled since the conduct of SPR-3702. The principal findings are:

1. Economies of scale. The decline in unit cost as the project size increases has been documented for all project types analyzed in this study.
2. Economies of bundling. Project cost are reduced as projects are bundled into a contract for all bridge work types, and most traffic, small structure and miscellaneous work types. For road work types, however, the reduction in project cost due to project bundling was only found for certain road project types.
3. Economies of competition. Increased market competition (more bidders) lowers costs for most bridge projects, but larger contracts can discourage all but the largest firms from bidding, which can lead to less competition, and therefore higher unit costs. This was investigated using both deterministic and probabilistic methods. According to the probabilistic model, the average number of bidders tends to be the highest when the number of projects is 2 to 4.
4. Project similarity (compatibility). Using a measure of similarity between different project types based on their constituent pay items, it was verified that project types in the same work category have a better (smaller) similarity distance compared to those in different work categories. The "similarity distance" measure can help identify candidate projects for bundling.
5. Maintenance of traffic (MOT) can be a major component of project cost. The MOT cost for most (but not all) bridge, road, traffic, and small structure work types was found to be generally reduced by project bundling. Of all work categories, road work was found to benefit the most from project bundling in terms of MOT cost savings.
6. Future bundling strategies. Use the "similarity distance" measure to identify projects suitable for combining into multiple-project contracts (MPCs). Use patterns found in this study to guide the number of projects to combine into MPCs.

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EXECUTIVE SUMMARY

CAPITAL PROGRAM COST OPTIMIZATION THROUGH CONTRACT AGGREGATION PROCESS

Introduction

An earlier study (SPR-3702) indicated that INDOT's practice of grouping (or bundling) projects into multiple-project contracts (MPCs) usually resulted in lower unit costs. Because the practice had not yet become common within INDOT, the data on such contracts were limited. Nevertheless, it was possible to confirm that economies of scale exist—that is, unit costs decline as project size increases. However, the declining trend in unit costs appeared to level off when bridge projects reached 20,000 square feet of deck area and road projects exceeded 10–20 lane miles. Other possible influences on unit costs (e.g., number of bidders and time of year for bid letting) were examined, without conclusive results. Because of limited data, only a few work types within the bridge and road work categories yielded statistically significant results in the earlier study. This follow-up study (SPR-4156) takes advantage of INDOT's increased use of project bundling and the data that have been assembled since the conduction of SPR-3702.

Findings

1. *Economies of scale.* Economies of scale—the decline in unit cost as the project size increases—have been documented for all project types analyzed in this study. This is true for both single-project contracts and multiple-project contracts.
2. *Economies of bundling.* Economies of bundling—the reduction in project cost as projects are bundled into a contract—have been found for all bridge work types, and most traffic, small structure and miscellaneous work types. For road work types, however, the reduction in project cost due to project bundling was only found for certain road project types. Having road work with one big project in a contract is more cost-effective than bundling several small projects into one contract.
3. *Economies of competition.* Increased market competition (more bidders) lowers costs for most bridge projects, but larger contracts can discourage all but the largest firms from bidding, which can lead to less competition and therefore higher unit costs. This was investigated and modeled using both deterministic and probabilistic methods. According to the probabilistic model, the average number of bidders tends to be the highest when the number of projects is 2 to 4.
4. *Project similarity (compatibility).* Using a measure of similarity between different project types based on their constituent pay items, it was verified that project types in the same work category have a better (smaller) similarity distance compared to those in different work categories. The "similarity distance" measure can help identify candidate projects for bundling.
5. *Maintenance of traffic (MOT).* MOT can be a major component of project cost. The study found that the MOT cost could be slightly reduced by bundling some bridge work types, while the MOT cost for other bridge project types might increase due to project bundling. The MOT cost for most road, traffic, and small structure work types was found to be generally reduced by project bundling. Of all work categories, road work was found to benefit the most from project bundling in terms of MOT cost savings.
6. *Past bundling strategy.* The most frequent combinations of work categories in the past bundled contracts include bridge with road work, traffic with road work, bridge with traffic and road work, and bridge with small structures work. The most common combinations of different project types include Intersection Improvement with Traffic Signals, New Bridge with New Road Construction, Bridge Replacement with Bridge Deck Overlay, and New Bridge with Signing and New Road Construction.
7. *Future bundling strategies.* Use the "similarity distance" measure to identify projects suitable for combining into multiple-project contracts (MPCs). Use patterns found in this study to guide the number of projects to combine into MPCs.

Implementation

The findings from this study are compatible with results of studies being done for INDOT by other researchers on related activities. The results of this study are based on the data available through INDOT's SPMS and other agency sources. The Business Owner and his staff are aware of the shortcomings of those data, but they are satisfied with the patterns that have been identified by this study. The study findings can be used as a guide to support project scheduling decisions. For example, a certain collection of individual projects may yield significant cost savings for INDOT, but the locations of the projects may create unacceptable disruption in traffic. As more projects are bundled, the related databases will continue to grow, as will evidence about which bundles saved money and which ones did not.

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FREQUENTLY USED TERMS AND ACRONYMS

Work Category (WC)	Group of Projects (e.g., Bridge Road, Traffic, Small Structure, Miscellaneous, Utility)
Project Type (PT)	Type of Project (e.g., B1-New Bridge, R2-Added Travel Lanes)
Project Bundling	Bundling multiple projects into one contract
Single Project Contract (SPC)	Contract containing only one project
Bundled Project Contract (BPC)	Contract containing multiple projects
Des	Project
Des Award (DA)	Award amount ($) of a project
Nr of Des	The number of projects bundled in a contract
Nr of Bids	The number of bids submitted for a contract
MOT Cost	Maintenance of traffic cost
MOT Cost Ratio	The ratio of MOT cost to the Des Award
Average Similarity Distance (ASD)	A variable used to measure the similarity between different project types
Optimal	"Optimal" threshold for Nr of Des that yields lowest "optimistic" unit cost; "Optimal" bundling strategy that maximizes the "optimistic" cost saving.
Optimistic	"Optimistic" (or highest) number of bidders estimated using the developed upper bound model (or called "Optimistic" market condition/competition)
	"Optimistic" Des Award or unit cost estimated under the "optimistic" market condition.
Economy of Scale	The decline in unit cost as the project size increases
Economy of Bundling	The reduction in project cost as more projects are bundled into a contract
Economy of Competition	Project cost decreases as the number of bidding competitors increases

1. INTRODUCTION

1.1 Background

Highway infrastructure has been recognized as one of the most important engines for economic growth (World Bank, 1994). A reliable infrastructure system strengthens the nation's economy, enhances public safety and can improve the quality of life. However, an increasing number of infrastructure assets in the U.S. are in urgent need of repair or replacement. The ever-rising cost of projects and difficulties in securing financing are significant obstacles in improving the highway infrastructure system. The strategy to bundle projects into large contracts has been identified as an efficient way to reduce costs and create a more cost-effective contract delivery process.

The concept of project bundling—combining assets into a single product—is gaining momentum. Projects can be delivered under a one-project-per-contract basis, or as multiple projects in one contract. The growing tendency toward the latter is emphasized by the increasing realization of the benefit of project bundling in terms of cost savings (Xiong, Fricker, & Labi, 2017). As such, highway agencies are looking for solutions in determining the feasibility and effectiveness of bundling multiple projects into a large contract.

The FAST Act added a Bundling of Bridge Projects provision as 23 U.S.C. 144(j), in which bundling was encouraged to "save costs and time by encouraging States to bundle multiple bridge projects as 1 project" (U.S. House of Representatives, 2015). The Congressional Budget Office (CBO, 2012) cited the increased possibility of project bundling as one of the advantages of the private provision of highways. By bundling the tasks that would otherwise be performed by separate entities under the traditional approach, the private sector may help reduce the total cost of the project. The motivation for this study is inspired by INDOT's goal to deliver projects in a cost-effective manner (INDOT, 2015). Although project bundling has been proven by past studies to be an efficient way to reduce project cost (Estache & Iimi, 2008, 2011), the question of how much saving can be gained by a certain bundling strategy is not trivial. How to measure and quantify the benefits of project bundling has been rarely investigated. This study therefore seeks to quantify the potential benefits and issues associated with project bundling using a data-driven approach that involves development of statistical project cost models that account for the effect of cost factors such as project size (economies of scale), bundling strategy (economies of bundling), and market condition (economies of competition). Fortunately, project cost data needed for developing these models are available in INDOT's Scheduling Project Management System (SPMS) database. These data can help ascertain the pattern of scale economy for past projects, determine the impact of various factors on project cost, and identify any increase or saving on the overall project cost under different bundling or unbundling scenarios. This is a great opportunity to test whether the past single-project contracts could have incurred lower overall costs if they had been grouped, and to provide guidance on the development of appropriate bundling strategies for the future.

1.2 Study Objectives

Based on the study background discussed above, the principal objectives of this study are to investigate the possible impacts of project bundling on project cost, in terms of economies of scale, economies of bundling, economies of competition, and other factors (e.g., project similarity), and to determine the feasibility of project bundling on the basis of criteria that include project type, project compatibility, spatial proximity (distance between projects), and temporal proximity (closeness of the contract letting dates). The ultimate goal of this study is to provide statistical models that can be used to estimate the cost of single and bundled projects, and to offer recommendations on future bundling strategies.

1.3 Research Scope

This study covers various project types in six work categories—bridge, road, traffic, miscellaneous, small structure and utility—in the state of Indiana from Year 2008 to Year 2017. The report discusses specific potential benefits and issues associated with project bundling, including economies of scale, economies of bundling and economies of competition. It also describes the development of various statistical models to estimate market competition, overall project cost, maintenance of traffic cost and the total contract cost. The study also provides insights and recommendations on future bundling strategies, based on the results of the developed models and scenario analysis.

1.4 Report Structure

This report is organized into seven chapters. Chapter 1 presents the problem statement, objectives, and the scope of the study. Chapter 2 contains a literature review, including a synthesis of bundling methodologies that have been used by several states and localities. Chapter 3 describes the data on past contract work completed in the State of Indiana, and provide statistics and distribution plots for variables that are considered in the study. In Chapter 4, comprehensive preliminary analysis was conducted to investigate the effects of various factors on overall project cost, and maintenance of traffic (MOT) cost through scatter plots. Quantitative models were developed to determine the relationship between project bundling and market competition, and to quantify the similarity between different project types based on their pay items. In addition, several corridor analyses were conducted to compare, for past projects, the overall project cost and MOT cost of stand-alone projects and bundled projects along the same corridor. In Chapter 5, we developed cost models for overall project cost and MOT cost for projects in each work

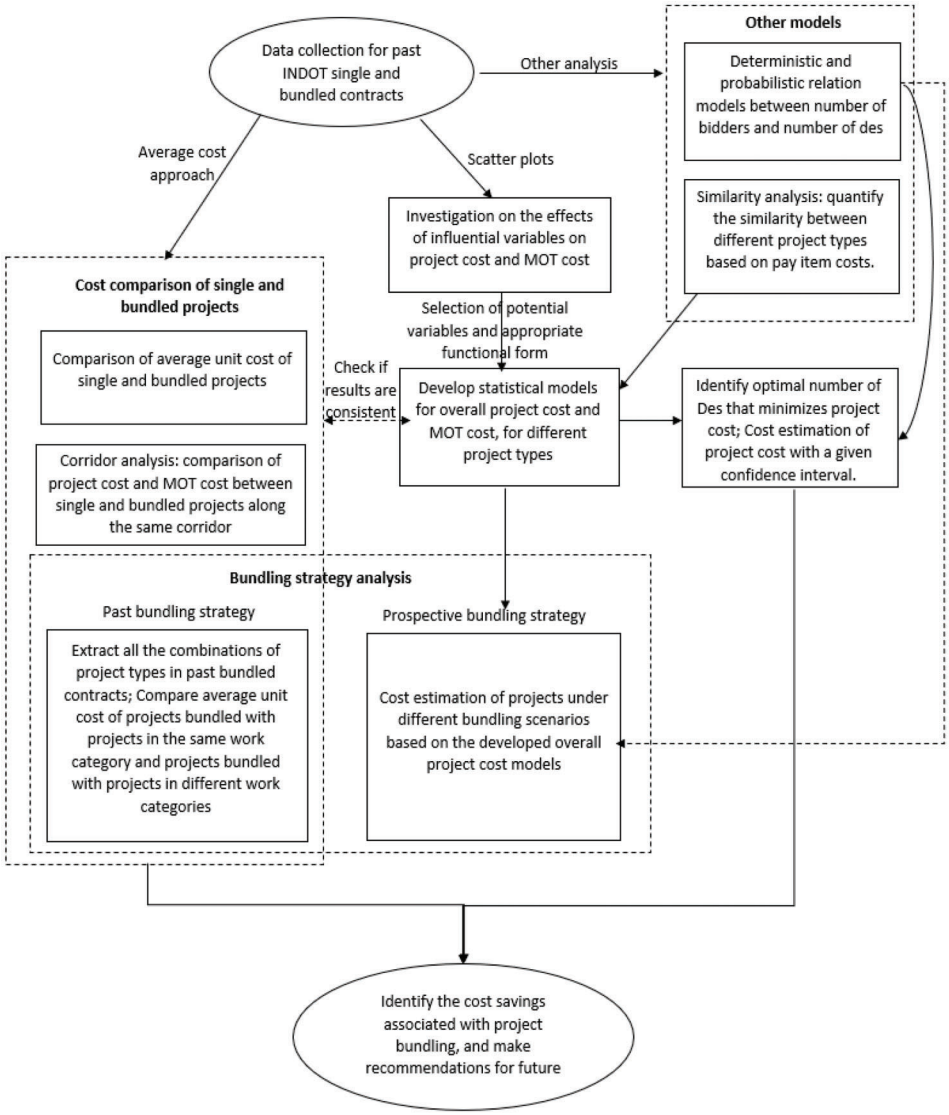


Figure 1.1 Flow chart of study framework.

category. Marginal effect and sensitivity analyses were also provided, followed by model application. In Chapter 6, scenario analyses were conducted, based on the developed cost model, to compare different bundling strategies. Chapter 7 concludes the report with the implications and limitations of project grouping, and recommendations for future research.

The flow chart in Figure 1.1 illustrates the study framework. The research was designed to address the study objective, that is, to determine whether specific projects should be bundled, the associated cost savings, if any, the uncertainty associated with such estimates, and cost savings under different bundling strategies.

2. LITERATURE REVIEW

2.1 Factors Affecting Project Cost

Highway related expenditures may be broadly classified into agency costs, user costs and community costs (Sinha & Labi, 2017). Typically, agency costs include the costs of initial construction, future rehabilitation and preventive maintenance, project overhead, and traffic control. User costs include vehicle operation, user delay, and crash costs (Boile, Ozbay, & Narayanan, 2001). Community cost includes pollution. All cost categories are important and should be taken into account when making decisions on highway infrastructure improvement or replacement. However, due to the lack of data needed for calculating the user cost and community cost (e.g., work zone duration, lane closure information, and condition data on highway assets), this study considers only the agency cost during construction period.

The cost of highway construction can vary greatly, depending on the project type and site conditions (Labi, 2014). According to past studies, the main factors determining the cost of construction project include, but are not limited to, the size and duration of project, costs of materials, competition and market conditions,

TABLE 2.1
Internal and External Factors Affecting Project Cost

Type of Factors	Potential Influential Factors
Internal	Project Type
	Project Size (Economies of Scale)
	Project Bundling/Contract Size (Economies of Bundling)
	Timing of the Letting
	Design and Specification
	Project Duration
External	Market Condition (Economies of Competition)
	Macroeconomic Factors
	Site Condition

project-specific factors, and macroeconomic factors (Damnjanovic, Anderson, Wimsatt, Reinschmidt, & Pandit, 2009). The agency has control over only some of these factors. For example, factors such as design, specifications, project scope, and size of the contract, are controllable, while it would be impossible to control global demand for materials or macroeconomic factors. The number of available contractors cannot be controlled or known in advance, but sometimes can be predicted with some uncertainty. The various internal and external factors that might affect project costs are summarized in Table 2.1, while the current study only focuses on factors that can be controlled by the agency or can be predicted with reasonable reliability.

2.1.1 Project Size (Economies of Scale)

In microeconomics, the term *economies of scale* refers to economic efficiencies that result from carrying out a process on a larger scale (Pearson & Weisner, 1993). Often, economies of scale happen when size, output, or an operation's scale for an enterprise yields cost advantages. Fixed costs are spread out over more units of output, thus lowering the cost per unit of output as the scale increases (Scherer & Ross, 1990).

In the construction industry, it has been recognized that economies of scale play an important role in determining highway construction project costs (Bhargava, Labi, & Sinha, 2010). Construction economies of scale occur when construction costs rise as construction size increases, albeit in a manner that is less proportional. In other words, the larger the project, the lower the unit cost would be. Large construction projects typically benefit from economies of scale, because of the large portion of fixed costs involved in the total construction costs (i.e., costs associated with making construction possible, beyond materials, supplies, and labor) that can remain the same, regardless of the project size.

2.1.2 Market Competition (Economies of Competition)

Another important factor that affects project cost is the degree of competition for a contract. Competition is desired by the agency, because it typically leads to higher quality and reduced cost of the delivered product (Lamb & Merna, 2004). It is, however, difficult to know the number of bidders for a contract in advance, because market competition is affected by many internal and external factors that outside the agency's control. Typically, the number of bidders for a particular project can be determined by the project type, duration and size of the project, and the location and timing of project letting.

2.1.3 Project Bundling (Economies of Bundling)

2.1.3.1 Benefits of Project Bundling. The most visible benefits of project bundling is the attainment of economies of scale, which translates into a reduction in overall cost of program delivery (Xiong et al., 2017). Damnjanovic et al. (2009) stated that the possible benefits of bundling include the reduction of the ratio of fixed cost to overall cost, ultimately resulting in reduced bid price. Using data and anecdotal evidence on Public Private Partnerships from United Kingdom and Germany, Frank and Merna (2003) noted that some individual projects are commercially viable as stand-alone projects while others are not, and that when projects are bundled together, an overall portfolio of projects may meet a promoter's minimum acceptable rate of return (MARR) and be deemed financially viable.

Based on the analyses of past project data by Estache and Iimi (2008, 2011) and Iimi (2006), project bundling could potentially reduce agency costs by as much as one-third, due to significant economies of scale and scope in procurement and the reductions in public expenses and administrative costs of tendering and supervising. Also, the benefits of project bundling have been recognized in by numerous public agencies. For example, by combining twelve individual paving projects into five bundled contracts in the City of Clarksville, Indiana, the unit project cost for concrete was reduced by over 50% (Koesters, 2012). Washington DOT identified that bundling local federal aid projects at the planning phase can enhance efficiency in pricing, contract administration and construction efforts (McCarthy, Mensching, & Horgan, 2011). Further, a number of DOTs determined that combining multiple projects can lead to reduced paperwork, staff time, resources, and overall project cost.

In addition, project bundling can enhance the cost-effectiveness of traffic maintenance during construction. For individual projects located along a corridor, a coordinated bundled contract made up of these projects may reduce the total length of workzone durations, compared with individual contracts for each project that would lead to separate road use restrictions at different times for the different projects (Xiong et al., 2017). The reduction in workzone duration would not only bring benefits to the agency by reducing bid amount and risk of injury/fatality associated with construction, but can also benefit the road users and neighborhoods in terms of reduced traffic interruptions that lead to reduced travel time, and a lower level of environmental degradation caused by construction activities such as

air and noise pollution. Project bundling can also potentially reduce the overall duration of construction projects, particularly where the bundled projects are in the same area and where the project types are similar (Bordat, McCullouch, Labi, & Sinha, 2003). This offers a contractor greater flexibility to move and coordinate resources (materials, equipment, and personnel) around different projects, which can reduce waste and time. As a result, a lower likelihood of project delay and more cost-effective project delivery can be expected. For example, Missouri DOT grouped three highway projects to form a single a multiple-project contract which was completed a month ahead of schedule, $2.4 million under budget, and with minimal interruptions to the road users (AASHTO, 2012).

2.1.3.2 Issues of Project Bundling. Although project bundling has been proven to be an efficient way to reduce project cost, it does not mean that the project unit cost will always decrease as more and more projects are bundled together. In other words, even though bundling multiple projects into one large contract may offer benefits associated with economies scale, it could also lead to lower market competition because the contract might be too large for some companies. Lower market competition often cause higher bid prices. An important subject to investigate in this study, therefore, is how to achieve the balance between the economies of bundling and the economies of competition.

This balance has been examined by researchers such as Estache and Iimi (2008, 2011) who argued that the benefits of project bundling are earned at the expense of market competition. These researchers stated that bundling of infrastructure projects could lead to severe limitations in market competition, due to larger contract sizes that deter the entry of small and mid-size contractors into the bidding market. Thousands of small businesses lose federal contracts every year because government agencies bundle contracts into larger packages and award them to larger businesses (Lubbock Avalanche-Journal, 2000).

An unbundling strategy that separates a contract into individual projects or splits one large project into several small projects could be a superior alternative to project bundling under some circumstances. For example, bundling projects might not be appropriate when a great deal of heterogeneity exists in potential bidders (Estache & Iimi, 2011) and in cases where entry costs are high to newer and smaller contractors (Chakraborty, 2006). In addition, unbundling strategy might be beneficial when there are only a few large competitors in the market able to take on a large project. By splitting the large project into several medium-size projects, a larger pool of contractors would be attracted to bid (Damnjanovic et al., 2009). This could take advantage of competition effects or stimulate local procurement and employment (Estache & Iimi, 2011; Grimm, Pacini, Spagnolo, & Zanza, 2006).

In an AASHTO survey on the strategies and methods to address increasing highway construction costs and reduction in competition, a method based on bundling small projects or splitting large projects was ranked in the top 10 most effective strategies to reduce construction costs (Sanderson, 2006). To obtain an efficient bundling strategy that can satisfy the need to balance competitive bidding in procurement, while reducing costs to the agency, a more quantitative assessment of the effectiveness of bundling or unbundling strategies is needed. This can be done by analyzing previous bids submitted on projects versus contract size. Therefore, this study not only determines project types that can be benefited by bundling, but also seeks the "optimal" contract size beyond which project might no longer benefit by bundling due to the reduced market competition.

2.1.4 Project Characteristics, Locations and Timing of Project Letting

Project characteristics, location and letting time can also influence project costs. Typically, more complicated projects, such as those with new construction, interchange work, or complicated engineering problems, can cost more than less complicated projects such as preventive maintenance, due to the higher requirements for materials, equipment and labor, and a higher level of risk involved. Besides, highway project costs can differ across different locations. For example, highways are often more expensive to build in mountainous areas than in flat areas, and projects in urban areas can be more expensive than those in rural areas (Kishore & Abraham, 2008). This can be due to many factors, including availability and prices of materials and restrictions on construction noise and traffic interruption. Variations in project cost at different locations is also partly attributable to different market competition. For example, smaller firms are more interested in projects nearer to their headquarters. Also, very specialized projects typically involve fewer players; hence, higher bid prices are expected due to lack of competition. Some DOTs also consider that the timing of project letting may be a factor influencing the bid price, mostly because the number of available jobs in the market at a particular time of year can significantly affect competition and thus indirectly cause uncertainties in project costs (Damnjanovic et al., 2009).

2.1.5 Project Similarity (Compatibility) and Spatial Proximity

Project compatibility (similarity between the project types in a bundled contract) is an important consideration in project bundling. Projects that involve similar materials and resources can be considered compatible and thus are prime candidates for simultaneous delivery through project bundling. For example, new bridge and bridge replacement can be considered as similar project types, while bridge deck overlay and thin deck overlay might be more similar to each other than to other project types.

The cost of a bundled project can be also affected by spatial proximity: multiple projects in the same corridor

are generally expected to benefit from project bundling, because it offers contractors more flexibility to move and coordinate resources around, and thus are considered more appropriate for bundling. For example, crack sealing projects at different locations within a county or subdistrict constitute an example of a prime candidate for location-based project bundling (Xiong et al., 2017).

2.2 State Practices in Transportation Project Bundling

2.2.1 Examples of Successful Project Bundling

In the survey by McCarthy et al. (2011), nearly half of the surveyed states reported adopted the strategy of project bundling in their construction projects. The practice of project bundling has been carried out at many state agencies, such as Oregon DOT, Missouri DOT, Pennsylvania DOT, Minnesota DOT, North Dakota DOT and New York DOT.

The Oregon Department of Transportation (ODOT) reported that an effective project delivery method was the ability to "bundle" multiple projects under a broader environmental document (McCarthy et al., 2011). For example, ODOT had successfully bundled the following projects:

- Multiple Project 508. This $43 million design-build highway project bundled several projects located between mile point (MP) 154.54 and MP 163.43 on Interstate 5; and between MP 18.47 and MP 53.29 on highway OR126, into one contract. The project consisted of the design and replacement of six bridges along with the repair of one other. The goals of the combined approach include efficiencies in design, construction, quality management, environmental management, and cost (Slayden, 2007).
- Multiple Project 414. US395: McKay Creek to Silvies Slough. This was a $40 million design-build project that included replacement of seven deteriorated bridges along a 250 miles sensitive waterway and wild and scenic corridor (Otak, n.d.).

As this report is written, Oregon DOT remains the most active agency regarding bundling. ODOT recently completed a 10-year, $1.3 billion program to repair or replace hundreds of aging bridges statewide (ODOT, n.d.) Bridges were placed into 68 bundles to "reduce effects on mobility while encouraging competition" (ODOT, 2015). The size of a typical bundle was 4-5 bridges. ODOT tried to keep the contract amount in the $40-50 million range, so as not to exceed the bonding capacity of smaller contractors (R. Mabey, 2017, personal communication). The bridges in a bundle tended to be fairly close together, but not so close together that excessive detours were created (T. Rogers, 2017, personal communication). ODOT plans to continue bundling projects that have "homogeneous project types" (R. Mabey, 2017, personal communication).

Another example of a DOT's project bundling is the Highway I-270 improvement plan in the State of Missouri. I-270 is the busiest highway in the State of Missouri, carrying more than 180,000 vehicles per day through the St. Louis metro area. In order to mitigate traffic congestion and reduce vehicle crashes, the Missouri Department of Transportation (MoDOT) decided to conduct three highway projects to alleviate these problems, including two redesigned interchanges and the rehabilitation of an interstate bridge. Instead of tackling each project separately, MoDOT bundled all three together into one contract with a budget of $34.8 million. This single contract allowed for a major bidding advantage and also allowed MoDOT to minimize public impact (as opposed to three separate projects and construction schedules). This multiple-project contract was completed a month ahead of schedule, $2.4 million under budget, and with minimal interruptions to the road users (AASHTO, 2012).

The Pennsylvania Department of Transportation (PennDOT) has embarked on the challenge to bundle similar bridge projects together to capitalize on economies of scale and achieve cost savings and shorter construction periods. In 2014, a landmark $899 million contract signed by PennDOT, bundled the design, construction and maintenance of 558 deficient bridges into the single Rapid Bridge Replacement Project. The 558 bridges were selected from more than 2,000 bridges after screening, and must be replaced within 36 months upon agreement. The bridges are primarily crossings on smaller state highways, many in rural areas, rather than interstate bridges or large river crossings (Walsh, 2017). PennDOT identified these key advantages following the completion of the contract: economies-of-scale savings, faster project delivery, lower life-cycle costs, and standardized design and construction. In addition, bundling these projects together could minimize the impact on road users and neighborhoods caused by the construction activities (PennDOT, n.d.). As part of PennDOT's Innovative Financing Techniques initiative, the Bridge Bundling Program aims to bundle the replacement or rehabilitation of locally owned bridges with state-owned bridge projects (Haste, 2014). The program, which seeks to bundle multiple bridges to be replaced or rehabilitated as a single project utilizing similar designs, is intended to save time and costs, thus creating economies of scale in design and construction. To be eligible for bundling, the bridges must be within reasonable geographical proximity and should be of similar size.

New York DOT bundled 21 state road segments on the basis of geographic proximity to form one multiple-project contract (NYSDOT, 2012). Also, Caltrans has bundled safety projects and pavement rehabilitation projects (McCarthy et al., 2011). At the Washington DOT, project bundling has been carried out for federal-aid local projects.

The Georgia Department of Transportation (GDOT) uses bridge bundles, a method of design-build contracts organized by geography, to help "accelerate the replacement" of 25 bridges across the state. According to GDOT, the process is particularly effective in rural areas because the projects are "low-impact with no widening or additional right-of-way and limited approach work," and that it "expedites delivery, minimizes public

inconvenience, maximizes industry participation and allows us to get the best overall product for the lowest price" (Hill, 2016).

While attending a conference, a member of the Purdue research team learned that Thay Bishop at the FHWA office in Atlanta GA is aware of many bundling programs in the US. During a telephone call, Ms. Bishop mentioned state DOT activity in Ohio, New York, Oregon, Georgia, Pennsylvania, Missouri, Nebraska, and Rhode Island (T. Bishop, 2017, personal communication). She suggested contacting two individuals in Oregon, and provided the contact information. This led to the helpful practical experience on ODOT's bridge bundling program that was cited earlier in this section. Ms. Bishop's Implementation Team is in the process of assembling a national Bundling Guide to help local public agencies. The Guide is expected to be ready in spring 2018.

2.2.2 Adoption of Project Bundling in the State of Indiana

With the goal of "planning, building, maintaining and operating a superior transportation system enhancing safety, mobility and economic growth" (INDOT, 2015), INDOT has been striving to adopt policies, plans, and designs that enhance the upkeep of Indiana's state highway infrastructure. With the increasing realization of the benefit of project bundling, INDOT has been undertaking more bundled projects than ever before. As shown in Figure 2.1, an increasing percentage of bundled projects is observed in the recent years.

Some typical bundled highway improvement projects implemented by INDOT during the past few years include:

- Accelerate 465—This $423 million project began in 2007 and was substantially completed in the fall of 2012, initiated by the needs of expanding transportation capacity, improving motorist safety and interstate access, and upgrading the road design to current standards. The contract consisted of multiple project types, including 11-miles of freeway reconstruction, upgrades of interchange ramps and mainline capabilities, improved geometrics and access upgrades to major destinations along the corridor such as the Indianapolis Motor Speedway, the Indianapolis International Airport, Eagle Creek Park, Indianapolis Raceway Park, and downtown (INDOT, 2012).
- I-65 and US 50 Rehabilitation Plan—In July 2013, INDOT launched a $55 million pavement project in the Seymour District to repair and repave 21 miles of Interstate 65 and rehabilitate 20 bridges between US 50 in Jackson County and SR 56 in Scott County. This large contract consists of projects including full-depth concrete patching, partial depth HMA (asphalt) patching, undersealing the roadbed, removing old underdrains and installing new ones, overlays at on- and off-ramps, rehabilitation of 10 sets of bridge decks, and completing a functional resurfacing of I-65 from between Seymour and Scottsburg. The contract was completed on November 30, 2014 (INDOT, 2014a).
- Indiana's Operation Indy Commute I-69 addressed the bottlenecks on I-69 in Marion and Hamilton Counties between the I-465 interchange and 116th Street/SR 37 exits, and at the I-465/I-65 interchange on the south side of Indianapolis. The project consisted of an $18 million contract to make capacity and configuration improvements to the I-69 Exit 205 interchange at SR 37 and 116th Street and a second $11 million contract to ASD lanes to I-69 between 116th Street and I-465 (INDOT, 2014b).
- SR 46 Reconstruction at Spencer—This is a $7,952,260 pavement replacement project for rebuilding SR 46 at Spencer during the 2017 and 2018 construction seasons. This project replaces the existing pavement and addresses drainage concerns between Fairview Avenue on the east side and the SR 46-US Highway 231/SR 67 split on the west side. This large bundled project includes new full-depth pavement replacement, storm sewers, sanitary sewers and water lines, sidewalks, curbs and ADA-compliant ramps, traffic signals at US 231, Main Street and the SR 46-US 231/SR 67 split, and coordination with town's ornamental street lighting project.
- I-70 Fifteen Bridge Preservation Project Awarded—This is a $4.6 million bundled bridge preservation contract for 15 structures along Interstate 70 between the Ronald Reagan/Ameriplex Parkway interchange and I-465 on

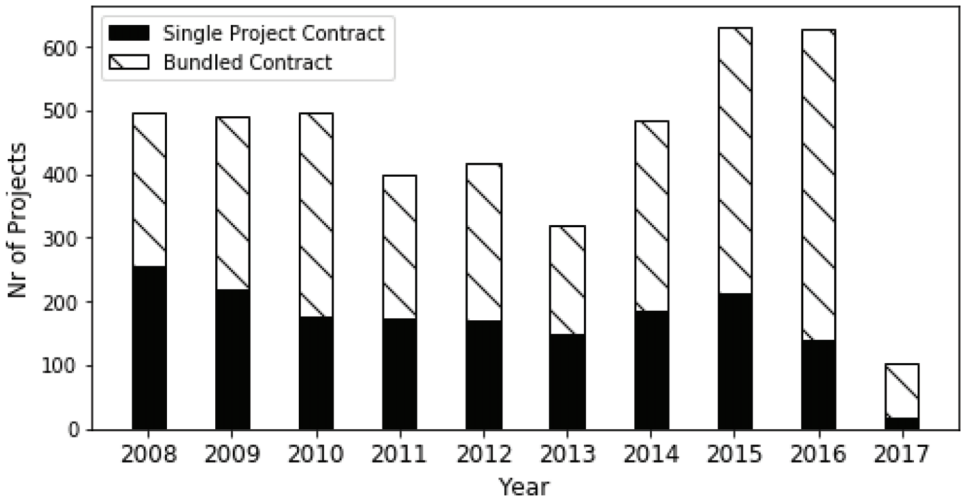


Figure 2.1 Variations in bundling practice, 2008–2017.

the west side of Indianapolis. The project intends to protect and extend the life of each structure by applying modified concrete overlays to the bridge decks, sealing bridge joints, and repairing various concrete bridge components.

- SR 9 Modernization in Huntsville—A $4.6 million bundled construction project on SR 9 was awarded in Year 2017 that will modernize a variety of infrastructure between Interstate 69 and Huntsville Road. Major features of the project include repairing and resurfacing pavement, replacing a box culvert at Prairie Creek, and adding left-turn lanes and installing new traffic control signals at Huntsville Road.

3. DATA

3.1 Data Sources and Variable Description

Data used in this study were provided by Indiana DOT in the form of the INDOT Official Bid Tabulation database, the INDOT Site Manager database, and the INDOT Scheduling Project Management System (SPMS) database. All the above datasets were merged to yield a large dataset, containing comprehensive contract information for projects awarded from Year 2008 to Year 2017 in the State of Indiana. Table 3.1 summarizes all the relevant variables contained in our dataset, including contract and project information, cost information, road and traffic information, and location information.

Each contract has a unique 'Contract ID.' and contains single or multiple projects identified by a unique "Des ID." "Nr of Des" is the number of projects in a contract. A contract is defined as a "single-project contract" or "standalone contract" when there is only one project in the contract, and as "bundled contract" when multiple projects comprise the contract. The "lead des" in a contract refers to the main project (typically, the largest in terms of cost). The variable of "Nr of Bids" refers to the number of bidders involved in the contract bidding process. The "Letting Date" is the day the bids are opened up, and the "Award Date" is the day the contracts are awarded to the contractor. In this study, the letting date was used for analysis.

The projects in the dataset are bundled into six families (work categories) and 36 classes (project types). For a single-project contract, the work category of the contract is determined by the single project. For a bundled contract, the contract type and work category is determined by the work category of the lead des. This study excludes design-build projects. An NBI (National Bridge Inventory) number is given for each project in the bridge work category. Bridge information (e.g., deck area, condition of bridge components, built year) was extracted from the NBI dataset based on the bridge's NBI number. The deck area is a proxy for the bridge project size. For other project types, the project size was measured in terms of the project length (miles) and number of lanes, or the number of units constructed.

The expenditure data can be classified into three different levels: contract level, project level and pay item level. The "Des Award" is the award amount (dollars) of a project, and the sum of the "Des Award" of all projects in a contract is equal to the contract's award amount (Contract Award). At the pay item level, unit cost, quantity and total amount are provided for each pay item in a project. The sum of the total amount of all pay items in a project is equal to the 'Des Award' of that project.

Projects are located on state, US and Interstate routes in urban and rural areas. Projects on local roads and route type of SP, ST, IR and VA are excluded from the analysis. Traffic count data (ADT) at the project locations are available in the dataset. Project location information (district, route number and latitude/longitude) are also provided in the dataset.

3.2 Data Statistics and Distribution of Variables

3.2.1 Classification of Project

There are 4,611 projects (des) and 2,528 contracts in the dataset. The projects in this study can be categorized into 6 work categories (i.e., bridge, road, traffic, small structure, miscellaneous, and utility), and can be further classified into 36 different project types. Figure 3.1 shows the distribution of project types in the dataset. Almost half of the projects for Years 2008 to 2017 are bridge projects. Table 3.2 summarizes the number of projects and the number of contracts for each of the 36 project types. "Bridge Deck Overlay" (395 instances), "Misc. Bridge Rehab & Repair" (647 instances), and "Partial 3" (66 instances) are the most common of all the project types.

At the contract level, the work category of a contract is determined by the work category of the lead des in the contract. For example, if there are road, bridge and traffic projects bundled in one contract but the lead des is a road project, then the contract is designated as a

TABLE 3.1
Summary of Variables

Contract Information	Project Information	Cost Information	Road and Traffic Information	Location Information
Contract ID	Des ID	Des Award	Urban or Rural	District
Nr of Des	Work Category	Contract Award	Functional Class	County
Lead Des	Project Type	Engineer Estimates	Route Type	Route Number
Nr of Bids	Project Length	Pay Item Cost Details	ADT	Location
Letting Date	No. of Lanes			Latitude/Longitude
Award Date	NBI# (If Bridge)			

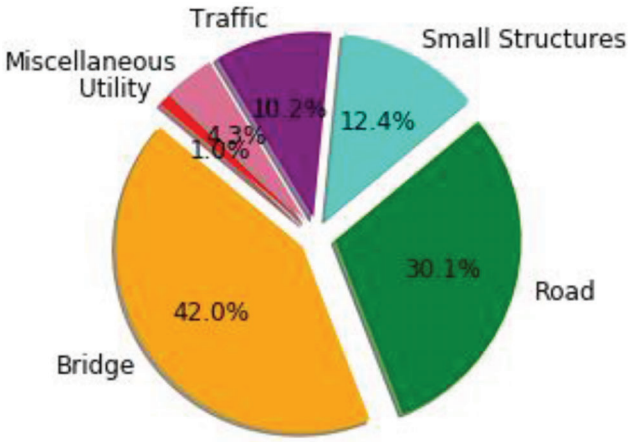


Figure 3.1 Distribution of project work categories.

"road work" contract. Figure 3.2 presents the distribution of different contract types. Of the different project types, the road work is the most likely to be the lead des in a contract, because road work is usually much more expensive than other project types. Table 3.2 presents the distribution of the number of projects in which each project type is included. The table also presents the number of contracts in which each project type is the lead des.

3.2.2 Project Size

Project size has a profound impact on project cost. Generally, the larger the project size is, the lower the unit cost. This phenomenon is called "economies of scale." Figure 3.3 shows the distribution of project size for projects in different work categories. For bridge projects, the project size is measured by the deck area (sq. ft.), which can be retrieved from the NBI dataset. For other work categories, the unit of project size is miles, number of lanes, or lane-miles, count, and so on.

3.2.3 Bundling Projects

A "single-project contract" or "stand-alone project contract" is defined here as one project of a specific project type being delivered in a single geographic location. A "bundled contract" is defined as a group of single projects of similar or different project types delivered under a single contract; the project types do not have to be the same but must be compatible. One of the objectives of this study is to investigate the bundling effect on project cost ("economies of bundling"). For some project types, below a certain threshold, the more projects that are bundled into a contract, the lower the unit cost. However, project bundling can lead to decreased market competition for an agency's contracts because, as contract size increases, some contractors refrain from bidding. Therefore, when the number of des or the overall contract cost passes a certain threshold, the unit cost of the contract might start increasing due to the reduced market competition.

To show how projects have been bundled in the past, Figure 3.4 (a) presents, at a contract level, the number of single project contracts (1744) and bundled contracts (784) for each category of work (i.e., bridge, traffic, road, small structure, miscellaneous and utility) in our dataset. (The work category of a contract is determined by the lead des in a contract.) Figure 3.4 (b) shows, at a project level, the number of projects in the single project contracts (1746), and the number of projects in the bundled contracts (2865). It was found that bridge work is more likely to be bundled than road work.

Figure 3.5 presents the distribution of the number of des in bundled contracts. In most bundled contracts, the number of projects bundled are between 2 to 4. Utility projects are excluded from Figure 3.5 because in the current dataset, utility work is never a lead des in a bundled contract.

In realizing the benefit of project bundling, there is a generally increasing number of bundled projects in the state of Indiana, particularly after Year 2014. Figure 3.6 presents change in the percentage of bundled projects from 2008 to 2016.

3.2.4 Number of Bidders in a Contract

In addition to "economies of scale" and "economies of bundling," "economies of competition" is another factor that may affect the contract price. Competition is desired, because it typically leads to higher quality and reduced cost of the delivered product (Lamb & Merna, 2004). Figure 3.7 shows the number of bidders for all the past contracts in different work categories from Year 2008 to 2017.

For most work categories, the number of bidders is most often between 3 and 5. For road work, the distribution of number of bidders is highly left skewed, and most contracts have 2 to 3 number of bidders. This is because road projects are typically the most expensive of the six work categories, leading to lower market competition. In Chapter 4, the relationship between number of bidders and contract size (in terms of contract price or number of projects) is analyzed.

3.2.5 Timing of Letting Dates

The projects considered in this study are with letting dates between January 09, 2008 and January 19, 2017. Figure 3.8 shows the number of projects in each letting year for different work categories. It is observed that year 2015 and 2016 have the highest number of projects. Also, there is a general increasing trend for bridge work and small-structure work, and a slightly decreasing trend for road work over the given period.

Figure 3.9 presents the number of projects let in the different letting seasons of the year (1st/2nd/3rd/4th quarters). "Season" might be a factor that influences project unit cost. Projects that are open for bidding in different seasons might have different unit costs due to market conditions. The seasonal effect on project cost is analyzed in Chapter 4.

TABLE 3.2
Distribution of Number of Projects and Number of Contracts

Category	Code	Project Type	Nr of Projects	Nr of Contracts (lead des)
Bridge	B1	New Bridge	329	55
	B2	Bridge Replacement	238	140
	B3	Superstructure Replacement	64	39
	B4	Deck Replacement	90	50
	B5	Bridge Widening	54	13
	B6	Bridge Deck Overlay	395	178
	B7	Thin Deck Overlay	180	56
	B8	Misc. Bridge Rehab & Repair	647	184
	Total		1997	715
Road	R1	New Road Construction	77	71
	R2	Added Travel Lanes	70	64
	R3	Patch & Rehab Pavement	127	88
	R4	Partial 3	666	595
	R5	Road Rehabilitation (3R/4R)	46	39
	R6	Wedge & Level Only	21	20
	R7	Sight Distance Correction	27	21
	R8	Shoulder Rehab & Repair	2	0
	R9	Pavement, Other	11	8
	R10	Pavement Replacement	163	145
	R11	Intersection Improvement	114	103
	R12	Interchange Work	41	34
	Total		1365	1188
Small Structure	S1	Pipe Lining	268	122
	S2	Small Structure Installation	243	167
	S3	Small Str. Maintenance & Repair	45	32
	Total		556	321
Miscellaneous	M1	Demolition	84	80
	M2	Channel and Ditch Work	51	23
	M3	Stormwater Improvements	5	2
	M4	Slide Correction	37	27
	M5	Paths, Sidewalks & Curb Ramps	16	8
	Total		193	140
Traffic	T1	ITS	27	17
	T2	Signing	128	16
	T3	Traffic Signals	211	68
	T4	Pavement Markings	14	7
	T5	Guard Rail, Cable Barrier & Wall	48	42
	T6	Lighting	29	13
	Total		457	163
Utility	U1	Railroad Work	2	1
	U2	Utility Relocation	41	0
	Total		43	1

3.2.6 Functional Class and Traffic

Route type and functional class may have some effect on project cost. It can be hypothesized that projects on interstate highways are typically associated with higher unit cost due to higher traffic volume and higher design or construction standards. If a significant difference is found between the patterns of project cost on different route types, then it might be necessary to develop a separate cost model for each route type. In developing regression models for project cost where the sample size is not large enough to develop separate models, traffic volume (ADT), as a continuous variable, can be used as a proxy for the road function, class. Figures 3.10 and 3.11 present the counts of projects on different route types and functional classes. Figure 3.12 presents the distribution of traffic on the road where projects were implemented.

3.2.7 Project Location and Distance

From Figure 3.13, the distribution of projects from 2008 to 2017 in the six districts are fairly even for road, small structure and utility work, while there are significantly more projects for traffic and slightly more projects for bridges in the Greenfield District.

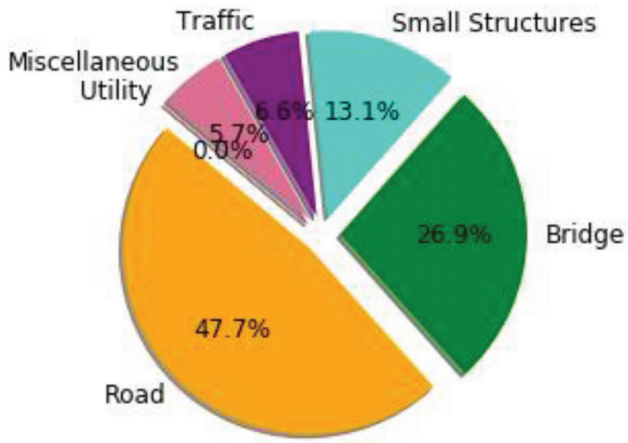


Figure 3.2 Distribution of contract work categories (based on the Lead Des).

Multiple projects might be bundled if they are close enough to each other. The distance between projects in a bundled contract might have some impact on project cost or contract cost. It is expected that projects located more closely would enjoy more savings from project bundling. Figure 3.14(a) shows the distribution of average paired distance among projects in a contract. This distance is calculated by dividing the sum of distance between each pair of projects in a contract by the number of pairs. Figure 3.14(b) shows the average distance from one project to all other projects in a contract. This distance is obtained by dividing the sum of the distance between the project to its kins, i.e., all other projects in the contract by the number of kin projects.

3.2.8 Cost Data

The main task of this research is to investigate the effect of project size, project bundling market competition and other important factors on project cost. In this study, the project cost is measured at three levels.

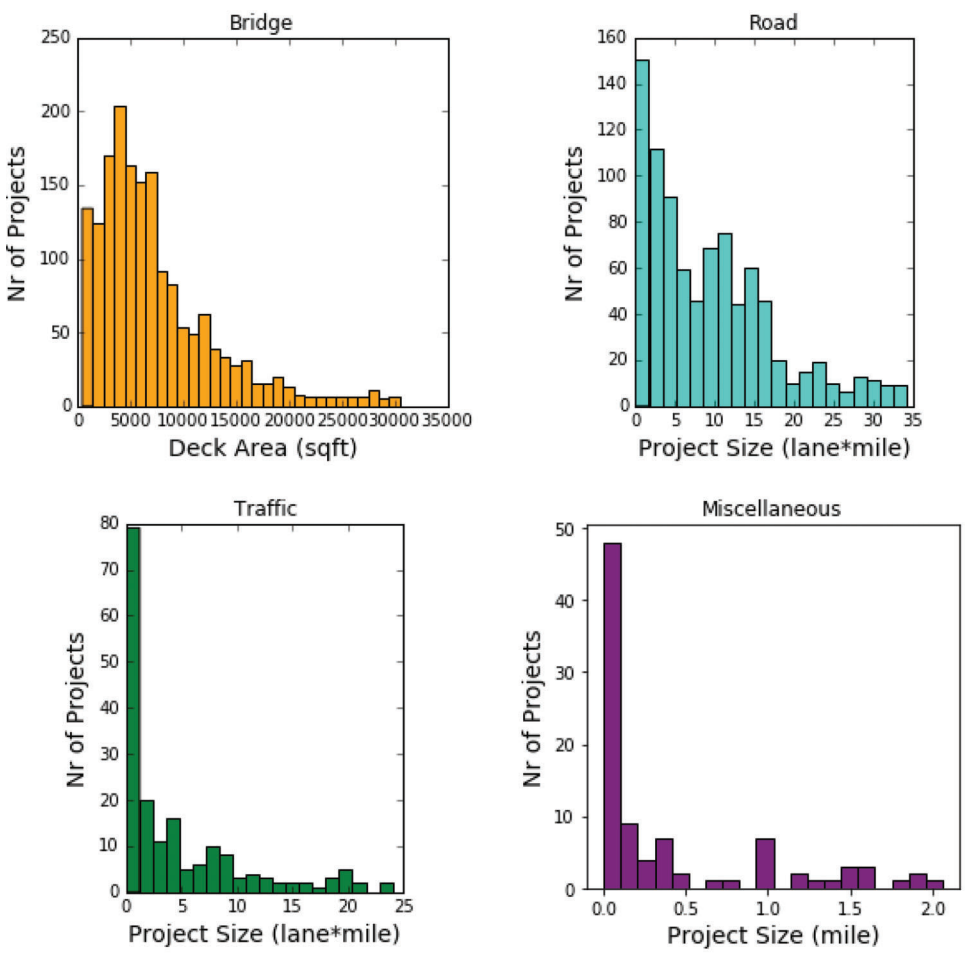
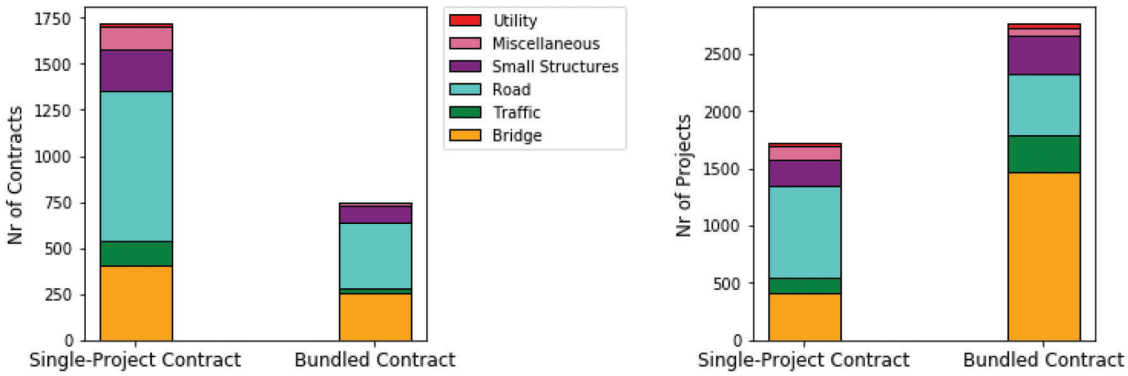


Figure 3.3 Distribution of project size for projects in different work categories.



(a) Number of contracts (b) Number of projects

Figure 3.4 Distribution of single-project and bundled contracts for different work categories.

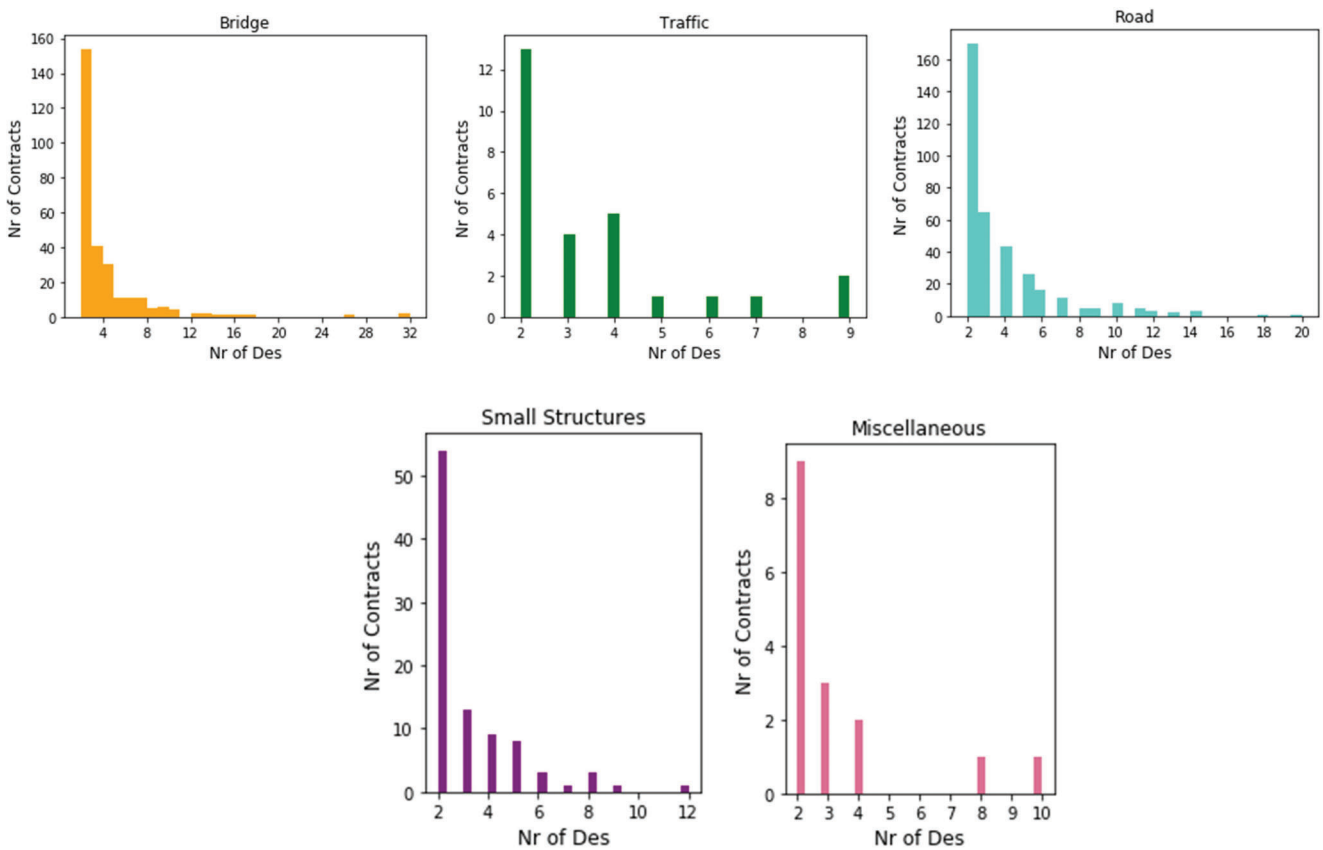


Figure 3.5 Distribution of number of des in a bundled contract.

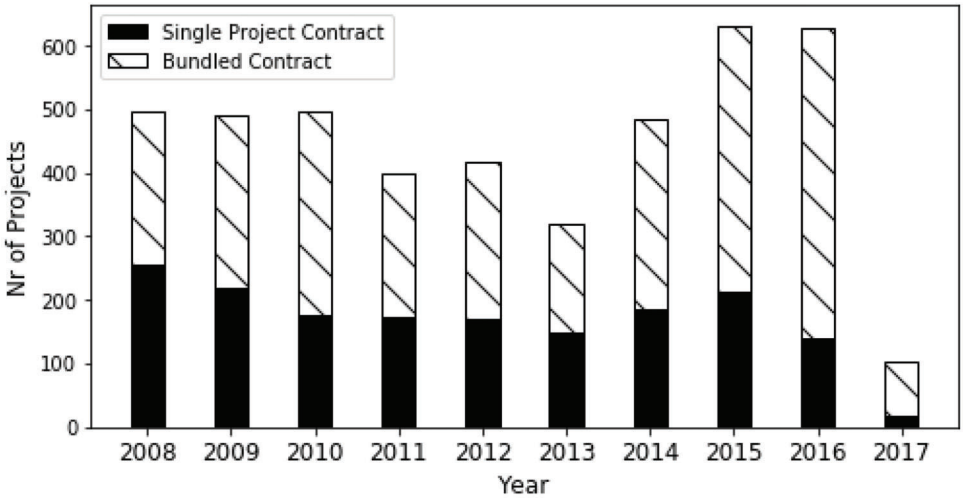


Figure 3.6 Variations in bundling practice, 2008–2016.

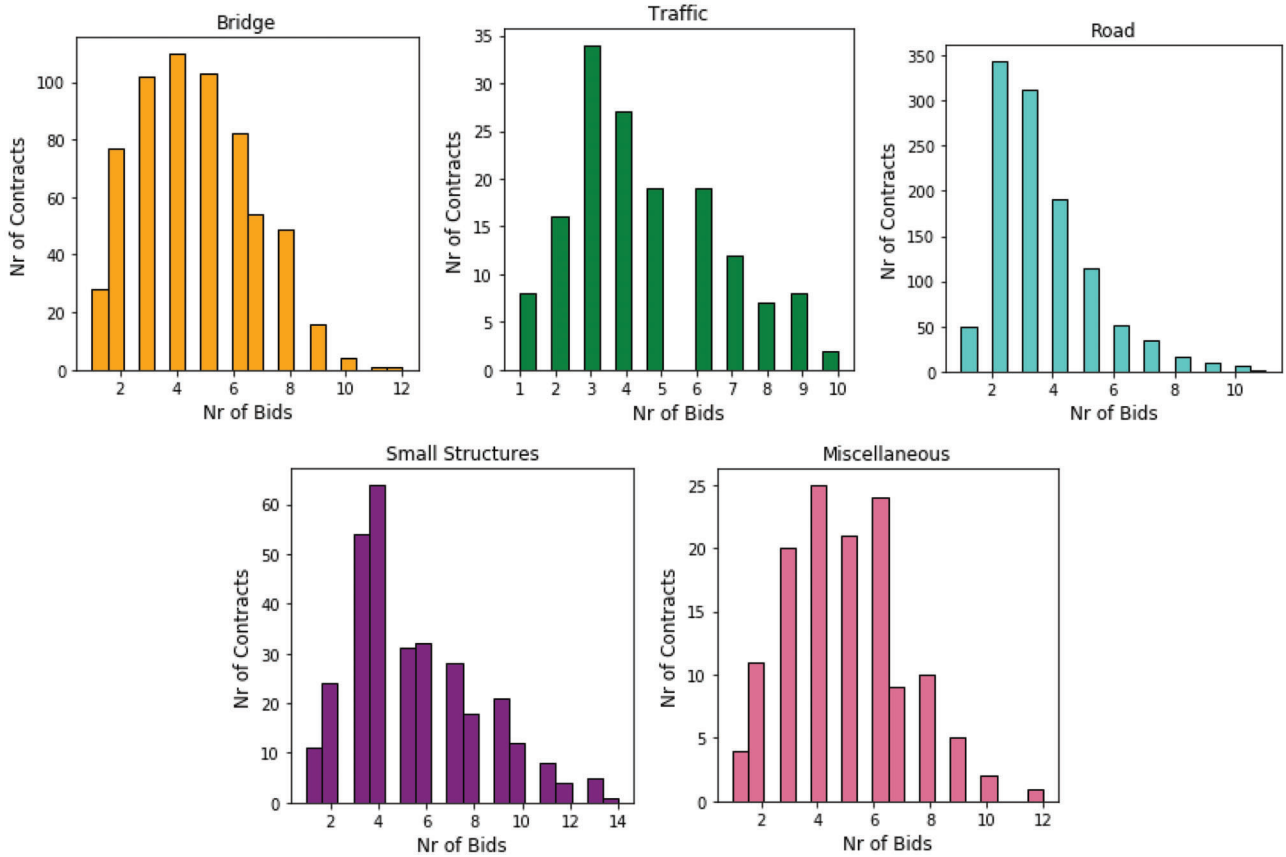


Figure 3.7 Distribution of number of bids in a bundled contract.

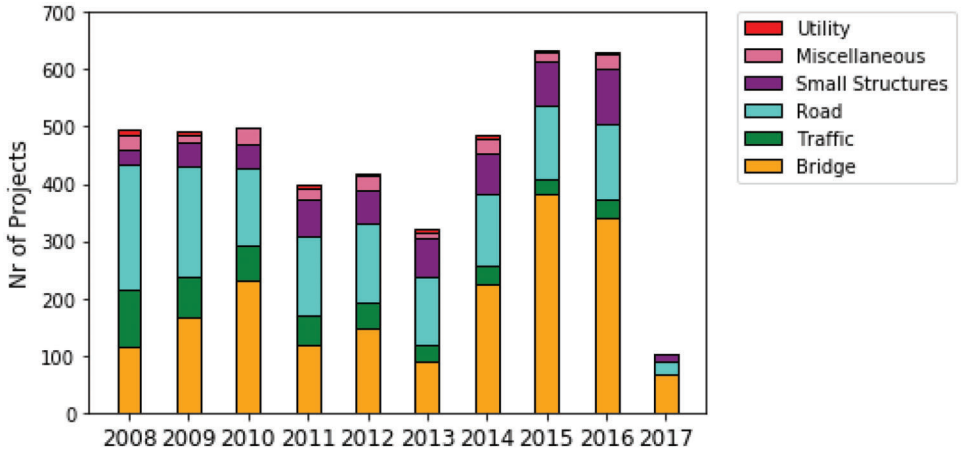


Figure 3.8 Distribution of projects over years (year 2008 to year 2017).

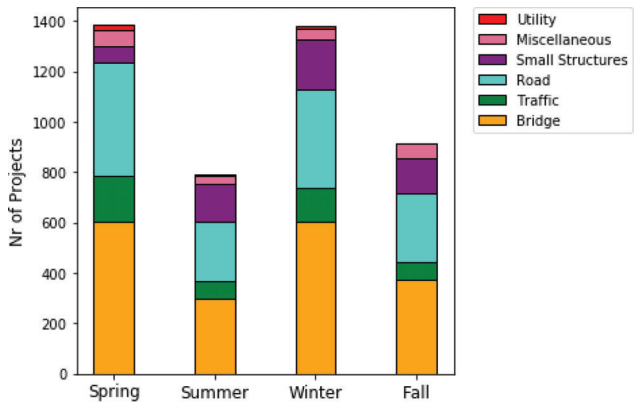


Figure 3.9 Distribution of projects over seasons.

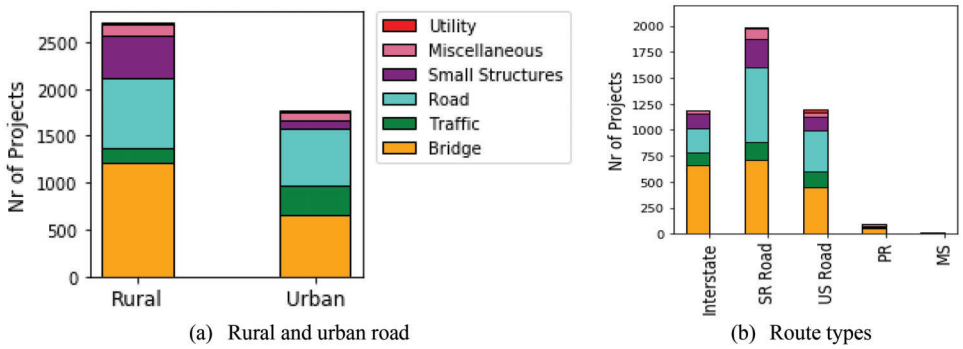


Figure 3.10 Number of projects on different route types.

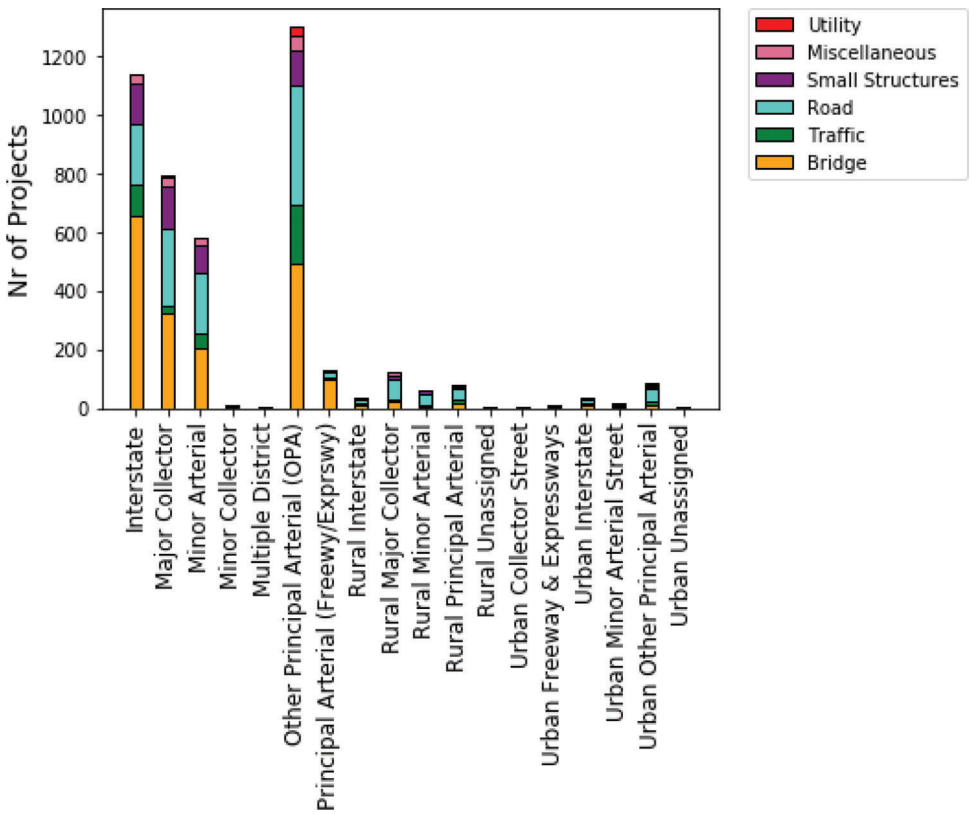


Figure 3.11 Distribution of projects on different functional classes.

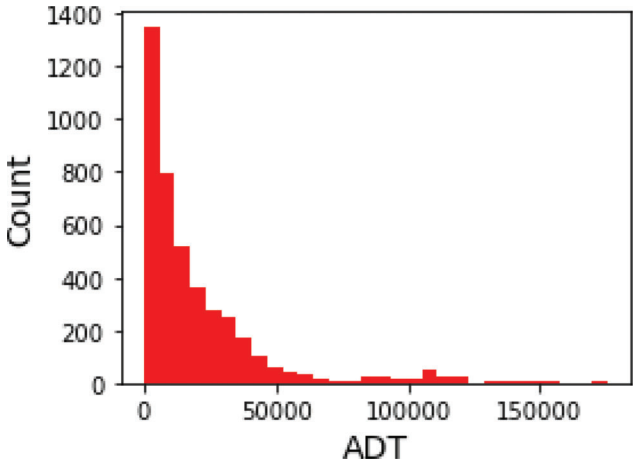


Figure 3.12 Distribution of ADT on the road or over the bridge.

- At a contract level, the cost is the award amount of a contract (contract award). The contract award is also the sum of Des Award of all projects in that contract.
- At the project level, the cost is the Des Award of each project in a single project contract or a bundled contract.
- At the pay item level, the cost is measured by the cost of each pay item for a project. The sum of the cost of all the pay items is equal to the Des Award for that project. For a design-build project, there is only one lump sum item, and the item cost is the Des Award. In this study, design-build projects are excluded.

For all the analyses in this study, cost data have been adjusted to account for inflation across the different years of cost reporting. The Construction Price Index (CPI) from the Bureau of Labor Statistics (BLS) was used, and the base year is 2015.

3.2.8.1 Contract Level. Figure 3.15 presents the distribution of contract award for different ranges. The chart's bars are set with different interval widths in order to present a more useful distribution. The contract award of many contracts is between $0.1 million and $5 million. Contracts with award amounts more than $10 million might contain some expensive project types or a large number of projects.

3.2.8.2 Des (Project) Level. Figure 3.16 presents the distribution of costs at a project level. Each bar represent the counts of projects that have a Des Award within a certain cost range, segmented by different colors that indicate a certain work category. The most frequent Des Award amounts are between $0.1 million to $5 million. Some projects have Des Awards more than $5 million; most of these are road projects.

Figure 3.17 (a) and (b) shows the distribution of Des Awards for different project types in the categories of bridge and road work. It can be found that, for bridge work, bridge replacement and new bridge are the most expensive projects. For road work, new road construction is the project type with largest expenditure outlay. Table 3.3 summarizes the counts of Des Award and contract award within different cost ranges for each project type in the six work categories.

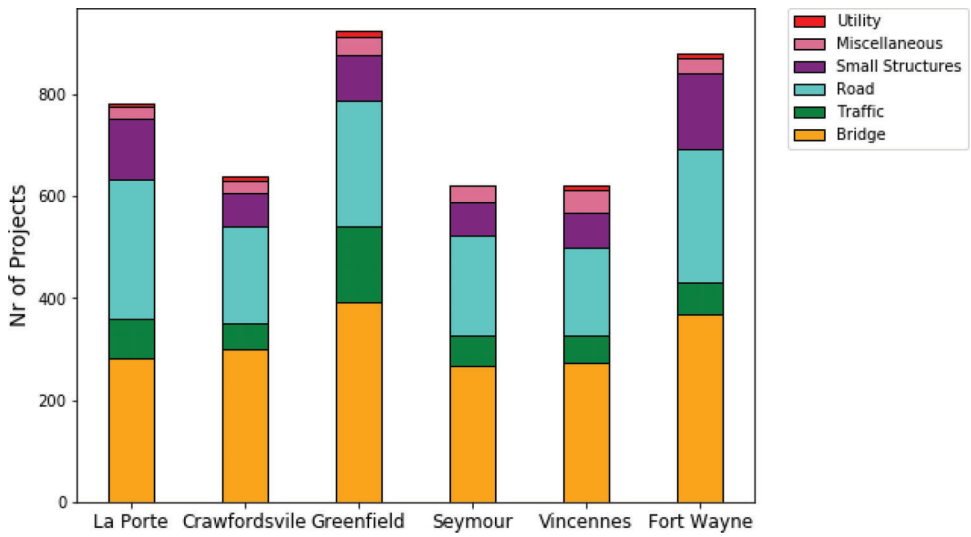
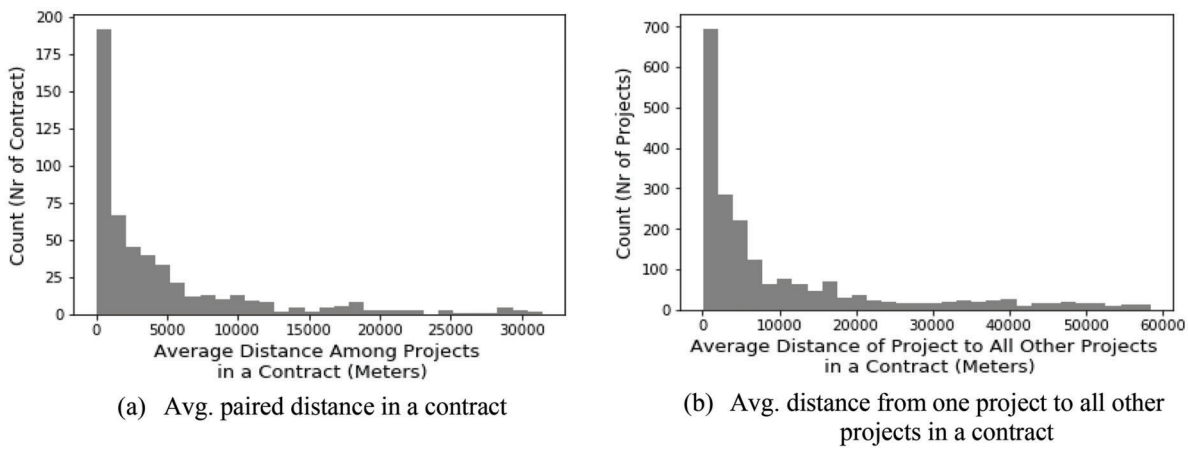


Figure 3.13 Distribution of project types in the six INDOT districts.



(a) Avg. paired distance in a contract

(b) Avg. distance from one project to all other projects in a contract

Figure 3.14 Distribution of average distance for bundled projects.

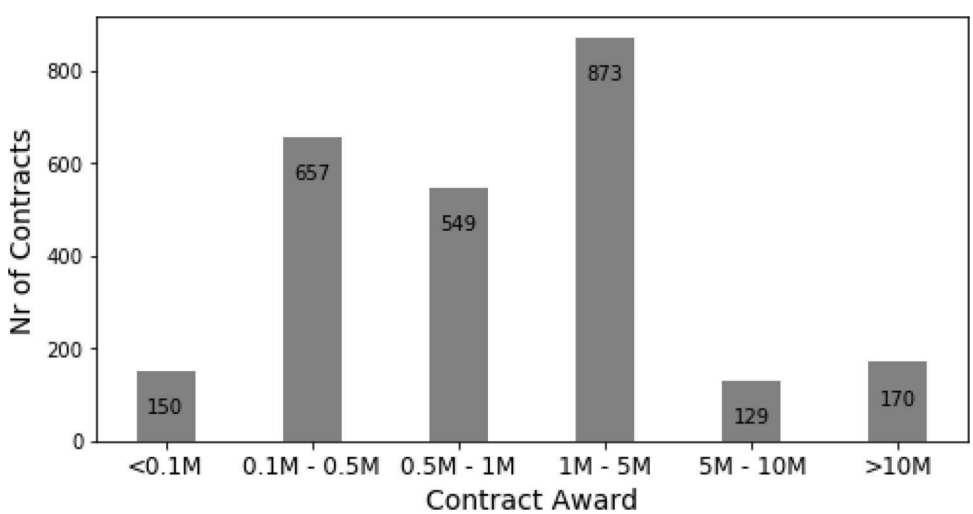


Figure 3.15 Count of INDOT contracts by contract award.

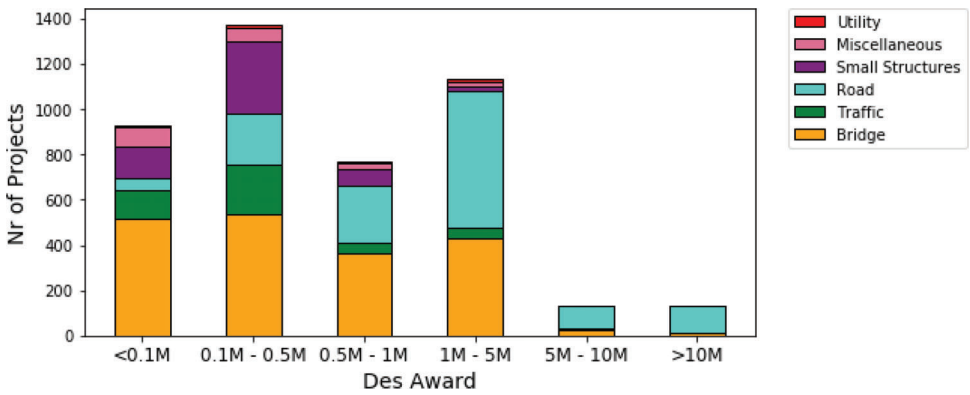


Figure 3.16 Number of projects by Des Award for different work categories.

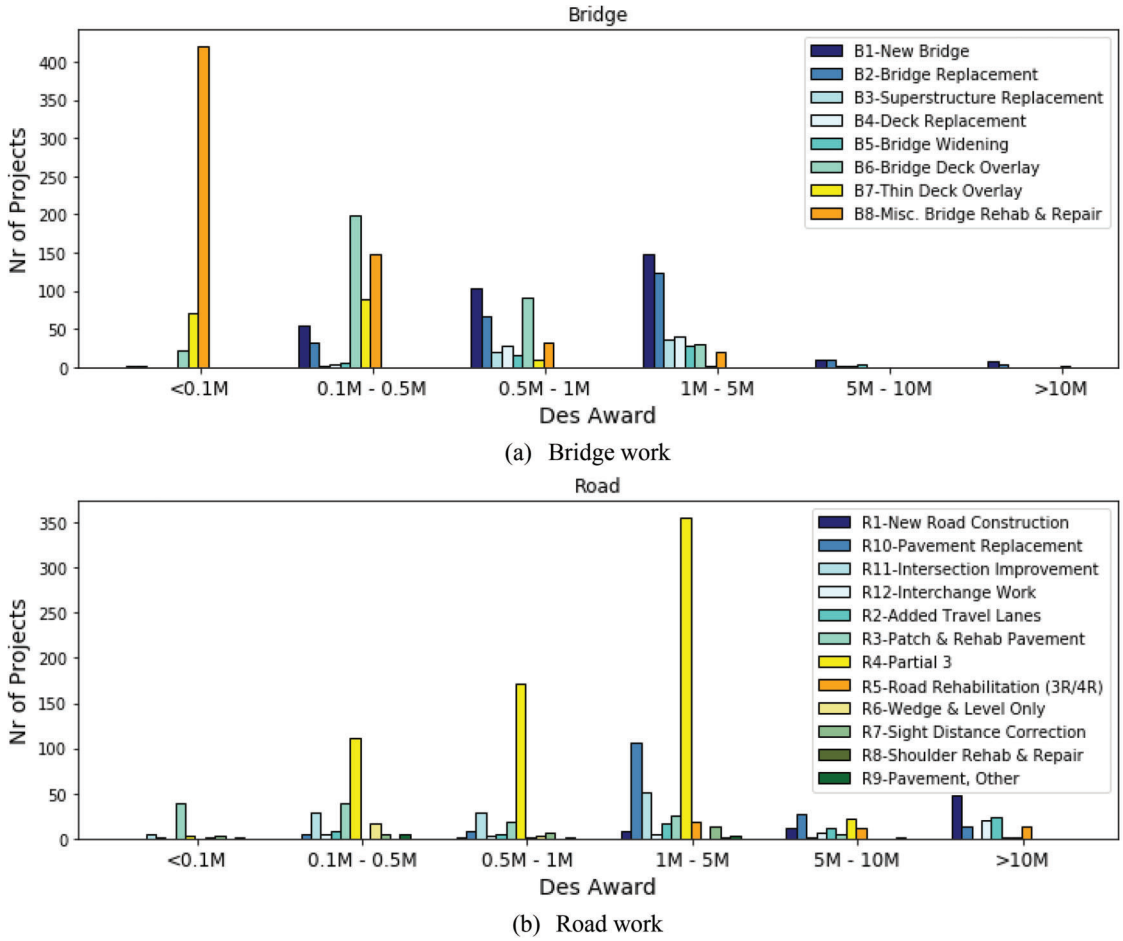


Figure 3.17 Count of INDOT projects by Des Award for different project types in two work categories.

3.2.8.3 Pay Item Level. At the pay item level, the project cost is given in terms of the detailed cost of each pay item in a des. The pay item cost will be used to quantify the similarity between different project types: projects that share more common pay items have less similarity or are compatible to each other. In Chapter 4, the similarity between each pair of project types is calculated based on the distribution of pay item cost using Euclidean distance method. In the current dataset, after merging the pay item dataset with the contract dataset and removing item 104 (design/build), there are in total 6,175 different pay items, each with a unique "Item Nr" (e.g., 110-01001: Mobilization and Demobilization). These pay items can be grouped into 8 item sections (i.e., Sec 100, Sec 200, …, Sec 800), and 119 item subsections ("Item Sub"). Figure 3.18 presents the structure of the pay item dataset.

Figure 3.19 shows the average cost in the dataset for each item subsection. Pay items belonging to item

TABLE 3.3
Distribution of Des Award for Different Project Types

		Des Award ($) Counts (Nr of projects) by Cost Category						
Work Category	**Project Type**	**<0.1M**	**0.1M–0.5M**	**0.5M–1M**	**1M–5M**	**5M–10M**	**>10M**	**Total**
Bridge	B1	2	54	103	151	10	9	329
	B2	1	32	67	125	10	3	238
	B3	0	2	20	40	1	1	64
	B4	0	3	30	56	1	0	90
	B5	0	6	15	29	4	0	54
	B6	21	223	116	35	0	0	395
	B7	73	96	9	2	0	0	180
	B8	425	166	33	20	0	3	647
	Total	522	582	393	458	26	16	1997
Miscellaneous	M1	52	16	10	4	2	0	84
	M2	30	14	4	2	1	0	51
	M3	2	1	1	1	0	0	5
	M4	2	14	9	11	1	0	37
	M5	1	10	2	3	0	0	16
	Total	87	55	26	21	4	0	193
Road	R1	0	0	1	8	11	57	77
	R2	0	0	2	19	12	13	46
	R3	2	16	3	0	0	0	21
	R4	3	5	6	13	0	0	27
	R5	0	0	0	2	0	0	2
	R6	2	4	1	3	1	0	11
	R7	0	5	9	106	28	15	163
	R8	4	29	29	51	1	0	114
	R9	1	5	3	5	7	20	41
	R10	0	9	4	16	11	30	70
	R11	40	39	18	25	4	1	127
	R12	3	111	171	356	22	3	666
	Total	55	223	247	604	97	139	1365
Small Structure	S1	118	131	12	7	0	0	268
	S2	9	161	59	14	0	0	243
	S3	7	30	8	0	0	0	45
	Total	134	322	79	21	0	0	556
Traffic	T1	0	8	4	12	3	0	27
	T2	40	54	16	17	1	0	128
	T3	79	120	10	2	0	0	211
	T4	1	10	2	1	0	0	14
	T5	4	15	10	14	4	1	48
	T6	6	17	6	0	0	0	29
	Total	130	224	48	46	8	1	457
Utility	U1	0	2	0	0	0	0	2
	U2	6	15	8	11	1	0	41
	Total	6	17	8	11	1	0	43

Contract	Des NO	Work Type	Line No	Item No	Item Sec	Item Sub	Item Desc	Unit	Unit Price	Quantity	Amount
26727	9608820	New Br, Reinforced Concrete Construction	9	110-01001	100	110	Mobilization And Demobilization	LS	45560	1	45560
26727	9608820	New Br, Reinforced Concrete Construction	10	201-52370	200	201	Clearing Right Of Way	LS	15000	1	15000
26727	9608820	New Br, Reinforced Concrete Construction	11	202-51330	200	202	Present Structure Remove	LS	20000	1	20000
26727	9608820	New Br, Reinforced Concrete Construction	12	202-96133	200	202	Pipe Remove	LFT	5	143	715
26727	9608820	New Br, Reinforced Concrete Construction	13	203-02000	200	203	Excavation Common	CYS	12	4882	58584
26727	9608820	New Br, Reinforced Concrete Construction	14	203-02070	200	203	Borrow	CYS	12	566	6792
26727	9608820	New Br, Reinforced Concrete Construction	15	205-03371	200	205	Sediment Remove	CYS	1	20	20
26727	9608820	New Br, Reinforced Concrete Construction	16	205-06931	200	205	Temporary Check Dam Revetmen	TON	30	50	1500
26727	9608820	New Br, Reinforced Concrete Construction	17	205-06936	200	205	Temporary Sediment Trap	TON	30	45	1350
26727	9608820	New Br, Reinforced Concrete Construction	18	205-06937	200	205	Temporary Silt Fence	LFT	1.75	1772	3101
26727	9608820	New Br, Reinforced Concrete Construction	19	205-09543	200	205	No 2 Stone	TON	18	396	7128
26727	9608820	New Br, Reinforced Concrete Construction	20	207-08263	200	207	Subgrade Treatment Type Ia	SYS	6	5440	32640
26727	9608820	New Br, Reinforced Concrete Construction	21	207-08267	200	207	Subgrade Treatment Type IIIa	SYS	13	350	4550
26727	9608820	New Br, Reinforced Concrete Construction	22	211-02050	200	211	B Borrow	CYS	24	1401	33624
26727	9608820	New Br, Reinforced Concrete Construction	23	211-09264	200	211	Structure Backfill Type 1	CYS	32	139	4448
26727	9608820	New Br, Reinforced Concrete Construction	24	211-09265	200	211	Structure Backfill Type 2	CYS	35	1196	41860

Figure 3.18 Sample pay item dataset.

sub 215 (e.g., 215-07043: Chemical Modification, Soils), 304 (e.g., 304-07491: HMA Patching, Type C), 501 (e.g., 501-06325: QC/QA-PCCP, 350 Mm), 506 (e.g., 506-06333: PCCP Patching, Full Depth), and 707 (e.g., 707-05979: Structural Members, Concrete Box Beam, C) are found to have the largest unit cost, with average amounts exceeding $200,000.

For different project types, the composition of pay items can vary greatly. Figure 3.20 presents, by item section, the counts of all the pay items for all the projects in a certain work category. The similarity between the compositions of pay items of different project types can serve as a good measure of the compatibility between different project types. A compatibility analysis based on similarity of pay items is conducted and discussed in Chapter 4.

In addition, the pay item level data provides a way to analyze the bundling effect on a certain pay item. In this study, we are interested to see how the maintenance of traffic (MOT) cost is affected by project bundling. The MOT-related pay items (identified with assistance from INDOT) are listed in Table 3.4. The "pay item contribution" is the ratio of the total cost of the pay item in the contract to the total contract cost. It was found that Mobilization and Demobilization costs were capped at 5% of the overall total contract cost in Indiana (Hanna, Whited, & Menke, 2007). A comprehensive analysis of MOT for different project types is conducted in the subsequent chapters.

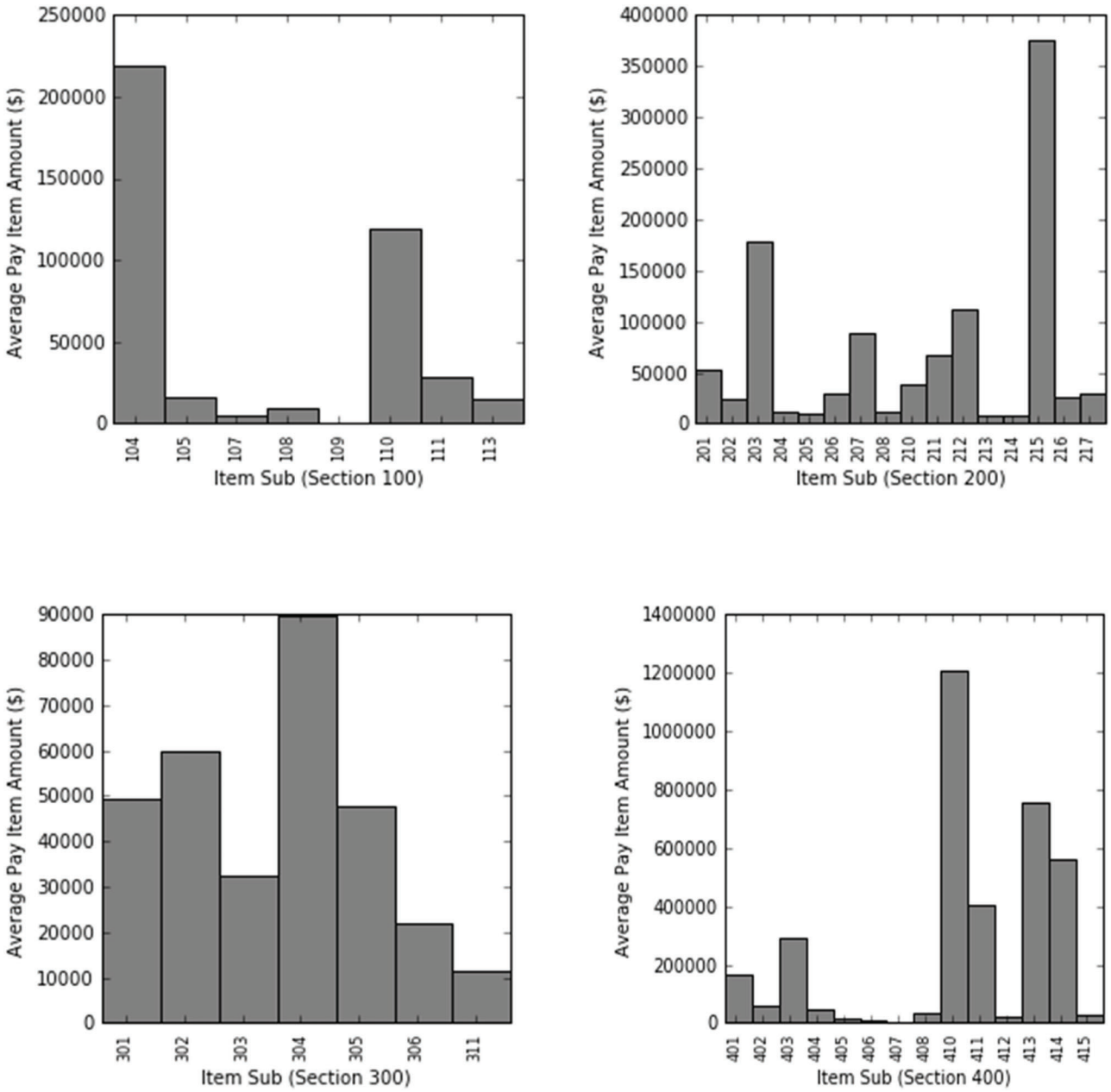


Figure 3.19. Average pay item cost in the 120 item sub. (Figure continued on next page.)

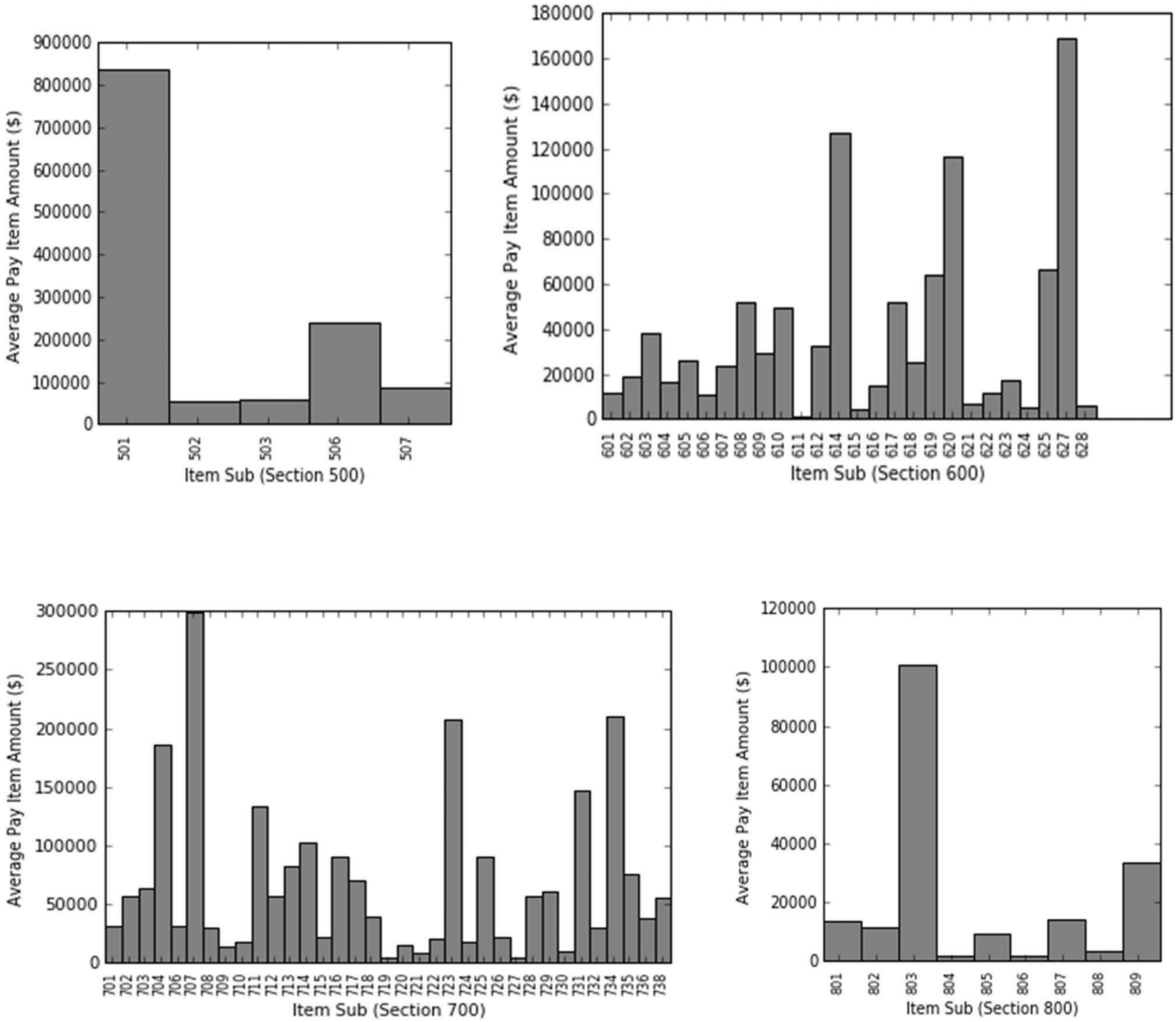


Figure 3.19 (Continued).

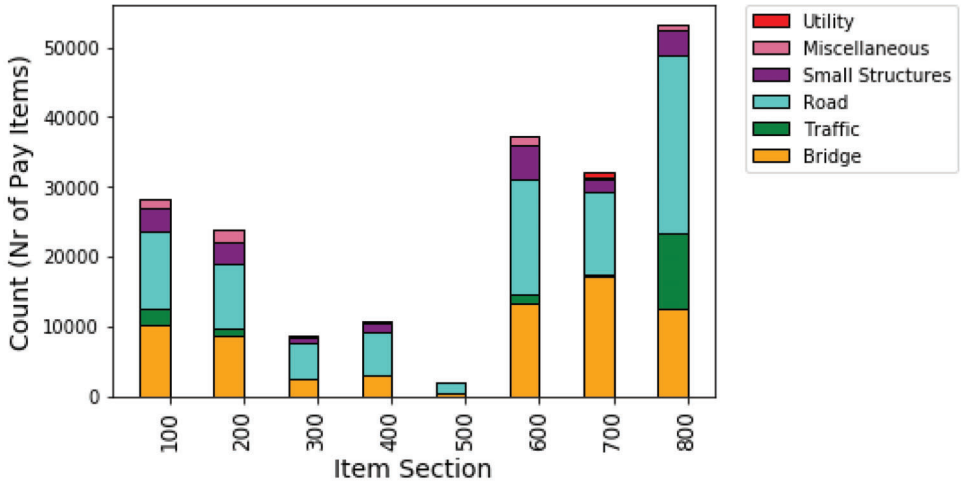


Figure 3.20 Compositions of pay items for projects in different work categories.

TABLE 3.4
List of MOT Related Pay Items

Main Sec.	Section	Item	Description	Unit	Pay Item Contribution (%)
100	110	110-01001	Mobilization and Demobilization	LS	5.13
300	303	303-08210	Compacted Aggregate No. 53 Temporary For Driveways	TON	0.41
400	402	402-10083	HMA For Temporary Pavement, A	TON	1.01
400	402	402-10084	HMA For Temporary Pavement, B	TON	2.53
400	402	402-10086	HMA For Temporary Pavement, C	TON	3.25
400	402	402-10087	HMA For Temporary Pavement, D	TON	4.22
600	601	601-02205	Temporary Guardrail Transition, Tgb	EACH	0.04
600	601	601-02206	Temporary Guardrail, W Beam, 6 ft-3 in Spacing	LFT	0.36
600	601	601-97080	Temporary Guardrail End Treatment, Os	EACH	0.27
700	713	713-04509	Temporary Pipe	LS	3.32
700	713	713-04643	Temporary Access Lane	LS	2.76
700	713	713-04858	Temporary Bridge	LS	3.56
700	713	713-11199	Temporary Pipe	LFT	0.20
700	713	713-51334	Temporary Pipe and Approaches	LS	4.25
700	713	713-51335	Temporary Bridge and Approaches	LS	10.79
700	713	713-91028	Temporary Runaround	LS	3.92
700	713	713-99365	Guardrail, W Beam 6.3 ft Spacing Temporary Bridge Approaches	LFT	0.33
800	801	801-06775	Maintaining Traffic		4.20
800	808	808-01428	Temporary Transverse Markings White Stop Line 24 In	LFT	0.05

4. PRELIMINARY ANALYSIS

This chapter describes various preliminary data analyses, including:

- average unit cost comparison between single-projects and bundled projects (Section 4.1),
- investigation on the effect of various factors on project cost (Section 4.2),
- model development for the relationship between project size and market competition (Section 4.3),
- similarity (compatibility) analysis between different project types based on the compositions of pay items (Section 4.4),
- maintenance of traffic (MOT) analysis (Section 4.5), and
- corridor analysis which compares the unit cost of stand-alone project and bundled projects along the same corridor (Section 4.6).

The analysis results reveal useful information about the impact of various factors on project cost, and provide guidance for the subsequent development of statistical cost models in Chapter 5.

4.1 Average Cost

Project cost vary greatly by different project types. Road and bridge work generally have higher unit costs compared to projects in other work categories. New construction or replacement work is often the most costly project type, followed by major rehabilitation, maintenance and repair work are typically the least costly project types. In this section, an average cost approach was used to compare the project cost and unit cost across various project types (See Table 4.1.). The average project cost of a given project type calculated here is the total project cost (Des Award) of all projects divided by the number of projects. The average unit cost for a given project type is the Des Award divided by the project size (i.e., deck area, project length, number of lanes). The unit cost can be measured as $ per square foot, $ per lane mile, or $ per mile depending on the project type. For some project types, such as interchange work and small structure installation, the unit cost is measured as $ per unit. Data with missing project size (e.g., deck area, project length or number of lanes) were removed from analysis. In addition, to get a more reliable estimation, data outside the 90% confidence interval were removed as outliers. It was noticed that project B8-Misc. Bridge Rehab & Repair has a very high standard deviation on the unit cost (higher than the mean). This is because this project type encompasses many different project types including fiber-wrapping columns, repairing deck joints, patching, bridge rail repair, repairing approach slabs and so on. In realization of this issue, we excluded project type B8 from bundling scenario analysis in this study. Nevertheless, the preliminary analysis and cost model results are still provided for B8 with limited accuracy and reliability.

A main task of this study is to investigate the benefit of project bundling in terms of project cost saving. In this section, the average unit cost approach was used to examine how the unit cost of a bundled project differs from that of a single project. As shown in Figure 4.1, the benefit (reduction in unit cost) of project bundling was evident for all bridge projects, and most traffic, miscellaneous, and small structure work. The reduction in project unit cost for bridge projects was found to be the most significant. For road projects, however, a slight decrease in unit cost was found only for R3-Patch & Rehab Pavement, R7-Sight Distance Correction and R9-Pavement, Other. For all the other road project types, project bundling seems to lead to a higher unit cost.

TABLE 4.1
Average Des Award and Unit Cost for Different Project Types

Work Category	Project Type	Count	Avg. Des Award	Avg. Unit Cost	Unit	Standard Deviation
Bridge	B1	264	$1,632,864	$279	$ per sqft	$191.95
	B2	186	$2,049,968	$429	$ per sqft	$240.50
	B3	52	$1,514,271	$207	$ per sqft	$81.95
	B4	62	$1,187,132	$136	$ per sqft	$47.41
	B5	48	$1,634,899	$151	$ per sqft	$70.10
	B6	308	$513,330	$76	$ per sqft	$38.23
	B7	154	$185,106	$23	$ per sqft	$18.79
	B8	545	$144,789	$14	$ per sqft	$17.88
Work Category	**Project Type**	**Count**	**Des Award**	**Unit Cost**	**Unit**	**Standard Deviation**
Road	R1	36	$17,087,744	$5,445,926	$ per lane mile	$1,973,463
	R2	41	$18,184,356	$8,364,996	$ per mile	$7,234,558
	R3	99	$1,137,987	$64,078	$ per lane mile	$84,035
	R4	552	$1,696,038	$124,498	$ per lane mile	$65,121
	R5	32	$8,176,634	$1,100,037	$ per lane mile	$753,423
	R6	16	$346,488	$75,375	$ per lane mile	$63,862
	R7	17	$1,092,600	$1,876,604	$ per lane mile	$1,901,855
	R8	1	$1,037,601	$124,413	$ per mile	NA
	R9	6	$1,770,575	$313,614	$ per lane mile	$213,920
	R10	134	$4,571,604	$512,590	$ per lane mile	$542,699
	R11	41	$1,228,278	$1,228,278	Each	$1,140,889
	R12	26	$11,473,858	$11,473,858	Each	$9,409,293
Work Category	**Project Type**	**Count**	**Des Award**	**Unit Cost**	**Unit**	**Standard Deviation**
Traffic	T1	19	$1,905,869	$195,144	$ per lane	$170,464.70
	T2	65	$602,567	$843,884	$ per lane	$2,576,046.91
	T3	69	$256,137	$4,619,192	$ per lane	$6,708,289.24
	T4	8	$216,189	$20,662	$ per lane	$6,231.97
	T5	24	$2,067,720	$1,050,704	$ per mile	$2,002,839.45
	T6	16	$299,641	$544,313	$ per mile	$539,091.71
Work Category	**Project Type**	**Count**	**Des Award**	**Unit Cost**	**Unit**	**Standard Deviation**
Small Structure	S1	28	$219,168	$659,675	$ per mile	
	S2	65	$411,548	$411,548	Each	
	S3	12	$362,610	$362,610	Each	
Work Category	**Project Type**	**Count**	**Des Award**	**Unit Cost ($ per mile)**	**Unit**	**Standard Deviation**
Miscellaneous	M1	31	$120,058	$1,453,183	$ per mile	$3,626,450
	M2	18	$627,778	$1,474,318	$ per mile	$1,525,230
	M3	3	$254,104	$228,253	$ per mile	$214,091
	M4	16	$600,969	$11,026,317	$ per mile	$22,468,022
	M5	3	$199,704	$267,412	$ per mile	$81,470
Work Category	**Project Type**	**Count**	**Des Award**	**Unit Cost**	**Unit**	**Standard Deviation**
Utility	U1	1	$112,514	$5,625,678		NA
	U2	25	$1,252,938	$698,230	$ per mile	$616,633.70

The average cost approach, however, does not provide the full information needed to show the bundling effect, because it does not consider economies of scale and other important variables. Additional analysis is carried out in subsequent sections to determine whether road work projects bundling in fact save money in road work.

4.2 Effect of Various Factors on Project Unit Cost

The average cost method can provide some information and comparison on project cost across different project types. However, project cost is influenced by many other factors besides project type. As shown in Table 4.1, the standard deviation of the average unit cost is very large. This high level of variation may be coming from differences in project size, market competition, topography, land prices, environment, and/or traffic loads. Another factor accounting for the observed variation is that a des number is simply a tracking number to account for work on a project. For example, a des number with a bridge project type can include roadway, lighting and drainage pay items, while the majority of the work is for the bridge structure.

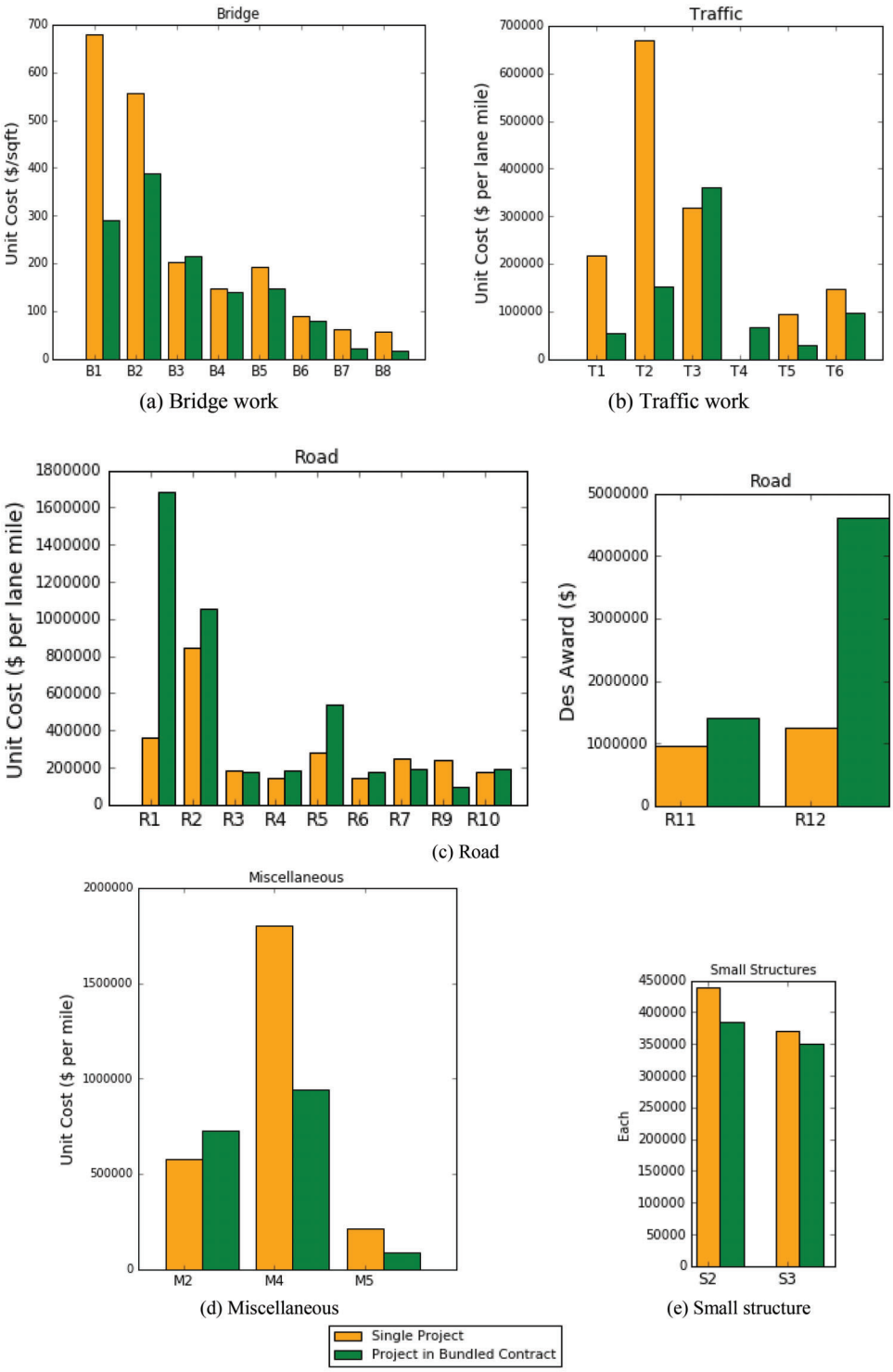


Figure 4.1 Comparison of average unit cost for projects in single contract project and bundled project.

A diagram listing a set of influential variables considered in this study that might have positive or negative effects on project cost is shown in Figure 4.2. The three major factors are, hypothetically speaking, economies of scale (project size), economies of bundling (number of des) and economies of competition (number of bidders in a contract). The interactions between the three factors are also presented in Figure 4.2. An increase in project size and number of des can lead to a decrease in the number of bidders in a contract, because some contractors refrain from bidding if the contract becomes very expensive. The project size and number of des also

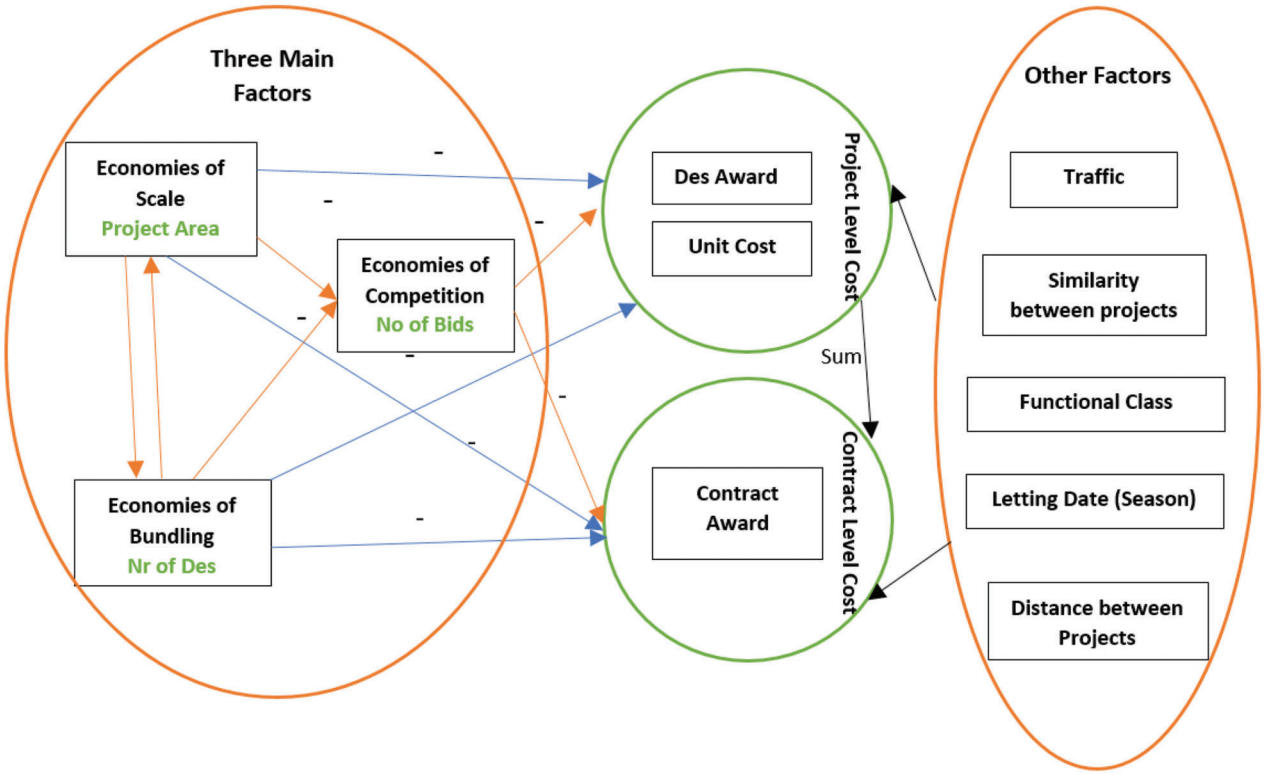


Figure 4.2 Diagram showing how project cost is affected by various variables.

affect each other. For example, it is less likely for a project that is already very large to be bundled with other projects. On the other hand, if several projects are bundled into a contract, then the average project size or size per des is likely to be smaller, compared to the size of a stand-alone project. To account for the influence of all the relevant variables and the interactions between them, it is necessary to develop a statistical model instead of using the average cost approach.

In this section, the effect of various variables on project cost were investigated using two- and three-dimensional scatter plots. The complex relationship and interaction between these variables and project cost might not be easily explained by scatter plots alone. However, a preliminary analysis on these factors can give guidance on variable selection, and can provide some justification for the results of the cost models developed in Chapter 5.

4.2.1 Three Major Factors

4.2.1.1 Economies of Scale. Economies of scale is the probably the most dominant factor among all the variables that may affect the cost of a project. The unit cost of a project decreases dramatically as the project size (expressed in deck area or lane-miles) increases, as shown in Figures 4.3 and 4.4. The rate of change in unit cost decreases as the project size continues to increase. When the project size passes a certain value, the unit cost stops decreasing and may even start increasing. (See, for example, Project types B7 and B8 in Figure 4.3.) The relationship between unit cost and project size is defined as the "unit cost pattern." In the following sections, analysis is conducted on the effect of other important factors on this unit cost pattern.

4.2.1.2 Economies of Bundling. Another factor that may influence project cost is called economies of bundling. This refers to the effect of bundling multiple projects into a single contract on project unit cost. A project that is bundled with other projects (kins) in one contract is expected to have a lower unit cost compared to a stand-alone project, when other conditions are similar. As presented in Section 4.1, the average unit cost of bundled projects is smaller than the cost of single projects for most bridge (except B3), traffic (except T3), small structure and miscellaneous work (except M2), while this bundling benefit is not found for most road work (except R3, R7 and R9). The average unit cost method however does not take project size (economies of scale) and other important factors into consideration. To account for the economies of scale, scatter plots of unit cost vs. deck area (unit cost pattern) for bridge work are shown in Figure 4.5, with single projects indicated by yellow dots and bundled projects by green dots. The unit costs of single projects were found to be generally higher than for bundled projects with similar project size (deck area) in project types B1, B2, B7, and B8. The benefits of project bundling on B1, B2, B7, and B8 were also found to be more significant compared to other project types in Section 4.1.

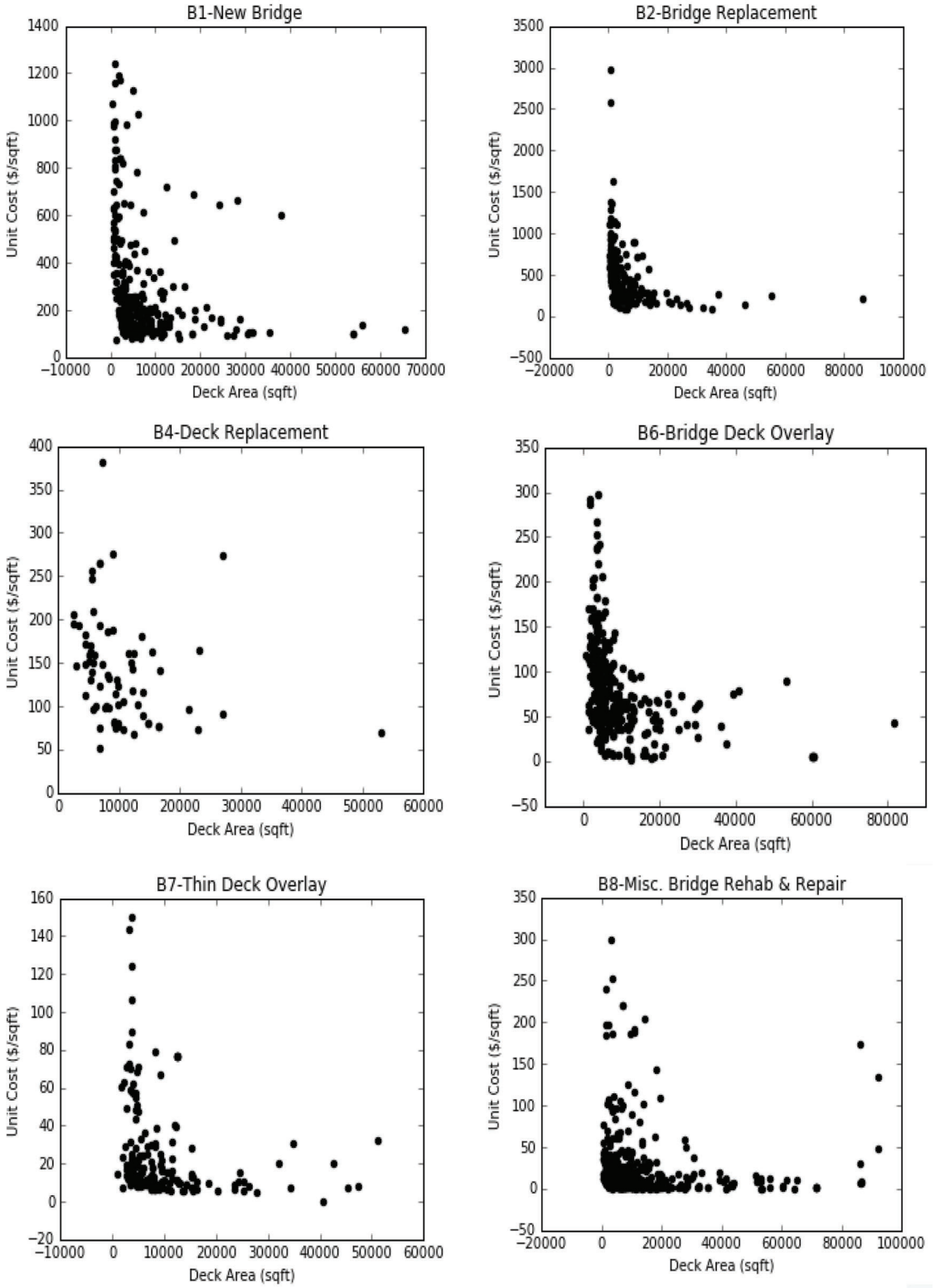


Figure 4.3 Unit cost vs. project size (economies of scale) for bridge work.

Project cost is not only affected by whether the project is bundled, but it is also influenced by how the project is bundled. For example, the cost savings due to project bundling might be more significant when a project is bundled with the same project types than when bundled with different project types. Also, projects bundled along the same corridor might benefit morefrom project bundling, compared to projects

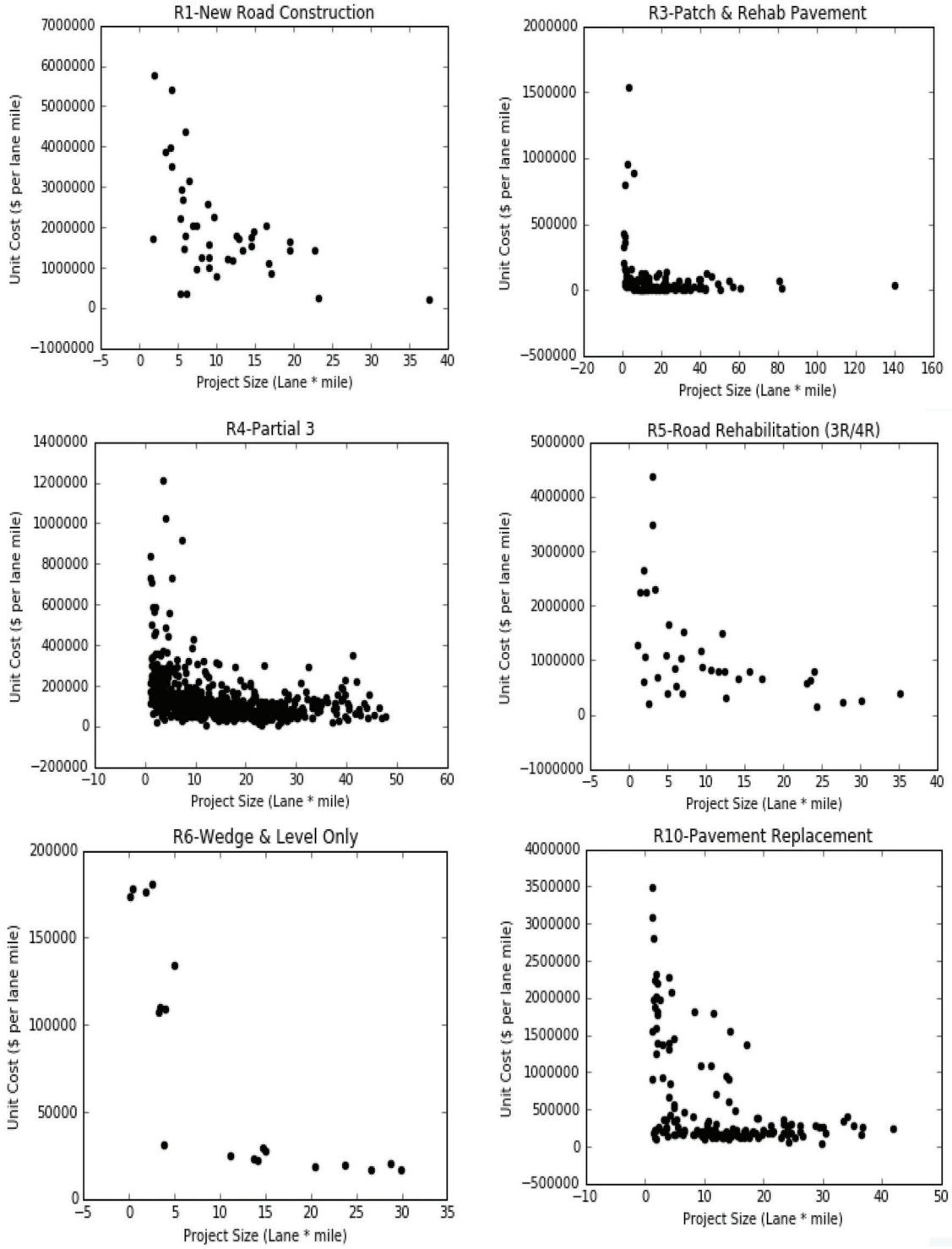


Figure 4.4 Unit cost vs. project size (economies of scale) for road work.

bundled from different corridors located over a wide area. These factors are discussed in Sections 4.4 (similarity analysis) and 4.6 (corridor analysis).

In this section, the bundling effect was further investigated in terms of how the unit cost of a project is affected by the number of its kins in the contract. The scatter plots of unit cost versus the number of des for different bridge projects are shown in Figure 4.6. A general decreasing trend was found for all bridge project types, which means a higher number of projects bundled into a contract can lead to a lower unit cost. Project types B1, B2, B7 and B8 are again found to

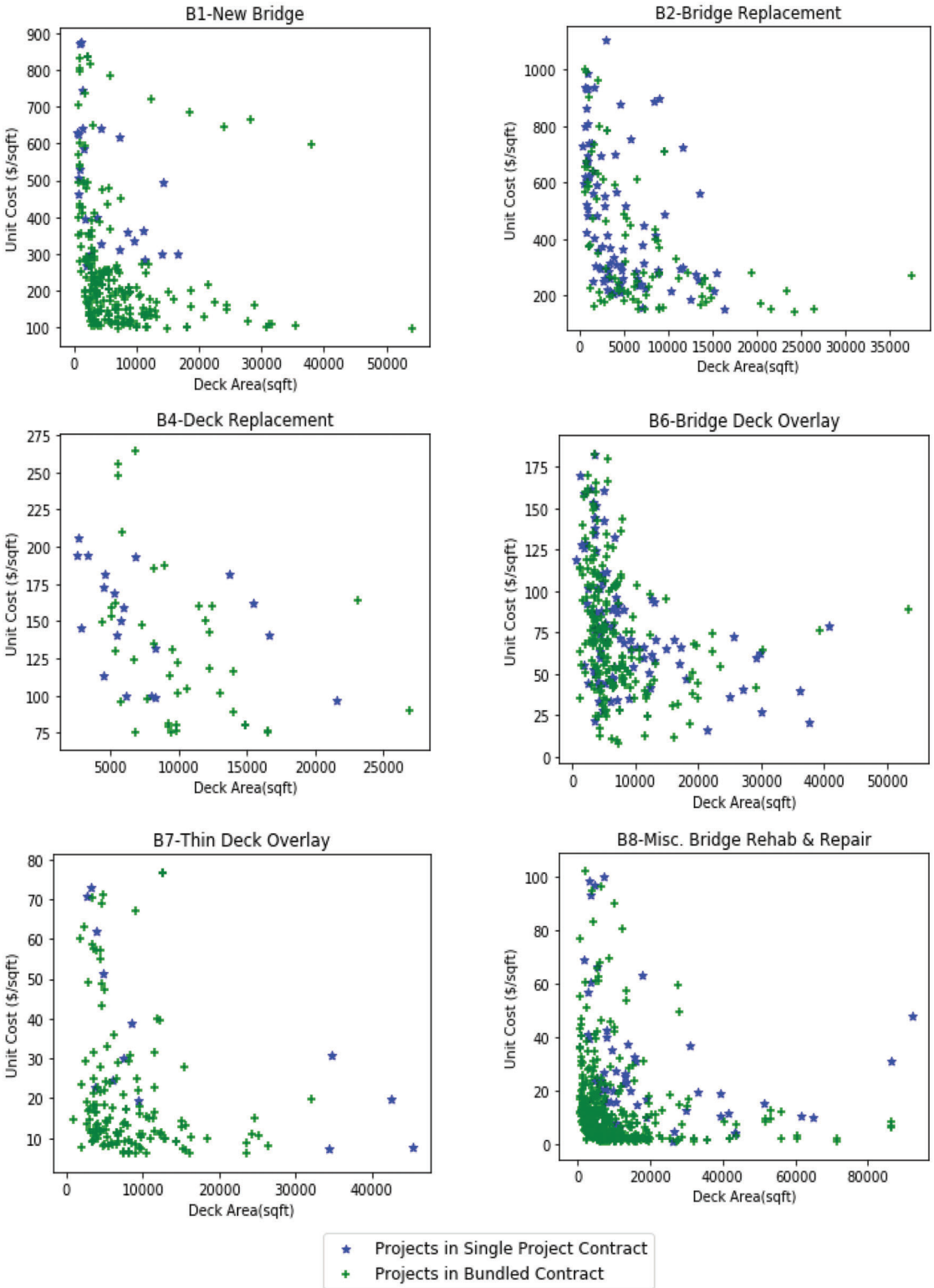


Figure 4.5 Unit cost pattern for projects in single and bundled contracts (bridge work).

have the largest decreasing rate of unit cost, indicating these project types benefit more significantly from project bundling compared to other bridge project types.

The scatter plot in Figure 4.6 does not show the effect of project size on project unit cost (economies of scale), only the effect of number of des in contract. Deck area is added in Figure 4.7 to show how the

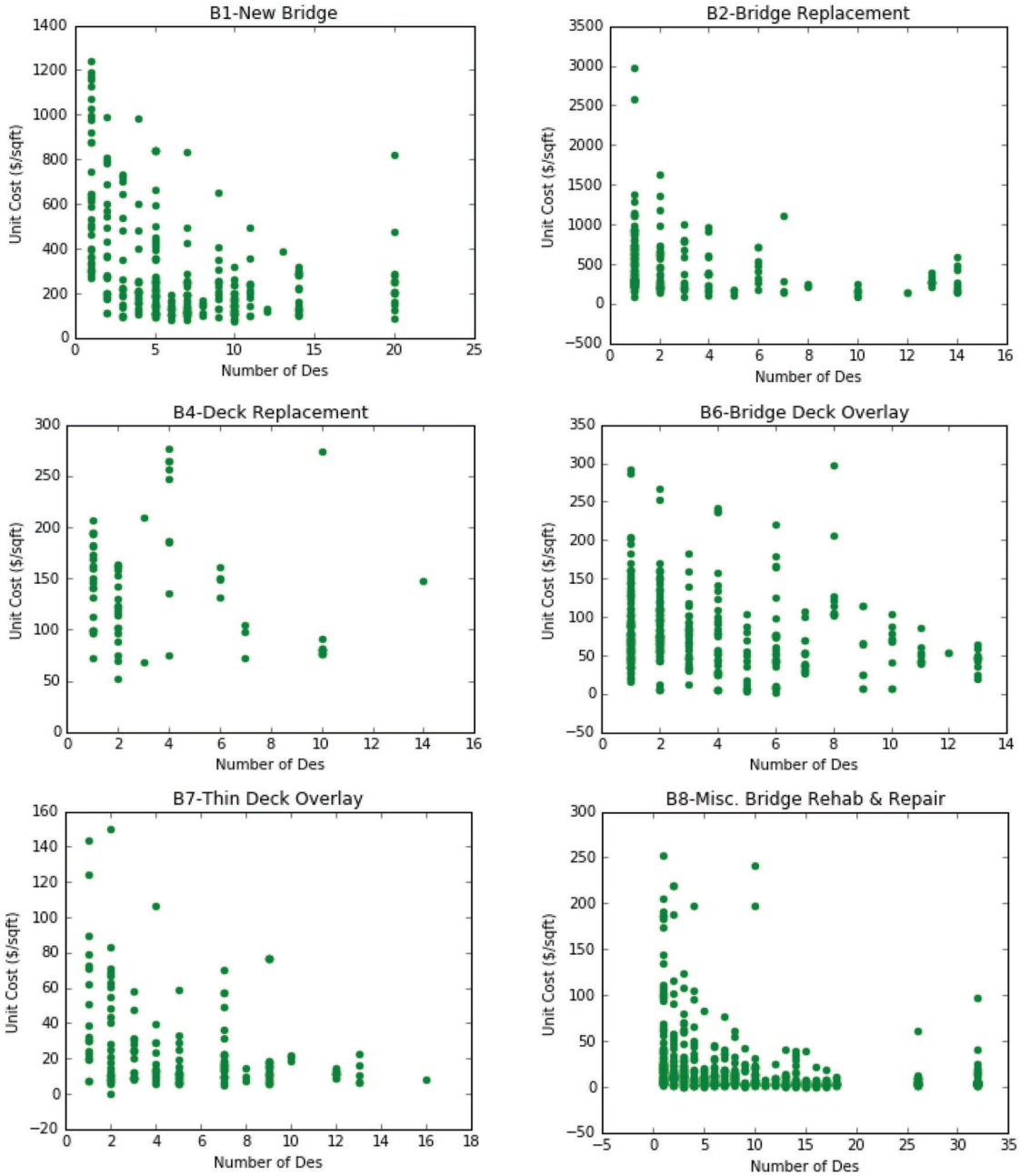


Figure 4.6 Unit cost vs. number of des (economies of bundling) for bridge work.

relationship between unit cost and project size is affected by the number of des (indicated by different colors) in the bundled contracts. When the deck area is similar, the blue stars (2 des) and green plus signs (3 to 4 des) in general have higher unit costs than the orange triangles (5 to 10 des) and red circles (>10 des).

A similar analysis was then conducted for project types in the road work category. As shown in Figure 4.8, economies of bundling is only found for R3-Patch & Rehab Pavement, R7-Sight Distance Correction (consistent with the results in Section 4.1), and R10-Pavement Replacement. We believe that this is because, for certain road projects, the economies of scale dominates the economies of bundling. It means that, for these roadprojects, the cost savings associated with one large project in a single-project contract outweighs the cost increase associated with unbundling or no bundling.

4.2.1.3 Economies of Competition. The third major factor is the economies of competition, which refers to the effect of market competition on project unit cost. A high number of bidders is typically desired during the project bidding process, because market competition

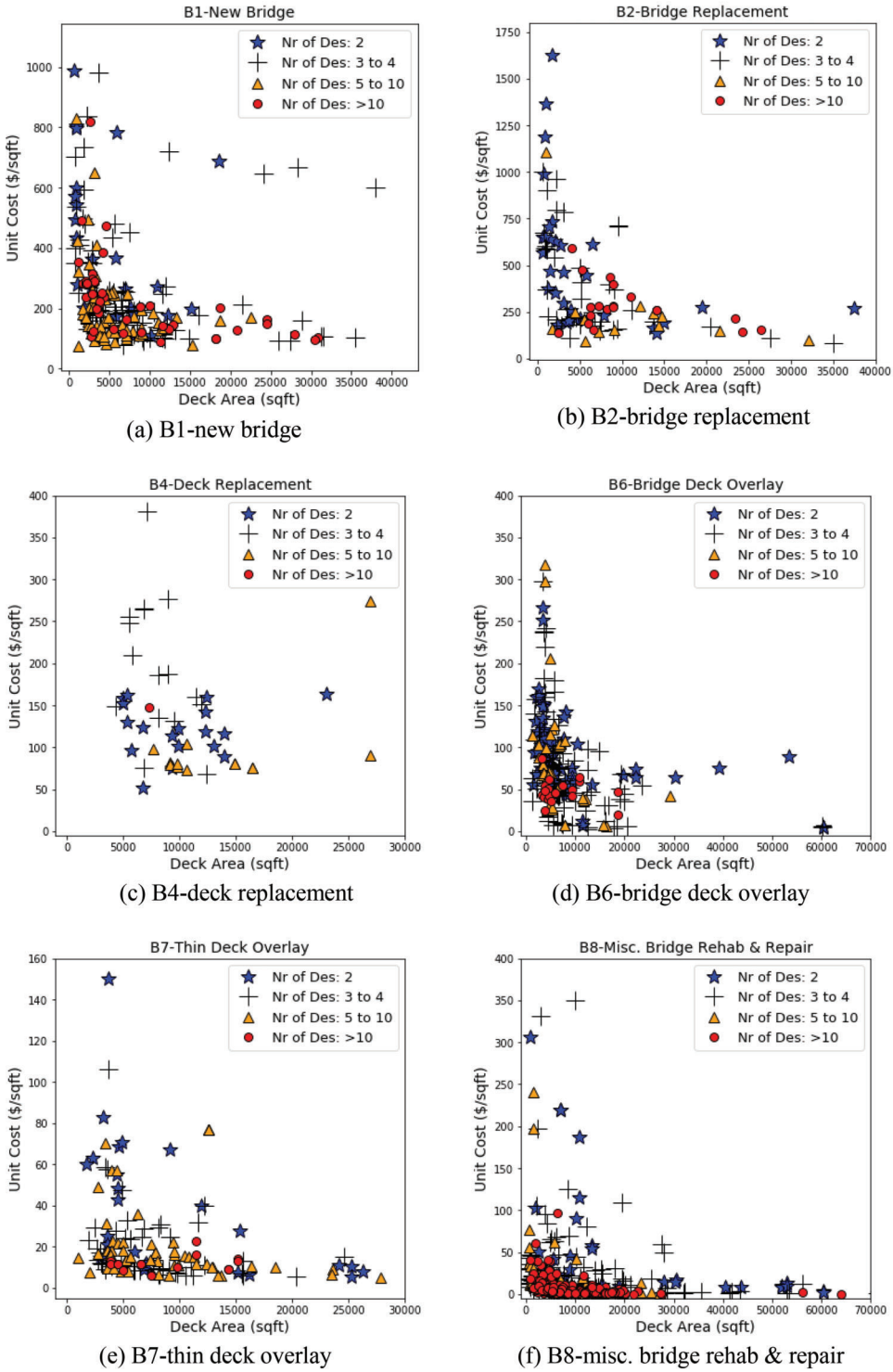


Figure 4.7 Unit cost pattern for bundled contracts with different number of des (bridge work).

can be expected to lead to a lower contract price. To show the effect of the number of bidders, we developed unit cost plots that include project size and number of bidders (Figure 4.9) for different bridge projects. The effect of economies of bundling is missing in Figure 4.9, therefore it is still difficult to see clearly how the unit cost is affected by the number of bidders. For project types B6, B7, and B8, when the project size is similar, the red dots (more than 7 bidders) and orange triangles (5 to 6 bidders) are located below the green plus signs

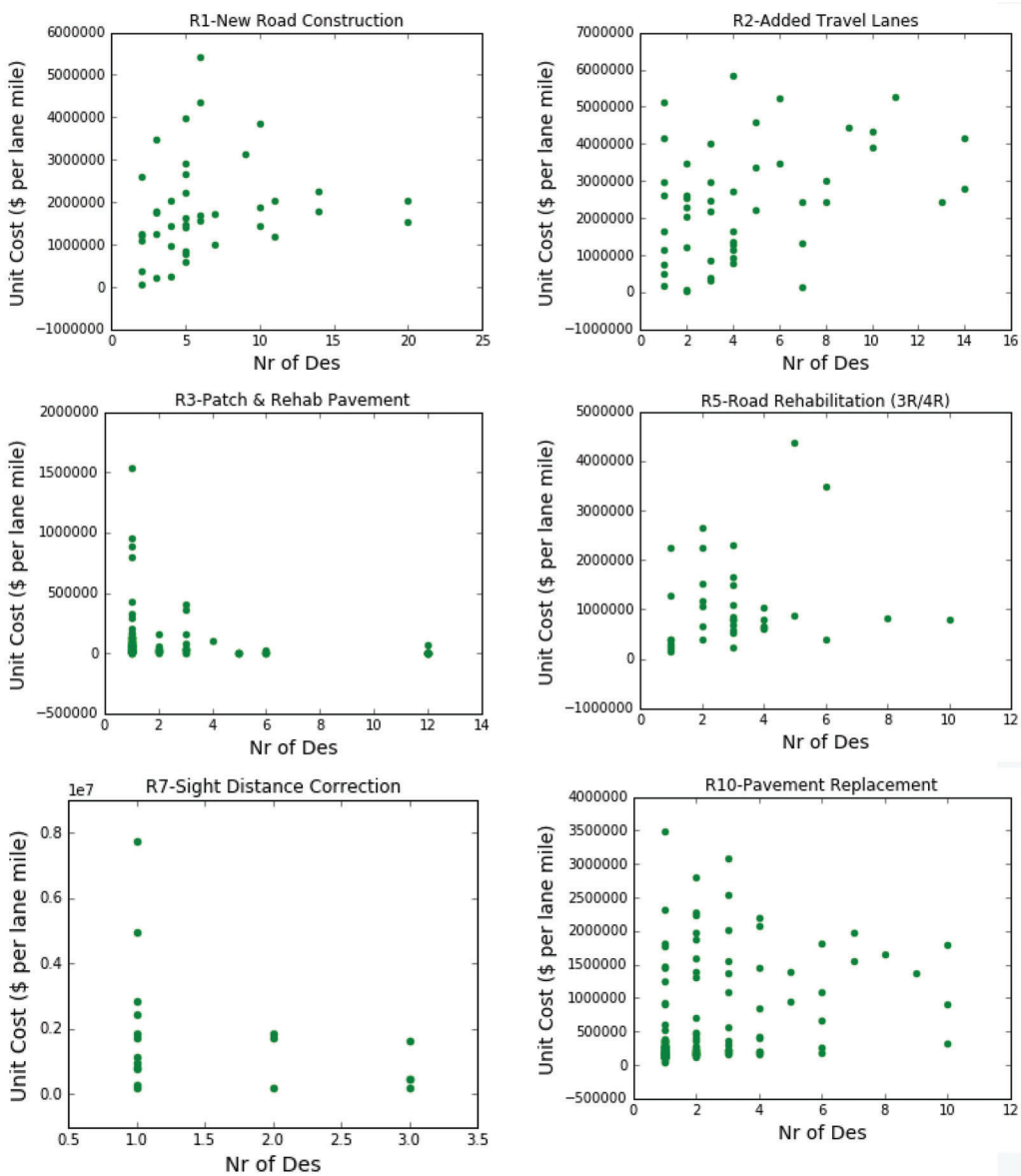


Figure 4.8 Unit cost vs. number of des (economies of bundling) for road work.

(3 to 4 bidders) and the blue stars (1 to 2 bidders). For project types B1 and B2, points with different colors are mixed together. This might be because the effect of economies of bundling is greater than the effect of economies of competition for these project types, so the impact of Nr of Bidders on project unit cost is latent in the 2-D plot where, Nr of Des is not included.

4.2.2 Other Factors

In this section, we use bridge work, because it has the largest sample size and the most reliable project size data (deck area) among all the work categories. The section illustrates how other variables, in addition to the three major factors discussed above, influence project unit cost and unit cost pattern. These factors, as shown in the diagram in Figure 4.2, include road functional classes, letting season and project location. The similarity between projects is also considered as an influential variable on project cost, and its effect is discussed in Section 4.4. The maintenance of traffic (MOT) cost is a important component of project cost, which is analyzed in Section 4.5.

4.2.2.1 Road Functional Classes. First, the effect of functional classes on the unit cost pattern was investigated for bridge projects on rural and urban roads, as shown in Figure 4.10. It seems that, for bridge replacement, projects on urban roads have slightly higher unit cost than projects in rural areas. For the New Bridge, project type, projects on rural roads have a higher project unit cost. In general, no significant difference is found between the unit cost pattern for bridge projects on rural and urban roads.

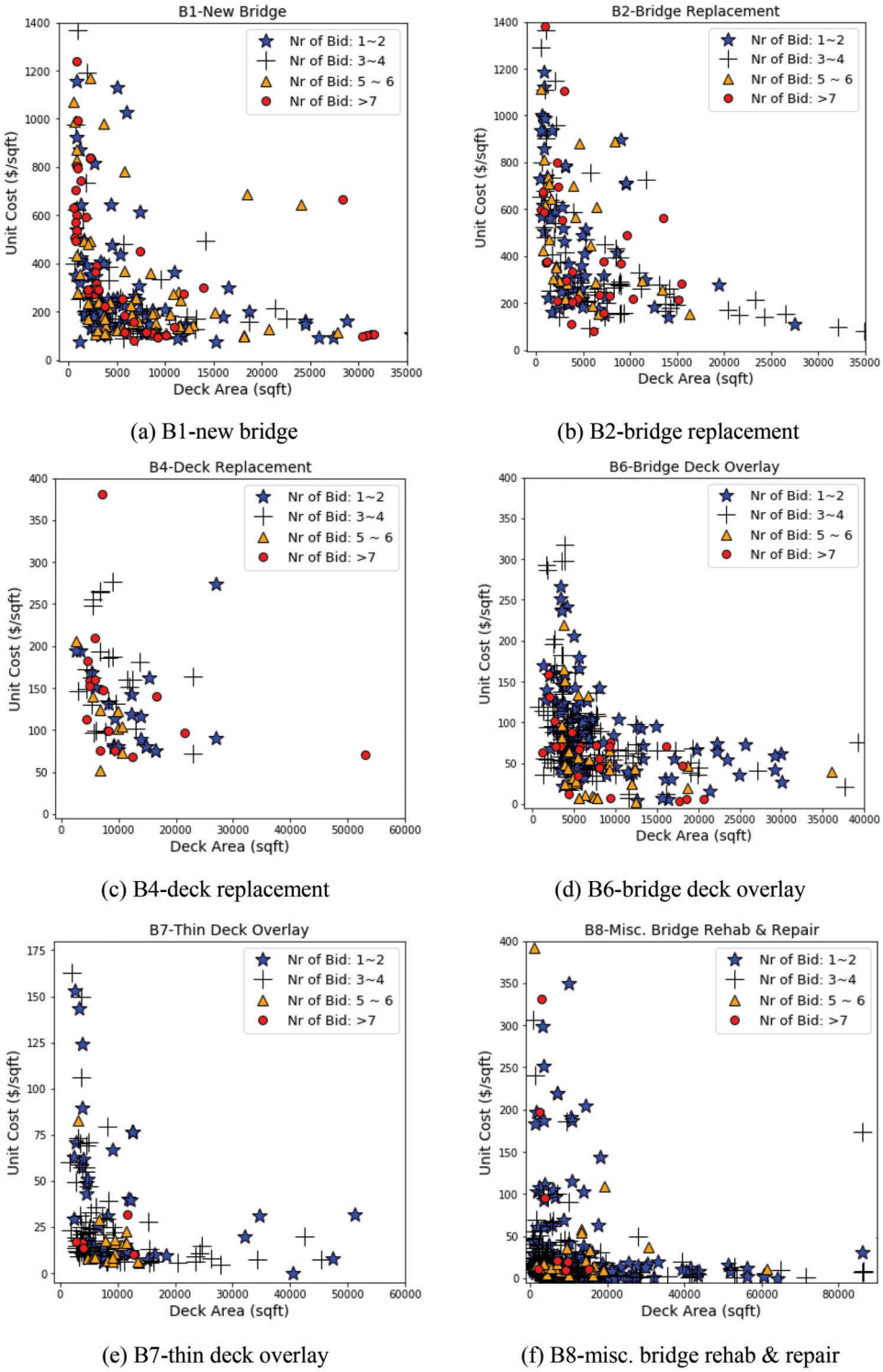


Figure 4.9 Unit cost pattern for bridge projects with different number of bidders (economies of competition).

Similar analysis was carried out for bridge projects on Interstate, US, and state roads, as shown in Figure 4.11. There is no clear difference in unit cost between bridge projects on rural and urban roads, or on different road types (referred to herein as functional classes)—namely, Interstate, US road and state road.

4.2.2.2 Letting Season. This section investigates whether the time of year of letting affects the strategy of bidders, which would affect project unit costs. To begin an analysis of the effects of letting season on project costs, we examined project data for the bridge work with the largest sample size. Plots were made of project unit

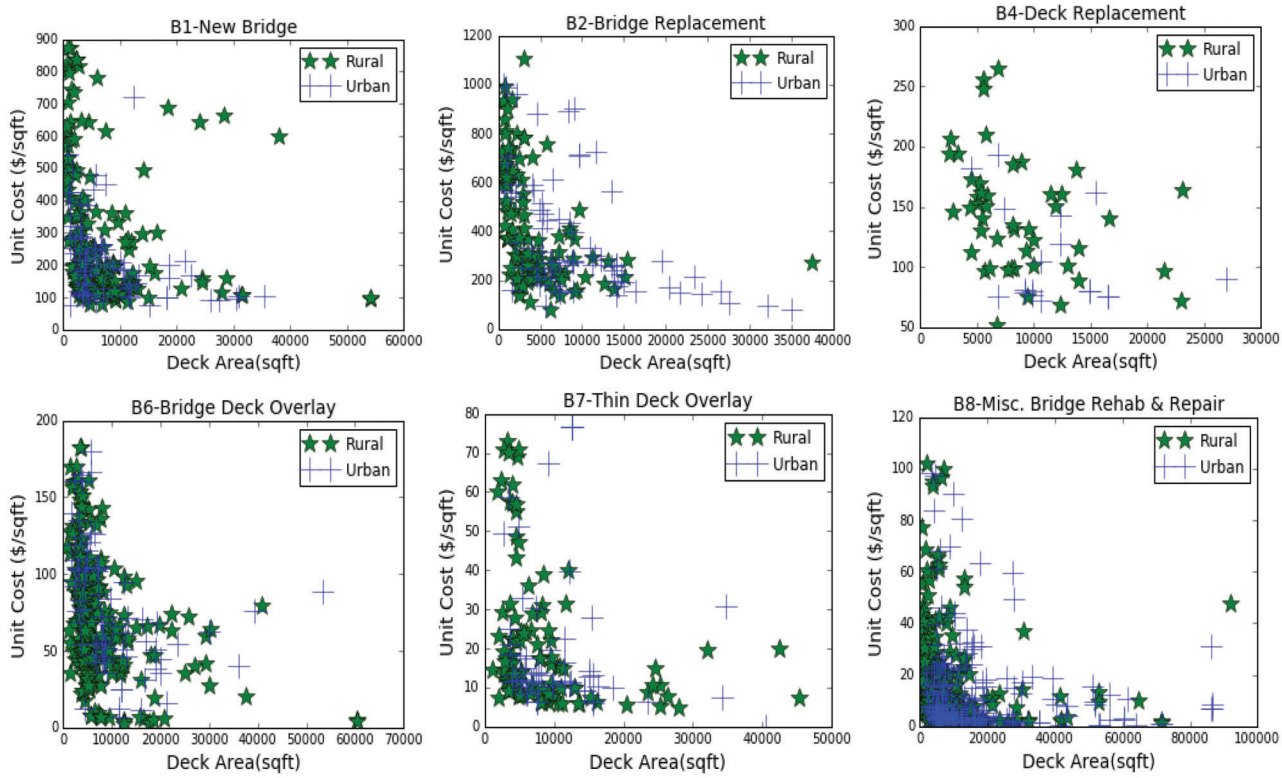


Figure 4.10 Unit cost pattern for contracts on different road types (urban and rural).

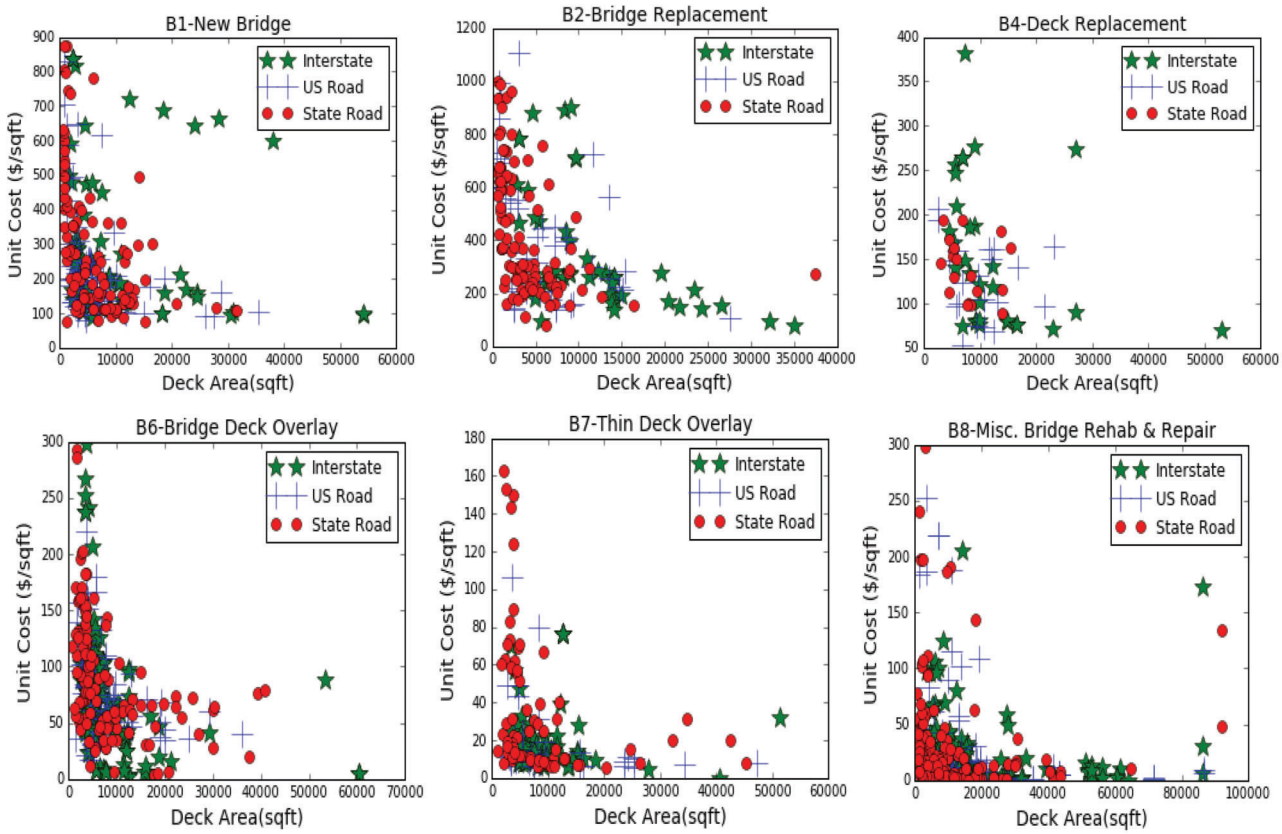


Figure 4.11 Unit cost pattern for projects on different roads (Interstate, US and state).

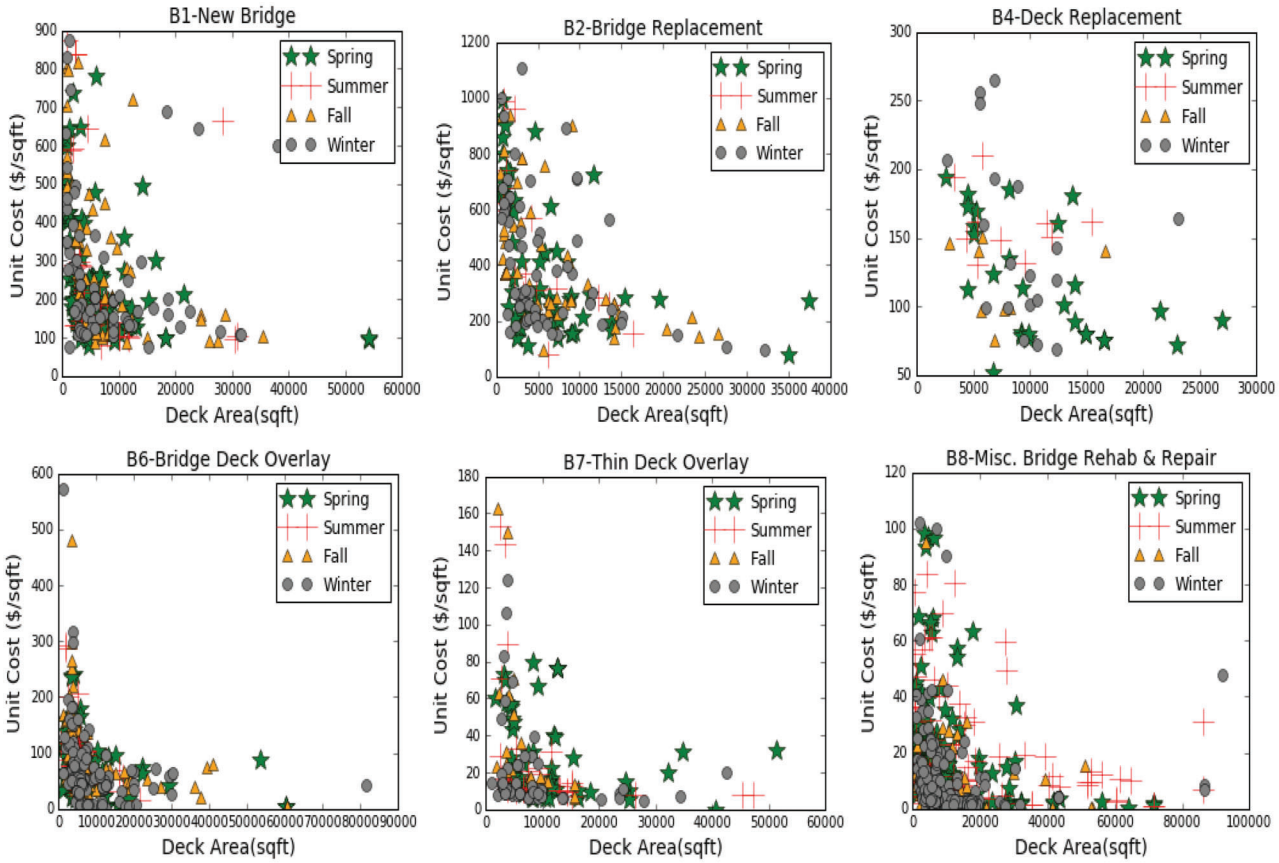


Figure 4.12 Unit cost pattern for projects at different seasons.

cost vs. deck area relationships (unit cost pattern) in terms of four seasons in a calendar year: winter (Jan.-Mar.), spring (Apr.-Jun.), summer (Jul.-Sep.), and fall (Oct.-Dec.). The projects were assigned to seasons based on the letting date information given in the SPMS dataset. The unit cost patterns of projects in different letting seasons are presented in Figure 4.12 for several bridge project types. It was found that, for project B8, the unit cost of projects that are let in spring and summer is higher compared to projects let in fall and winter. For other project types, the scatter plots suggest that there is no evidence that the unit cost in a certain season is different from that of the others.

4.2.2.3 Project Location. As shown in Section 3.2.7, projects are located in INDOT's six highway districts. Seymour and Vincennes Districts are in the southern region, Crawfordsville and Greenfield are in the central region, and Fort Wayne and LaPorte are in the northern region. The unit cost pattern for bridge work in the three different regions are shown in Figure 4.13. For New Bridge, Bridge Replacement and Deck Replacement projects, no clear difference was found between the unit cost patterns of projects located in different regions. However, for Deck Replacement, Bridge Deck Overlay, Thin Deck Overlay, when the deck area is relatively small, the projects in northern or central districts have somewhat higher unit cost than projects in southern districts.

4.3 Relationship between Market Competition and Contract Size

As discussed previously, contract size and number of bidders affect project unit cost simultaneously and interactively. An increase in contract size (measured in terms of the number of the des or the contract price) leads to lower market competition (decreased number of bidders). Therefore an investigation into the relation between number of bidders and contract size is a necessary prerequisite to the development of the cost model in Chapter 5.

4.3.1 Relation between Number of Bidders and Contract Price

First, the relationship between the number of bidders and contract price for each work category is presented in Figure 4.14. The figures show that the number of bidders generally decreases as the contract cost increases; this indicates that a more expensive contract leads to lower market competition. Also, it was found that, when the contract award amount is very small, the variation of the number of bidders is very high, ranging between

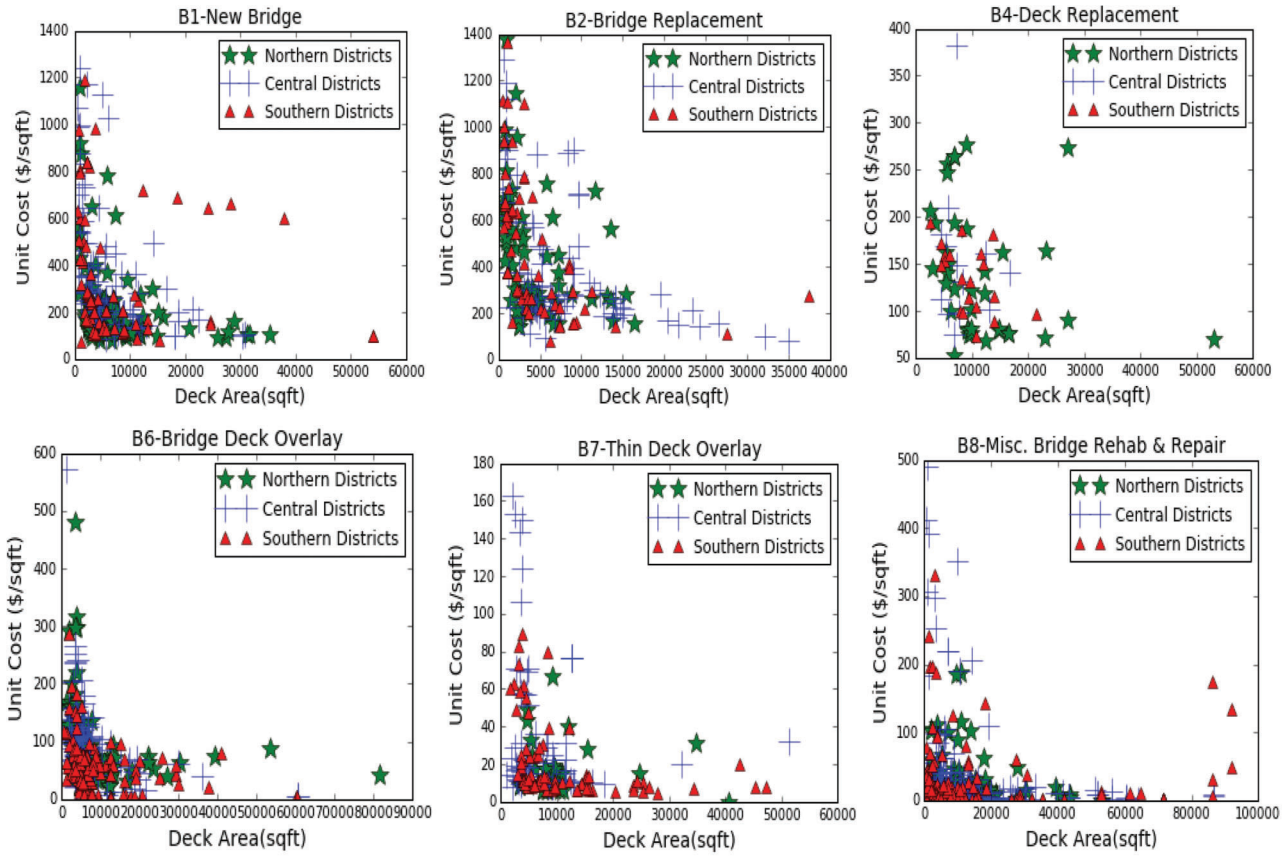


Figure 4.13 Unit Cost pattern for bridge projects in different regions of Indiana.

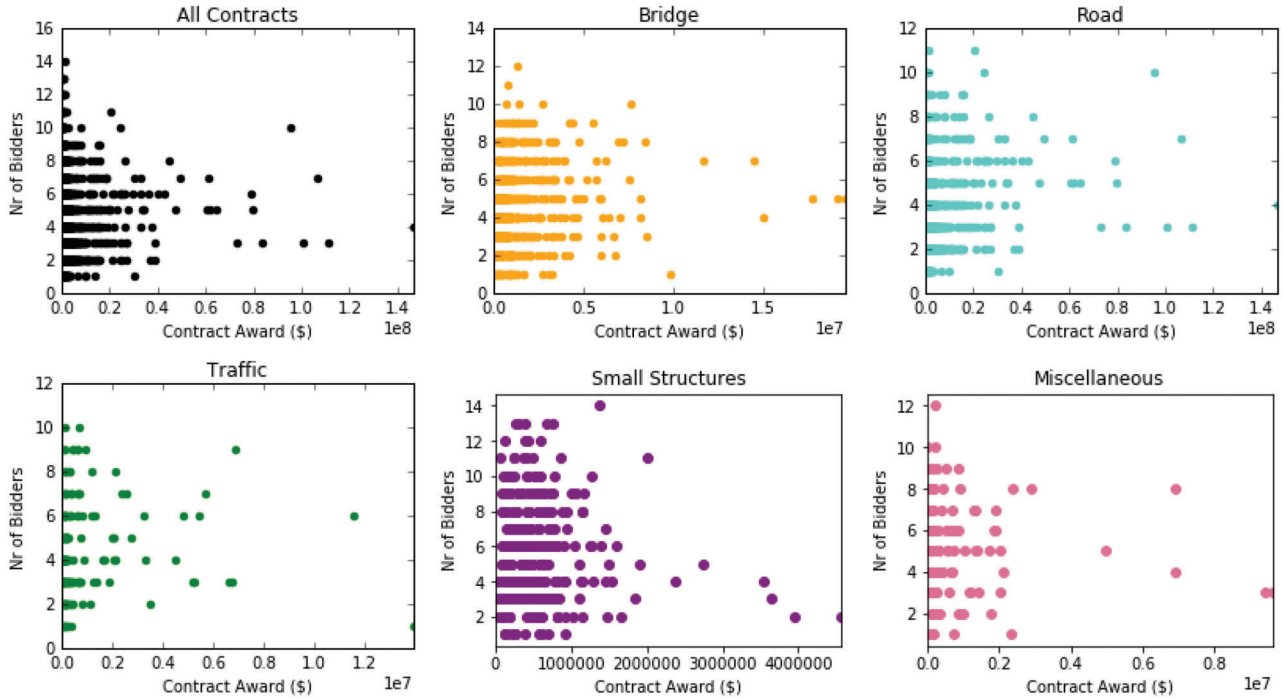


Figure 4.14 Relation between number of bidders with contract price.

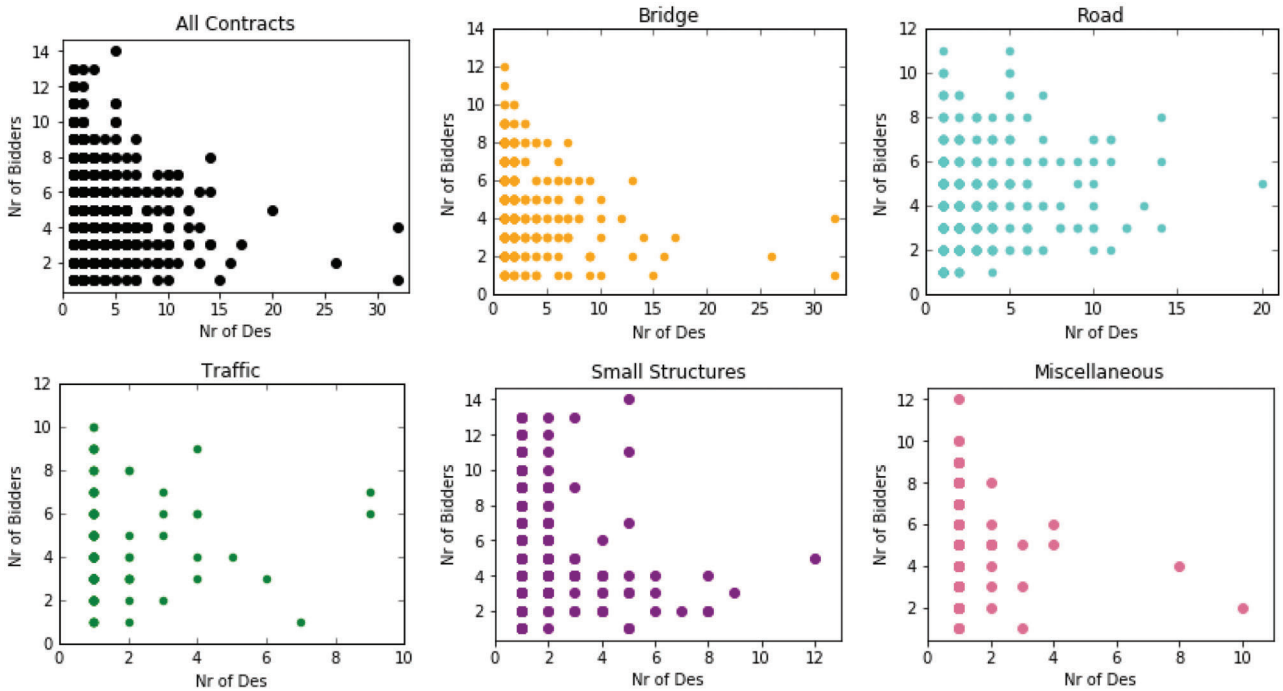


Figure 4.15 Relation between number of bidders with number of des in a contract.

1 bidder and 14 bidders. This means that, although *maximum* number of bidders is generally higher for contracts that are less expensive, the *average* number of bidders is not necessary higher. A very small contract sometimes can be less attractive to contractors compared to a large contract.

4.3.2 Relation between Number of Bidders and Number of Des

Similar analysis was conducted between the number of bidders and number of des in a contract (which is another indicator of contract size), as shown in Figure 4.15. The findings are similar to the relation between the number of bidders and contract award. There is a general decreasing trend and higher variation when the number of des is small. Although Contract Award would be a more accurate measurement of project size (because the number of des does not take project type and cost into account), the number of des measure is more useful in some applications. The contract award is what we want to predict, but it is unavailable until the contract is awarded. The *number of des* variable can be controlled during the planning phase, and it can be used to predict the number of bidders and the project cost before a contract is awarded. This section reveals the relationship between Nr of Bidders and Nr of Des in a contract, and describes models that can predict the number of bidders, given the number of des in a contract.

4.3.2.1 Deterministic Upper Bound Model. An attempt was made to develop a regression model that can predict the average (most likely) number of bidders in a contract. However, no good model was found after trying different combinations of variables and various functional forms. This could be because:

1. The number of bidders in a contract is affected by unknown factors, or at least factors that are not available in the current dataset.
2. The variation of the number of bidders is very high when the number of des is small, as discussed in the previous section. It is therefore difficult to find one general functional form that explains all these variations.
3. Large contracts are sometimes won by large contractors, who then hire smaller firms as subcontractors.

No evident relationship was found between the number of des and the most likely number of bidders in a contract. When the contract size is small, the variation of the number of bidders is large, which means there could be a small number or a large number of bidders. When the contract size becomes large, although the average number of bidders does not change significantly, the highest number of bidders available for a contract is bounded by a smaller number. Therefore, a clear decreasing trend was found between the number of des and the maximum number of bidders. See Figure 4.16. This means that a reasonable estimate of the maximum number of bidders to be expected for a contract can be made.

To capture this relationship, we provide a deterministic upper bound model as an alternative to the standard regression model. The scatter plots on the left side of Figure 4.16 show the actual observations of Nr of Bidders versus Nr of Des in a contract for all the contracts in our dataset. To create the upper bound model,

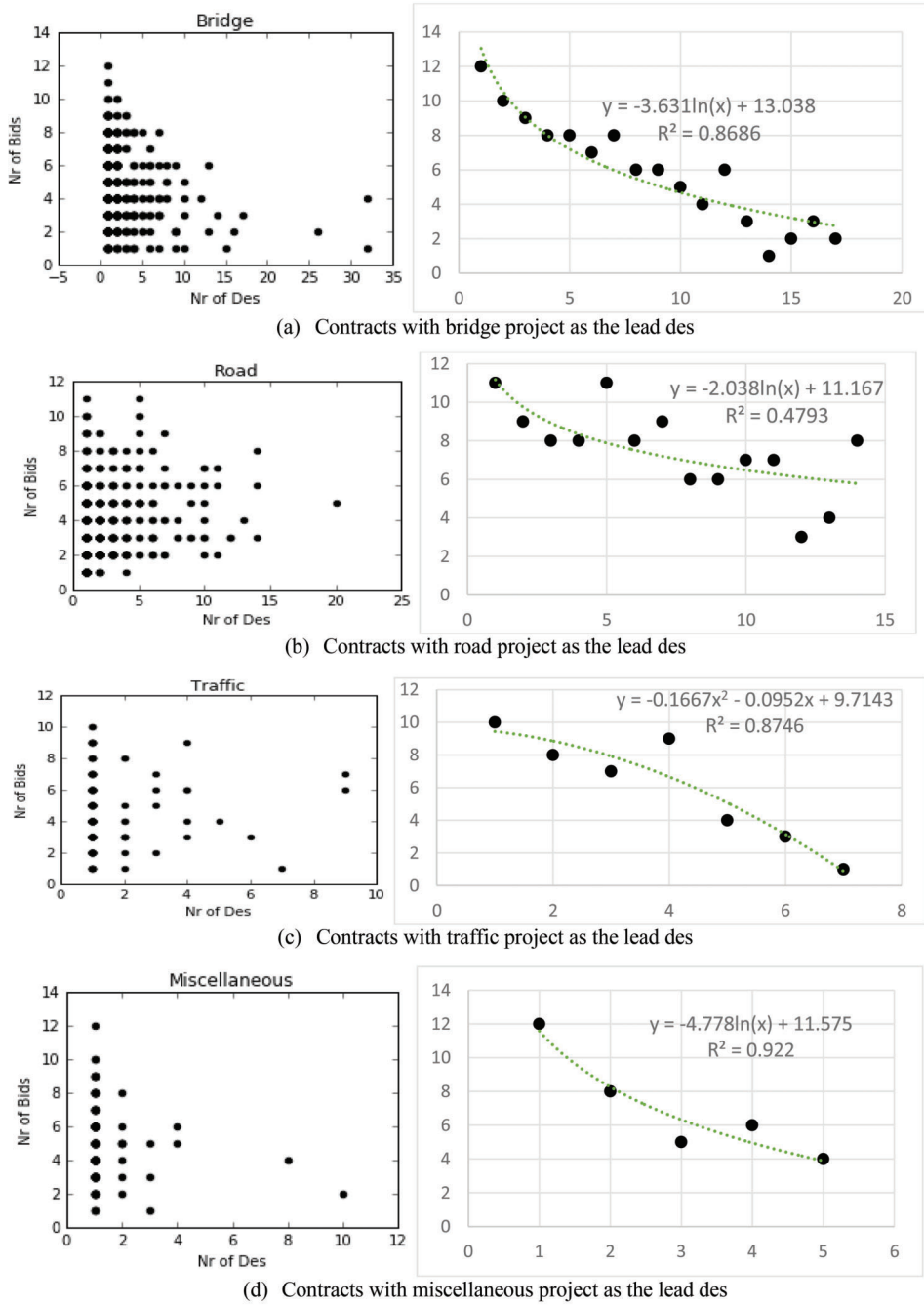


Figure 4.16 Upper-bound model to predict the number of bidders.

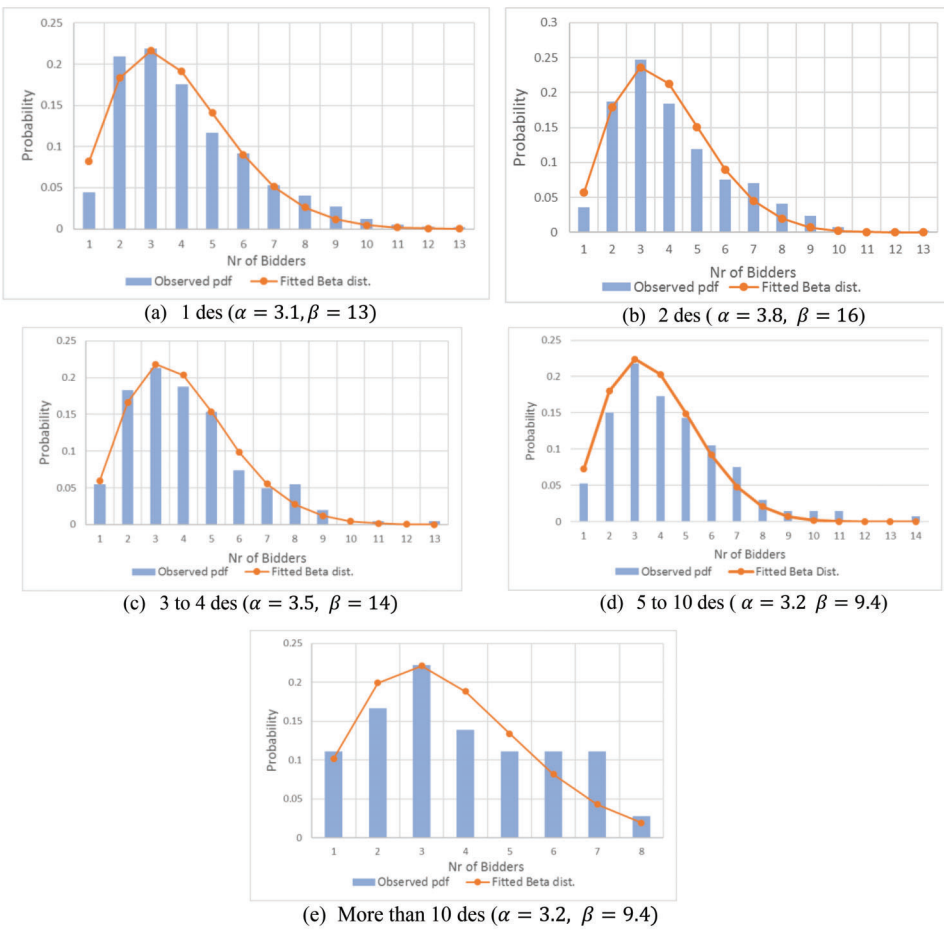
the point with the highest Nr of Bidders under each Nr of Des was selected. A regression curve was then fitted to these selected observations for each work category, as shown in Figures 4.16(a)-(f).

Different functional forms, including linear, polynominal, logarithmic, power and exponential, were tested. The functional form with the highest R^2 was chosen for each work category. These are presented in Table 4.2.

The upper-bound model estimates the maximum number of bidders for a contract with a given number of des, and can be therefore used to predict an approximate lower bound on project unit cost. Because the upper-bound models in Table 4.2 have adequate predictive power, we use them to estimate lower-bound (or "optimistic") costs that allow us to compare the costs of different bundling scenarios on a consistent basis. When estimating the actual cost of a project using the project total cost model developed in Chapter 5, one should use a better estimate of the most likely number of bidders instead of using the maximum number of bidders, if that were ever possible. We return to this issue in Chapter 6.

TABLE 4.2
Developed Upper-Bound Models

Project Type	Model	R^2
Bridge	Nr of Bids = 13.038 – [3.631 * ln(Nr of Des)]	0.869
Road	Nr of Bids = 11.167 – [2.038 * ln(Nr of Des)]	0.479
Traffic	Nr of Bids = 9.7143 – [1.667 * (Nr of Des)^2] – [0.0952 * Nr of Des]	0.875
Small Structure	Nr of Bids = 15.538 – [1.517 * ln(Nr of Des)]	0.664
Miscellaneous	Nr of Bids = 11.575 – [4.778 * ln(Nr of Des)]	0.922
All Contracts	Nr of Bids = 15.710 – [4.037 * ln(Nr of Des)]	0.737



(a) 1 des ($\alpha = 3.1, \beta = 13$)
(b) 2 des ($\alpha = 3.8,\ \beta = 16$)
(c) 3 to 4 des ($\alpha = 3.5,\ \beta = 14$)
(d) 5 to 10 des ($\alpha = 3.2\ \beta = 9.4$)
(e) More than 10 des ($\alpha = 3.2,\ \beta = 9.4$)

Figure 4.17 Distribution of number of bidders for contracts with different numbers of des.

In the meantime, we will use the upper-bound model to estimate maximum expected number of bidders to compute the resulting "optimistic" cost estimates.

4.3.2.2 Probabilistic Model. The upper bound model assumes the highest number of bidders likely for a certain number of des. The model can help in estimating project cost in the best case, because higher market competition can lead to lower unit cost. However, the upper bound model ignores all the variations under the curve. To find the true distribution of the number of bidders for a contract, we created a histogram of Nr of Bidders under a certain Nr of Des. A Beta distribution was then used to fit the actual histograms. (See Figure 4.17.)

The Beta probability distribtion function (pdf) is given in Equation 4.1.

$$f(x,\alpha,\beta) = \frac{1}{B(\alpha,\beta)} * x^{\alpha-1}(1-x)^{\beta-1} \qquad (4.1)$$

where α,β are parameters, x is the number of bidders, and $f(x,\alpha,\beta)$ is the probability that a contract has x number of bidders when the number of des is given.

Parameters α and β were tuned to minimize the difference between the actual histogram and the fitted Beta distribution. The values of α and β that were found to fit the actual histogram with the smallest errror are presented in Table 4.3 for each of several different

TABLE 4.3
Parameters Estimated for fitted Beta Distribution with Different Number Des

Number of Des	α	β
1	3.1	13
2	3.8	16
3 to 4	3.5	14
5 to 10	3.2	9.4
More than 10	2.8	8.8

number of des. The fitted Beta distribution curves are shown in Figure 4.17. Each point on the curve indicates the probability of a contract having a certain number of bidders. For example, in Figure 4.17 (a), the probability of a contract having 1 bidder (that is, a single-project contract) is about 0.08, as indicated by the first point on the curve.

The developed probability curve is an alternative to the upper bound deterministic model, and can be used to estimate the probabilities of having all possible number of bidders for a contract with certain number of des. Unlike the upper bound model, which only considers the maximum number of bidders for a given number of des, in the probabilistic model, the actual data distribution under the maximum number of bidders was also taken into account. This probabilistic model for the number of bidders is used in Chapter 5 to estimate project cost with a certain level of confidence, but is not used in the comparison of various bundling scenarios due to its inconvenience.

4.4 Similarity Analysis

As discussed in Chapter 3, the similarity between the compositions of pay items for different project types can be used to measure the compatibility between projects (i.e., projects that have more pay items in common are generally more compatible). In this section, the composition of pay items for each project type was obtained. Also, the similarity between each pair of project types based on the obtained pay item compositions was quantified using Euclidean distance method.

4.4.1 Composition of Pay Items

The composition of pay items for each project type is calculated as follows:

- For each project (identified by "Des ID"), calculate the average percentage of each pay item in the project by dividing the total cost of each pay item (identified by "Item Sub") by the "Des Award."
- Calculate the average percentage of each pay item for each project type by dividing the sum of the average percentage of the item calculated in the first step for all projects by the number of projects that belong to this project type.

Figure 4.18 summarizes the total number of different pay items that appeared in the dataset for a certain project type (the red bar that is the left-hand bar of each pair of bars), and the number of different pay items that have average percentage of more than 1% (the black, or right-hand bar). It was found that road projects have the highest number of different pay items, followed by bridge work, while traffic and utility work have the lowest number of pay items. Table 4.4 and Table 4.5 show the compositions of pay items that have at least 1% of a bridge or road project.

4.4.2 Distance between Different Project Types

To measure the similarity between projects by comparing the composition of pay items, a pay item composition matrix was built; an excerpt of this is shown in Table 4.6. Each row represents the average percentage of each pay item for a certain project type. For example, for "B1-New Bridge," an average of 0.81% of the total project cost (Des Award) is from Item 105. Based on this matrix, we can calculate the Euclidean distance between each pair of different project types as a measurement of project similarity using the following equation:

$$d(R_i, R_j) = d(R_j, R_i)$$

$$= \sqrt{(R_{i,1} - R_{j,1})^2 + (R_{i,2} - R_{j,2})^2 + \ldots + (R_{i,N} - R_{j,N})^2} \quad (4.2)$$

where:

R_i is the i-th row

R_j is the j-th row in the matrix in Table 4.6.

$d(R_i, R_j)$ represents the Euclidean distance between project type i and project type j.

This Euclidean distance is used to measure the similarity between different project types. The shorter the distance, the higher the similarity between two different project types. We define this distance as "similarity distance." The similarity distances between all the pairs of different project types were calculated using Equation 4.2. Figure 4.19 and Figure 4.20 are some examples for bridge and road projects of the similarity distance between a certain project type with all other project types. It was confirmed that the similarity distance between projects in the same work category is smaller compared to projects in different work categories.

Some interesting findings were found from comparing the similarity distance between different project types from the same category. For example, as shown in Table 4.7 within the bridge work category B1-New Bridge and B2-Bridge Replacement are more similar to each other—with a much smaller similarity distance (0.14)—compared to other project types. B3-Superstructure Replacement and B4-Deck Replacement are found to be the most similar project types, with a distance of 0.074. B6-Bridge Deck Overlay is found to be most similar to B7-Thin Deck Overlay, with a similarity distance of 0.261. The similarity between B8-Misc. Bridge Rehab & Repair and all other bridge projects is high, because this project type itself is a mix of many different project types. If the agency seeks to bundle

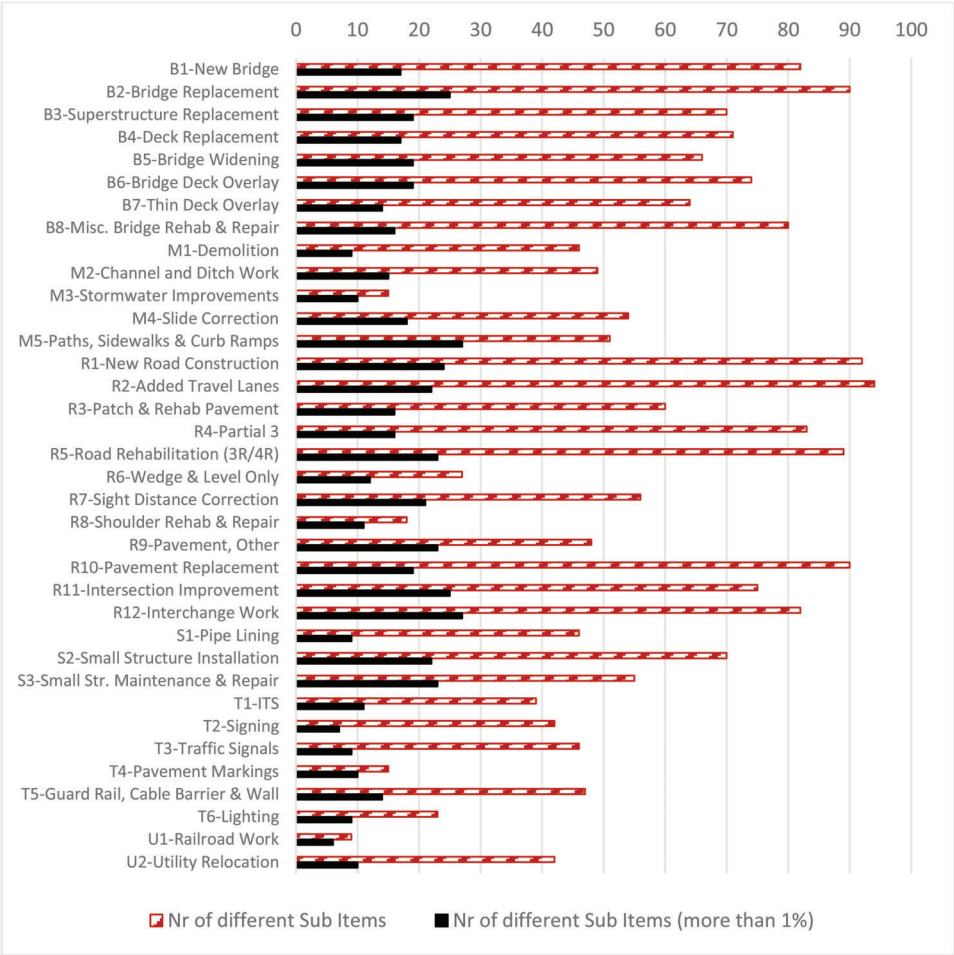


Figure 4.18 Number of different sub items in a des, for different project types.

TABLE 4.4
Compositions of Pay Items (with percentage ≥1%) for Bridge Work

B1-New Bridge		B3-Superstructure Replacement		B4-Deck Replacement		B5-Bridge Widening		B6-Bridge Deck Overlay	
Item Sub	Average Percentage	Item Sub	Average Percentage	Item Sub	Average Percentage	Item Sub	Average Percentage	Item Sub	Average Percentage
707	14.33	704	15.78	704	18.39	704	16.62	722	23.33
704	13.13	202	14.34	202	13.68	202	13.00	202	18.15
723	9.14	703	9.50	703	11.20	711	10.61	801	9.35
703	8.97	711	8.55	711	7.21	703	9.16	609	4.27
211	8.62	707	5.87	801	6.73	702	9.02	703	4.27
701	7.84	801	5.57	110	4.24	701	4.80	110	4.00
731	6.30	702	4.50	401	3.42	706	3.88	706	3.17
702	6.15	110	4.42	706	2.82	110	3.84	704	3.12
110	3.49	402	3.36	619	2.79	619	2.77	401	2.85
203	3.33	706	2.88	402	2.70	609	2.60	601	2.14
711	2.55	609	2.62	609	2.57	722	2.38	616	2.04
616	2.43	601	2.08	702	2.23	801	2.30	709	1.85
706	1.95	401	1.79	601	1.93	206	2.20	724	1.82
609	1.90	207	1.60	207	1.70	707	1.80	628	1.74
714	1.83	628	1.49	616	1.29	616	1.43	738	1.52
202	1.27	616	1.29	709	1.13	201	1.29	619	1.48
707	14.33	203	1.25	628	1.13	211	1.27	710	1.34
		502	1.20			402	1.24	702	1.29
		713	1.02			601	1.05		
		704	15.78						

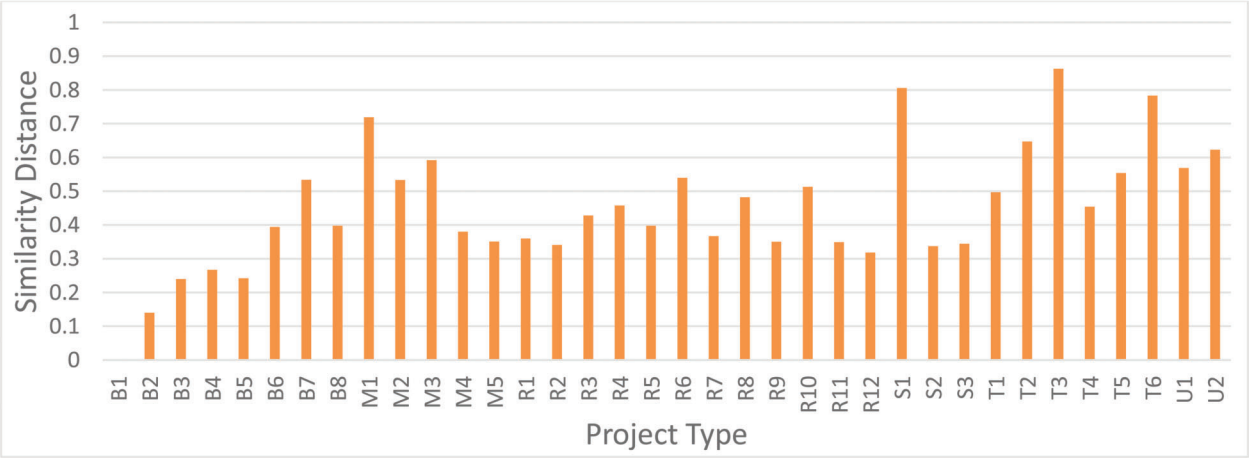
TABLE 4.5
Compositions of Pay Items (with percentage ≥1%) for Road Work

R1-New Road Construction		R4-Partial 3		R5-Road Rehabilitation (R3/R4)		R10-Pavement Replacement		R11-Intersection Improvement	
Item Sub	Average Percentage	Item Sub	Average Percentage	Item Sub	Average Percentage	Item Sub	Average Percentage	Item Sub	Average Percentage
203	21.35	401	33.20	401	28.13	401	42.65	401	15.45
401	13.28	304	9.56	203	7.58	801	5.33	402	7.99
501	8.59	801	6.37	715	6.27	304	4.79	207	7.64
110	5.42	306	5.25	801	4.72	110	4.71	203	7.10
211	3.65	411	4.81	110	4.57	610	3.88	801	6.73
207	3.55	110	4.60	207	4.33	306	3.34	805	6.05
715	3.42	506	4.12	402	3.39	715	2.86	110	5.10
201	2.78	808	3.81	610	2.42	207	2.52	715	4.78
205	2.67	414	3.61	720	2.36	203	2.29	610	3.01
302	2.65	610	3.20	202	2.26	506	2.15	720	2.62
714	2.57	402	2.72	714	2.10	601	1.82	605	2.53
105	2.18	410	2.31	604	1.85	303	1.74	105	2.26
202	2.17	604	2.02	301	1.75	402	1.59	202	1.97
801	2.04	303	1.29	306	1.71	202	1.56	301	1.96
621	1.74	628	1.26	304	1.67	808	1.55	628	1.95
503	1.70	805	1.22	718	1.63	604	1.54	506	1.93
303	1.67			211	1.58	720	1.33	621	1.81
301	1.61			605	1.44	501	1.12	808	1.77
731	1.61			201	1.42	605	1.05	304	1.71
402	1.57			616	1.35			201	1.65
215	1.42			621	1.28			211	1.59
718	1.36			105	1.25			604	1.31
616	1.34			601	1.19			306	1.20
601	1.00							303	1.17
								205	1.00

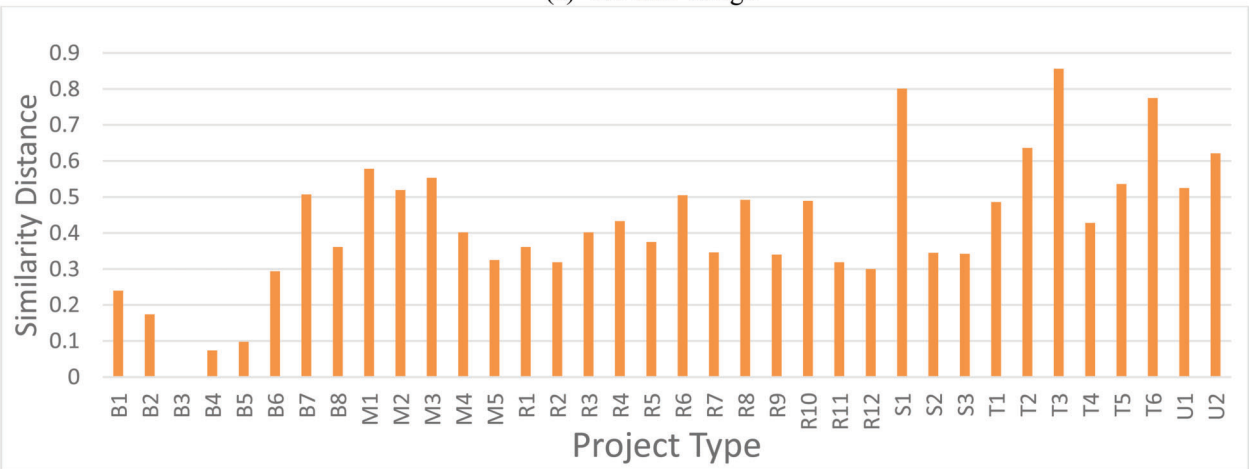
TABLE 4.6
Sample of Pay Item Composition Matrix

Project Type	105 (%)	107 (%)	108 (%)	109 (%)	110 (%)	111 (%)	113 (%)	201 (%)	……	809 (%)
B1	0.81	0.00	0.00	0.00	3.49	0.00	0.01	0.40	……	0.00
B2	1.02	0.00	0.00	0.00	5.31	0.00	0.00	1.26	……	0.00
B3	0.56	0.00	0.00	0.00	4.42	0.00	0.00	0.57	……	0.00
B4	0.79	0.00	0.00	0.00	4.24	0.00	0.00	0.59	……	0.00
B5	0.78	0.00	0.00	0.00	3.84	0.00	0.00	1.29	……	0.00
B6	0.74	0.00	0.00	0.00	4.00	0.00	0.01	0.76	……	0.04
B7	0.95	0.00	0.00	0.00	4.03	0.00	0.00	0.53	……	0.09
B8	0.82	0.00	0.01	0.00	5.66	0.00	0.00	1.37	……	0.01
R1	2.18	0.01	0.02	0.00	5.42	0.01	0.06	2.78	……	0.00
R2	1.47	0.17	0.01	0.00	5.71	0.00	0.04	1.85	……	0.00
R3	1.28	0.06	0.00	0.06	4.18	0.00	0.00	0.06	……	0.00
R4	0.66	0.00	0.00	0.01	4.60	0.00	0.00	0.04	……	0.00
R5	1.25	0.01	0.03	0.00	4.57	0.02	0.03	1.42	……	0.00
R6	1.09	0.00	0.00	0.00	4.14	0.00	0.00	0.00	……	0.00
R7	2.91	0.00	0.00	0.00	4.59	0.00	0.12	1.77	……	0.00
R8	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	……	0.00
R9	1.23	0.00	0.00	0.00	4.42	0.00	0.00	0.45	……	0.01
……										
U2	0.003	0	0	9E-06	0.051	0	0	0.003	……	0.00%

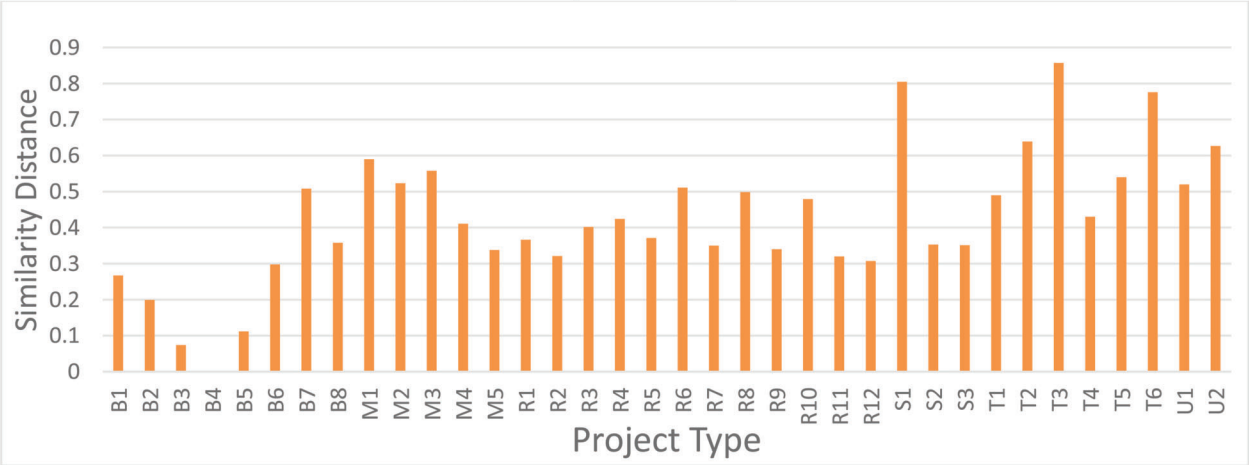
these project types into different categories based on the similarity distance, B1, B2, B3, B4, and B5 could be placed into one bundle (with all paired similarity distances ≤0.267), while B6, B7, and B8 can be placed in another bundle (with all paired similarity distance ≤0.351).



(a) B1-new bridge

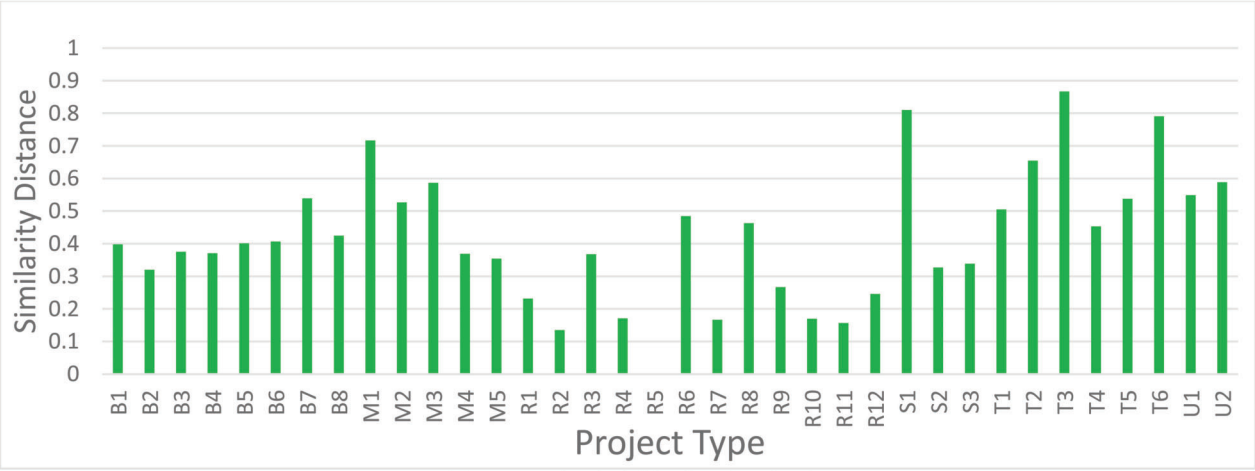


(b) B3-superstructure replacement

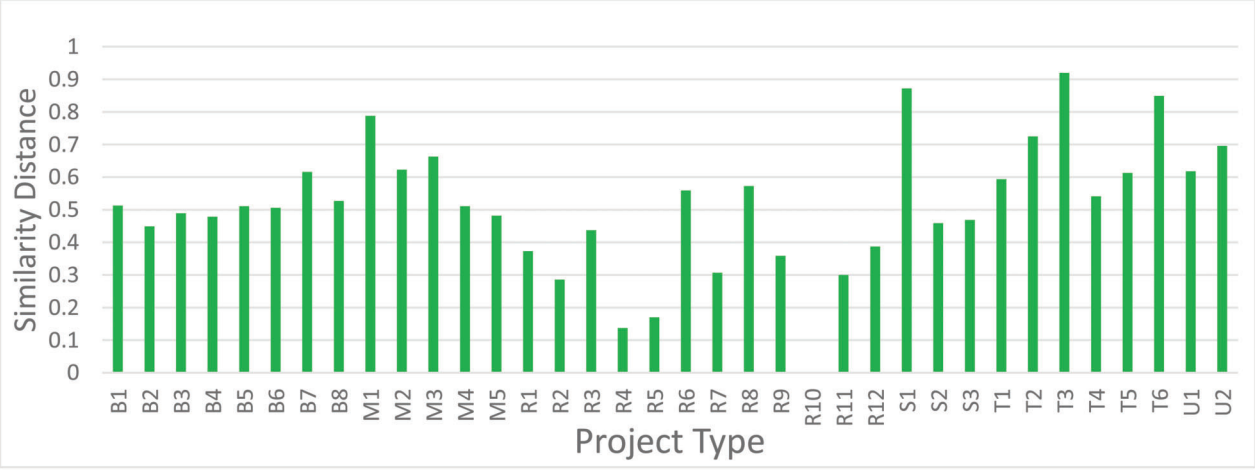


(c) B4-deck replacement

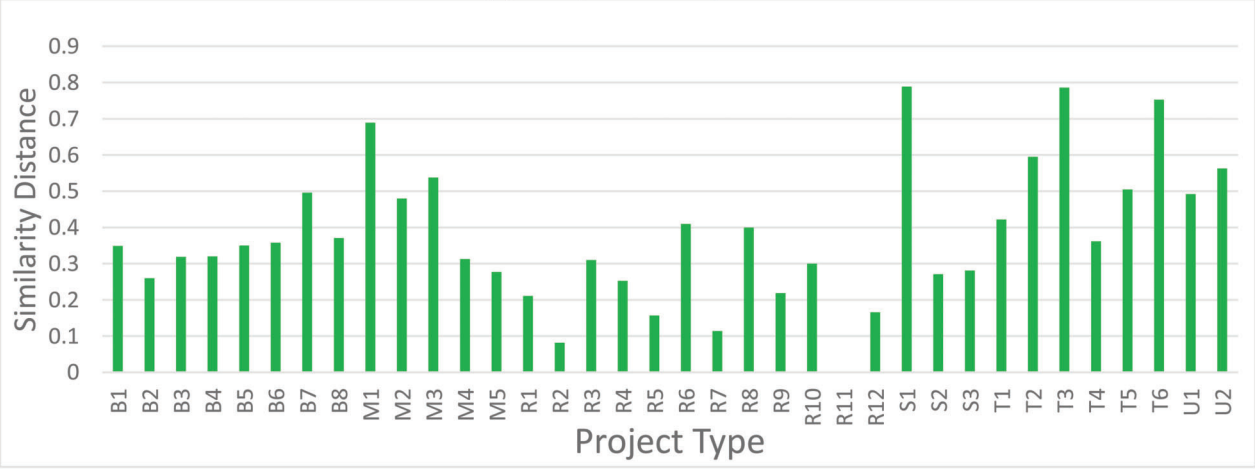
Figure 4.19 Distance between project types for bridge work.



(a) R5-road rehabilitation (R3/R4)



(b) R10-pavement replacement



(c) R11-interchange improvement

Figure 4.20 Distance between project types for road work.

TABLE 4.7
Similarity Distance Matrix, Bridge Work Category

Project Type	B1	B2	B3	B4	B5	B6	B7	B8
B1	0	0.14	0.24	0.267	0.242	0.394	0.534	0.398
B2	0.14	0	0.174	0.199	0.189	0.315	0.492	0.342
B3	0.24	0.174	0	0.074	0.098	0.294	0.507	0.361
B4	0.267	0.199	0.074	0	0.112	0.298	0.508	0.358
B5	0.242	0.189	0.098	0.112	0	0.305	0.517	0.362
B6	0.394	0.315	0.294	0.298	0.305	0	0.261	0.351
B7	0.534	0.492	0.507	0.508	0.517	0.261	0	0.476
B8	0.398	0.342	0.361	0.358	0.362	0.351	0.476	0

TABLE 4.8
Similarity Distance Matrix, Road Work Category

Project Type	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12
R1	0	0.183	0.396	0.348	0.232	0.515	0.191	0.367	0.27	0.373	0.211	0.156
R2	0.183	0	0.336	0.253	0.135	0.438	0.133	0.42	0.219	0.286	0.082	0.136
R3	0.396	0.336	0	0.34	0.368	0.439	0.357	0.393	0.283	0.437	0.31	0.34
R4	0.348	0.253	0.34	0	0.171	0.49	0.276	0.506	0.279	0.137	0.253	0.34
R5	0.232	0.135	0.368	0.171	0	0.485	0.167	0.463	0.267	0.17	0.157	0.246
R6	0.515	0.438	0.439	0.49	0.485	0	0.386	0.498	0.451	0.559	0.41	0.451
R7	0.191	0.133	0.357	0.276	0.167	0.386	0	0.383	0.264	0.307	0.114	0.199
R8	0.367	0.42	0.393	0.506	0.463	0.498	0.383	0	0.417	0.573	0.4	0.396
R9	0.27	0.219	0.283	0.279	0.267	0.451	0.264	0.417	0	0.359	0.219	0.211
R10	0.373	0.286	0.437	0.137	0.17	0.559	0.307	0.573	0.359	0	0.3	0.387
R11	0.211	0.082	0.31	0.253	0.157	0.41	0.114	0.4	0.219	0.3	0	0.166
R12	0.156	0.136	0.34	0.34	0.246	0.451	0.199	0.396	0.211	0.387	0.166	0

Within the road project work category (Table 4.8), R1-New Road Construction is found to be most similar to R2-Added Travel Lane (a distance of 0.183). R4-Partial 3 and R5-Road Rehabilitation (3R/4R) are most similar to each other, with a distance of 0.171. The similarity between R2-Added Travel Lane, R11-Interchange Work and R12-Interchange Improvement was also found to be very high.

The full similarity distance matrix is presented as Figure 4.21. In Chapter 5, the similarity distance is subsequently used as a possible explanatory variable when developing the project cost regression models, to account for the effect of project similarity on the cost of a contract consisting of multiple projects.

4.5 Maintenance of Traffic (MOT) Cost Analysis

4.5.1 Average MOT Cost Ratio Comparison

MOT can be a major component of project cost. For some project types, MOT as a percentage of the total project cost (Des Award) is very high (e.g., 23.7% for thin deck overlay in Table 4.6). The MOT-related pay items are listed in Section 3.2.8.3. The average MOT Cost and MOT cost ratio (MOT cost/Des Award) are presented for each work category in Table 4.9. It was found that road work, on average, has a much higher MOT cost than projects in other work categories; however, bridge work is associated with the highest MOT cost ratio (12.27% on average).

The average cost approach was then used to calculate the average MOT cost and MOT cost ratio for single and bundled project for each project type, as shown in Table 4.10. For all road projects, small structure, and most traffic work, reduction in the average MOT cost ratio occurred when projects are bundled into a contract. For bridge work, the benefits of project bundling on MOT cost saving were found for new bridge, bridge replacement, deck replacement and bridge deck overlay. For most miscellaneous work (except M5-Paths, Sidewalks & Curb Ramps), a higher MOT cost ratio was found for the bundled projects.

Road and traffic work seem to benefit the most from project bundling in terms of MOT cost saving. As shown in Figures 4.22 and 4.23, for road work, reduction in the MOT cost ratio due to project bundling was found to be most significant for R2-Added Travel Lanes, R6-Wedge & Level Only, and R12-Interchange Work. For traffic work, T4-Pavement Marking is associated with the highest reduction—a 21.55% decrease in the MOT cost ratio by bundling projects.

Project Type	B1	B2	B3	B4	B5	B6	B7	B8	M1	M2	M3	M4	M5	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	S1	S2	S3	T1	T2	T3	T4	T5	T6	U1	U2
B1	0	0.14	0.24	0.267	0.242	0.394	0.534	0.398	0.719	0.533	0.592	0.38	0.351	0.36	0.341	0.428	0.458	0.398	0.54	0.367	0.482	0.35	0.513	0.349	0.318	0.806	0.337	0.344	0.497	0.647	0.863	0.454	0.554	0.783	0.569	0.623
B2	0.14	0	0.174	0.199	0.189	0.315	0.492	0.342	0.635	0.483	0.547	0.325	0.287	0.285	0.257	0.37	0.392	0.32	0.484	0.279	0.436	0.285	0.449	0.26	0.236	0.783	0.265	0.275	0.458	0.616	0.841	0.401	0.509	0.757	0.513	0.593
B3	0.24	0.174	0	0.074	0.098	0.294	0.507	0.361	0.578	0.519	0.553	0.402	0.325	0.361	0.319	0.402	0.433	0.375	0.505	0.346	0.492	0.34	0.489	0.319	0.3	0.801	0.345	0.342	0.486	0.636	0.856	0.428	0.536	0.775	0.525	0.621
B4	0.267	0.199	0.074	0	0.112	0.298	0.508	0.358	0.59	0.523	0.558	0.411	0.338	0.366	0.321	0.402	0.424	0.371	0.511	0.35	0.499	0.34	0.479	0.32	0.307	0.805	0.353	0.351	0.49	0.639	0.857	0.43	0.54	0.776	0.52	0.627
B5	0.242	0.189	0.098	0.112	0	0.305	0.517	0.362	0.6	0.526	0.564	0.419	0.331	0.381	0.347	0.424	0.456	0.401	0.536	0.377	0.507	0.353	0.511	0.35	0.326	0.806	0.365	0.358	0.495	0.642	0.861	0.448	0.55	0.78	0.557	0.63
B6	0.394	0.315	0.294	0.298	0.305	0	0.261	0.351	0.558	0.539	0.566	0.436	0.378	0.399	0.358	0.429	0.454	0.407	0.545	0.388	0.528	0.326	0.506	0.358	0.341	0.818	0.381	0.381	0.513	0.656	0.872	0.448	0.559	0.792	0.524	0.649
B7	0.534	0.492	0.507	0.508	0.517	0.261	0	0.476	0.789	0.629	0.684	0.552	0.516	0.532	0.499	0.537	0.566	0.539	0.638	0.525	0.628	0.484	0.616	0.496	0.484	0.882	0.519	0.516	0.608	0.738	0.934	0.542	0.655	0.86	0.585	0.735
B8	0.398	0.342	0.361	0.358	0.362	0.351	0.476	0	0.714	0.52	0.598	0.401	0.382	0.409	0.374	0.427	0.468	0.425	0.55	0.401	0.524	0.365	0.527	0.371	0.352	0.812	0.39	0.379	0.508	0.658	0.872	0.438	0.565	0.791	0.504	0.651
M1	0.719	0.635	0.578	0.59	0.6	0.558	0.789	0.714	0	0.775	0.739	0.741	0.678	0.703	0.687	0.741	0.761	0.717	0.819	0.7	0.795	0.71	0.788	0.689	0.674	1.011	0.682	0.688	0.786	0.874	1.049	0.755	0.812	0.983	0.822	0.866
M2	0.533	0.483	0.519	0.523	0.526	0.539	0.629	0.52	0.775	0	0.695	0.495	0.484	0.488	0.479	0.55	0.581	0.527	0.647	0.5	0.609	0.503	0.623	0.48	0.465	0.842	0.498	0.488	0.608	0.742	0.937	0.552	0.655	0.86	0.6	0.709
M3	0.592	0.547	0.553	0.558	0.564	0.566	0.684	0.598	0.739	0.695	0	0.616	0.479	0.588	0.545	0.562	0.616	0.587	0.686	0.578	0.629	0.556	0.663	0.538	0.544	0.92	0.577	0.576	0.663	0.779	0.964	0.619	0.671	0.894	0.692	0.768
M4	0.38	0.325	0.402	0.411	0.419	0.436	0.552	0.401	0.741	0.495	0.616	0	0.361	0.225	0.314	0.44	0.468	0.369	0.532	0.288	0.347	0.369	0.511	0.313	0.271	0.816	0.341	0.349	0.518	0.671	0.88	0.468	0.559	0.799	0.554	0.639
M5	0.351	0.287	0.325	0.338	0.331	0.378	0.516	0.382	0.678	0.484	0.479	0.361	0	0.321	0.288	0.396	0.423	0.354	0.521	0.322	0.442	0.317	0.482	0.277	0.276	0.795	0.334	0.334	0.43	0.589	0.798	0.396	0.524	0.749	0.544	0.599
R1	0.36	0.285	0.361	0.366	0.381	0.399	0.532	0.409	0.703	0.488	0.588	0.225	0.321	0	0.183	0.396	0.348	0.232	0.515	0.191	0.367	0.27	0.373	0.211	0.156	0.805	0.299	0.317	0.486	0.642	0.857	0.443	0.529	0.775	0.555	0.598
R2	0.341	0.257	0.319	0.321	0.347	0.358	0.499	0.374	0.687	0.479	0.545	0.314	0.288	0.183	0	0.336	0.253	0.135	0.438	0.133	0.42	0.219	0.286	0.082	0.136	0.788	0.27	0.28	0.44	0.594	0.821	0.385	0.505	0.757	0.503	0.537
R3	0.428	0.37	0.402	0.402	0.424	0.429	0.537	0.427	0.741	0.55	0.562	0.44	0.396	0.396	0.336	0	0.34	0.368	0.439	0.357	0.393	0.283	0.437	0.31	0.34	0.819	0.391	0.389	0.511	0.66	0.867	0.417	0.567	0.793	0.487	0.651
R4	0.458	0.392	0.433	0.424	0.456	0.454	0.566	0.468	0.761	0.581	0.616	0.468	0.423	0.348	0.253	0.34	0	0.171	0.49	0.276	0.506	0.279	0.137	0.253	0.34	0.839	0.409	0.415	0.54	0.68	0.881	0.466	0.576	0.813	0.551	0.674
R5	0.398	0.32	0.375	0.371	0.401	0.407	0.539	0.425	0.717	0.527	0.587	0.369	0.354	0.232	0.135	0.368	0.171	0	0.485	0.167	0.463	0.267	0.17	0.157	0.246	0.81	0.327	0.339	0.505	0.655	0.867	0.453	0.538	0.791	0.549	0.589
R6	0.54	0.484	0.505	0.511	0.536	0.545	0.638	0.55	0.819	0.647	0.686	0.532	0.521	0.515	0.438	0.439	0.49	0.485	0	0.386	0.498	0.451	0.559	0.41	0.451	0.889	0.479	0.477	0.618	0.744	0.936	0.546	0.658	0.865	0.602	0.736
R7	0.367	0.279	0.346	0.35	0.377	0.388	0.525	0.401	0.7	0.5	0.578	0.288	0.322	0.191	0.133	0.357	0.276	0.167	0.386	0	0.383	0.264	0.307	0.114	0.199	0.803	0.283	0.299	0.484	0.638	0.851	0.432	0.526	0.778	0.542	0.603
R8	0.482	0.436	0.492	0.499	0.507	0.528	0.628	0.524	0.795	0.609	0.629	0.347	0.442	0.367	0.42	0.393	0.506	0.463	0.498	0.383	0	0.417	0.573	0.4	0.396	0.868	0.446	0.46	0.589	0.725	0.921	0.54	0.63	0.842	0.629	0.706
R9	0.35	0.285	0.34	0.34	0.353	0.326	0.484	0.365	0.71	0.503	0.556	0.369	0.317	0.27	0.219	0.283	0.279	0.267	0.451	0.264	0.417	0	0.359	0.219	0.211	0.79	0.316	0.32	0.438	0.61	0.811	0.375	0.519	0.751	0.49	0.609
R10	0.513	0.449	0.489	0.479	0.511	0.506	0.616	0.527	0.788	0.623	0.663	0.511	0.482	0.373	0.286	0.437	0.137	0.17	0.559	0.307	0.573	0.359	0	0.3	0.387	0.872	0.459	0.469	0.594	0.725	0.92	0.541	0.613	0.849	0.618	0.696
R11	0.349	0.26	0.319	0.32	0.35	0.358	0.496	0.371	0.689	0.48	0.538	0.313	0.277	0.211	0.082	0.31	0.253	0.157	0.41	0.114	0.4	0.219	0.3	0	0.166	0.789	0.271	0.281	0.422	0.595	0.786	0.362	0.505	0.753	0.492	0.563
R12	0.318	0.236	0.3	0.307	0.326	0.341	0.484	0.352	0.674	0.465	0.544	0.271	0.276	0.156	0.136	0.34	0.34	0.246	0.451	0.199	0.396	0.211	0.387	0.166	0	0.781	0.263	0.271	0.428	0.593	0.819	0.366	0.499	0.74	0.473	0.565
S1	0.806	0.783	0.801	0.805	0.806	0.818	0.882	0.812	1.011	0.842	0.92	0.816	0.795	0.805	0.788	0.819	0.839	0.81	0.889	0.803	0.868	0.79	0.872	0.789	0.781	0	0.789	0.739	0.86	0.956	1.113	0.832	0.895	1.044	0.891	0.93
S2	0.337	0.265	0.345	0.353	0.365	0.381	0.519	0.39	0.682	0.498	0.577	0.341	0.334	0.299	0.27	0.391	0.409	0.327	0.479	0.283	0.446	0.316	0.459	0.271	0.263	0.789	0	0.08	0.484	0.639	0.858	0.429	0.527	0.777	0.526	0.585
S3	0.344	0.275	0.342	0.351	0.358	0.381	0.516	0.379	0.688	0.488	0.576	0.349	0.334	0.317	0.28	0.389	0.415	0.339	0.477	0.299	0.46	0.32	0.469	0.281	0.271	0.739	0.08	0	0.482	0.637	0.855	0.421	0.528	0.774	0.515	0.588
T1	0.497	0.458	0.486	0.49	0.495	0.513	0.608	0.508	0.786	0.608	0.663	0.518	0.43	0.486	0.44	0.511	0.54	0.505	0.618	0.484	0.589	0.438	0.594	0.422	0.428	0.86	0.484	0.482	0	0.466	0.599	0.384	0.624	0.685	0.617	0.675
T2	0.647	0.616	0.636	0.639	0.642	0.656	0.738	0.658	0.874	0.742	0.779	0.671	0.589	0.642	0.594	0.66	0.68	0.655	0.744	0.638	0.725	0.61	0.725	0.595	0.593	0.956	0.639	0.637	0.466	0	0.783	0.523	0.753	0.853	0.752	0.806
T3	0.863	0.841	0.856	0.857	0.861	0.872	0.934	0.872	1.049	0.937	0.964	0.88	0.798	0.857	0.821	0.867	0.881	0.867	0.936	0.851	0.921	0.811	0.92	0.786	0.819	1.113	0.858	0.855	0.599	0.783	0	0.682	0.944	1.022	0.946	0.969
T4	0.454	0.401	0.428	0.43	0.448	0.448	0.542	0.438	0.755	0.552	0.619	0.468	0.396	0.443	0.385	0.417	0.466	0.453	0.546	0.432	0.54	0.375	0.541	0.362	0.366	0.832	0.429	0.421	0.384	0.523	0.682	0	0.584	0.761	0.469	0.663
T5	0.554	0.509	0.536	0.54	0.55	0.559	0.655	0.565	0.812	0.655	0.671	0.559	0.524	0.529	0.505	0.567	0.576	0.538	0.658	0.526	0.63	0.519	0.613	0.505	0.499	0.895	0.527	0.528	0.624	0.753	0.944	0.584	0	0.873	0.657	0.733
T6	0.783	0.757	0.775	0.776	0.78	0.792	0.86	0.791	0.983	0.86	0.894	0.799	0.749	0.775	0.757	0.793	0.813	0.791	0.865	0.778	0.842	0.751	0.849	0.753	0.74	1.044	0.777	0.774	0.685	0.853	1.022	0.761	0.873	0	0.865	0.921
U1	0.569	0.513	0.525	0.52	0.557	0.524	0.585	0.504	0.822	0.6	0.692	0.554	0.544	0.555	0.503	0.487	0.551	0.549	0.602	0.542	0.629	0.49	0.618	0.492	0.473	0.891	0.526	0.515	0.617	0.752	0.946	0.469	0.657	0.865	0	0.755
U2	0.623	0.593	0.621	0.627	0.63	0.649	0.735	0.651	0.866	0.709	0.768	0.639	0.599	0.598	0.537	0.651	0.674	0.589	0.736	0.603	0.706	0.609	0.696	0.563	0.565	0.93	0.585	0.588	0.675	0.806	0.969	0.663	0.733	0.921	0.755	0

Figure 4.21 Entire Similarity Distance Matrix.

TABLE 4.9
Average MOT Cost for Different Work Categories

Work Category	MOT Cost	MOT to Des Award Ratio (%)
Bridge	$68,829	12.27
Miscellaneous	$37,116	9.52
Traffic	$38,915	7.63
Small Structures	$22,394	6.89
Road	$288,826	8.83
Utility	$75,067	8.05

TABLE 4.10
Average MOT Cost to Des Award Ratio for Different Project Types

Project Type	Total Count	Average MOT Cost to Des Award Ratio (%)	Average Ratio for Single Projects (%)	Average Ratio for Bundled Projects (%)	MOT Cost Ratio Reduction due to Bundling (%)
B1-New Bridge	303	5.78	6.13	5.73	0.41
B2-Bridge Replacement	210	7.19	7.54	6.94	0.60
B3-Superstructure Replacement	56	9.26	6.20	10.71	-4.52
B4-Deck Replacement	63	8.12	8.45	8.00	0.45
B5-Bridge Widening	50	6.68	6.15	6.78	-0.63
B6-Bridge Deck Overlay	325	8.70	9.36	8.44	0.93
B7-Thin Deck Overlay	167	16.12	11.51	16.68	-5.17
B8-Misc. Bridge Rehab & Repair	556	19.93	12.10	21.40	-9.30
M1-Demolition	72	6.64	6.48	8.69	-2.21
M2-Channel and Ditch Work	48	15.40	10.50	17.42	-6.92
M3-Stormwater Improvements	3	10.48	9.53	12.39	-2.86
M4-Slide Correction	35	8.35	7.24	9.68	-2.45
M5-Paths, Sidewalks & Curb Ramps	16	7.25	8.17	6.53	1.64
R1-New Road Construction	66	5.77	6.26	5.75	0.51
R2-Added Travel Lanes	61	8.17	11.41	7.02	4.39
R3-Patch & Rehab Pavement	101	11.34	11.79	10.21	1.59
R4-Partial 3	556	9.17	9.30	8.78	0.52
R5-Road Rehabilitation (3R/4R)	37	7.10	7.31	7.04	0.27
R6-Wedge & Level Only	15	8.04	8.33	4.00	4.34
R7-Sight Distance Correction	22	6.97	7.59	5.66	1.93
R8-Shoulder Rehab & Repair	2	5.39	NA	5.39	NA
R9-Pavement, Other	11	8.63	8.66	8.53	0.13
R10-Pavement Replacement	138	8.22	8.51	7.81	0.70
R11-Intersection Improvement	106	8.92	9.46	8.45	1.00
R12-Interchange Work	39	8.75	14.54	7.70	6.84
S1-Pipe Lining	244	5.86	7.69	5.20	2.49
S2-Small Structure Installation	219	7.78	8.45	7.10	1.35
S3-Small Str. Maintenance & Repair	45	8.11	8.10	8.13	-0.03
T1-ITS	25	6.53	6.22	6.76	-0.54
T2-Signing	123	7.13	8.75	6.93	1.81
T3-Traffic Signals	192	7.45	7.46	7.44	0.02
T4-Pavement Markings	14	14.81	30.20	8.65	21.55
T5-Guard Rail, Cable Barrier & Wall	38	8.58	8.71	7.89	0.82
T6-Lighting	27	7.24	9.33	5.80	3.53
U1-Railroad Work	1	61.71	61.71	NA	NA
U2-Utility Relocation	38	6.63	NA	6.63	NA

4.5.2 Investigation of the Effect of Various Factors on MOT Cost

As discussed before, the average cost approach does not take into account various factors that affect MOT cost. Cost models that include all the relevant and available variables are developed in Chapter 5 in order to have a more reliable estimate of the MOT cost. In this section, the effects of various variables, including Des Award, number of des, and functional class, were analyzed by studying scatter plots. These analyses can provide some insights into the relation between the MOT cost and cost ratio (MOT Cost/Des Award) with each of the possible explanatory variables. The analysis

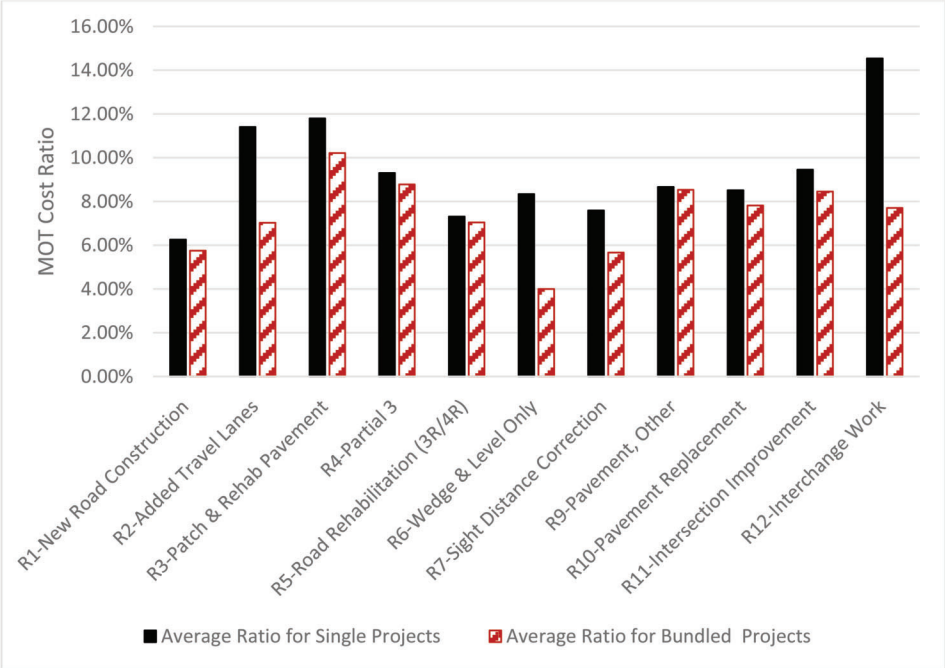


Figure 4.22 Comparison of MOT to Des Award ratio for single project and bundled projects (road work).

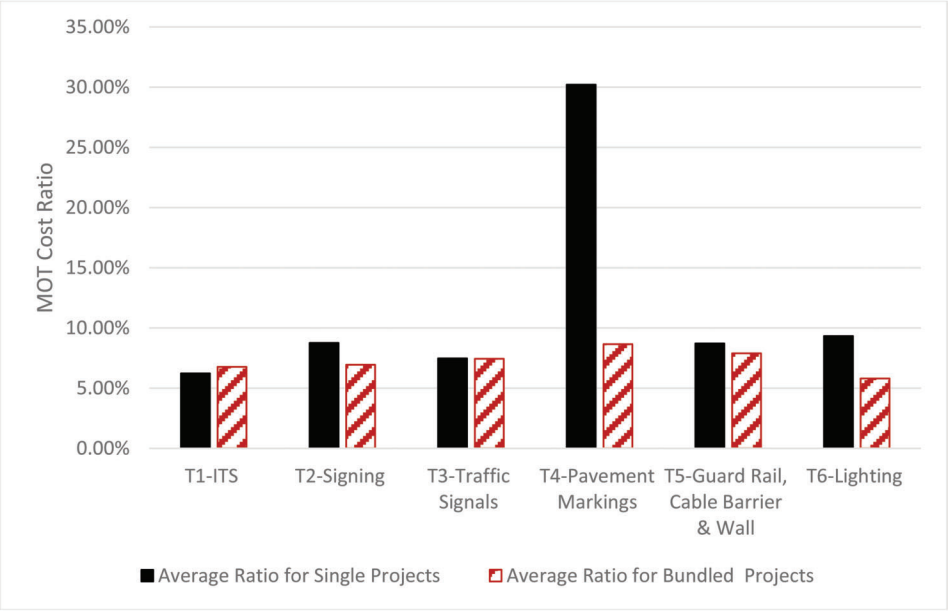


Figure 4.23 Comparison of MOT to Des Award ratio for single project and bundled projects (traffic work).

in this section also provides valuable information for the development of regression models in Chapter 5.

4.5.2.1 Effect of Des Award. As a part of project cost (Des Award), the MOT cost is expected to be largely determined by the project cost (Des Award). In general, the MOT cost is expected to increase as overall project cost increases (see Figure 4.24); however, the MOT cost ratio is found to decrease as Des Award increases for most project types (see Figure 4.25). This means that, as a project cost increases, the percentage of MOT cost of the total project cost gets smaller, although the MOT cost keeps increasing.

4.5.2.2 Effect of Project Bundling. One of the benefits of project bundling is that it can lead to more cost-effective maintenance of traffic during the construction period. The MOT cost ratio is expected to decrease as more projects are bundled into a contract. As shown in Figure 4.26, a significant decrease in the MOT cost

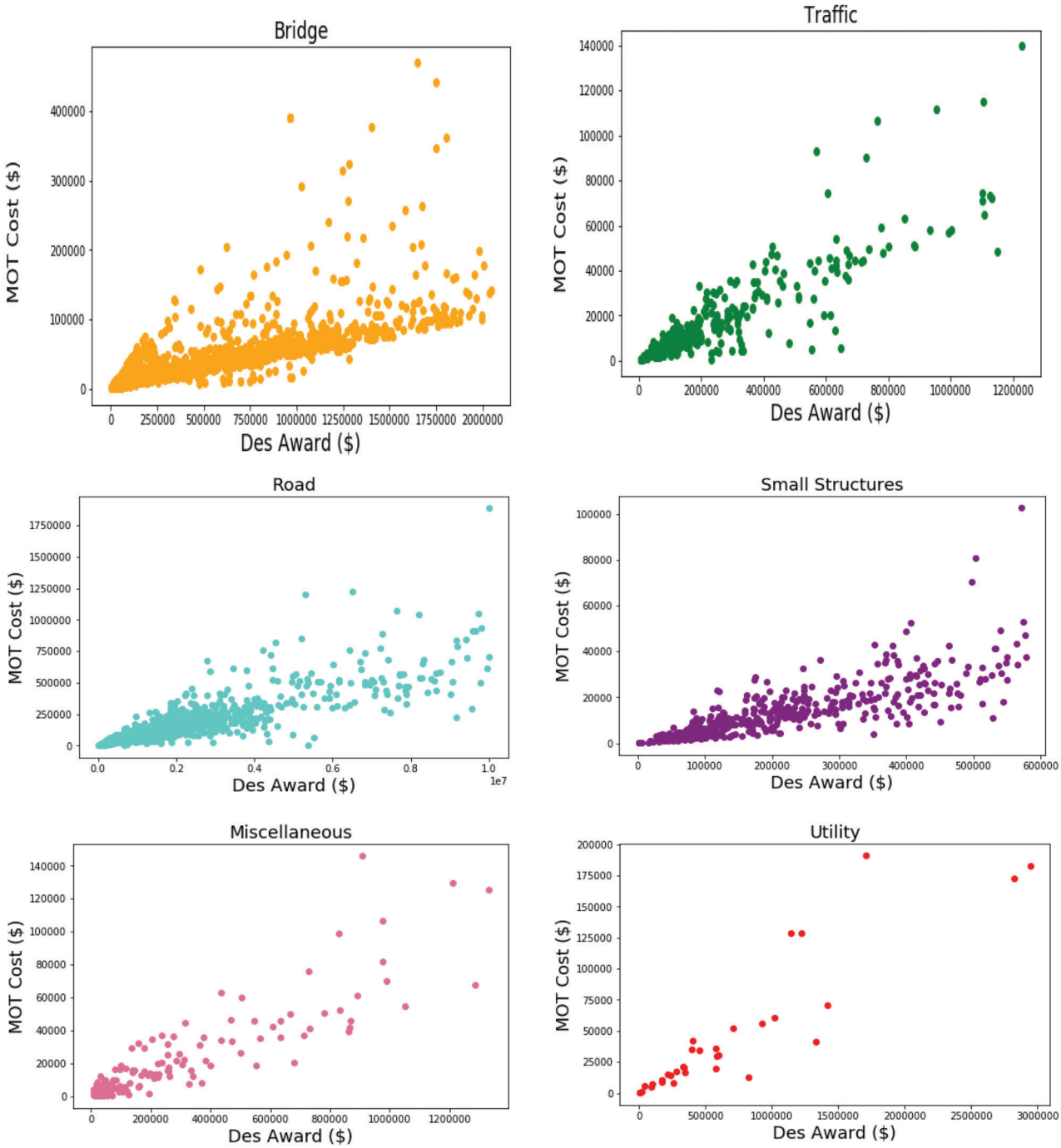


Figure 4.24 Effect of Des Award on MOT cost for different work categories.

ratio can be found for road, traffic, and small structure work as the number of des increases—particularly when the number of des increases from 1 to 2. This indicates that, as more projects are bundled into a contract, more cost savings could be obtained on maintenance of traffic. However, when the number of des passes a certain point, the MOT cost ratio stops decreasing or even starts increasing. This indicates that, when the contract becomes very large, benefits of project bundling in terms of the percentage share of the maintenance of traffic work becomes smaller. For bridge, miscellaneous, and utility work, the trend between MOT cost ratio and number of des is not very clear. Additional analysis of the bundling effects on MOT cost are provided in Section 4.6.2 for projects that are bundled along a corridor.

4.5.2.3 Effect of Road Type or Functional Class. The effect of road functional class in terms of rural and urban roads, and Interstate roads, US roads, and state roads, were investigated (Figure 4.27 and Figure 4.28).

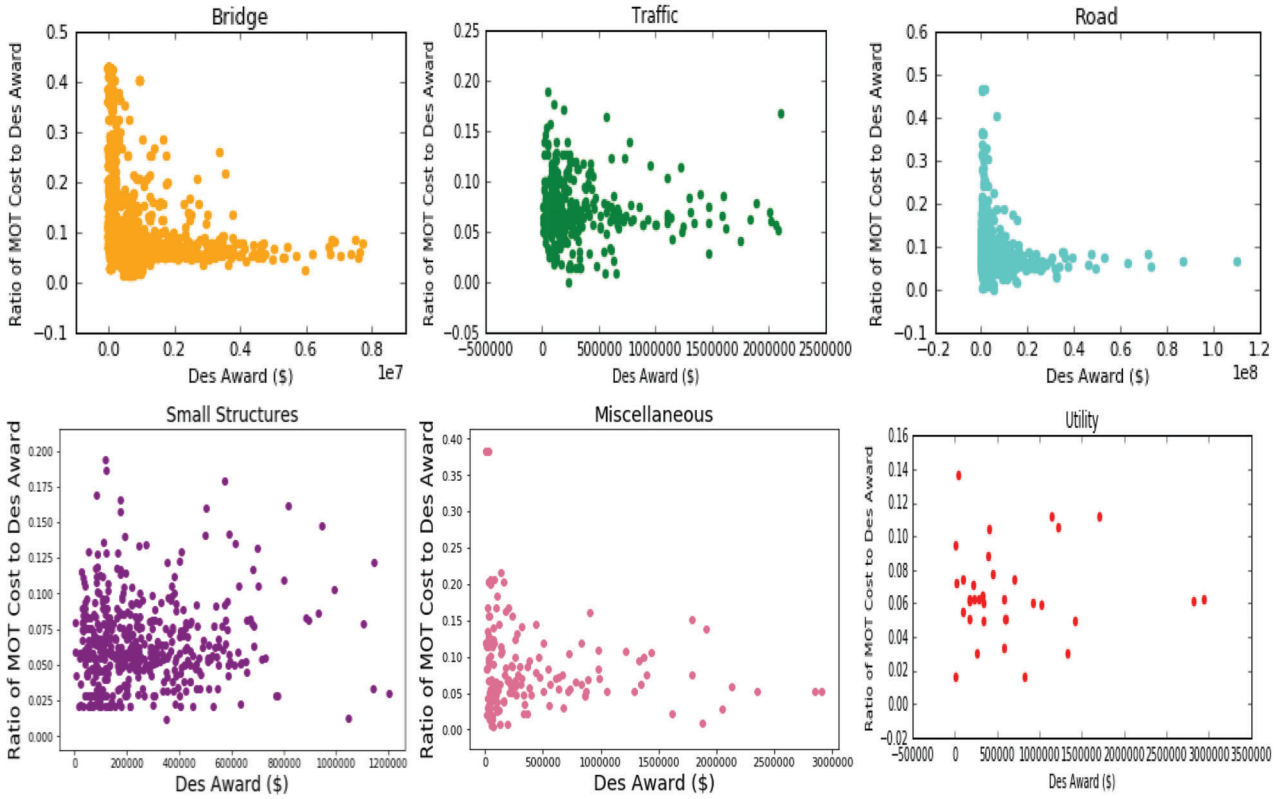


Figure 4.25 Effect of Des Award on MOT cost ratio for different work categories.

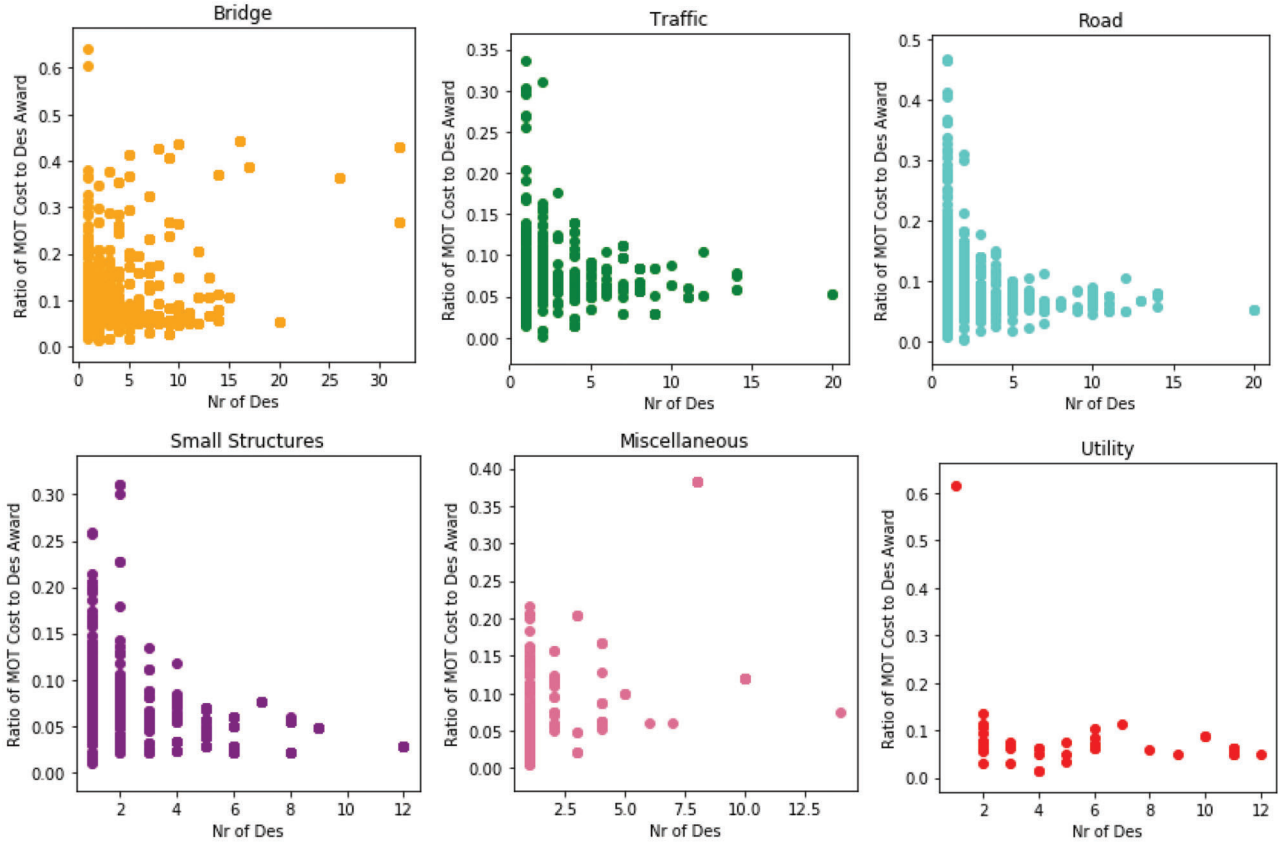


Figure 4.26 Effect of project bundling (Nr of Des) on MOT cost ratio for different work categories.

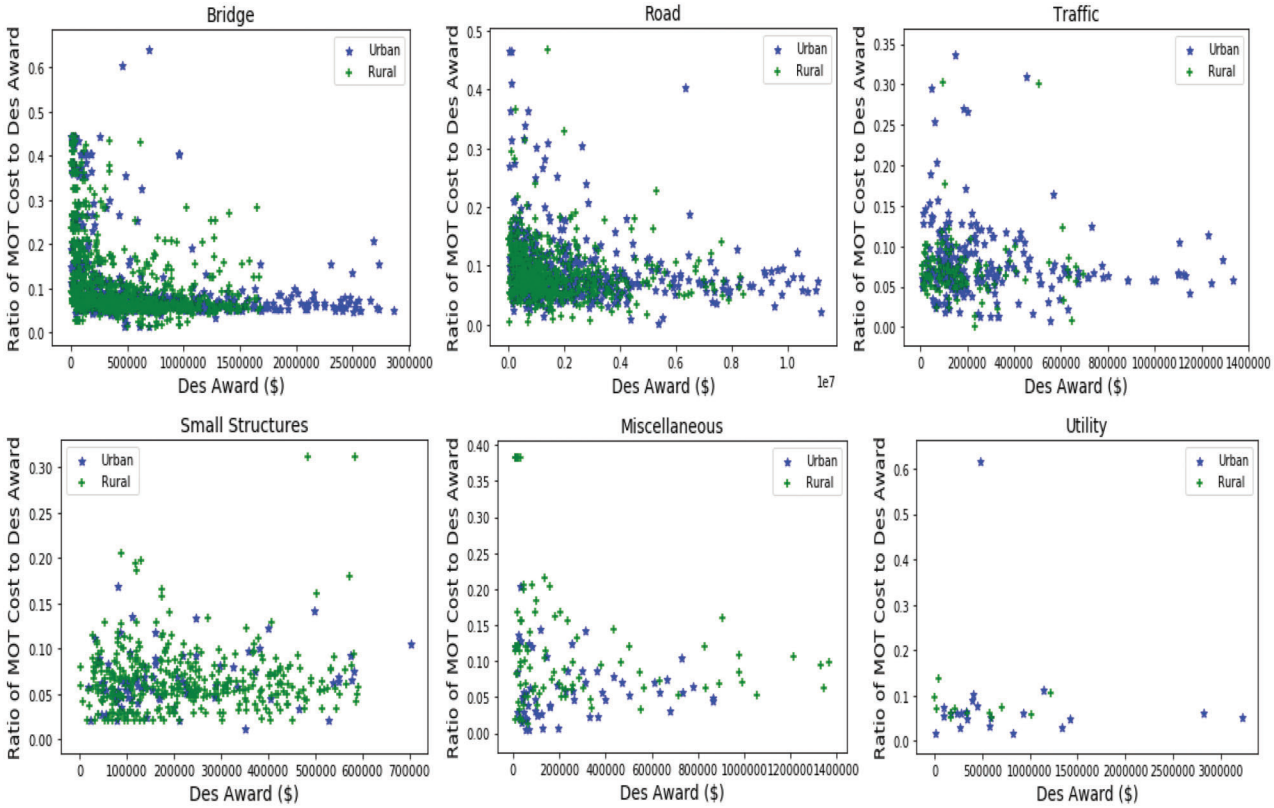


Figure 4.27 Effect of location (rural vs. urban) on MOT cost ratio for different work categories.

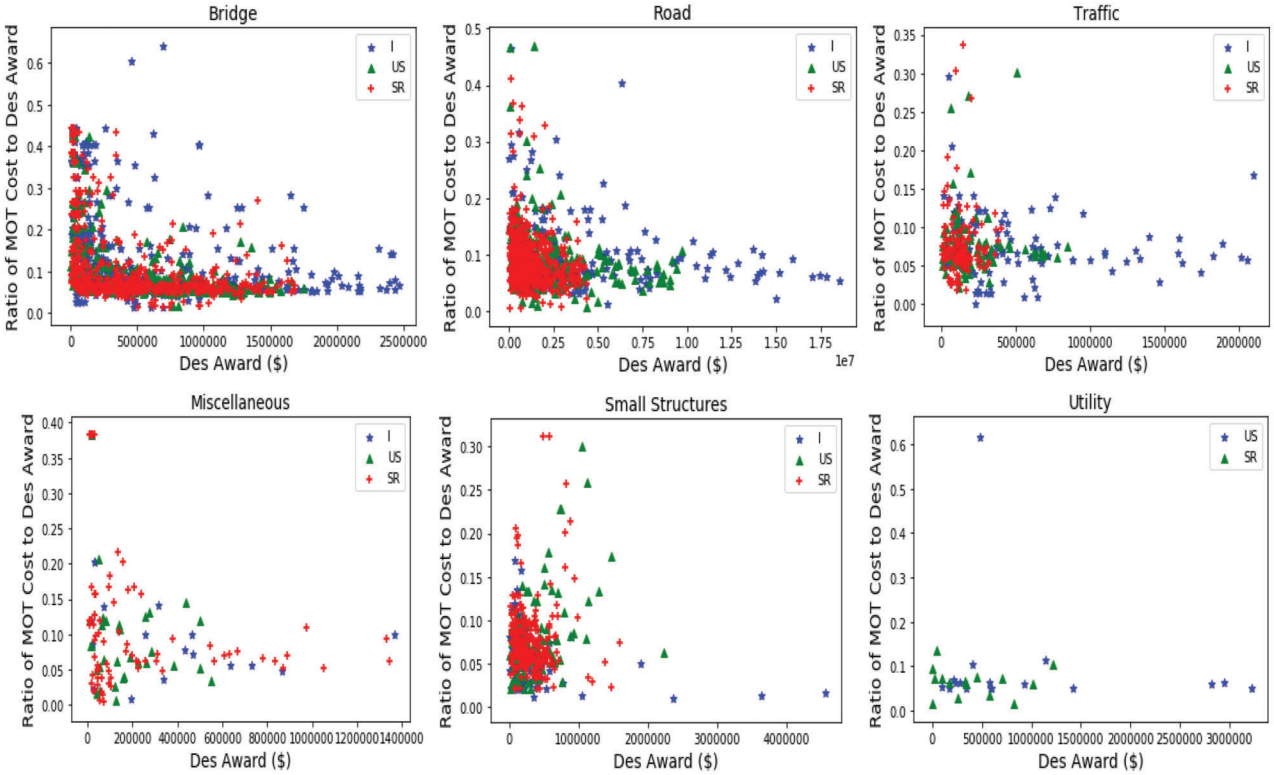


Figure 4.28 Effect of functional classes on MOT cost ratio for different work categories.

The MOT cost ratio is higher on urban roads (green plus sign) than on rural roads (blue star) for road, bridge and traffic work. No significant difference was found for small structure, miscellaneous, and utility work. Similarly, for road, bridge, and traffic work, the MOT cost ratio is significantly higher for projects on Interstate roads (blue stars), followed by US roads (green triangles), then projects on state roads (red plus signs). However, for small structures, miscellaneous, and utility work, no clear difference was found.

4.6 Corridor Analysis

Corridor analyses were carried out to compare costs for stand-alone projects and bundled projects on the same road. In the current dataset, projects in most bundled contracts are located along the same road corridor. Of the 771 bundled contracts, only 198 contracts contain projects from different corridors; for the other 573 contracts, all projects in a contract were located along the same corridor (same road). It is hypothesized that the benefit of project bundling would generally be greater when projects are bundled along the same corridor. This is because resources, construction materials, and maintenance of traffic costs can be shared and coordinated more easily if all projects in the contract are located on the same road.

In this section, the average project unit costs of stand-alone project and bundled projects were compared. Several major roads in the state of Indiana that have had multiple projects in the past few years were selected for corridor analysis, including I-65, I-69, I-70, I-465, US 31, US 24 and SR 25. The number of past single projects and projects along the same corridor are shown for each road and project type in Table 4.11. Projects with unusually high or low unit cost were excluded from

TABLE 4.11
Number of Projects on Several Major Roads in Indiana

	Number of Single (S) and Bundled (B) Projects from 2008 to 2017													
	I-65		I-69		I-70		I-465		US 31		US 24		SR 25	
Project Type	**S**	**B**	**S**	**B**	**S**	**B**	**S**	**B**	**S**	**B**	**S**	**B**	**S**	**B**
B1	0	1	0	2	0	36	0	2	2	65	0	15	6	48
B2	1	8	2	25	1	5	2	25	1	10	2	1	0	2
B3	0	4	0	0	2	11	0	0	1	0	0	0	0	0
B4	1	7	0	0	2	1	0	0	1	3	0	0	0	0
B5	0	7	1	4	0	1	1	4	0	1	0	0	0	0
B6	2	19	0	2	5	24	0	2	3	3	2	2	0	1
B7	0	9	0	8	0	11	0	8	1	2	0	3	0	3
B8	14	48	5	11	4	50	5	11	1	14	0	12	0	0
R1	0	0	4	0	0	0	4	0	7	0	0	0	2	0
R2	1	1	0	0	1	2	0	0	1	1	0	0	0	0
R3	0	0	0	0	0	0	0	0	1	0	0	1	0	0
R4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
R5	0	0	0	0	0	0	0	0	0	0	0	0	1	1
R6	0	0	0	0	0	9	0	0	1	17	0	4	0	13
R7	1	0	0	7	2	3	0	7	0	5	0	0	1	0
R8	6	3	3	1	2	1	3	1	3	2	0	0	1	2
R9	16	12	2	1	8	8	2	1	12	2	11	1	4	2
R10	1	1	0	0	0	0	0	0	0	3	0	0	0	0
R11	0	0	0	0	0	0	0	0	0	0	1	0	0	0
R12	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2	0	0	0	0	1	0	0	0	0	1	0	0	0	0
T3	1	3	0	0	0	0	0	0	1	0	0	1	0	0
T4	0	0	0	0	0	0	0	0	1	2	0	1	1	0
T5	0	5	0	10	1	7	0	10	0	3	0	1	1	0
T6	8	43	4	5	1	21	4	5	3	7	1	17	0	0
S1	0	0	1	0	0	0	1	0	2	0	2	0	1	2
S2	1	0	1	0	0	0	1	0	0	0	2	3	1	0
S3	1	6	6	0	0	1	6	0	0	3	0	0	0	0
M1	1	5	1	4	0	6	1	4	0	12	0	4	0	3
M2	0	0	0	4	2	2	0	4	3	9	1	4	0	0
M3	0	0	0	0	0	0	0	0	0	1	0	0	0	0
M4	8	1	0	0	5	1	0	0	1	0	0	0	0	0
M5	1	1	0	3	1	0	0	3	0	0	0	0	0	0
U1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
U2	0	0	0	0	0	0	0	0	0	4	0	2	0	0
Total	**64**	**184**	**30**	**87**	**38**	**200**	**30**	**87**	**46**	**170**	**22**	**72**	**19**	**77**

analysis as outliers, and project type B8 was also removed due to the issue discussed earlier in Section 4.1.

4.6.1 Overall Project Cost Analysis along Selected Corridors

4.6.1.1 The I-65 Corridor. First, we use the I-65 corridor, which has had the most projects in recent years, to illustrate how the project unit cost of a stand-alone project differs from the same type of project that is bundled with other projects along the corridor. The differences in the unit cost of projects that are bundled with different numbers of kins were also compared.

In a previous section, bridge work was found to benefit the most from project bundling compared to all other work categories. Therefore, corridor analysis was carried out for project type B2-Bridge Replacement in the I-65 corridor. The bridge replacement projects conducted along the I-65 corridor from Year 2008 to 2017 are listed in Table 4.12. The Nr of Des refers to the total number of projects (same type or different types) bundled in a contract on I-65, but only the des with project type B2-Bridge Replacement are listed in Table 4.12. For example, there are 3 des in Contract 35187, but only Des 1298696 is considered in the analysis, because the other two des in the contract are not Project Type B2. A project in a contract with only one des is, by definition, stand-alone (single) project. On corridor I-65, there is only one stand-alone project from Year 2008 to 2017 (Contract 31413: replacement of CSX railroad bridge over I-65). Since it is not appropriate to compare railroad bridge replacement with highway bridge replacement projects, this project was not considered in the analysis. In addition, Des 1296773 was excluded from analysis as an outlier, because it has a much lower unit cost ($184/sq ft) than the other projects in the contract.

According to the corridor analysis results (Table 4.12 and Figure 4.29), the unit cost of the project in Contract 35187 (2 des) has the higher unit cost ($783/sq ft) than projects in Contract 35492 (6 des) and Contract 37549 (7 des). In this special case, project bundling along a corridor shows significant project cost savings, and the benefit is even more significant when a greater number of projects are bundled.

The corridor analysis was then carried out for B6-Deck Overlay. Whereas the project unit cost of bridge replacement decreased continuously as the number of projects bundled in a contract increased, the Bridge Deck Overlay project in the I-65 corridor shows a different

TABLE 4.12
Cost Comparison for B2-Bridge Replacement Projects along the I-65 Corridor

Contract Type	Contract No	Des No	Letting Year	Nr of Des	Des Award	Deck Area (sq ft)	Unit Cost ($/sq ft)	Average Unit Cost
Bundled Contract	35187	1298696	2014	3	$2,406,322	3072	$783	$783
	35492	1296631	2016	6	$2,415,973	3072	$786	$662
	35492	1296728	2016	6	$2,432,755	4980	$489	$662
	35492	1296776	2016	6	$6,828,587	9616	$710	$662
	37549	1173615	2014	7	$6,855,501	9616	$713	$497
	37549	1173617	2014	7	$3,424,164	12167	$281	$497

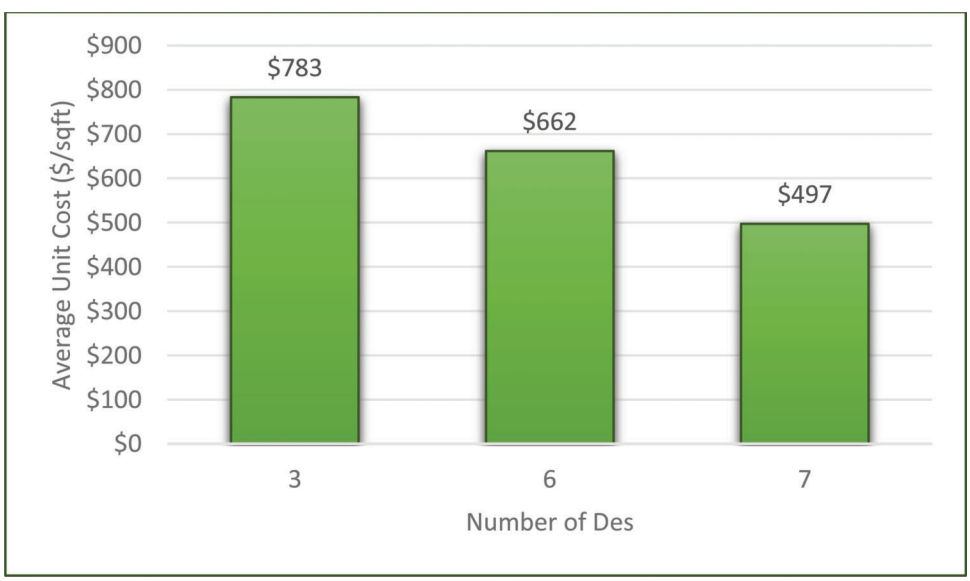


Figure 4.29 Comparison of average unit cost for B2-Bridge Replacement projects along the I-65 corridor.

TABLE 4.13
Cost Comparison for B6-Bridge Deck Overlay Projects along the I-65 Corridor

Contract Type	Contract ID	Des ID	Letting Year	Nr of Des	Project Cost (Des Award)	Deck Area (sq ft)	Unit Cost ($/sq ft)	Average Unit Cost ($/sq. ft)
Single Project	34680	1173861	2014	1	$566,632	8192	$69	$78
	35055	1296592	2015	1	$624,499	7187	$87	$78
Bundled Contract	35403	1296137	2016	3	$187,300	5460	$34	$34
	37980	1296975	2016	5	$534,111	12320	$43	$43
	34753	0300492	2014	5	$273,254	5426	$50	$73
	34753	0900524	2014	5	$468,197	5346	$88	$73
	34753	1173631	2014	5	$734,539	7124	$103	$73
	34753	1173632	2014	5	$546,364	6802	$80	$73
	33066	1297418	2013	7	$364,139	6697	$54	$54
	28973	0300462	2015	10	$270,489	3440	$79	$84
	28973	0300475	2015	10	$231,569	3440	$67	$84
	28973	0300485	2015	10	$259,761	2520	$103	$84
	28973	0300488	2015	10	$222,714	2520	$88	$84

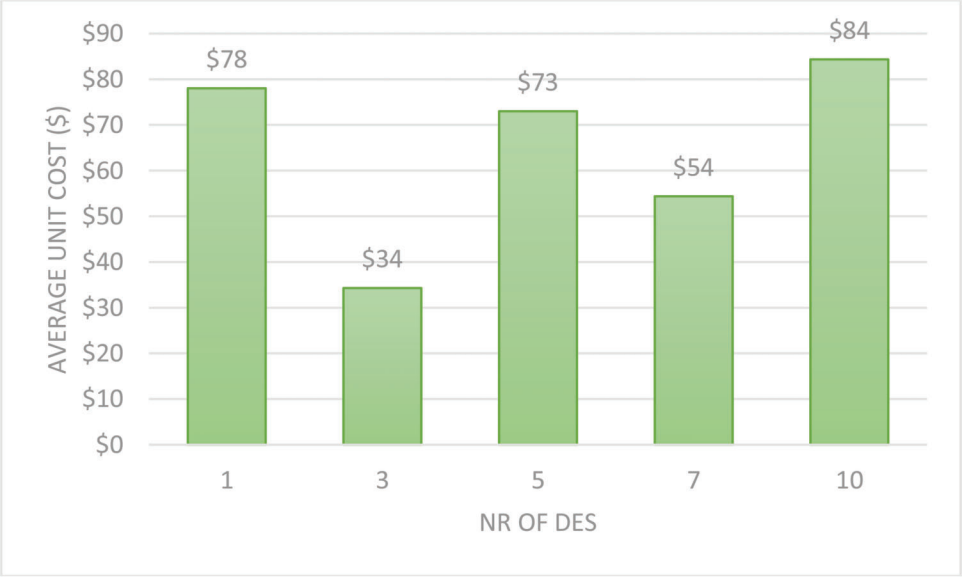


Figure 4.30 Relationship between Nr. of Des and average unit cost for B6-Bridge Deck Overlay projects along the I-65 corridor.

pattern (Table 4.13 and Figure 4.30). The unit cost of each stand-alone project is still higher than the average unit cost of bundled projects. A very significant reduction in average unit cost from ($78/sq. ft to $34/sq. ft) was observed when the Nr of Des increased from 1 to 3. It was found that the deck area of projects in Contract 35403 is smaller than the area of the two stand-alone projects, indicating the decrease on the unit cost from stand-alone project to bundled projects (2 des) would be even larger if the economies of scale can be taken into account. However, when the contract gets larger (Nr of Des ≥5), the unit cost starts increasing. This might mean that there exists a threshold on contract size, after which the project no longer benefits from project bundling. In general, however, the average unit cost of bundled projects is still much lower than the cost of the single projects in this corridor analysis. In addition, it was noticed that the deck area of projects in Contract 28973 is very small compared to other projects. This explains why the average unit cost of the four bundled projects is higher than that of the two single projects; the economies of bundling is outweighed by the economies of scale.

Although the benefit of project bundling was not found for some road project types in Section 4.1, corridor analysis on road work was nevertheless carried out. The available number of projects along the same corridor, however, is much lower for road projects than for bridge projects, making it difficult to make a reliable estimate of the average costs. Moreover, unlike bridge project, the project size of road projects can vary from a very small road section (less than 0.1 mile) to a long road corridor (more than 30 miles). This large variation in project size leads to an unfair comparison of average

costs due to the economies of scale. Therefore, when comparing the average unit cost for road work, one needs to pay more attention to the project size.

A corridor analysis along I-65 was conducted for R3-Patch & Rehab Pavement projects and R4-Partial 3R projects, as shown in Tables 4.14 and 4.15 and Figures 4.31 and 4.32. A significant reduction in the average unit cost was found for Patch & Rehab Pavement projects. Although the project length varies greatly over different number of des, the average project length of bundled projects is smaller than that of the single projects. This means that, if the economies of scale is taken into account, the average unit cost of bundled projects would be reduced more by project bundling. Therefore, we can conclude that, for this specific corridor, bundling projects would be very beneficial in terms of the cost saving. For R4-Partial 3R projects however, the average unit cost seems to increase slightly as number of des increases, and the average project size (lane-mile) of projects with different number of des is similar. This suggests that bundling R4 projects does not save money in this specific corridor. Both results are consistent with the results in Section 4.1 where we compared the average unit cost of single and bundled projects for projects on all the roads irrespective of corridor location.

4.6.1.2 Other Corridors. A similar corridor analysis was carried out for bridge projects along other corridors, because compared to the other project types,

TABLE 4.14
Cost Comparison for R3-Patch & Rehab Pavement Projects along the I-65 Corridor

Contract Types	Contract Number	Des ID	Letting Year	Nr of Des	Des Award	Project Length (mile)	Nr of Lanes	Unit Cost	Average Unit Cost
Single Project	35938	1382525	2013	1	$5,306,410	1.502	4	$883,224	$452,413
	39640	1601191	2016	1	$1,229,211	14.226	4	$21,601	$452,413
Bundled Projects	38255	1401165	2015	2	$230,791	0.363	4	$158,947	$158,947
	37123	1400679	2014	3	$4,613,776	34.992	4	$32,963	$32,963
	31959	0900314	2009	6	$446,061	7.37	4	$15,131	$15,131

TABLE 4.15
Cost Comparison for R4-Partial 3R Projects along the I-65 Corridor

Contract Number	Des ID	Letting Year	Nr of Des	Des Award	Project Length	Nr of Lanes	Unit Cost	Average Unit Cost
30329	0400605	2011	1	$1,199,238	2.603	6	$76,786	$140,471
30671	0710161	2013	1	$710,388	1.82	6	$65,054	$140,471
30903	0710622	2009	1	$4,894,999	9.76	4	$125,384	$140,471
31664	0710118	2010	1	$2,669,626	5.6	4	$119,180	$140,471
32291	0710115	2009	1	$3,445,981	10.1	4	$85,297	$140,471
33265	1005599	2010	1	$1,907,955	4.47	4	$106,709	$140,471
33813	1006431	2011	1	$9,197,038	9.943	4	$231,244	$140,471
34854	1173722	2014	1	$3,294,428	6.742	4	$122,161	$140,471
34902	1296970	2014	1	$2,795,375	8.722	6	$53,416	$140,471
35312	1297604	2013	1	$1,841,806	4.328	4	$106,389	$140,471
35314	1297607	2013	1	$1,475,514	1.201	4	$307,143	$140,471
35342	1297634	2014	1	$3,452,726	7.451	4	$115,848	$140,471
35931	1382521	2014	1	$2,783,549	5.931	4	$117,331	$140,471
36016	1296572	2016	1	$9,414,064	6.988	6	$224,529	$140,471
38324	1500344	2016	1	$975,297	0.973	4	$250,590	$140,471
29851	0501213	2008	2	$3,797,849	9.18	4	$103,427	$155,006
29851	0501214	2008	2	$1,797,997	2.79	4	$161,111	$155,006
35049	1173721	2015	2	$1,849,588	1.048	6	$294,146	$155,006
35343	1297635	2013	2	$269,806	0.25	6	$179,870	$155,006
37695	1383602	2016	2	$4,534,109	10.025	4	$113,070	$155,006
37695	1401310	2016	2	$2,222,507	7.269	4	$76,438	$155,006
38403	1500413	2016	2	$6,012,935	9.576	4	$156,979	$155,006
34142	1173041	2011	3	$4,112,222	6.736	6	$101,747	$203,927
37123	1005501	2014	3	$3,756,530	2.932	4	$320,304	$203,927
37123	1005502	2014	3	$3,864,831	4.882	4	$197,912	$203,927
37549	1005494	2014	3	$7,641,785	9.76	4	$195,742	$203,927
34753	1005685	2014	5	$2,940,844	4.345	4	$169,209	$169,209

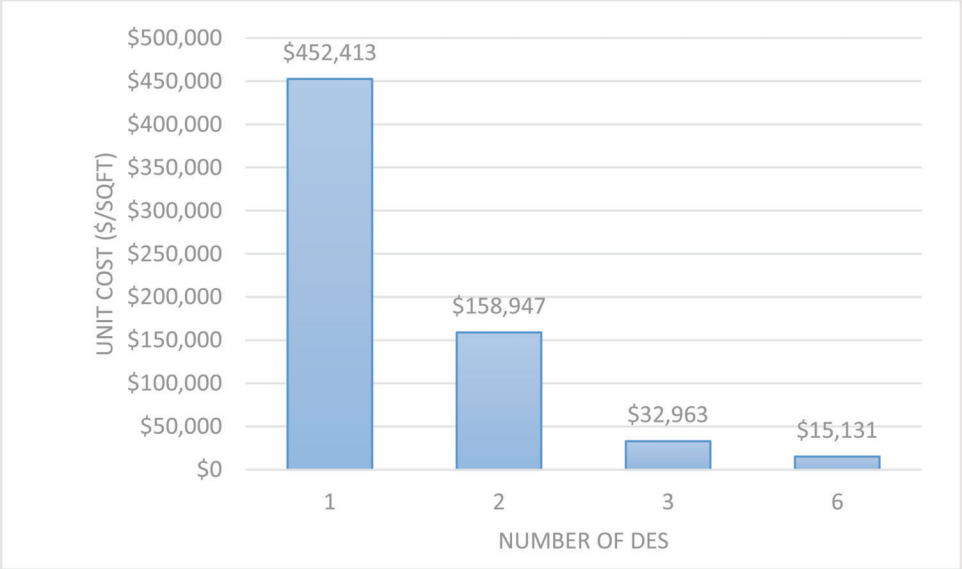


Figure 4.31 Comparison of average unit cost for R3-Patch & Rehab Pavement projects along the I-65 corridor.

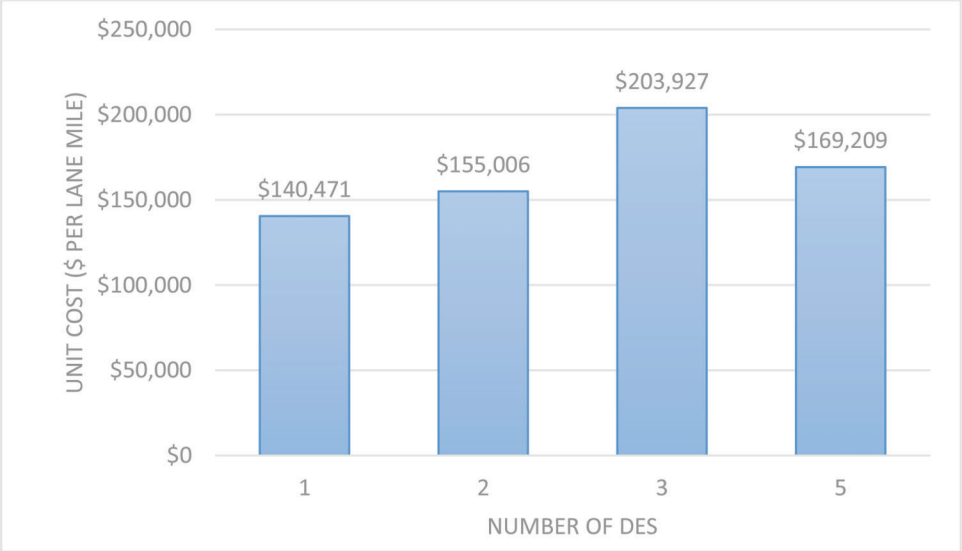
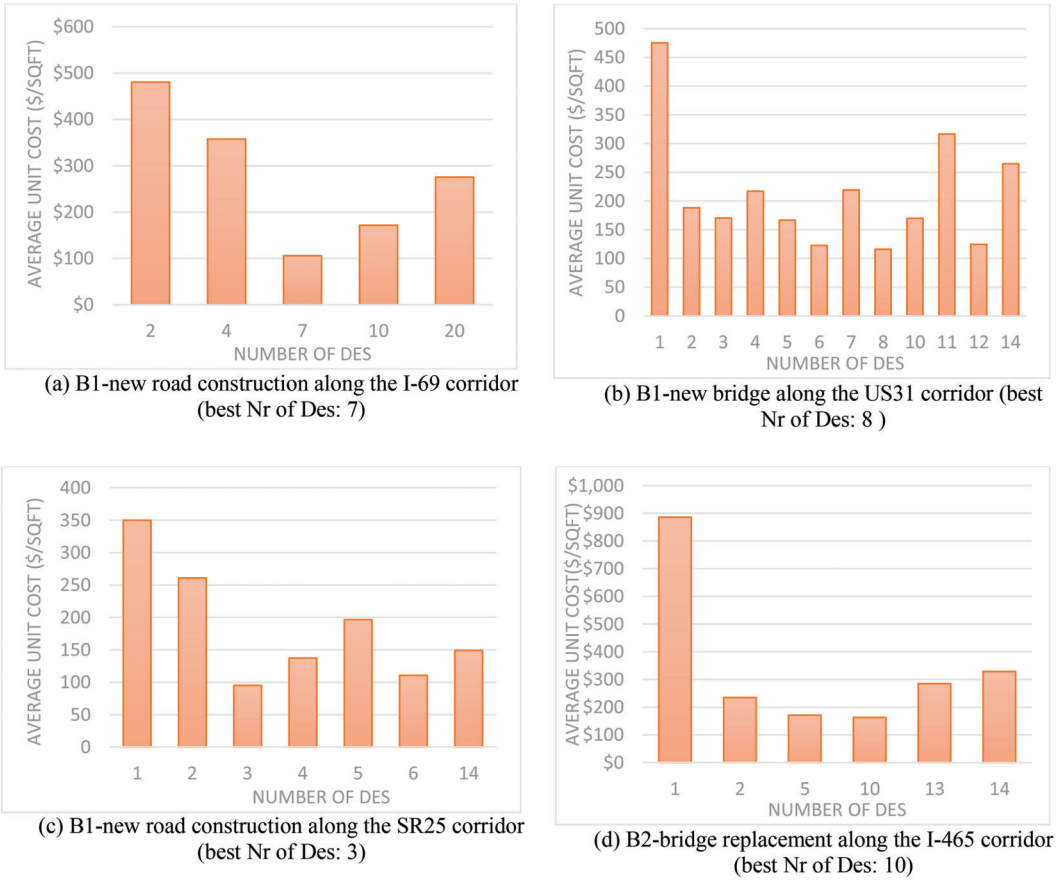


Figure 4.32 Comparison of average unit cost for R4-Partial 3R projects along the I-65 corridor.

bridge projects are found to benefit most from project bundling. Another reason for our focus on bridges here is that this project type has the largest sample size in the dataset. The results are shown in Figure 4.33. A "U" shape was found for most scenarios in the figure; the average unit cost seems to decrease significantly from single projects to bundled projects, until the number of des passes a certain value, after which the average unit cost becomes stable or starts increasing. This U-shaped pattern between unit cost and number of des is due to the interaction between project size and market competition, as discussed in Section 4.3; an increasing number of des can lead to a lower number of bidders, and the unit cost might start increasing at a certain point due to lower market competition. The best number of des for each scenario is listed in Table 4.16. This "optimal" number of des varies so much between corridors that other factors may be in play. In Section 5.1.3.1, a threshold analysis is conducted to identify the optimal number of des for specific project types.

4.6.2 MOT Cost Analysis along a Corridor

As stated in a previous section, the maintenance of traffic (MOT) cost is one of the major components of project cost. One of the benefits of bundling projects along a corridor is the potential savings in MOT cost. In Section 4.5, a significant reduction in the MOT cost ratio (% of total Des Award) due to project bundling was found for all road projects and most traffic and



(a) B1-new road construction along the I-69 corridor (best Nr of Des: 7)

(b) B1-new bridge along the US31 corridor (best Nr of Des: 8)

(c) B1-new road construction along the SR25 corridor (best Nr of Des: 3)

(d) B2-bridge replacement along the I-465 corridor (best Nr of Des: 10)

Figure 4.33 Comparison of average unit cost for bridge projects along different corridors.

TABLE 4.16
Corridor Analysis Results for Bridge Projects

Project Type	Corridor	Optimal Number of Des
B1-New Road Construction	I-69	7
B1-New Road Construction	US 31	8
B1-New Road Construction	SR 25	3
B2-Bridge Replacement along	I-465	10

small-structure projects. In this section, we analyze, at a corridor level, the difference between the MOT cost ratio for stand-alone projects and projects bundled along a corridor.

To quantify the benefit of project bundling on MOT cost savings at a corridor level, the "average MOT cost to Des Award" ratio for different number of des was calculated for projects in each work category along a certain corridor. The distributions of the calculated average MOT cost ratio are presented in Figures 4.34 through 4.39. The "optimal" number of des (with the lowest MOT cost ratio) and the least favorable number of des (with the highest MOT cost ratio) for each work category and each corridor are listed in Table 4.17. It can be found that at all corridors except US 24 and for all road work, the MOT cost ratio is always the highest when the number of des is equal to one, that is, a stand-alone project. The number of des that yields the lowest MOT cost ratio varies significantly, but mostly hovers between 9 and 12. This is consistent with the analysis in Section 4.5.1, where the single projects had a higher MOT cost ratio compared to the bundled projects irrespective of road project type. For bridge work, the MOT cost ratio sometimes slightly decreases as number of des increases, but starts increasing after a certain point and subsequently even exceeds the MOT cost ratio observed for single projects. In Section 4.5, we found that the average MOT cost ratio of bundled projects is higher than that of single projects, for most bridge projects, because the benefit of bundling dissipated when a project was bundled with too many kins. For traffic and small structure projects, a general decreasing or a "U" shape was observed for most of the corridors. For Miscellaneous projects, the MOT cost ratio generally increased as number of des increased. Also, these findings are consistent with the average MOT cost ratio comparison results obtained in Section 4.5.

4.7 Chapter Summary

In this chapter, an average cost approach was used to compare the overall project unit cost and average MOT cost ratio of single and bundled projects. It was found that bridge work benefits the most from project

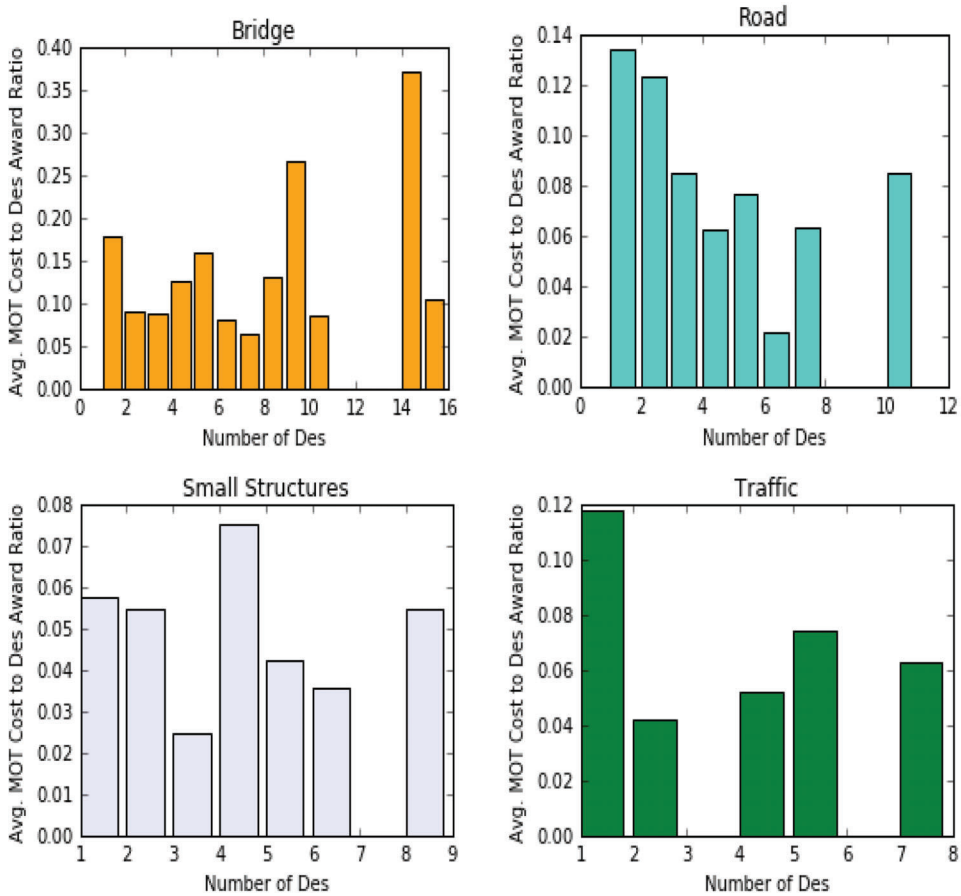


Figure 4.34 Comparison of MOT cost ratio for projects along the I-65 corridor.

bundling in terms of overall cost saving. Road work was found to benefit the most from project bundling in terms of MOT cost saving, although there is no evidence that the overall unit cost of road projects can be reduced by project bundling (except project types R3-Patch & Rehab Pavement, R7-Sight Distance Correction and R9-Pavement, Other). We believe that this is because, for other road projects, the economies of scale dominate the economies of bundling. It means that, for these road projects, having one large project in a single project contract leads to greater net savings compared to having several small projects bundled into a contract. Corridor analysis in terms of overall project cost and MOT cost were carried out for projects on I-65, I-69, I-70, I-465, US 31, US 24 and SR 25 at years 2008 to 2017. The results obtained are mostly consistent with the average project unit cost (and MOT cost ratio) comparison results.

Using scatter plots, the effect of various influential variables of the overall project cost and MOT cost were investigated, including economies of scale (project size), economies of bundling (number of des), economies of competition (number of bidders), and other relevant factors. These results reveal strong relationships between the contract outcomes (overall project cost, MOT cost) and each of the considered variables, and provide valuable information for the development of cost models in Chapter 5.

In addition, the relationship between project size and market competition was discussed in Section 4.3. A deterministic upper-bound model was developed, for each work category, to estimate the highest possible number of bidders (under the optimistic market condition) over different number of des. Also, a probabilistic beta distribution model was developed to estimate the actual distribution of the number of bidders under a certain number of des. The two models are subsequently used in Chapter 5 for threshold analysis and confidence bound estimation on project cost. Similarity analysis was carried out in Section 4.4, to quantify the kinship of different project types based on the similarity (lower Euclidean distance) between their constituent of pay items. This distance was considered as a potential influential variable in the cost models in Chapter 5, to measure the extent to which the kinship between projects in a contract could affect the project cost.

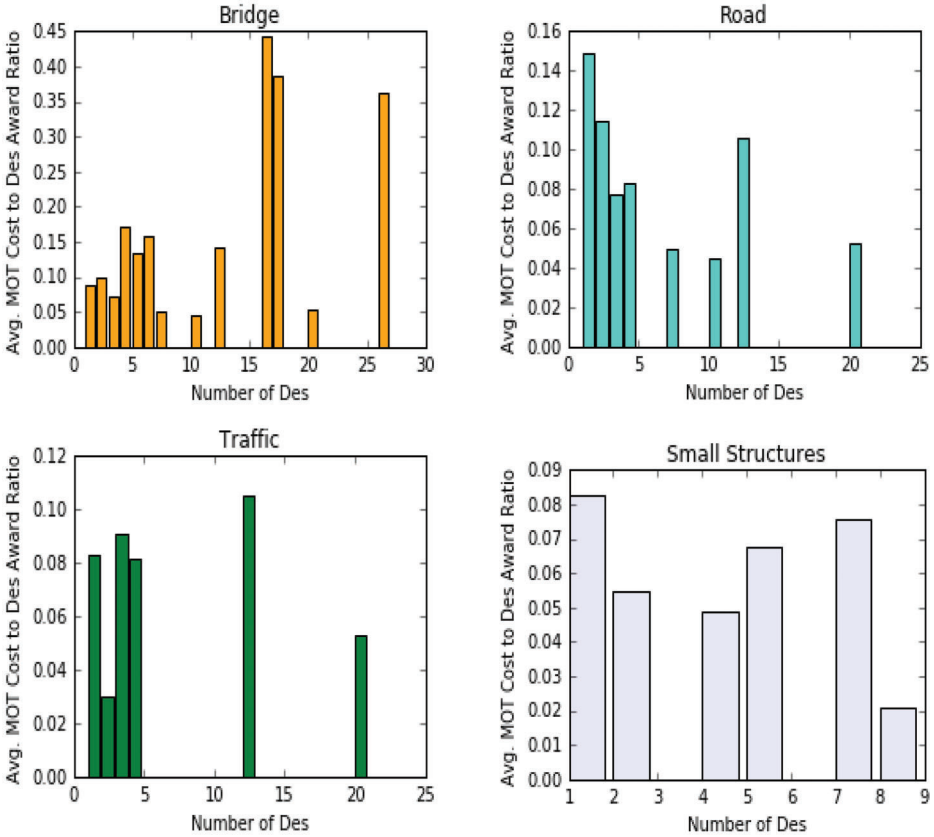


Figure 4.35 Comparison of MOT cost ratio for projects along the I-69 corridor.

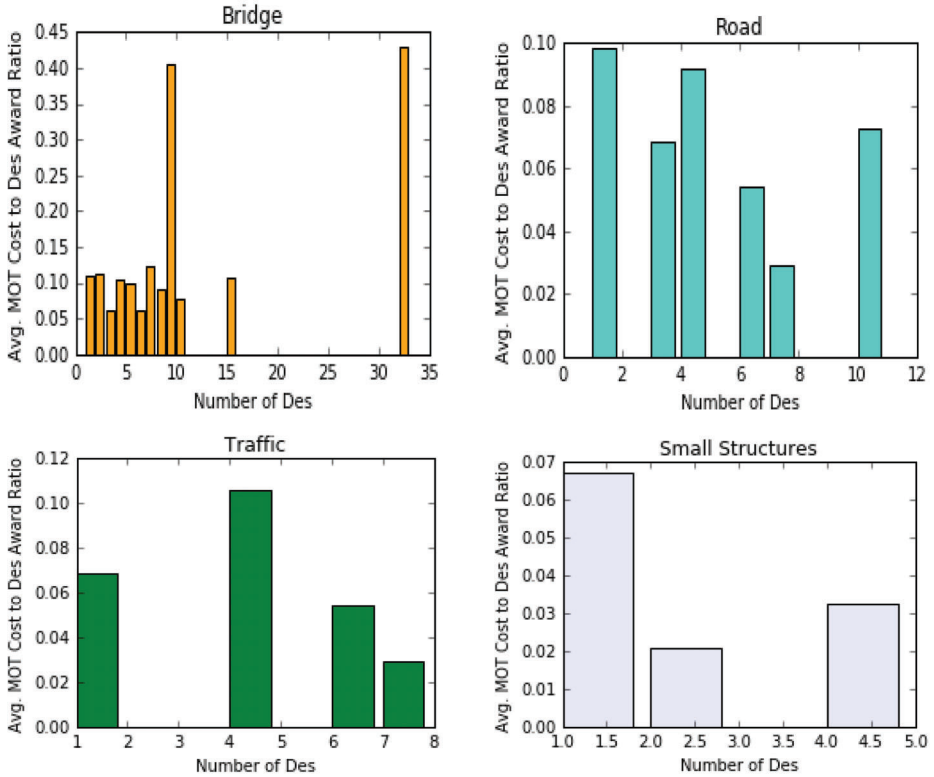


Figure 4.36 Comparison of MOT cost ratio for projects along the I-70 corridor.

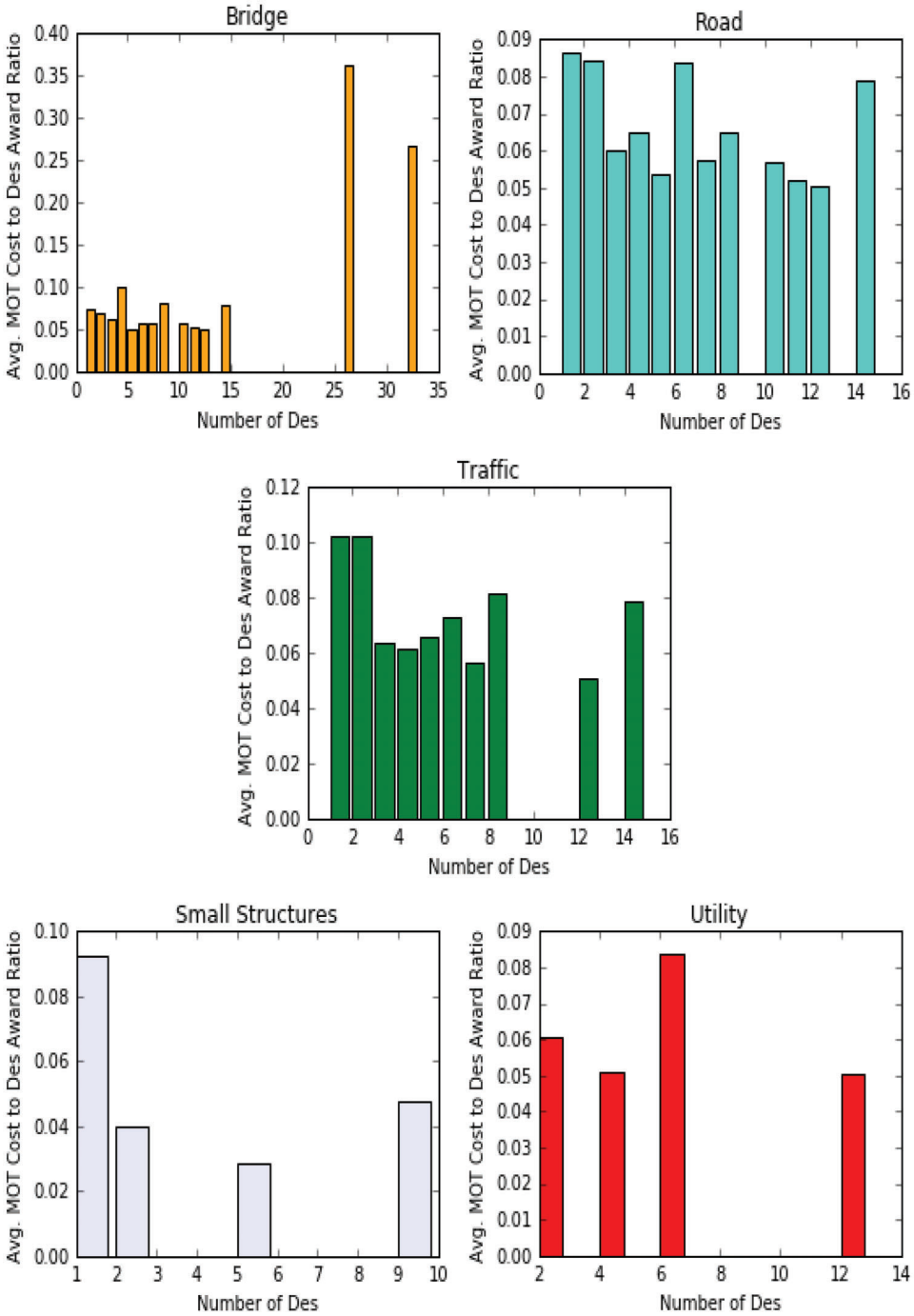


Figure 4.37 Comparison of MOT cost ratio for projects along the US 31 corridor.

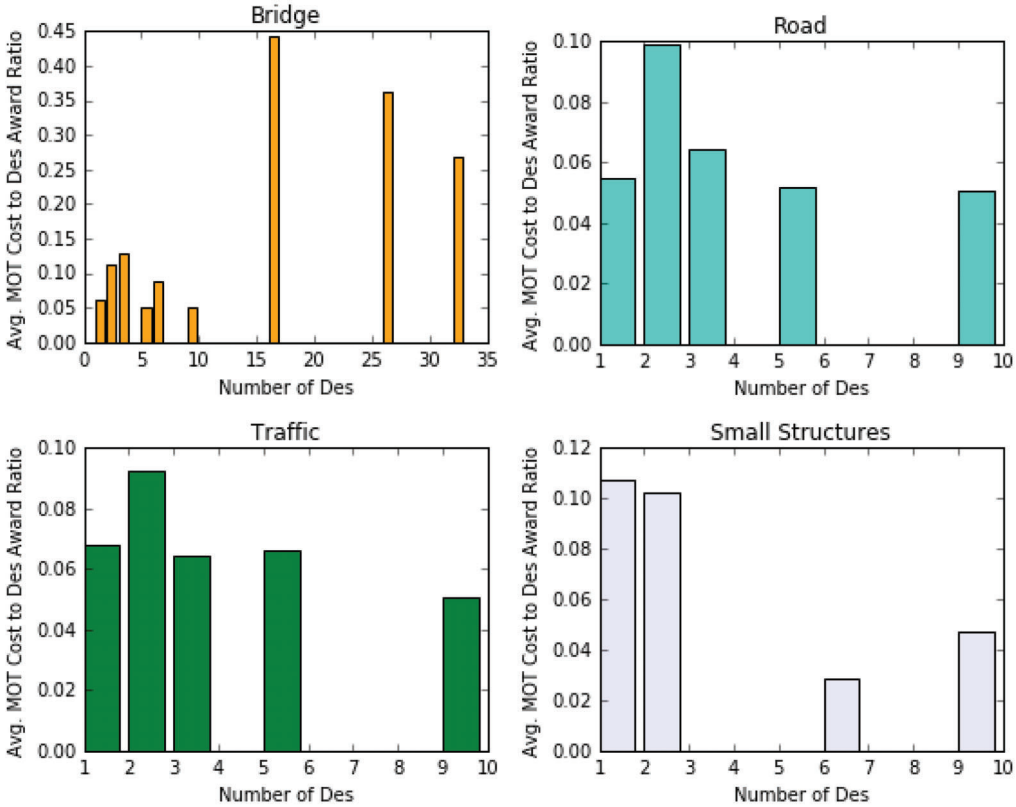


Figure 4.38 Comparison of MOT cost ratio for projects along the US 24 corridor.

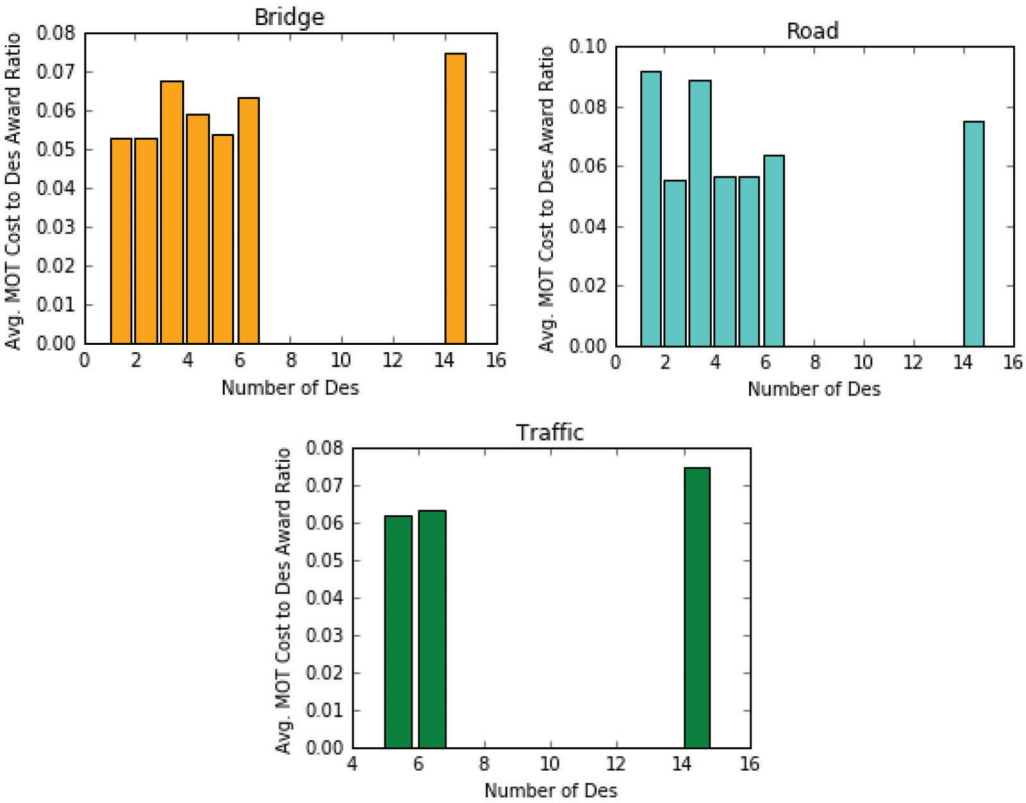


Figure 4.39 Comparison of MOT cost ratio for projects along the SR 25 corridor.

TABLE 4.17
Number of Des with Min and Max MOT Cost Ratio at Different Corridors

Corridor (Route)	Work Category	Counts	Nr of Des with Min MOT Cost Ratio	Min MOT Cost Ratio (%)	Nr of Des with Max MOT Cost Ratio	Max MOT Cost Ratio (%)
I-65	Bridge	12	7	6.3	14	37.1
	Traffic	5	2	4.2	1	11.8
	Road	8	6	2.1	1	13.4
	Small Structure	7	3	2.5	4	7.6
I-69	Bridge	13	10	4.5	16	44.3
	Traffic	6	2	3.0	12	10.5
	Road	8	10	4.5	1	14.9
	Small Structure	6	8	2.1	1	8.3
I-70	Bridge	12	3	6.1	32	43.0
	Traffic	4	7	2.9	4	10.6
	Road	6	7	2.9	1	9.9
	Small Structure	3	2	2.1	1	6.7
I-465	Bridge	8	13	6.8	9	40.5
	Traffic	5	14	5.8	5	9.2
	Road	8	14	5.8	1	14.7
	Small Structure	3	2	3.6	1	9.6
US 31	Bridge	14	12	5.1	26	36.2
	Traffic	10	12	5.1	2	10.3
	Road	12	12	5.1	1	8.6
	Small Structure	4	5	2.9	1	9.3
	Utility	4	12	5.1	6	8.4
US 24	Bridge	9	9	5.0	16	44.3
	Traffic	5	9	5.0	2	9.2
	Road	5	9	5.0	2	9.9
	Small Structure	4	6	2.8	1	10.7
US 25	Bridge	7	2	5.3	14	7.5
	Traffic	3	5	6.2	14	7.5
	Road	7	2	5.5	1	9.2
	Small Structure	2	1	7.0	3	11.2

5. COST MODELS

The use of an average number (Section 4.1) to represent the unit cost of a project is easy and convenient. However, this approach is suitable only in aggregate cost estimation at the network-level for planning purposes. This is because using the average cost tends to be unreliable in estimating individual project cost because of economies of scale and the large variation in site conditions across different project locations. Therefore, to estimate expected cost of an individual project, it is preferable to develop statistical cost models that incorporate, as explanatory variables, the project size and other influential variables.

This chapter describes the regression modeling process for estimating the project costs (Section 5.1.1) and maintenance of traffic (MOT) costs (Section 5.2.1). The overall project cost, marginal effect and sensitivity analysis are presented in Section 5.1.2. This is followed by the threshold analysis and confidence band estimation in Section 5.1.3. The marginal effect and sensitivity analysis for the MOT cost and MOT cost ratio are presented in Section 5.2.2, followed by a hypothetical case study of MOT cost estimation in Section 5.2.3. The models developed in this chapter can be used to predict project cost and to analyze bundling strategies as demonstrated in Chapter 6.

5.1 Project Overall Cost Model

5.1.1 Developed Cost Models

5.1.1.1 Bridge Work Cost Model. A model can be developed for the total project cost (Des Award) or the unit cost (Des Award/Project Size). Any one of these models can be derived from the other. In this section, both models (total cost and unit cost) are developed using several alternative functional forms for each. An intrinsically linear equation with logarithm transformation of each variable was finally selected (Equation 5.1). This equation can be transformed into a power function form, as shown in Equation 5.2. For bridge project types, it was found that the total cost model generally yields superior results compared to the unit cost model. Therefore, the regression model was built first for the

total cost (Des Award) and then transformed into a unit cost model by dividing the estimated Des Award amount by the bridge deck area (Equation 5.3).

$$ln(Des\ Award) = \beta_0 + \sum_{i=1}^{N} \beta_i * ln(V_i) \quad (5.1)$$

$$Des\ Award = e^{\beta_0} * \Pi_{i=1}^{N} V_i^{\beta_i} \quad (5.2)$$

$$Unit\ Cost = \frac{e^{\beta_0} * \Pi_{i=1}^{N} V_i^{\beta_i}}{Deck\ Area} = e^{\beta_0} * V_1^{\beta_1 - 1} * \Pi_{i \neq 1}^{N} V_i^{\beta_i} \quad (5.3)$$

where β_i is a parameter of the estimated coefficients, and V_i is the ith influential variable, N is the number of variables included in the model.

All the preliminary variables discussed in Section 4.2 were tested in the regression model, but only those found to be statistically significant and intuitive were kept in the model. A new variable was coined to represent the compatibility (similarity) between projects bundled in a contract. This variable, the Average Similarity Distance (ASD), is calculated as the ratio of the sum of the similarity distances (obtained in Section 4.4) between each pair of project types in the contract, to the total number of pairs.

Tables 5.1 presents the statistical models for total cost (Des Award) that were developed for 8 bridge project types. The models can be used to predict the total cost of a project and an example of the model is provided for Bridge Deck Overlay. The equation of the total cost model for Bridge Deck Overlay is shown in Equation 5.4 and the estimated coefficients are presented in Table 5.1. The equation can then be transformed into Equation 5.5 by taking the exponent of both sides of the equation. The Des Award of a Bridge Deck Overlay project can be estimated using Equation 5.5 by plugging in the values of the model variables (e.g., Deck Area, Nr of Des, Nr of Bids, ADT and Average Similarity Distance). The total cost model ($) can be easily transformed into a unit cost model ($/ft^2) (Equation 5.6) by dividing both sides of Equation 5.5 by the deck area.

$$ln(Des\ Award) = 9.823 + [0.428 * ln(Deck\ Area)] - [0.297 * ln(Nr\ of\ Des)] - [0.311 * ln(Nr\ of\ Bids)] + [0.01 * ln(ADT)] + [0.032 * ln(ASD)] \quad (5.4)$$

$$Des\ Award = e^{9.823} * Deck\ Area^{0.428} * Nr\ of\ Des^{-0.297} * Nr\ of\ Bids^{-0.311} * ADT^{0.01} * ASD^{0.032} \quad (5.5)$$

$$Unit\ Cost = \frac{Des\ Award}{Deck\ Area} = e^{9.823} * Deck\ Area^{0.428-1} * Nr\ of\ Des^{-0.297} * Nr\ of\ Bids^{-0.311} * ADT^{0.01} * ASD^{0.032} \quad (5.6)$$

As their representative explanatory variables suggest (Table 5.1), all the three major phenomena—economies of scale (Deck Area), economies of bundling (Nr of Des) and economies of competition (Nr of Bids)—are statistically significant, with intuitive signs for most project types (except B8). The deck area, as expected, is the most significant variable for all project types. The sign of the deck area is positive, but less than one. This means the project cost (Des Award) will increase at a decreasing rate as project size increases; and the unit cost will decrease as the project gets larger. Across all project types, the *Nr of Des* variable has a negative sign, indicating that generally, the more kins a bridge project is bundled with, the lower the overall cost of the bridge project cost. It means that the bridge project types can greatly benefit from project bundling in terms of cost savings. This is consistent with the average cost comparison results in Section 4.1. The Nr of Bids variable also has a negative sign, which means a higher number of bidders (higher market competition) can lead to a statistically significant reduction in project cost.

The model results also showed that across all the bridge project types, the three major variables representing the cost savings phenomena, particularly, project size, dominate the effects on project cost. Other variables, such as traffic loads and project compatibility, were found to be not very significant. The variable Average Similarity Distance (ASD) was somewhat significant, with a positive sign, for the following project types: New Bridge, Superstructure Replacement, Deck Replacement, Bridge Deck Overlay and Thin Deck Overlay. This indicates that the smaller the similarity distance (higher similarity) between projects bundled in a contract, the lower the project cost. The traffic load variable (ADT) was found to be significant with a positive sign only for Bridge Deck Overlay and Thin Deck Overlay indicating that the cost of these project types is generally higher for bridges that have high traffic volumes.

The r-squared metric included in Table 5.1 is a good measure of model performance. It tells how much variation in the data can be explained by the model. Among the eight bridge project types, New Bridge and Deck Replacement have the highest r-squared values (more than 0.5), while bridge deck overlay and thin deck overlay have relatively low r-squared values (less than 0.3). To show more clearly how the models fit the actual data, scatter plots of total project cost (Des Award) versus deck area are provided in Figure 5.1. The actual data are shown by red circles and predicted values are indicated with black triangles. The scatter plots suggest that the model explains most of the variation in the middle ranges of the cost data but do not fit the data well when the costs are very high or very low. The variation that is not explained by the model might be arising from some other variables that are not available in the current dataset or due to outliers in the data.

Figure 5.2 presents the predicted unit cost (Des Award/deck area) which are estimated by plugging in the model, the actual data for bridge project types B1, B6 and B7, to show how the estimated unit cost decreases

TABLE 5.1
Total Cost Models for Bridge Project Types (2015$)

Variables	Parameter	Coefficients	T-values	p-values	r-squared
	B1-New Bridge (209 Observations)				
Constant	β_0	8.677	13.638	4.20E-27	0.589
Deck Area	β_1	0.72	11.732	2.64E-22	0.589
Nr of Des	β_2	-0.389	-6.071	1.23E-08	0.589
Nr of Bids	β_3	-0.062	-1.424	2.73E-01	0.589
Average Similarity Distance	β_4	0.067	1.61	1.10E-01	0.589
	B2-Bridge Replacement (155 Observations)				
Constant	β_0	8.734	20.815	3.23E-46	0.579
Deck Area	β_1	0.67	14.355	5.12E-30	0.579
Nr of Des	β_2	-0.117	-2.355	1.98E-02	0.579
Nr of Bids	β_3	-0.041	-1.417	2.78E-01	0.579
	B3-Superstructure Replacement (54 Observations)				
Constant	β_0	9.265013	6.664506	3.12E-07	0.43021
Deck Area	β_1	0.632265	4.469077	1.18E-04	0.43021
Nr of Des	β_2	-0.10576	-1.7238	1.48E-01	0.43021
Nr of Bids	β_3	-0.31319	-1.91032	6.64E-02	0.43021
Average Similarity Distance	β_4	0.021	1.348	1.73E-01	0.43021
	B4-Deck Replacement (68 Observations)				
Constant	β_0	7.648	9.391	1.37E-13	0.533
Deck Area	β_1	0.746	8.483	5.11E-12	0.533
Nr of Des	β_2	-0.047	-1.753	1.54E-01	0.533
Nr of Bids	β_3	-0.242	-2.06	4.36E-02	0.533
Average Similarity Distance	β_4	0.014	1.391	1.97E-01	0.533
	B5-Bridge Widening (48 Observations)				
Constant	β_0	9.342	6.265	2E-07	0.319
Deck Area	β_1	0.593	3.787	5.03E-04	0.319
Nr of Des	β_2	-0.159	-1.767	8.48E-02	0.319
Nr of Bids	β_3	-0.299	-1.724	9.24E-02	0.319
	B6-Bridge Deck Overlay (319 Observations)				
Constant	β_0	9.823	19.319	2.71E-55	0.263
Deck Area	β_1	0.428	8.112	1.14E-14	0.263
Nr of Des	β_2	-0.297	-4.592	6.38E-06	0.263
Nr of Bids	β_3	-0.311	-4.194	3.57E-05	0.263
ADT	β_4	0.01	1.259	1.80E+00	0.263
Average Similarity Distance	β_5	0.032	1.339	2.00E-01	0.263
	B7-Thin Deck Overlay (155 Observations)				
Constant	β_0	9.658	10.571	7.76E-20	0.231
Deck Area	β_1	0.352	3.737	2.65E-04	0.231
Nr of Des	β_2	-0.503	-5.068	1.18E-06	0.231
Nr of Bids	β_3	-0.337	-2.099	3.75E-02	0.231
ADT	β_4	0.04	1.15	2.52E-01	0.231
Average Similarity Distance	β_5	0.06	1.241	2.16E-01	0.231
	B8-Misc. Bridge Rehab & Repair (462 Observations)				
Constant	β_0	9.196	18.862	3.58E-59	0.471
Deck Area	β_1	0.354	6.839	2.56E-11	0.471
Nr of Des	β_2	-0.721	-17.271	7.36E-52	0.471

with increasing deck area (of different Nr of Des's using different colors) and also with increasing number of des (of different deck areas using different colors).

5.1.1.2 Road Work Cost Model. Cost models were then developed for projects in the road work category. For road projects, the project size is measured by

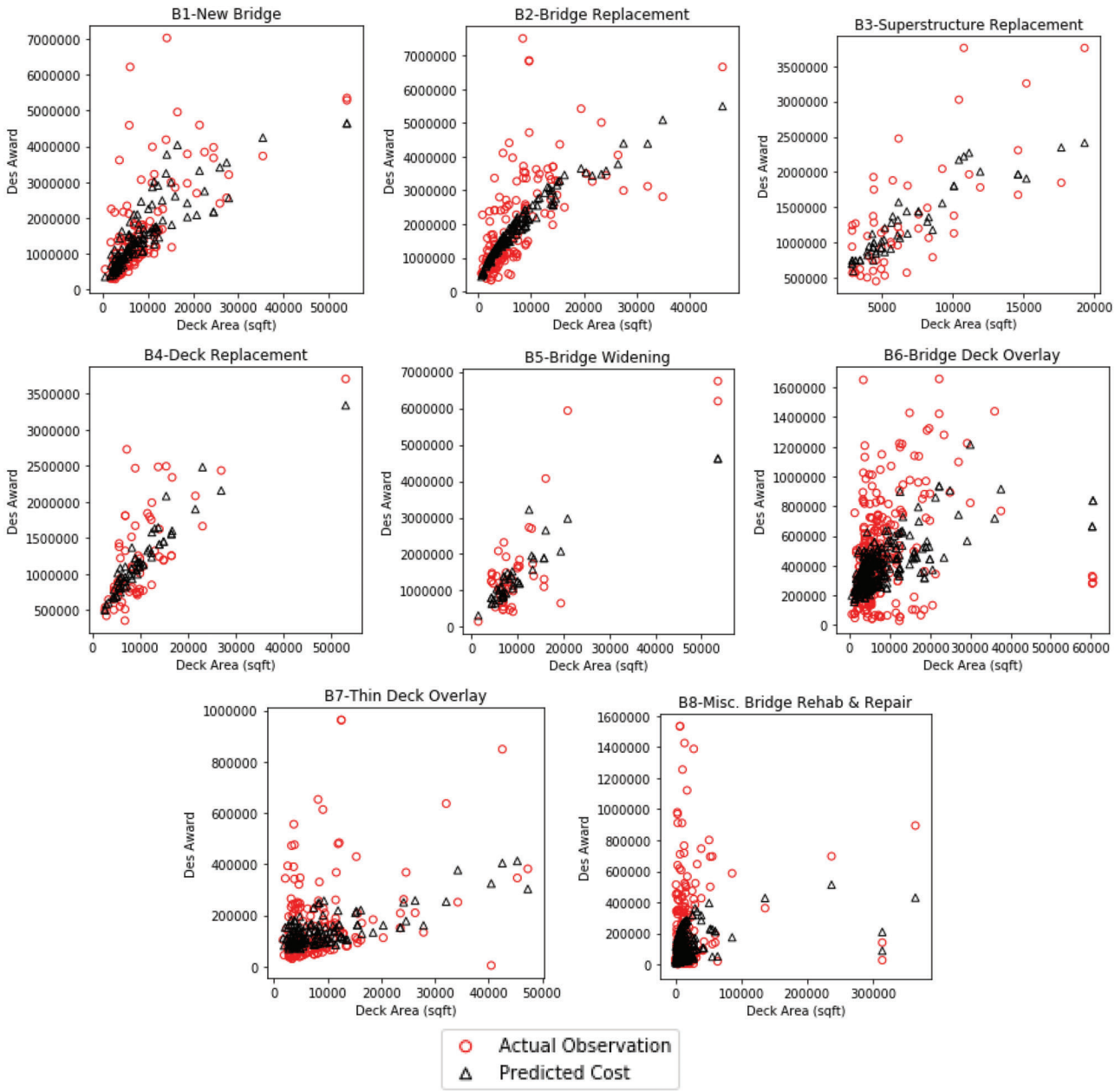


Figure 5.1 Actual and predicted Des Award ($) for bridge work (model performance).

project length and number of lanes. Therefore, the unit cost of a road project ($ per lane-mile) is calculated using the project cost (Des Award) divided by the project area (length by number of lanes). Again, models with unit cost and total cost as the dependent variable were developed for each project type. For road work, the unit cost models generally yielded superior results. The functional form used for regression is shown in Equation 5.7. It can be transformed into Equation 5.8 by taking the exponent of both sides. Using Equation 5.9, the Des Award can be estimated by plugging in the model, the actual or assumed values of the explanatory variables.

$$ln(Unit\,\mathrm{Cost}) = \beta_0 + \sum_{i=1}^{N} \beta_i * ln(V_i) \tag{5.7}$$

$$Unit\ Cost = e^{\beta_0} * \Pi_{i=1}^{N} V_i^{\beta_i} \tag{5.8}$$

$$Des\ Award = e^{\beta_0} * \Pi_{i=1}^{N} V_i^{\beta_i} * Project\ Length * Nr\ of\ Lanes \tag{5.9}$$

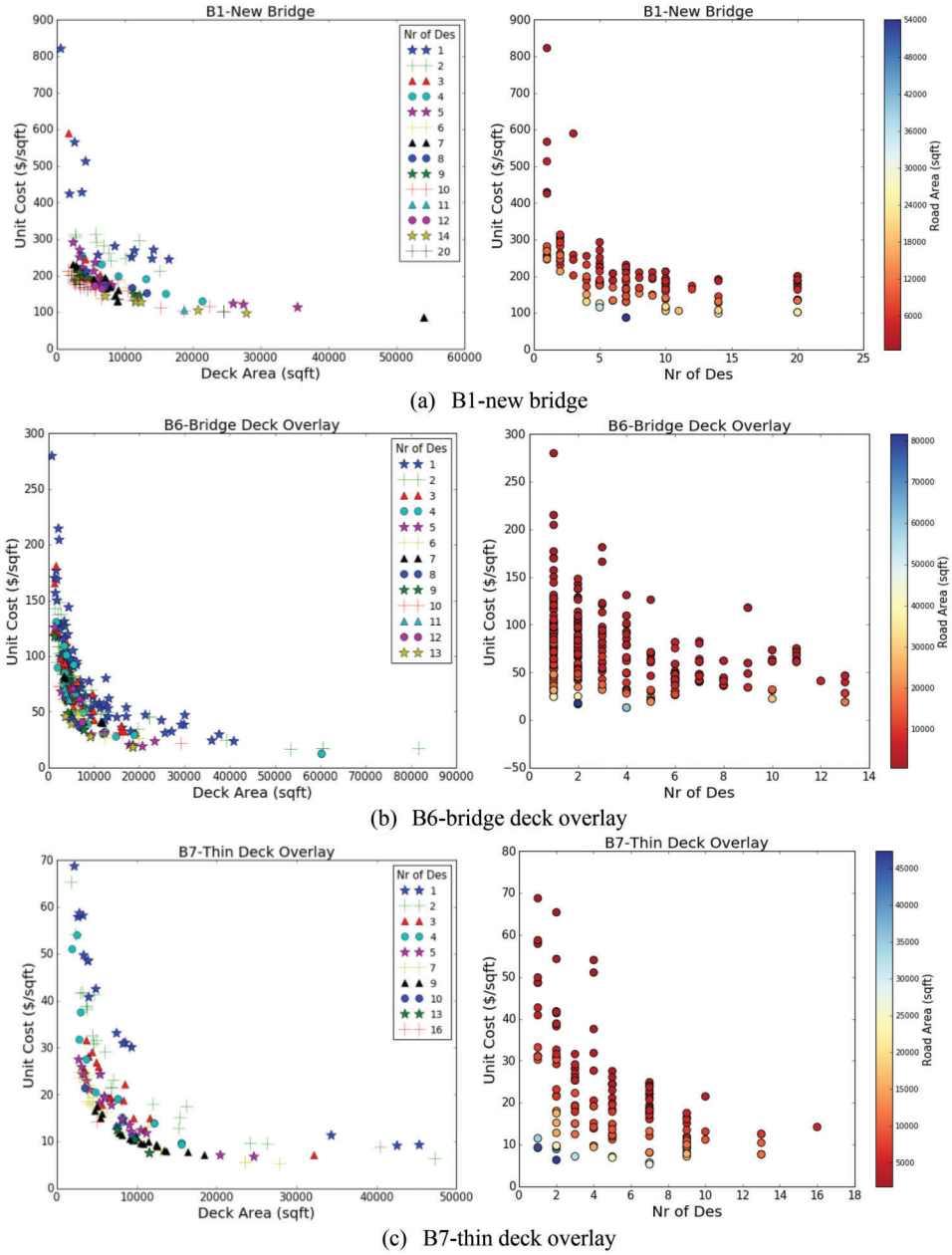


Figure 5.2 Predicted unit cost ($/sqft) for bridge work using the developed model.

The regression results are shown in Table 5.2 for the eight road project types for which there were adequate observations for model development. The variables Project Length and Nr of Lanes were both found to have negative signs, which means the unit cost of a project decreases as the project size increases (economies of scale). The variable Nr of Des, which accounts for the economies of bundling, is significant (with a negative sign) for only the following road project types: R3-Patch & Rehab Pavement, R4-Partial 3, and R7-Sight Distance Correction. This means that the unit cost of these three project types can often be reduced by project bundling. This bundling benefit was not found for other road project types because the variable Nr of Des is not significant. As discussed before, this might be because, for road projects, the economies of scale, compared to two other phenomena, have a more dominant effect on project cost. Therefore, having a very large single-project contract might be superior to (have lower total cost than) bundling several small projects into one contract, particularly when the constituent projects are very dissimilar (as indicated by the variable ASD in the developed model).

The Average Similarity Distance (ASD) variable turned out to be clearly significant for all road project types (except R1), with a positive sign. This indicates that a smaller average similarity distance (i.e., a higher similarity) between projects in a bundled contract can lead to,

TABLE 5.2
Project Overall Cost Regression Model Results for Road Work (2015$)

Variables	Parameter	Coefficients	T-values	p-values	r-squared
	R1-New Road Construction (42 Observations)				
Constant	β_0	16.58621	40.15322	9.91E-33	0.787
Project Length	β_1	-0.91215	-10.0173	3.25E-12	0.787
Nr of Lanes	β_2	-1.09047	-2.98315	4.96E-03	0.787
Average Similarity Distance	β_3	0.079946	0.596578	2.54E-01	0.787
	R2-Added Travel Lanes (50 Observations)				
Constant	β_0	16.00258	19.09572	3.27E-23	0.422
Project Length	β_1	-0.62485	-5.77578	6.71E-07	0.422
Nr of Lanes	β_2	-0.17293	-0.56719	5.73E-01	0.422
Nr of Bids	β_3	-0.32794	-1.79996	1.28E-01	0.422
Average Similarity Distance	β_4	0.484847	4.932147	1.15E-05	0.422
	R3-Patch & Rehab Pavement (114 Observations)				
Constant	β_0	13.60448	21.8656	1.83E-41	0.650
Project Length	β_1	-0.74738	-10.2265	1.42E-17	0.650
Nr of Lanes	β_2	-0.10298	-0.40467	6.87E-01	0.650
Nr of Des	β_3	-1.20922	-10.1557	2.06E-17	0.650
Nr of Bids	β_4	-0.42284	-1.92223	5.72E-02	0.650
Average Similarity Distance	β_5	0.233723	1.94238	5.47E-02	0.650
	R4-Partial 3 (620 Observations)				
Constant	β_0	12.80629	66.08821	2.57E-281	0.395
Nr of Lanes	β_1	-0.08097	-1.17615	2.40E-01	0.395
Project Length	β_2	-0.49956	-19.579	1.09E-66	0.395
Nr of Des	β_3	-0.07358	-0.85708	3.92E-01	0.395
Average Similarity Distance	β_4	0.115291	3.407832	6.98E-04	0.395
	R5-Road Rehabilitation (3R/4R) (38 Observations)				
Constant	β_0	15.2587	50.98071	1.05E-33	0.617
Project Length	β_1	-0.47769	-5.65551	2.41E-06	0.617
Nr of Lanes	β_2	-0.7808	-3.0379	4.55E-03	0.617
Average Similarity Distance	β_3	0.223835	4.365582	1.12E-04	0.617
	R6-Wedge & Level Only (19 Observations)				
Constant	β_0	13.816	10.36719	5.97E-08	0.744
Project Length	β_1	-0.5781	-6.36999	1.74E-05	0.744
Nr of Lanes	β_2	-1.31196	-2.60729	2.07E-02	0.744
Average Similarity Distance	β_3	0.247966	1.805865	9.25E-02	0.744
	R7-Sight Distance Correction (20 Observations)				
Constant	β_0	15.52708	9.399783	1.12E-07	0.400
Project Length	β_1	-0.06074	-0.21325	8.34E-01	0.400
Nr of Lanes	β_2	1.804219	1.909103	7.56E-02	0.400
Nr of Des	β_3	-2.84445	-2.5148	2.38E-02	0.400
Average Similarity Distance	β_4	0.593537	1.822249	8.84E-02	0.400
	R10-Pavement Replacement (152 Observations)				
Constant	β_0	14.02731	76.65026	5.17E-121	0.593
Project Length	β_1	-0.57118	-10.6084	6.60E-20	0.593
Nr of Lanes	β_2	-0.168497	-1.089297	2.78E-01	0.593
Average Similarity Distance	β_3	0.221229	7.609775	2.96E-12	0.593

on average, a lower project cost. This means that the benefits of project bundling in road work are more evident when projects of similar types are bundled. The Nr of Bids variable was found to be significant (with a negative sign) only for two project types: R2-Added Travel Lanes and R3-Patch & Rehab Pavement. This means that for most road project types, market competition does not have a significant impact on the project cost.

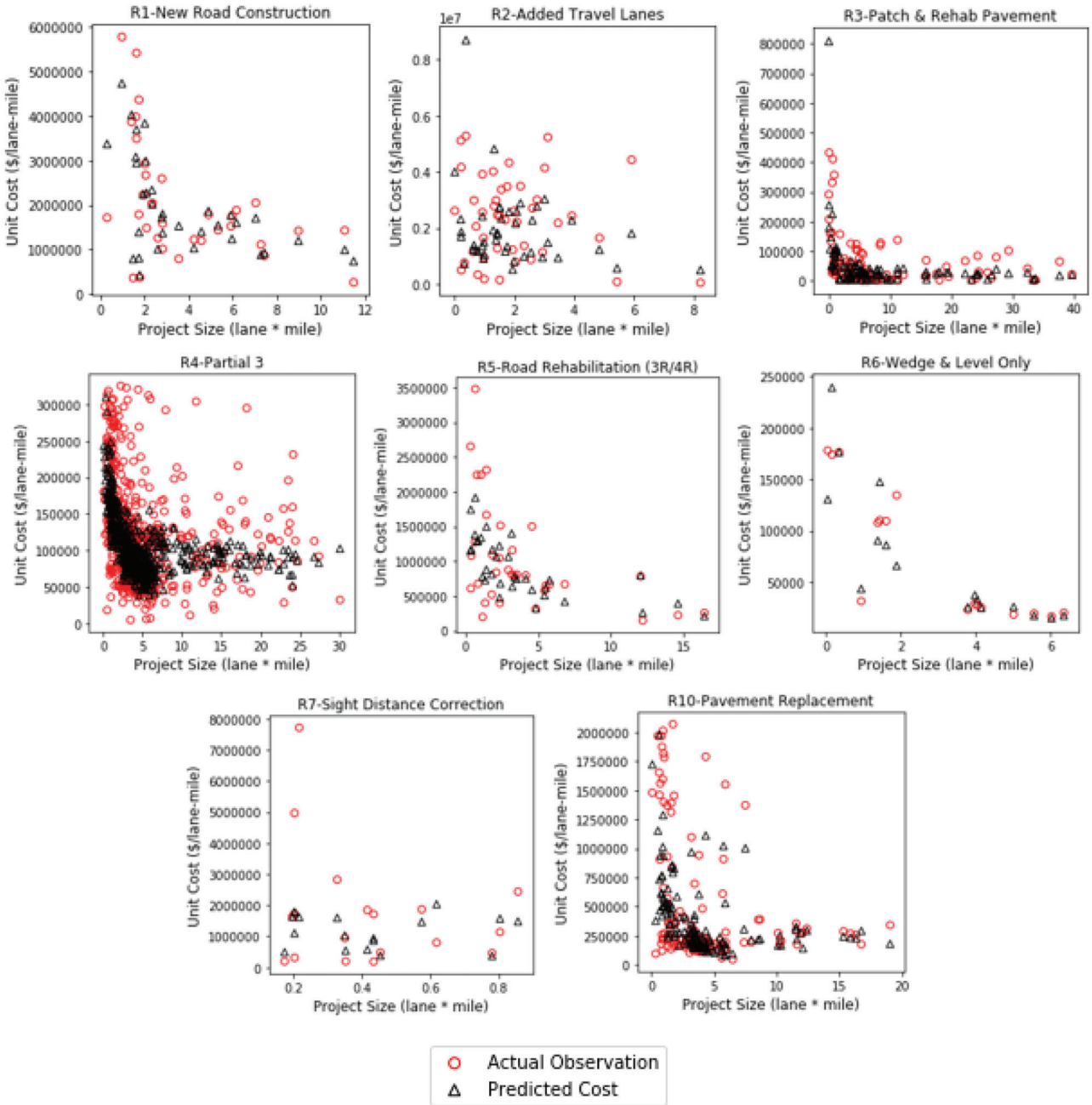


Figure 5.3 Road work model performance—actual vs. predicted unit costs ($/lane-mile).

To show how the models developed for unit cost versus project size fit the actual data, scatter plots that compare the actual unit cost (red circles) and the predicted unit cost (black triangles) for specific project sizes (Project Length * Nr of Lanes) are provided in Figure 5.3. The unit cost models generally fit the actual observations very well.

5.1.1.3 Cost Models for Traffic and Miscellaneous Work. With regard to traffic and miscellaneous work, statistical cost models were developed only for the following project types: T2-Signing, T3-Traffic Signals, M1-Demolition, M2-Channel and Ditch Work, and M4-Slide Correction. For the other project types, the sample size was not adequate to develop regression models. The unit cost models yielded superior results compared to the total cost models; and therefore were selected. The functional form is same as that used for road work (Equation 5.8). For both traffic and miscellaneous work, the project unit cost is measured by cost per mile, and therefore the economies of scale effect was investigated on the basis of the project length. From the regression results (Table 5.3 and Table 5.4), the project length is the most significant of the independent variables for all project types. The negative sign of its coefficient indicates that the greater the project length, the lower the

TABLE 5.3
Project Unit Cost Regression Model Results for Traffic Work (2015$)

Variables	Parameter	Coefficients	T-values	p-values	r-squared
	T2-Signing (70 Observations)				
Constant	β_0	12.595698	14.994776	8.84E-23	0.749
Project Length	β_1	-0.895899	-11.374374	4.15E-17	0.749
Nr of Lanes	β_2	1.386411	3.511715	8.15E-04	0.749
Nr of Des	β_3	-0.886908	-2.463035	1.64E-02	0.749
Nr of Bids	β_4	-0.555602	-2.380139	2.02E-02	0.749
	T3-Traffic Signals (87 Observations)				
Constant	β_0	12.6846	23.548905	5.51E-38	0.853
Project Length	β_1	-0.855045	-22.260411	2.88E-36	0.853
Nr of Lanes	β_2	0.66872	2.56057	1.23E-02	0.853
Nr of Des	β_3	-0.492623	-3.08659	2.77E-03	0.853
Nr of Bids	β_4	-0.139291	-1.598054	2.51E-01	0.853
Average Similarity Distance	β_5	0.241562	3.833454	2.49E-04	0.853

TABLE 5.4
Project Unit Cost Regression Model Results for Miscellaneous Work (2015$)

Variables	Parameter	Coefficients	T-values	p-values	r-squared
	M1-Demolition (37 Observations)				
Constant	β_0	14.874893	6.671872	1.58E-07	0.746
Project Length	β_1	-0.925085	-8.38409	1.40E-09	0.746
Nr of Lanes	β_2	1.666484	2.258367	3.09E-02	0.746
Nr of Bids	β_3	-0.579143	-0.89474	3.78E-01	0.746
Average Similarity Distance	β_4	0.932698	2.186588	3.62E-02	0.746
	M2-Channel and Ditch Work (23 Observations)				
Constant	β_0	15.665892	6.577817	0.000005	0.585
Project Length	β_1	-0.878132	-5.50769	0.000038	0.585
Nr of Des	β_3	-1.442479	-2.56193	0.020207	0.585
Nr of Bids	β_4	-0.788366	-0.92534	0.367741	0.585
Average Similarity Distance	β_5	0.448552	1.245293	0.229916	0.585
	M4-Slide Correction (19 Observations)				
Constant	β_0	14.449247	10.3386	3.22E-08	0.381
Project Length	β_1	-0.982487	-3.1312	6.87E-03	0.381
Nr of Des	β_2	-0.664148	-1.6421	1.21E-01	0.381
Average Similarity Distance	β_3	0.246388	0.752226	4.64E-01	0.381

unit cost would typically be. The variable Nr of Lanes is significant for T2, T3 and M1, but not significant for M2 and M4, because these project types are not affected by the number of lanes. The variable *Nr of Des* is significant for most project types (except M1) and has a negative sign. This suggests that project bundling is beneficial for most traffic and miscellaneous project types, in terms of reducing project costs. This is consistent with the results of average cost comparisons presented in Section 4.1. The variable Nr of Bids is found to be somewhat (but not very) significant for most project types (except M4), but generally indicated a positive impact of market competition in reducing the unit cost of the project. Figure 5.4 presents, for five project types, how the unit cost model fits the actual observations.

5.1.2 Marginal Effect and Sensitivity Analysis

5.1.2.1 Bridge Work Costs. As mentioned previously, the variables representing all three major phenomena that influence cost savings (economies of scale, economies of bundling, and economies of competition) were found to be intuitive and statistically significant in the cost models of most bridge project types. In this section, the effect of each of these phenomena is given closer scrutiny by computing the average marginal effects and conducting sensitivity analysis. This was done for each bridge project type.

Marginal effect is a measure of the instantaneous effect that a change in a particular explanatory variable has on the depended variable, when the other covariates are kept fixed. The marginal effect of an

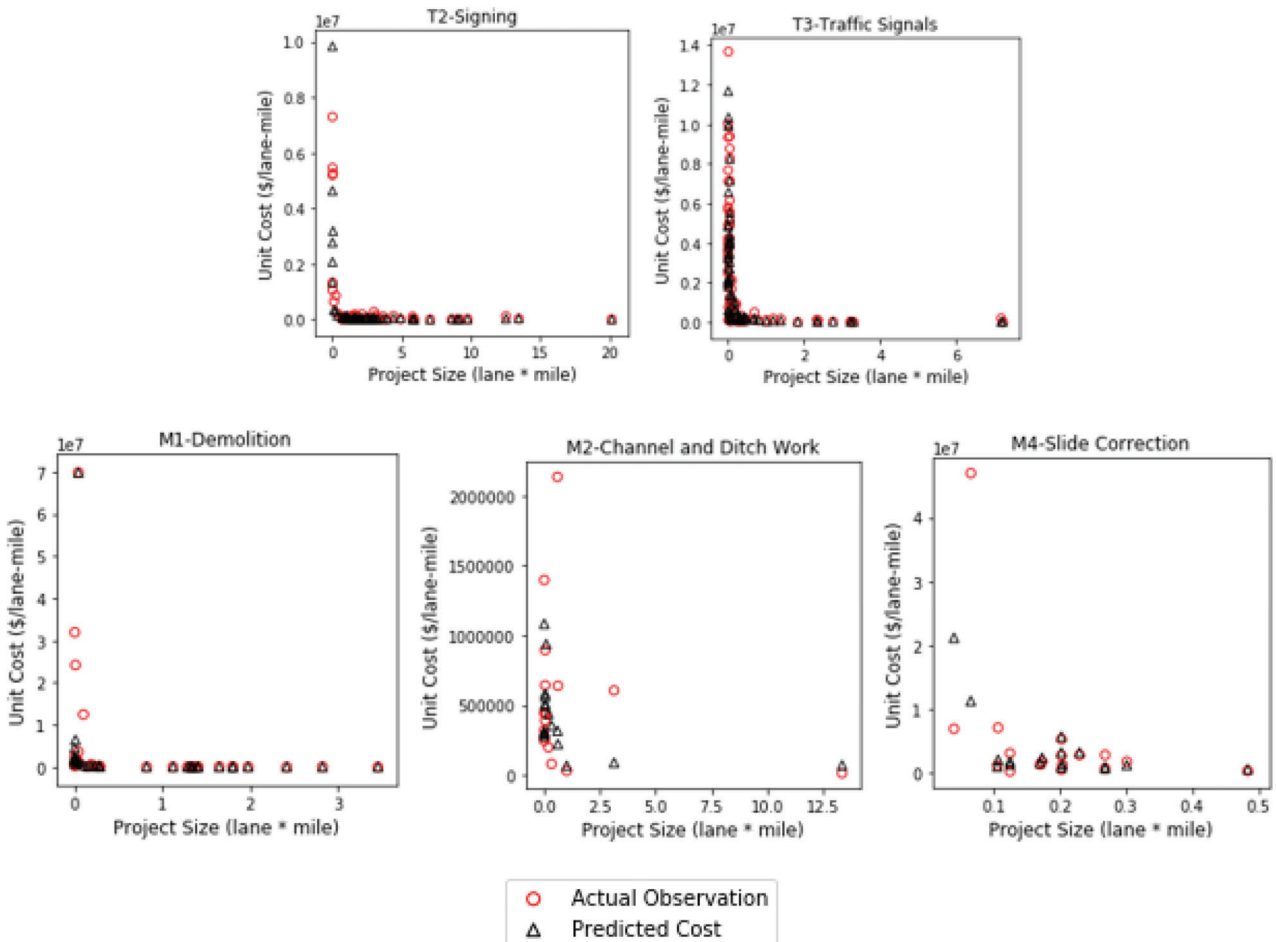


Figure 5.4 Actual and predicted unit cost ($/mile) for traffic and miscellaneous project types.

explanatory variable is obtained by computing the derivative of the conditional mean function with respect to that variable. For bridge work, the marginal effects of the three phenomena (economies of scale in terms of Deck Area, economies of bundling in terms of Nr of Des, and economies of competition in terms of Nr of Bids) were computed for each project type. The equations for computing the marginal effects of these variables on the project cost (Des Award) are shown in Equations 5.10, 5.11, and 5.12, respectively. The marginal effects on project unit cost can be derived similarly.

$$\frac{\partial\ (Des\ Award)}{\partial\ (Deck\ Area)} = \beta_1 * V_1^{\beta_1 - 1} e^{\beta_0} * \Pi_{i \neq 1}^{N}\ V_i^{\beta_i} \qquad (5.10)$$

$$\frac{\partial\ (Des\ Award)}{\partial\ (Nr\ of\ Des)} = \beta_2 * V_2^{\beta_2 - 1} e^{\beta_0} * \Pi_{i \neq 2}^{N}\ V_i^{\beta_i} \qquad (5.11)$$

$$\frac{\partial\ (Des\ Award)}{\partial\ (Nr\ of\ Bids)} = \beta_3 * V_3^{\beta_3 - 1} e^{\beta_0} * \Pi_{i \neq 3}^{N}\ V_i^{\beta_i} \qquad (5.12)$$

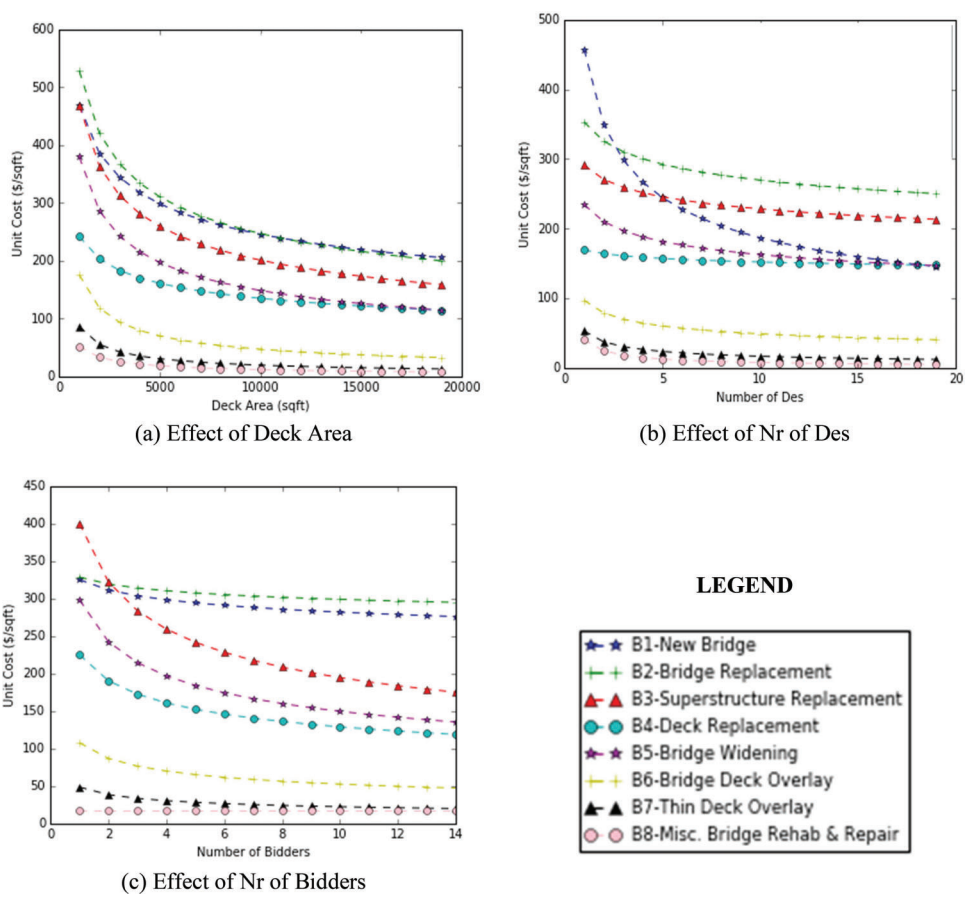
where β_i is the parameter value of the estimated coefficient i, and V_i is i^{th} variable.

The average marginal effects were computed as the average value of the marginal effects of all observations in the samples. Table 5.5 presents the computed average marginal effects of the three major factors on total cost and on unit cost, for the different bridge project types. Bridge Replacement was found to have the largest magnitude of the marginal effects of Deck Area and Nr of Des on the project unit cost (0.015901). The marginal effects of Nr of Bids on the unit cost for Superstructure Replacement was found to be the largest among all bridge project types (10.214815). It can be reasonably inferred that, among the bridge project types, on average, the unit cost of Bridge Replacement is the most sensitive to project size and project bundling, and the unit cost of Superstructure Replacement is the most sensitive to market competition.

Sensitivity analysis was also carried out, using the developed regression models on the three major factors. The results (Figure 5.5) show how the project unit cost changes as the deck area, number of des, and number of bidders increase. Figure 5.5 (a) suggests that the effect of the scale economies on the unit cost are significant

TABLE 5.5
Average Marginal Effects of the Three Major Factors on Bridge Work Costs

Project type	Deck Area	Nr of Des	Nr of Bids
	Average Marginal Effect on Total Des Award (2015$)		
B1-New Bridge	123.034	-61560.741	-14846.369
B2-Bridge Replacement	148.064	-43677.068	-20810.984
B3-Superstructure Replacement	117.664	-48959.310	-88189.545
B4-Deck Replacement	88.244	-15238.720	-61753.441
B5-Bridge Widening	67.715	-36931.552	-103456.906
B6-Bridge Deck Overlay	18.584	-14914.531	-27966.351
B7-Thin Deck Overlay	4.991	-7168.986	-7204.618
B8-Misc. Bridge Rehab & Repair	2.306	-4033.323	0
	Average Marginal Effect on Unit Cost (2015$/sqft)		
B1-New Bridge	-0.007643	-7.955941	-1.918704
B2-Bridge Replacement	-0.012841	-4.123360	-1.964673
B3-Superstructure Replacement	-0.010493	-5.670857	-10.214815
B4-Deck Replacement	-0.002963	-1.308148	-5.301143
B5-Bridge Widening	-0.004113	-2.799603	-7.842568
B6-Bridge Deck Overlay	-0.003104	-1.898110	-3.559161
B7-Thin Deck Overlay	-0.000994	-0.962788	-0.967573
B8-Misc. Bridge Rehab & Repair	-0.000172	-0.539574	0



(a) Effect of Deck Area

(b) Effect of Nr of Des

(c) Effect of Nr of Bidders

Figure 5.5 Sensitivity analysis results for the three major factors.

for all project types. Also, New Bridge, Bridge Replacement, Superstructure Replacement and Bridge Widening have greater decreasing rates of unit cost (as deck area increases) than other bridge project types when the deck area is small. When the deck area is large, this rate of decrease becomes similar. This trend was observed

TABLE 5.6
Average Marginal Effect of Influential Variables for Road Work

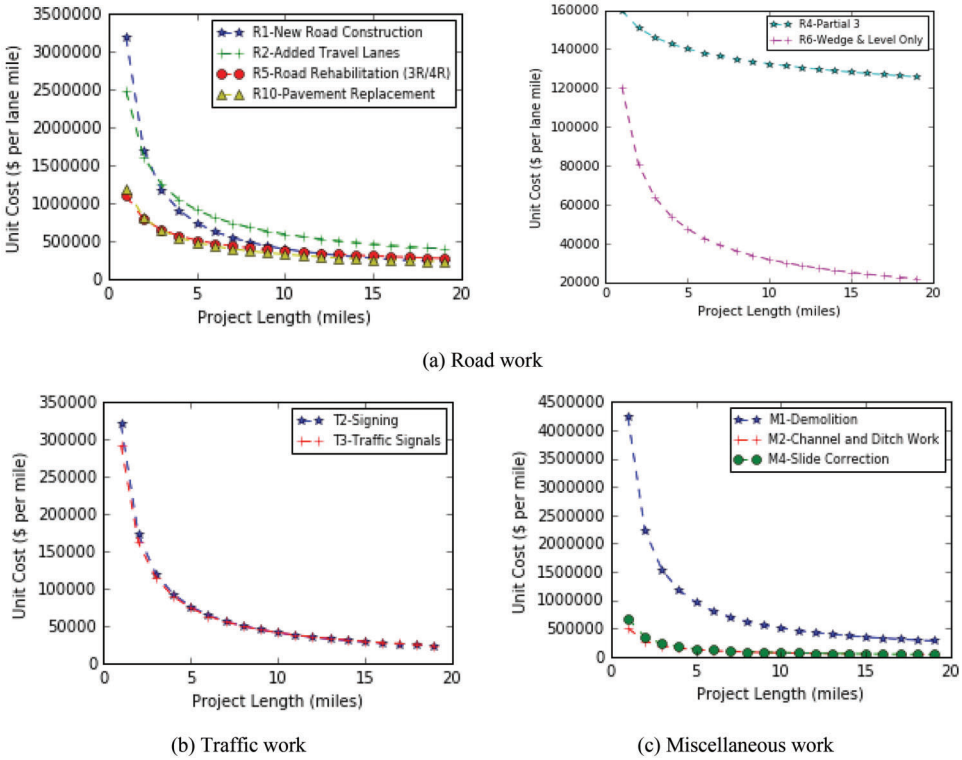
Project Types	Influential Variables				
	Project Length	Nr of Lanes	Nr of Des	Nr of Bids	Average Similarity Distance
	Average Marginal Effect on Total Cost (2015$/sqft)				
R1-New Road Construction	-374591.0	-466161.1	0	0	388303.6
R2-Added Travel Lanes	-513622.2	-85246.8	0	-59211.1	1935485.1
R3-Patch & Rehab Pavement	-1379.3	-639.9	-7840.6	-328.6	14875.6
R4-Partial 3	-2171.9	-23698.0	-3232.0	605.5	44292.1
R5-Road Rehabilitation	-102883.1	-222608.3	0	0	342571.6
R6-Wedge & Level Only	-289412.9	-77173.9	0	0	75871.0
R7-Sight Distance Correction	-144020.1	628223.9	-804723.1	0	1379909.0
R10-Pavement Replacement	-83453.4	36481.9	0	0	256334.8
	Average Marginal Effect on Unit Cost (2015$/sqft)				
R1-New Road Construction	-0.007643	-1.090	0	0	0.080
R2-Added Travel Lanes	-0.012841	-0.173	0	-0.328	0.485
R3-Patch & Rehab Pavement	-0.010493	-0.103	-1.209	-0.423	0.234
R4-Partial 3	-0.002963	-0.500	-0.074	0.062	0.115
R5-Road Rehabilitation	-0.004113	-0.781	0	0	0.224
R6-Wedge & Level Only	-0.003104	-1.312	0	0	0.248
R7-Sight Distance Correction	-0.000994	1.804	-2.844	0	0.594
R10-Pavement Replacement	-0.000172	0.168	0	0	0.221

TABLE 5.7
Marginal Effect of Influential Variables for Traffic and Miscellaneous Work

Project Types	Influential Variables				
	Project Length	Nr of Lanes	Nr of Des	Nr of Bids	Average Similarity Distance
	Average Marginal Effect on Total Des Award (2015$/sqft)				
T2-Signing	-23147.1	28037.9	-7280.2	-5101.2	0
T3-Traffic Signals	-287224.7	57296.4	-23282.1	-11697.6	100612.7
M1-Demolition	-1272651.9	114630874.8	0	-11381.3	202068.6
M2-Channel and Ditch Work	-2256107.4	311166.0	-917243.5	-337579.9	804584.6
M4-Slide Correction	-5931168.2	0	-803882.7	0	1274475.5
	Average Marginal Effect on Unit Cost (2015$/sqft)				
T2-Signing	-0.896	1.386	-0.556	-0.887	0.000
T3-Traffic Signals	-0.855	0.669	-0.493	-0.139	0.242
M1-Demolition	-0.925	1.666	0	-0.579	0.933
M2-Channel and Ditch Work	-0.878	0.489	-1.442	-0.788	0.449
M4-Slide Correction	-0.982	0	-0.664	0	0.246

for all project types. The effects of project bundling and market competition on project unit cost vary greatly across different project types. Among all project types, the New Bridge project type is most significantly affected by the economies of bundling, with a very large decreasing rate of the unit cost with the increasing Nr of Des, while Deck Replacement is only slightly affected by the bundling effect, with a very small decreasing rate. Of all the project types, Superstructure Replacement, Deck Replacement and Bridge Widening benefit most from market competition (high number of bidders) while New Bridge, Bridge Replacement and Misc. Bridge Rehab & Repair are only slightly (or not at all) affected by market competition.

5.1.2.2 Analysis for Other Work Categories (Road, Traffic and Miscellaneous). The average marginal effects of the influential variables on project total cost and unit cost were computed and presented in Tables 5.6 and 5.7 for projects in road, traffic, and miscellaneous work categories. It was noted that among the different road project types the unit cost of New Road Construction and Added Travel Lanes are the most sensitive to project size. The marginal effects of project size on unit cost are



(a) Road work

(b) Traffic work

(c) Miscellaneous work

Figure 5.6 Sensitivity analysis results for project length.

similar for traffic and miscellaneous project types. R7-Sight Distance Correction has the largest magnitude of the marginal effect of Nr of Des on the unit cost (-2.844), which indicates that among all road project types, the unit cost of this project type is the most sensitive to project bundling. Similarly, the unit cost of T2-Signing and M2-Channel and Ditch Work project types were found to be the most sensitive to project bundling among traffic and miscellaneous work, respectively. For the variable Nr of Bids, the unit cost of R2-Added Travel Lanes is much more sensitive to the number of bidders (market competition) than are other road project types. The unit cost of T2-Signing and M2-Channel and Ditch Work were found to be the most sensitive to market competition among traffic and miscellaneous work, respectively. For the variable Average Similarity Distance (which accounts for project compatibility), the unit costs of R7-Sight Distance Correction, T3-Traffic Signals, and M1-Demolition are the most sensitive to the similarity between projects bundled in a contract for road, traffic, and miscellaneous work, respectively.

Project length (economies of scale) and average similarity distance (project compatibility) are influential variables that were found to be significant and intuitive for most project types in the road traffic and miscellaneous work categories. Therefore, sensitivity analysis was carried out for these two variables. It was investigated how the project unit cost is affected by different values of (i) project size and (ii) similarity between projects bundled in a contract. The analysis results are presented in Figure 5.6 and Figure 5.7.

5.1.3 Project Cost Estimation

Sensitivity analysis shows how the unit cost changes with changes in one variable, while all other variables are kept unchanged. However, in the real life, some of these variables are not independent of each other. As discussed previously, the number of bidders is affected by the project size, i.e., a larger project can lead to fewer bidders which means weaker market competition.

Instead of keeping the number of bidders as a constant, this section predicted the number of bidders under different number of des using the two models developed in Section 4.3: the deterministic upper-bound model, which estimates the highest number of bidders, was used for threshold analysis to find the optimal number of des that yielded the lowest project unit cost. In Section 5.2.3, the probabilistic Beta function (which describes the distribution of the number of bidders) was applied to estimate, the unit cost of the project, with 90% confidence bounds.

5.1.3.1 Optimistic Unit Cost Estimation and Threshold Analysis. According to the developed project cost models, the *Number of Des* and *Number of Bidders* both have negative marginal effects on the project unit cost, indicating that an increase in each of the two variables generally leads to a lower project unit cost. However, an increasing number of des can also cause the number of bidders to decrease. Therefore, how the unit cost of a project is affected by these two variables simultaneously

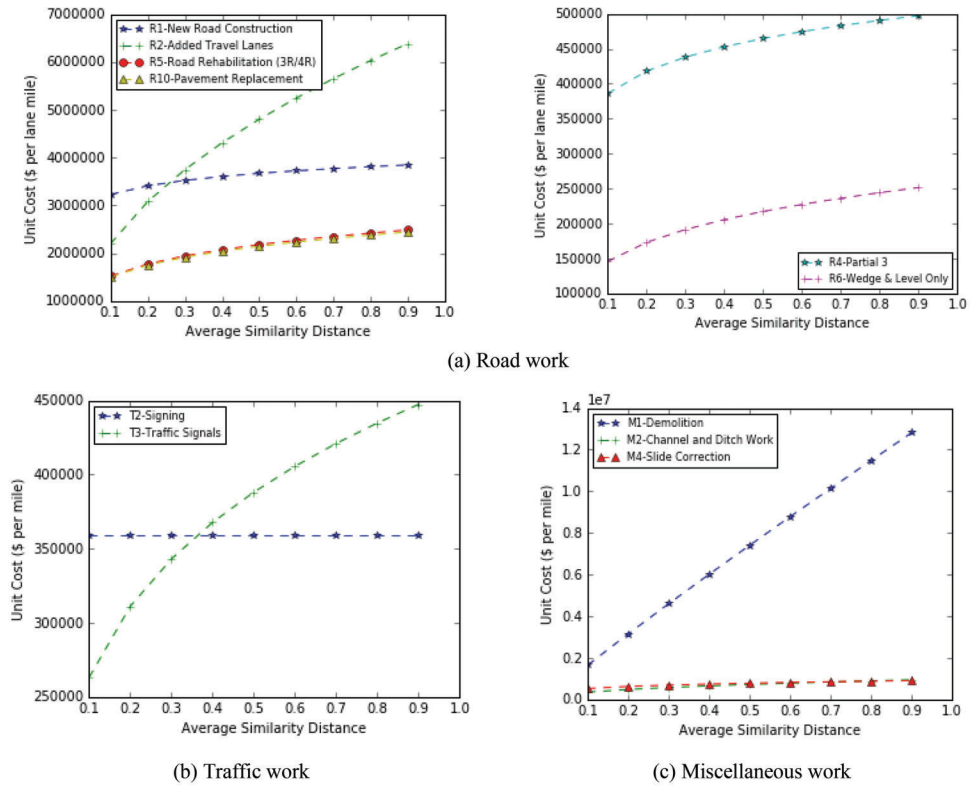


Figure 5.7 Sensitivity analysis results for average similarity distance.

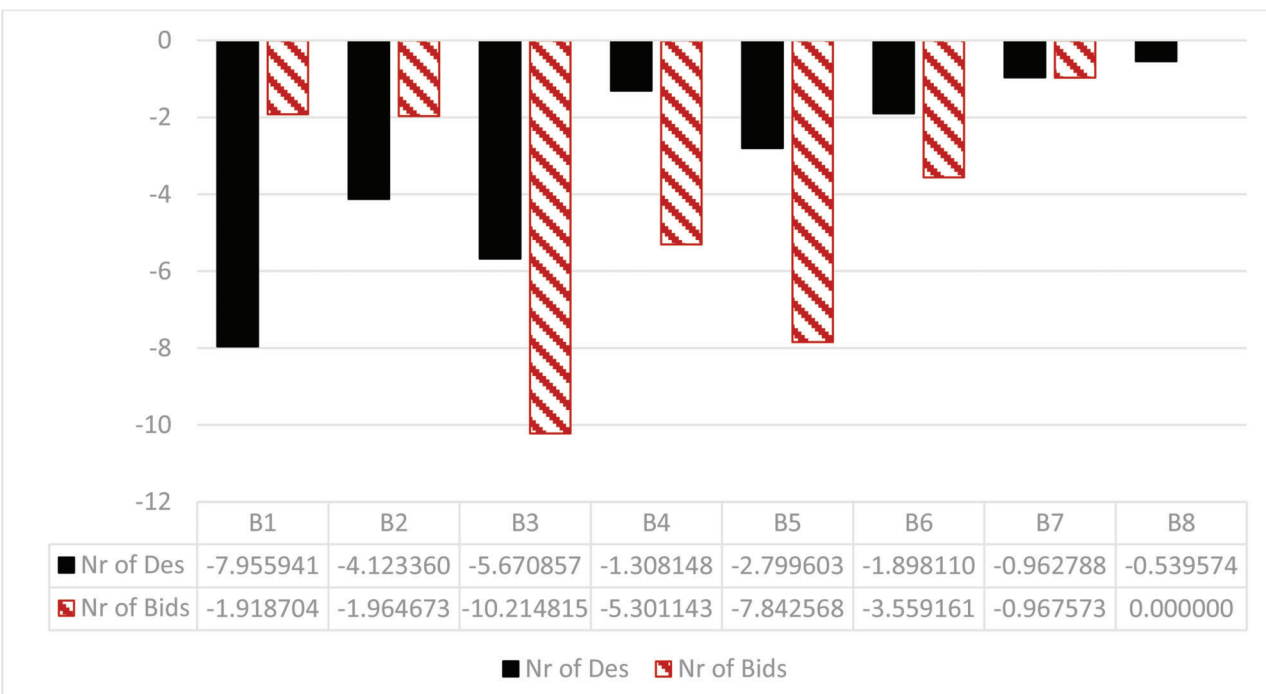


Figure 5.8 Comparison of the marginal effect of Nr of Des and Nr of Bids for different bridge project types.

is determined by not only the marginal effects of the two variables but also by the relationship between the two variables.

As shown in Figure 5.8, the Nr of Des variable has a greater magnitude of marginal effect for project types B1, B2, and B8, and the variable Nr of Bids has a larger

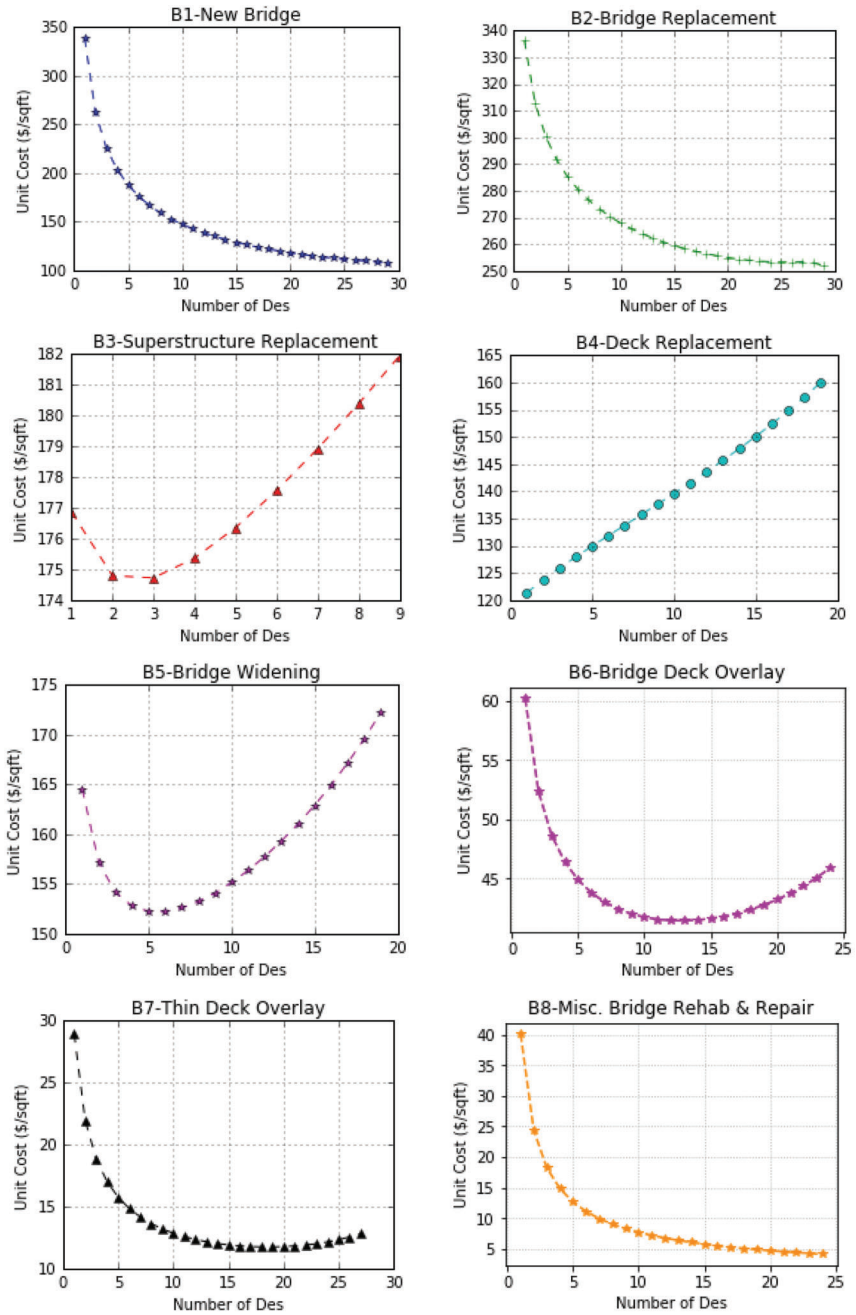


Figure 5.9 Optimistic unit cost estimation and threshold analysis based on the upper bound model of number of bidders.

magnitude of marginal effect for B3, B4, B5, and B6. For B7, the marginal effects of the two variables are similar. When Nr of Des is the dominating factor, the unit cost will always decrease as Nr of Des increases, in spite of the reduced Nr of Bidders caused by larger project sizes. However, when Nr of Bidders variable has a greater effect on the unit cost, a turning point for the Nr of Des variable might exist, after which the unit cost starts increasing. These results point to a threshold (optimal) value of the Nr of Des variable.

The upper-bound models developed in Section 4.3 were applied here to estimate the highest Nr of Bids which gives the lowest possible unit cost for a given Nr of Des under the optimistic market condition. The results are presented in Figure 5.9 for each bridge project type. It is seen that the unit cost of project B1, B2 and B8 always decreases as the Nr of Des increase. This is because according to the marginal effect results, the variable *Nr of Des* has greater impact on project cost compared to the variable Nr of Bids. This result is consistent across the three project types. It is seen that the unit cost thus continues to decrease with increasing project size even though the market competition reduces. However, in reality, there should be a limit on the Nr

of Des in a contract, because there could be no contractor left to bid if the contract is too big. For project types B3, B5, B6 and B7, an optimal threshold can be found for the Nr of Des that yield the lowest unit cost. This is because for these project types, the Nr of Bids, compared to the Nr of Des, has a greater impact on the unit cost. The results show that when the project size (Nr of Des) increases to a certain value, the unit cost start increasing due to the reduced market competition. The thresholds developed in this section can be improved if a better model is developed to capture the relationship between Nr of Des and Nr of Bids. For project B4, the unit cost always increases as the project size increases, because the marginal effect of the Nr of Des is small compared to the effect of the Nr of Bids.

5.1.3.2 Confidence Bound Estimation. As discussed in Section 4.3.2.1, the upper bound model, which assumes the highest number of bidders for a contract with a certain Nr of Des, can provide an estimate of the lower bound on project unit cost. However, it ignores all the cases where the actual number of bidders is below the upper bound. Therefore, probabilistic models, which estimate the distribution of the number of bidders for a given Nr of Des, are adopted in this section to estimate the most likely unit cost instead of the approximate lower bound.

The Beta probability distribution function (pdf) developed in Section 4.3.2.2 was applied to estimate 95% confidence bounds for the project unit cost using Monte Carlo Simulation. The method is presented as follows:

1. Generate 10,000 observations (Nr of Bidders) for Nr of Des equal to 1, using the corresponding Beta distribution models.
2. Plug the generated 10,000 Nr of Bidders values into the project cost model to estimate the unit cost (10,000 values).
3. Sort the estimated 10,000 unit cost values, and remove the lowest 2.5% and the highest 2.5% of those sorted values. The highest value and the lowest value in the remaining sorted list are the upper and lower bounds of a 95% confidence interval of project unit cost (in terms of the uncertainties about the number of bidders) when the Nr of Des is equal to 1.

Repeating this process for each Nr of Des value from 1 to 30 and for each project type, yields the 95% confidence bound on the estimated unit cost for each project type, as shown in Figure 5.10.

The data indicates that the *New Bridge and Bridge Replacement* project type has a very small interval between the upper and lower bounds. This is because from the cost model, the number of bidders have a very small effect on project unit cost. Therefore, the uncertainty surrounding the number of bidders is not expected to have a significant impact on the estimated unit cost. For Misc. Bridge Rehab & Repair, the two curves overlap with each other; the number of bidders is not included as an influential variable in the regression model, therefore the estimated unit cost is not affected by the distribution of number of bidders. The interval between the upper and lower bounds is very wide for Superstructure Replacement, Deck Replacement, Bridge Widening and Bridge Deck Overlay, indicating high uncertainty regarding the estimated cost. This is because, for these project types, the number of bidders has a great marginal effect on the project unit cost. This means that the unit cost will be greatly affected by the uncertainties associated with the number of bidders.

5.2 Maintenance of Traffic (MOT) Cost Model

5.2.1 Model Development

In this section, a statistical model for maintenance of traffic (MOT) cost for each work category is described. The (De)Mobilization cost item was removed before the development of MOT cost model, because it is almost always approximately 5% of the total award amount. The functional form used here is same as that used for the overall project cost model in Section 5.1.1. The form is shown in Equation 5.13. The initial linear equation (with a log transformation on each variable) can be translated into a power function form (Equation 5.14) by taking the exponent of both sides.

The MOT cost model can be also transformed into an MOT cost ratio model, as shown in Equation 5.15, by dividing both sides of Equation 5.14 by the Des Award. Various factors that were discussed in Section 4.5.2 were tested in the regression models, and only two variables (Des Award and Nr of Des) were kept as the influential variables that are significant and intuitive for most project types.

$$ln(MOT\ Cost) = \beta_0 + \beta_1 * ln(Des\ Award) + \beta_2 * ln(Nr\ of\ Des) \quad (5.13)$$

$$\text{MOT Cost} = e^{\beta_0} * Des\ Award^{\beta_1} * Nr\ of\ Des^{\beta_2} \quad (5.14)$$

$$\text{MOT Cost Ratio} = e^{\beta_0} * Des\ Award^{\beta_1 - 1} * Nr\ of\ Des^{\beta_2} \quad (5.15)$$

Table 5.8 presents the regression results for the developed MOT cost model for bridge work. According to the model results, both Des Award and Nr of Des are statistically significant for all bridge project types, but the effects of the two variables are different for different bridge project types. The coefficients of Des Award for B6 and B8 are positive and less than 1, indicating that, although the MOT cost increases as the project cost increases, the MOT cost ratio is decreasing. The coefficients of Des Award for B1 and B5 are almost equal to 1, which means that the increase of MOT cost is proportional to the increase of project cost (a linear increase), and the MOT cost ratio is close to constant. For other project types, the coefficient of Des Award is greater than 1, which indicates that both MOT cost and MOT cost ratio will increase as project cost increases.

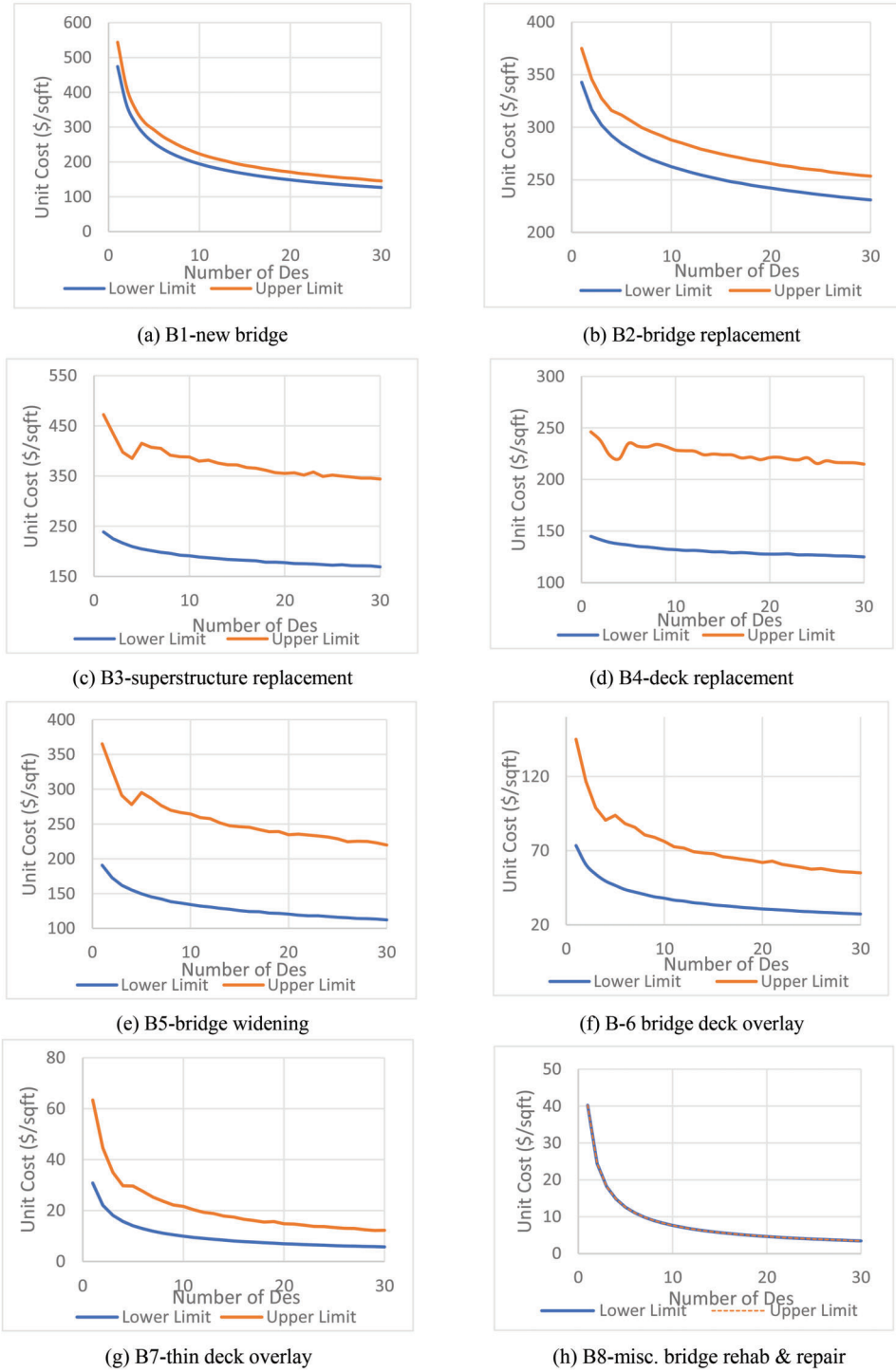


Figure 5.10. 95% confidence bounds on the estimated unit cost for bridge projects.

As shown in the data in Chapter 3, most observations of bridge work are from project types B6 and B8. That is why the scatter plot in Section 4.5.2 for bridge work shows that the MOT cost ratio in a project is reduced as the Des Award increases, although this is not true for other bridge project types.

In Section 4.5.2, the scatter plot of MOT cost ratio vs. the Nr of Des for bridge work does not show a clear pattern of how the MOT cost is affected by project bundling. In this section, the effect of project bundling on MOT cost was investigated, for each project type, by looking examining the coefficient of the variable Nr of Des in the developed regression model. From the regression results, it is observed that the Nr of Des is significant and has a negative sign for project types B1, B4, and B6, indicating that the MOT cost for these

TABLE 5.8
MOT Cost Models for Bridge Work*

Variable	Parameter	Coefficients	T-values	p-values	r-squared
	B1-New Bridge (295 Observations)				
Constant	β_0	-5.216222	-3.92991	1.06E-04	0.315
Des Award	β_1	1.017418	10.97279	1.10E-23	0.315
Nr of Des	β_2	-0.256676	-2.59455	9.95E-03	0.315
	B2-Bridge Replacement (203 Observations)				
Constant	β_0	-8.905819	-6.60011	3.61E-10	0.494
Des Award	β_1	1.310605	13.59651	3.02E-30	0.494
Nr of Des	β_2	0.14266	1.605959	1.10E-01	0.494
	B3-Superstructure Replacement (56 Observations)				
Constant	β_0	-11.755411	-2.89034	0.005566	0.374
Des Award	β_1	1.506922	5.218383	0.000003	0.374
Nr of Des	β_2	0.958868	2.987231	0.004257	0.374
	B4-Deck Replacement (62 Observations)				
Constant	β_0	-8.235134	-2.43605	1.79E-02	0.343
Des Award	β_1	1.329573	5.480312	9.24E-07	0.343
Nr of Des	β_2	-0.436587	-2.7665	7.55E-03	0.343
	B5-Bridge Widening (50 Observations)				
Constant	β_0	-5.250884	-1.86599	0.068291	0.352
Des Award	β_1	1.019608	5.098221	0.000006	0.352
Nr of Des	β_2	0.381577	1.831071	0.073433	0.352
	B6-Bridge Deck Overlay (323 Observations)				
Constant	β_0	-1.709568	-1.67468	9.50E-02	0.304
Des Award	β_1	0.84866	10.93002	7.66E-24	0.304
Nr of Des	β_2	-0.138534	-1.81012	7.12E-02	0.304
	B7-Thin Deck Overlay (161 Observations)				
Constant	β_0	-4.692234	-3.43986	7.45E-04	0.401
Des Award	β_1	1.1216	10.3105	2.20E-19	0.401
Nr of Des	β_2	0.267349	2.120827	3.55E-02	0.401
	B8-Misc. Bridge Rehab & Repair (545 Observations)				
Constant	β_0	-1.215009	-2.11	3.53E-02	0.355
Des Award	β_1	0.778868	17.119	7.74E-53	0.355
Nr of Des	β_2	0.506257	8.820237	1.56E-17	0.355

*See Equation 5.13 for the functional form.

project types can be reduced by project bundling. For other bridge project types, the Nr of Des is also significant, but with a positive sign. This means that the MOT cost in these project types might be higher compared to others due to project bundling.

To measure the performance of the MOT cost models, scatter plots of MOT cost vs. Nr of Des are provided in Figure 5.11. The actual observations are shown as hollow red circles and the predicted values are shown as black triangles, showing how the MOT cost model fits the actual observations.

The same functional form and influential variables were used to develop MOT cost models for road project types (except R8 and R9, due to limited data availability). The regression results are shown in Table 5.9. Des Award and Nr of Des are both very significant for all road projects. The coefficients of Des Award for most road project types (R2, R3, R4, R7, R10, R11, and R12) are positive and less than one, which means that, as project cost increases, the MOT cost increases, but the MOT cost ratio gets smaller. For R1 and R5, the coefficients of Des Award are close to 1, indicating that the MOT cost increases linearly as project cost increases, and the MOT cost ratio is approximately constant.

The variable *Nr of Des* was found to be significant and has a negative sign for most road projects (except R3 and R12). This indicates that project bundling can reduce the cost for maintenance of traffic work and the MOT cost ratio in a project for these project types. This is consistent with findings from the MOT cost vs. Nr of Des scatter plot for road work in Section 4.5.2, where the MOT cost and MOT cost ratio were both

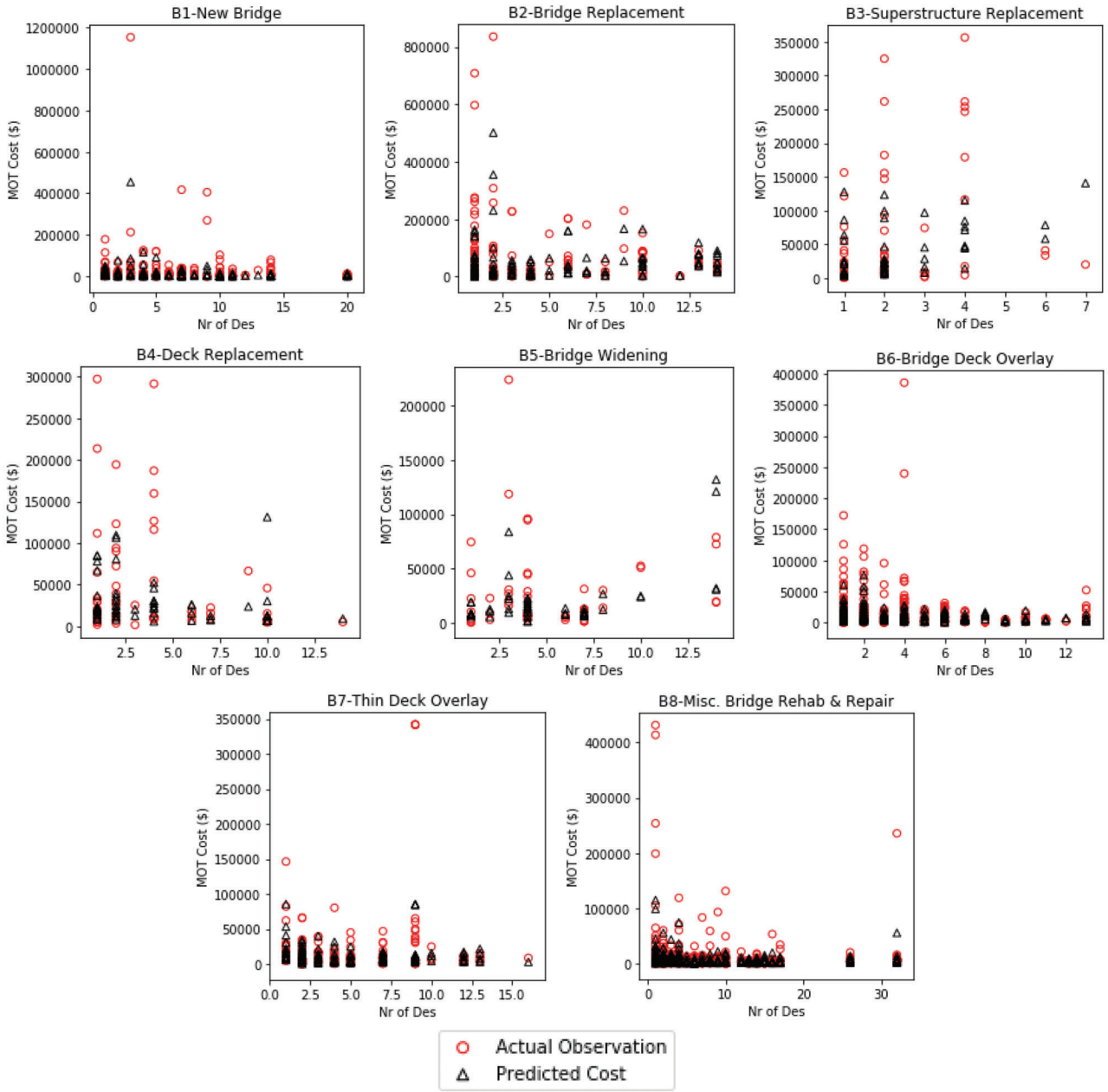


Figure 5.11 Validation of the bridge work MOT cost model.

seen to decrease as the Nr of Des increases. The marginal effects and sensitivity analysis results are presented in Section 5.2.2 to show the extent to which the MOT cost can be reduced by project bundling.

Figure 5.12, which presents the performance of the MOT cost model for road work, suggests that most variation in the data can be explained by the model.

The MOT cost regression models were then developed for traffic project types. The regression results are presented in Table 5.10. Similar to the model results for road project types, the coefficients of Des Award for traffic projects are smaller or close to 1, and the coefficients of Nr of Des for most traffic projects (e.g., T1, T2, T3, and T4) are negative. This means that for these project types, project bundling can lead to more cost-effective maintenance of traffic.

The performance of MOT cost model for traffic work is fairly good (except for T6), with a R^2 greater than 0.4. As shown in Figure 5.13, the Roadwork MOT Cost models fit the actual observations very well.

Finally, MOT cost models were developed for small structure (S) and miscellaneous (M) project types. From the regression results (Table 5.11), the coefficients of Des Award for all project types are smaller or close to 1. The benefits of project bundling on reducing cost for the maintenance of traffic work were evident for the small structure project types S1 and S2, but not for the miscellaneous project types.

TABLE 5.9
MOT Cost Regression Model Results for Road Work*

Variable	Parameter	Coefficients	T-values	p-values	r-squared
	R1-New Road Construction (48 Observations)				
Constant	β_0	-5.900446	-1.427045	0.160469	0.249
Des Award	β_1	1.075682	4.1182	0.000161	0.249
Nr of Des	β_2	-0.575483	-1.997656	0.051821	0.249
	R2-Added Travel Lanes (60 Observations)				
Constant	β_0	-0.905679	-0.871585	3.87E-01	0.764
Des Award	β_1	0.807493	10.702341	2.36E-15	0.764
Nr of Des	β_2	-0.153546	-0.897982	3.73E-01	0.764
	R3-Patch & Rehab Pavement 0 (77 Observations)				
Constant	β_0	-1.848904	-1.623721	1.09E-01	0.607
Des Award	β_1	0.910735	10.542401	2.17E-16	0.607
	R4-Partial 3 (462 Observations)				
Constant	β_0	-1.861367	-2.475382	1.37E-02	0.366
Des Award	β_1	0.885595	16.397933	6.72E-48	0.366
Nr of Des	β_2	-0.108538	-0.959304	3.38E-01	0.366
	R5-Road Rehabilitation (3R/4R) (41 Observations)				
Constant	β_0	-5.434935	-2.716313	9.88E-03	0.640
Des Award	β_1	1.112459	8.414257	3.29E-10	0.640
Nr of Des	β_2	-0.266869	-1.445196	1.57E-01	0.640
	R7-Sight Distance Correction (22 Observations)				
Constant	β_0	-0.731465	-0.25169	0.803983	0.515
Des Award	β_1	0.751716	3.563017	0.002076	0.515
Nr of Des	β_2	-1.002441	-1.706272	0.10425	0.515
	R10-Pavement Replacement 136				
Constant	β_0	-1.960213	-1.19943	2.32E-01	0.321
Des Award	β_1	0.877475	7.901976	9.20E-13	0.321
Nr of Des	β_2	-0.129699	-0.851861	3.96E-01	0.321
	R11-Intersection Improvement 103				
Constant	β_0	-0.519269	-0.382496	7.03E-01	0.367
Des Award	β_1	0.78754	7.811053	5.78E-12	0.367
Nr of Des	β_2	-0.369729	-1.876656	6.35E-02	0.367
	R12-Interchange Work 39				
Des Award	β_0	0.703364	4.87712	0.000022	0.604
Constant	β_1	0.378207	0.189631	0.850664	0.604

*See Equation 5.13 for the functional form.

The model performance is among the highest (R^2 greater than 0.5) for project types S1, M1, and M2, but not very good (R^2 smaller than 0.3) for S2, M4, and M5. The comparisons between the actual MOT cost and the MOT cost predicted from the models are presented in Figure 5.14 for the small structure and miscellaneous project types.

5.2.2 Marginal Effect and Sensitivity Analysis of MOT Costs

The average marginal effects of Des Award and Nr of Des on MOT cost (and MOT cost ratio) were determined for all project types. The results are presented in Table 5.12 and Figures 5.15 and 5.16. Comparing the magnitudes of the marginal effects of Des Award and Nr of Des for different project types in each work category, it was found that the total MOT cost of B7, R3, T5, M1, and S2 are the most sensitive to the project cost (Des Award), while the MOT cost of B3, R5, T1, M4 and S2 are the most sensitive to the Nr of Des.

Sensitivity analysis was then conducted to evaluate how the MOT cost and MOT cost ratio (MOT Cost/Des Award) are affected by the change of Des Award and Nr of Des. According to Parts (a) and (b) in Figures 5.16, 5.17, 5.18, and 5.19, for most project types, the MOT cost

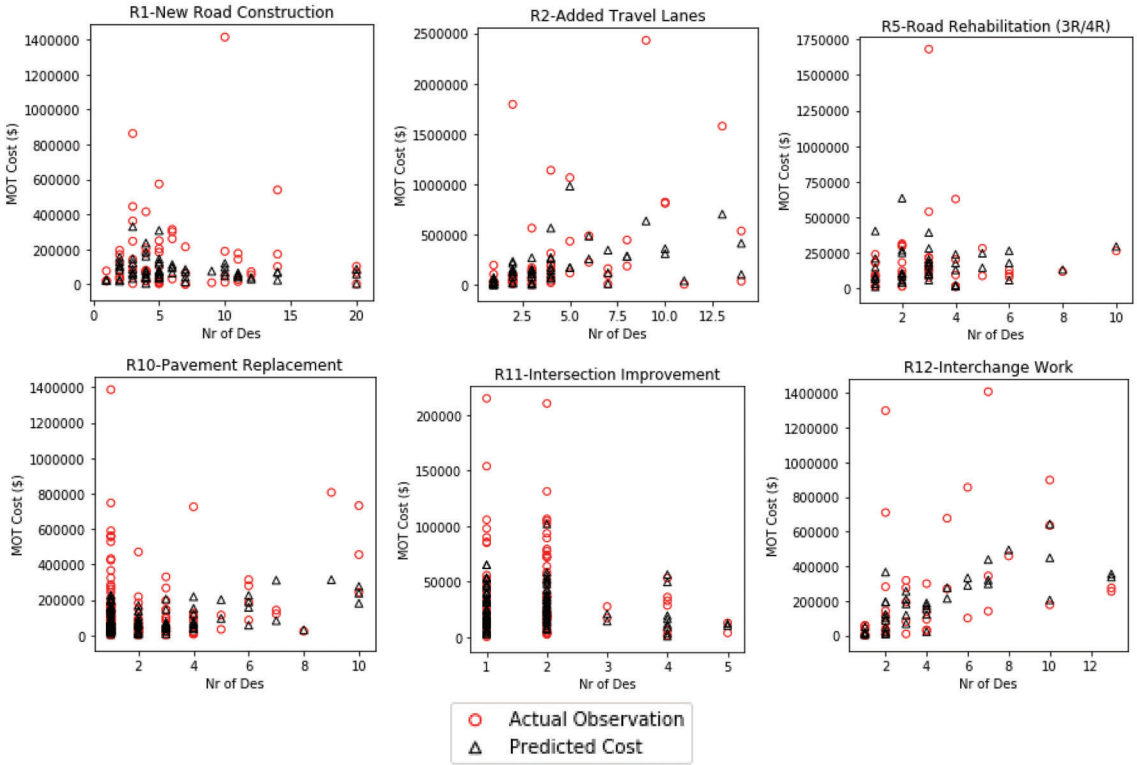


Figure 5.12 Validation of the roadwork MOT cost model.

TABLE 5.10
MOT Cost Regression Model Results for Traffic Work*

Variable	Parameter	Coefficients	T-values	p-values	r-squared
	T1-ITS (25)				
Constant	β_0	-3.52278	-1.94926	6.41E-02	0.714
Des Award	β_1	0.994996	7.678214	1.16E-07	0.714
Nr of Des	β_2	-0.25789	-1.16998	2.55E-01	0.714
	T2-Signing (122)				
Constant	β_0	-5.61155	-5.80175	5.53E-08	0.666
Des Award	β_1	1.14521	15.17298	1.36E-29	0.666
Nr of Des	β_2	-0.39978	-2.50516	1.36E-02	0.666
	T3-Traffic Parameter Signals (191)				
Constant	β_0	-3.85888	-3.85792	1.57E-04	0.423
Des Award	β_1	0.984901	11.74225	3.10E-24	0.423
Nr of Des	β_2	-0.00556	-0.06044	9.52E-01	0.423
	T4-Pavement Parameter Markings (14)				
Constant	β_0	6.449769	1.686606	0.119799	0.577
Des Award	β_1	0.292389	0.931191	0.371741	0.577
Nr of Des	β_2	-1.03002	-4.34134	0.001172	0.577
	T5-Guard Rail, Cable Barrier & Wall (38)				
Constant	β_0	-0.9804	-0.94984	3.49E-01	0.756
Des Award	β_1	0.817218	10.70453	1.39E-12	0.756
	T6-Lighting (27)				
Constant	β_0	11.443	2.211915	0.036741	0.172
Des Award	β_1	-0.35381	-0.80513	0.42865	0.172
Nr of Des	β_2	0.940596	2.354663	0.027057	0.172

*See Equation 5.13 for the functional form.

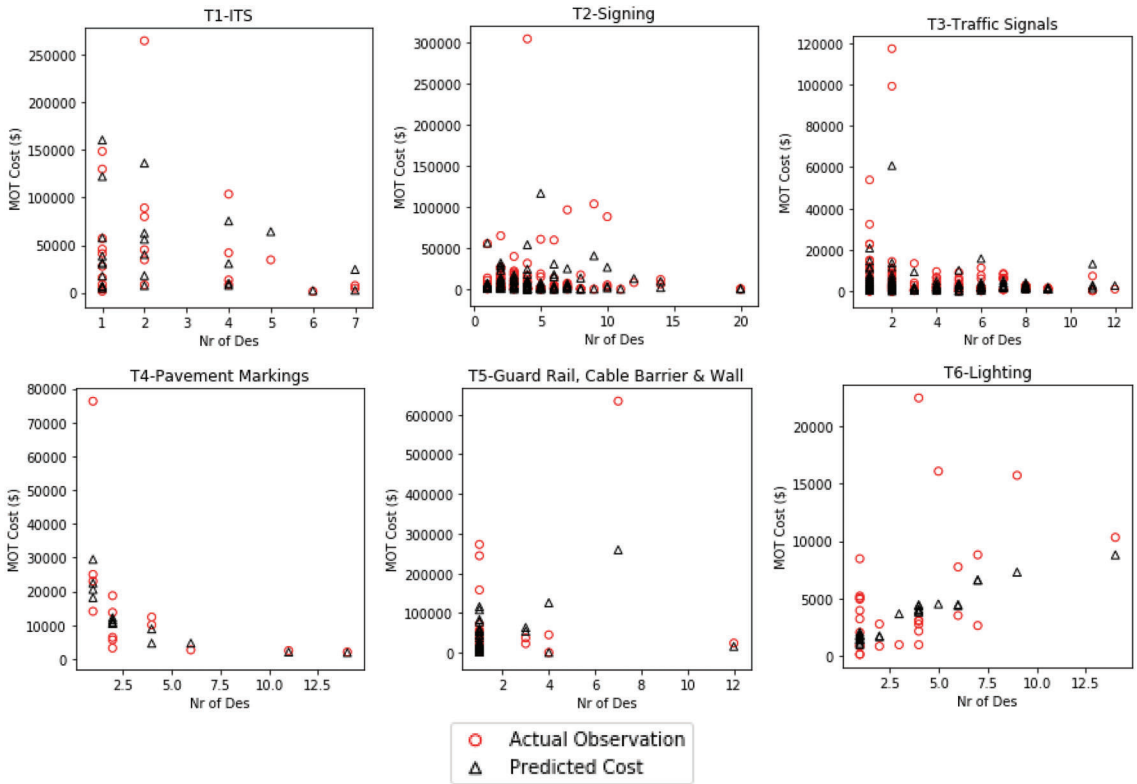


Figure 5.13 Validation of the roadwork MOT cost model.

TABLE 5.11
MOT Cost Regression Model Results for Small Structure and Miscellaneous Work*

Variable	Parameter	Coefficients	T-values	p-values	r-squared
	S1-Pipe Lining (244 Observations)				
Constant	β_0	-1.112715	-2.00898	4.57E-02	0.659
Des Award	β_1	0.773298	16.68261	4.66E-42	0.659
Nr of Des	β_2	-0.604459	-10.7575	2.68E-22	0.659
	S2-Small Structure Installation (213 Observations)				
Constant	β_0	-5.566726	-3.45388	6.68E-04	0.300
Des Award	β_1	1.124275	8.966549	1.71E-16	0.300
Nr of Des	β_2	-0.37781	-2.60731	9.78E-03	0.300
	M1-Demolition (37 Observations)				
Constant	β_0	-7.548989	-3.23839	2.68E-03	0.542
Des Award	β_1	1.277867	6.579147	1.54E-07	0.542
	M2-Channel and Ditch Work (46 Observations)				
Constant	β_0	1.752874	1.181568	0.243871	0.526
Des Award	β_1	0.576887	4.910614	0.000014	0.526
	M4-Slide Correction (34 Observations)				
Constant	β_0	2.294957	1.084214	0.28663	0.232
Des Award	β_1	0.508249	3.26616	0.002663	0.232
Nr of Des	β_2	0.566162	2.14112	0.040236	0.232
	M5-Paths, Sidewalks & Curb Ramps (16 Observations)				
Constant	β_0	3.775003	1.303638	0.214971	0.220
Des Award	β_1	0.408057	1.869764	0.084203	0.220
Nr of Des	β_2	-0.231936	-0.78954	0.44396	0.220

*See Equation 5.13 for the functional form.

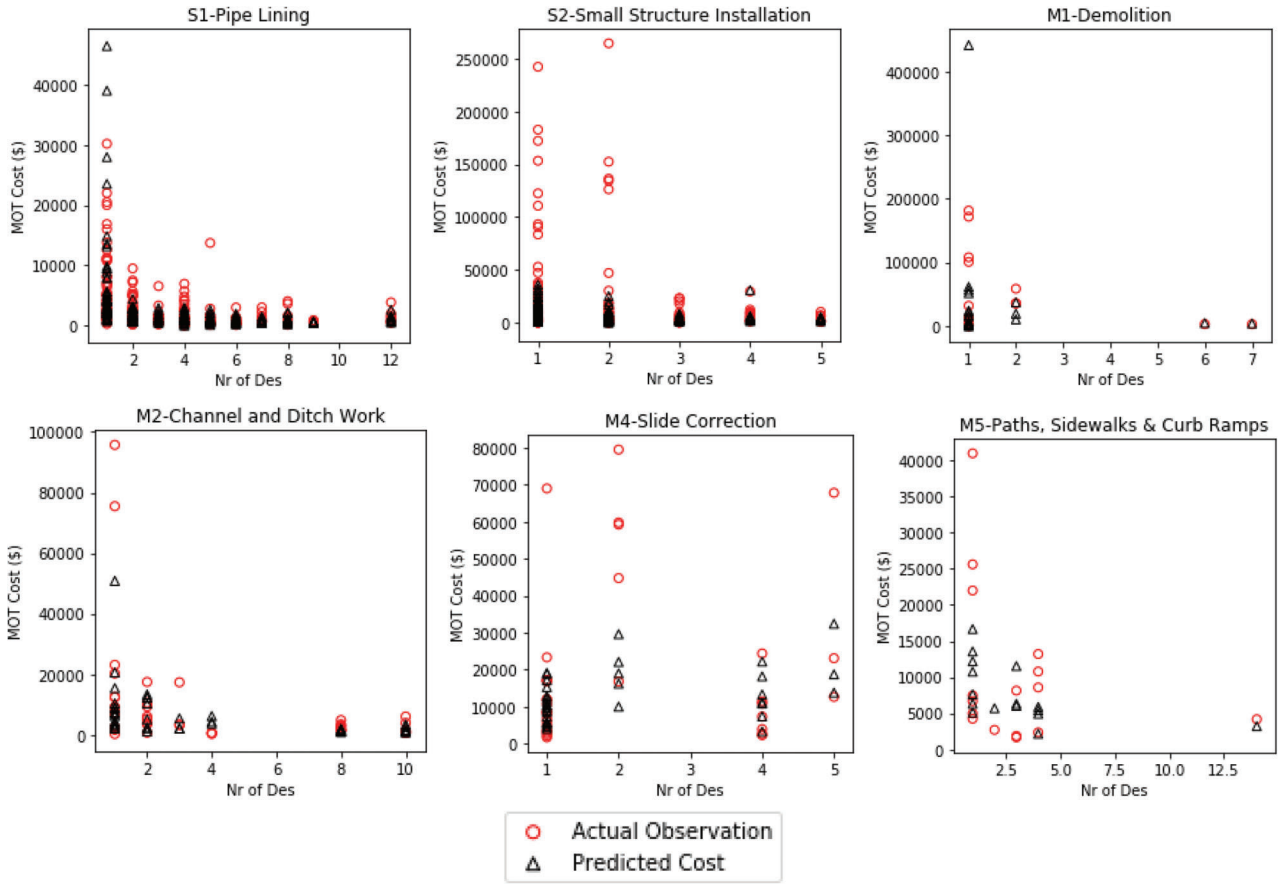
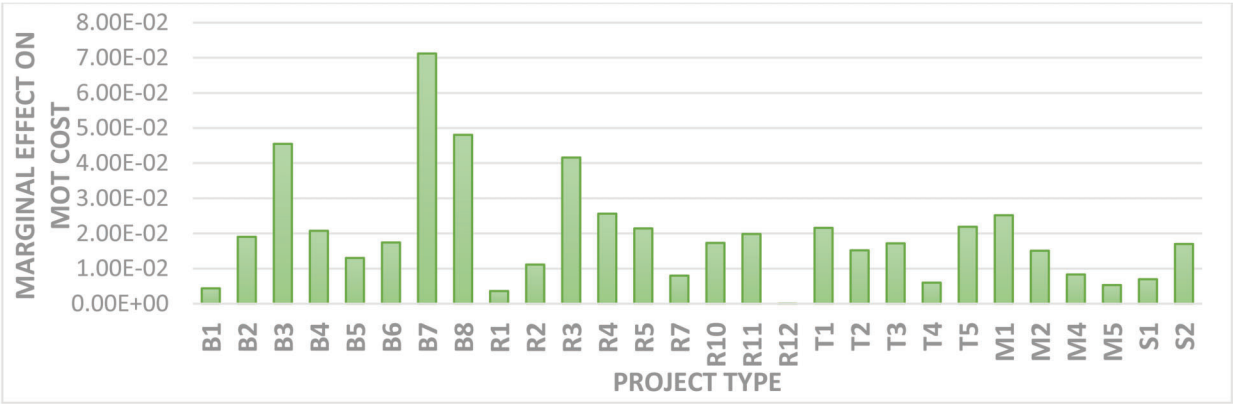


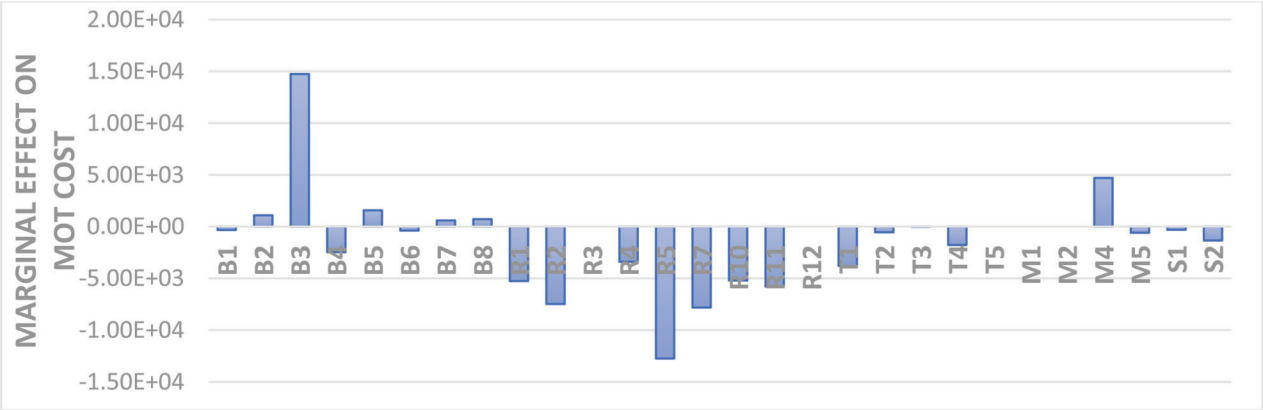
Figure 5.14 Actual and predicted MOT cost for small structure and miscellaneous work.

TABLE 5.12
Average Marginal Effect

	Average Marginal Effect on Total MOT Cost (2015$) in a Des		Average Marginal Effect on MOT Cost Ratio (MOT Cost/Des Award)	
Project Types	**Des Award (2015$)**	**Nr of Des**	**Des Award (2015$)**	**Nr of Des**
B1-New Bridge	4.37E-03	-3.20E+02	3.87E-11	-1.66E-04
B2-Bridge Replacement	1.90E-02	1.10E+03	2.37E-09	5.76E-04
B3-Superstructure Replacement	4.55E-02	1.47E+04	1.01E-08	9.76E-03
B4-Deck Replacement	2.07E-02	-2.47E+03	3.72E-09	-1.78E-03
B5-Bridge Widening	1.30E-02	1.58E+03	1.56E-10	9.85E-04
B6-Bridge Deck Overlay	1.74E-02	-3.77E+02	-6.07E-09	-7.37E-04
B7-Thin Deck Overlay	7.12E-02	5.96E+02	4.00E-08	3.09E-03
B8-Misc. Bridge Rehab & Repair	4.81E-02	7.26E+02	-5.96E-08	3.17E-03
R1-New Road Construction	3.60E-03	-5.26E+03	1.47E-11	-3.05E-04
R2-Added Travel Lanes	-5.69E-10	-1.18E-02	-1.90E-10	-8.49E-10
R3-Patch & Rehab Pavement	4.16E-02	0	-3.90E-09	0
R4-Partial 3	2.56E-02	-3.40E+03	-2.02E-09	-2.08E-03
R5-Road Rehabilitation (3R/4R)	2.14E-02	-1.27E+04	2.89E-10	-1.70E-03
R7-Sight Distance Correction	7.98E-03	-7.82E+03	-2.49E-09	-7.37E-03
R10-Pavement Replacement	1.73E-02	-5.20E+03	-5.67E-10	-1.22E-03
R11-Intersection Improvement	1.98E-02	-5.79E+03	-4.91E-09	-5.31E-03
R12-Interchange Work	3.25E-05	0.00E+00	-5.00E-12	0.00E+00
T1-ITS	2.16E-02	-3.80E+03	-6.40E-11	-2.24E-03
T2-Signing	1.52E-02	-5.44E+02	4.12E-09	-1.16E-03
T3-Traffic	1.72E-02	-4.53E+00	-1.50E-09	-2.59E-05
T4-Pavement	5.99E-03	-1.78E+03	-4.54E-08	-5.57E-03
T5-Guard Rail, Cable Barrier & Wall	2.19E-02	0	-2.62E-09	0
T6-Lighting	-4.12E-03	9.35E+02	-5.20E-08	3.09E-03
M1-Demolition	2.52E-02	0	1.20E-08	0
M2-Channel and Ditch Work	1.51E-02	0	-3.19E-08	0
M4-Slide Correction	8.31E-03	4.71E+03	-7.70E-09	4.51E-03
M5-Paths, Sidewalks & Curb Ramps	5.30E-03	-5.90E+02	-1.31E-08	-1.00E-03
S1-Pipe Lining	6.97E-03	-2.99E+02	-9.65E-09	-1.41E-03
S2-Small Structure Installation	1.70E-02	-1.34E+03	4.24E-09	-3.02E-03

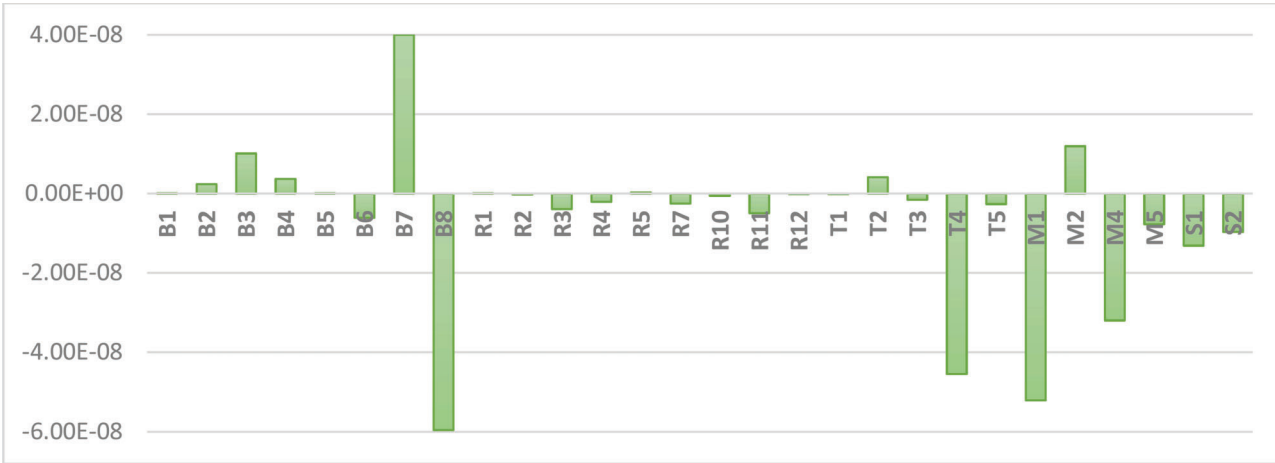


(a) Marginal effect of Des Award on MOT cost

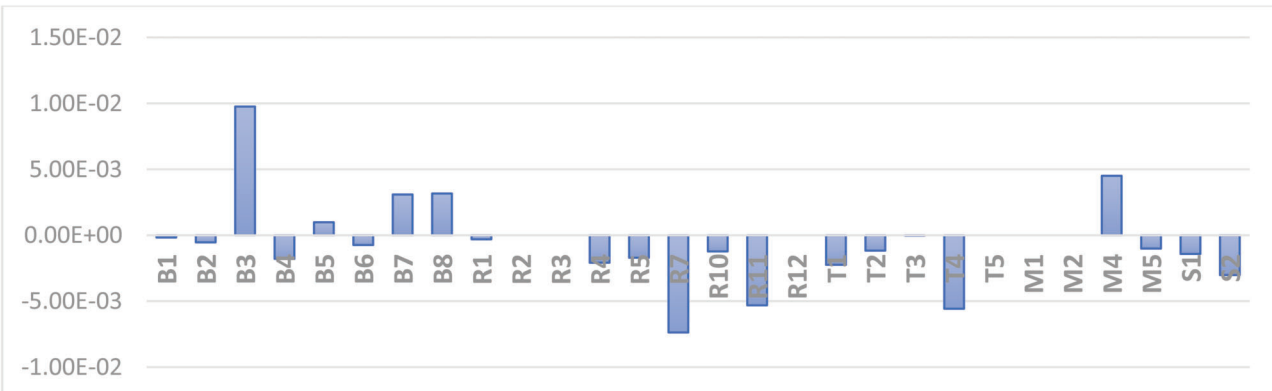


(b) Marginal effect of Nr of Des on MOT cost

Figure 5.15 Comparison of marginal effects on MOT cost for different project types.



(a) Marginal effect of Des Award on MOT cost ratio



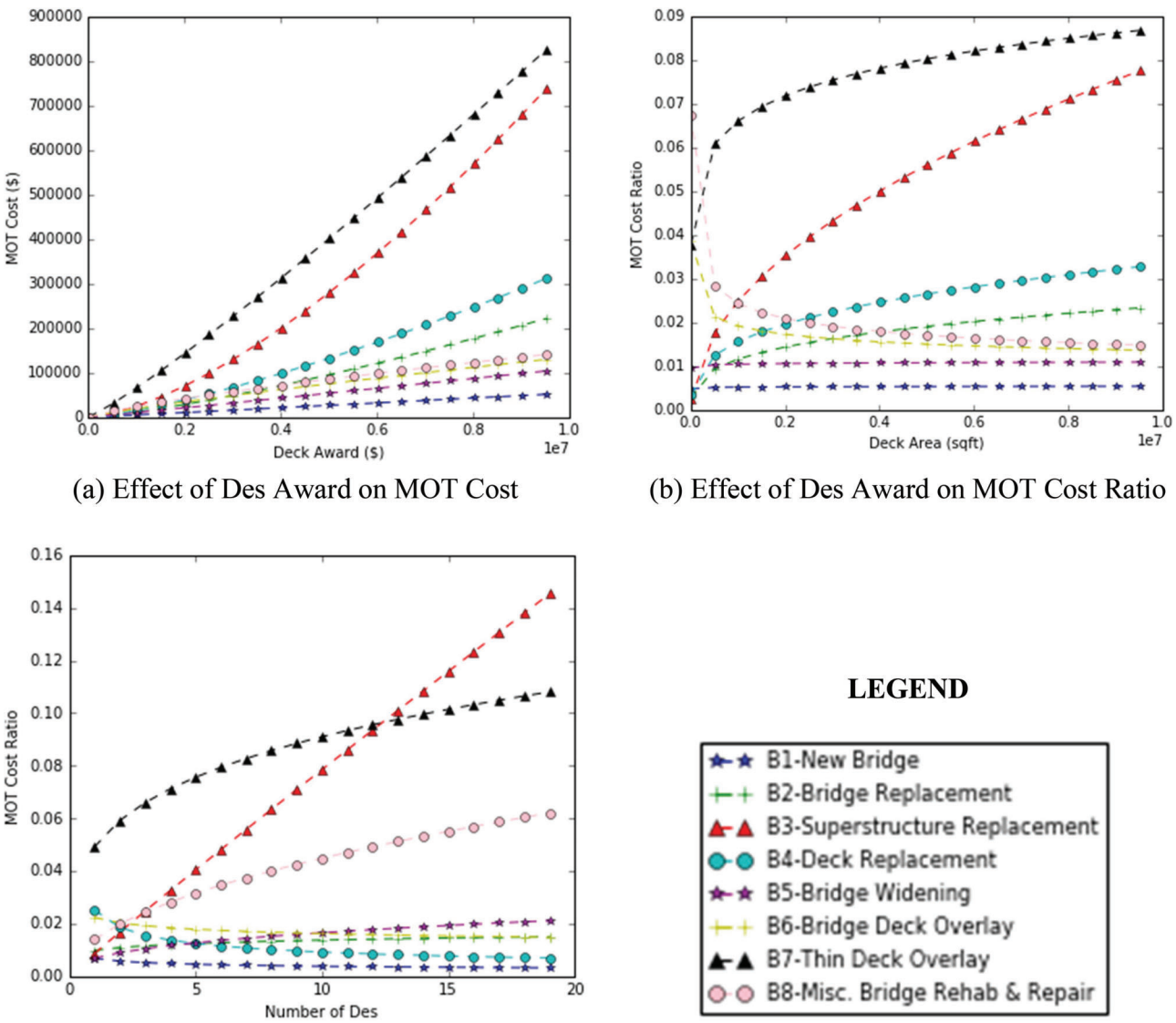
(b) Marginal effect of Nr of Des on MOT cost ratio

Figure 5.16 Comparison of marginal effects on MOT cost ratio across the different project types.

is always increasing as the Des Award increases, but the MOT cost ratio might decrease or increase, depending on the project type. For the effects of Nr of Des (economies of bundling), the MOT cost ratio continues to decrease as more projects are being bundled for most road projects (except R3-Patch & Rehab Pavement and R12-Interchange Work), as shown in Figure 5.17(c). This indicates that project bundling can reduce the cost spent on maintenance of traffic work for most road project types. For most bridge projects, however, project bundling does not appear to lead to savings on the MOT work. The MOT cost ratio even increases slightly for some project types, according to the sensitivity plots in Figure 5.18(c). For traffic work, project bundling can reduce the MOT cost ratio for T1-ITS, T2-Signing, and T4-Pavement, as shown in Figure 5.19(c). For miscellaneous work, only M5-Paths, Sidewalks & Curb Ramps is benefited by project bundling in terms of MOT cost saving according to Figure 5.20(c). For the Small Structure project types that were evaluated, MOT costs benefit from project bundling, as shown in Figure 5.20(c).

5.2.3 Hypothetical Case Study

Before applying the developed MOT cost models, the analyst needs to know or estimate the project cost (Des Award) which is an influential variable in the model. In this section, a hypothetical case study is presented for a Bridge Deck Overlay (BDO) project to illustrate how the developed overall project cost model and MOT cost model can be applied together to estimate the MOT cost and MOT cost ratio. The bridge information and corresponding model equations are listed in Table 5.13. The bridge deck is assumed to have an area of 6,000 square ft, with an average ADT of 10,000 veh/day. The BDO project is assumed to be bundled with other projects that have an average similarity distance (ASD) of 0.3 (when Nr of Des >1). In reality, the average similarity distance should not be a constant when the Nr of Des changes, because the combination of projects bundled in the contract would be altered. For simplicity in this MOT case study, however, we assume the ASD is constant.



(a) Effect of Des Award on MOT Cost

(b) Effect of Des Award on MOT Cost Ratio

(c) Effect of Nr of Des on MOT Cost Ratio

Figure 5.17 Effect of Des Award and Nr of Des on MOT cost for bridge work.

A sample calculation is provided here for the MOT cost estimation of the BDO project when the project is unbundled. In this case, the Nr of Des is 1, and the estimated highest number of bidders is 13 using the equation $-3.631 * ln(1) + 13.038$. The Des Award of the BDO project is estimated as $e^{9.832} * 6{,}000^{0.428} * 1^{-0.297} * 13^{-0.311} * 10{,}000^{0.01} * 0^{0.032} = \$362{,}711$. Then, the MOT cost is predicted using the equation $e^{-1.710} * \$362{,}711^{0.848} * 1^{-0.138} = \$9{,}373$. Finally, the MOT cost ratio is obtained by dividing the MOT cost by the Des Award, which is equal to 2.58% ($9,373/$362,711) in this case.

The results of the case study are shown in Table 5.14 and Figure 5.21. For each Nr of Des, the highest number of bidders was estimated using the upper-bound model developed for bridge project types. The project cost for the evaluated bridge deck overlay project was then predicted using the overall project cost model as shown in Table 5.14. Finally, the MOT cost model can be used to estimate the total MOT cost and the MOT cost ratio (MOT cost/Des Award). As shown in Figure 5.21(a), the project cost for the evaluated BDO project decreases as the Nr of Des increases for small values of Nr of Des, but it starts increasing after a certain point (when Nr of Des > 11). The pattern between MOT cost (or MOT cost ratio) and the number of des bundled with the BDO project is shown in Figure 5.21(b). The MOT cost stops decreasing and starts increasing slightly when the Nr of Des is greater than 20; however, the MOT cost ratio continuously decreases as more projects are bundled with the BDO project in question.

5.3 Chapter Summary

In this chapter, regression models were developed for overall project cost and maintenance of traffic

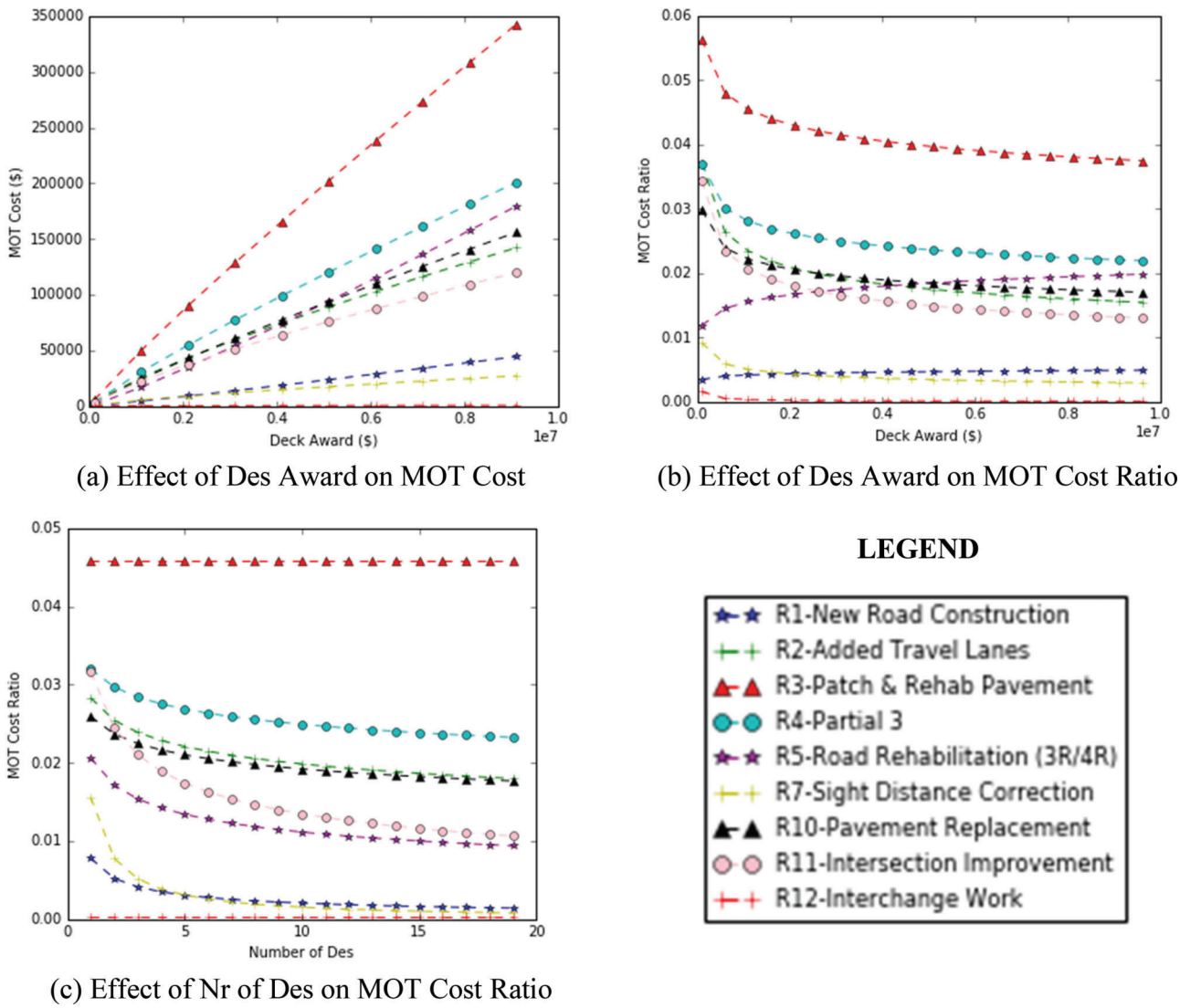
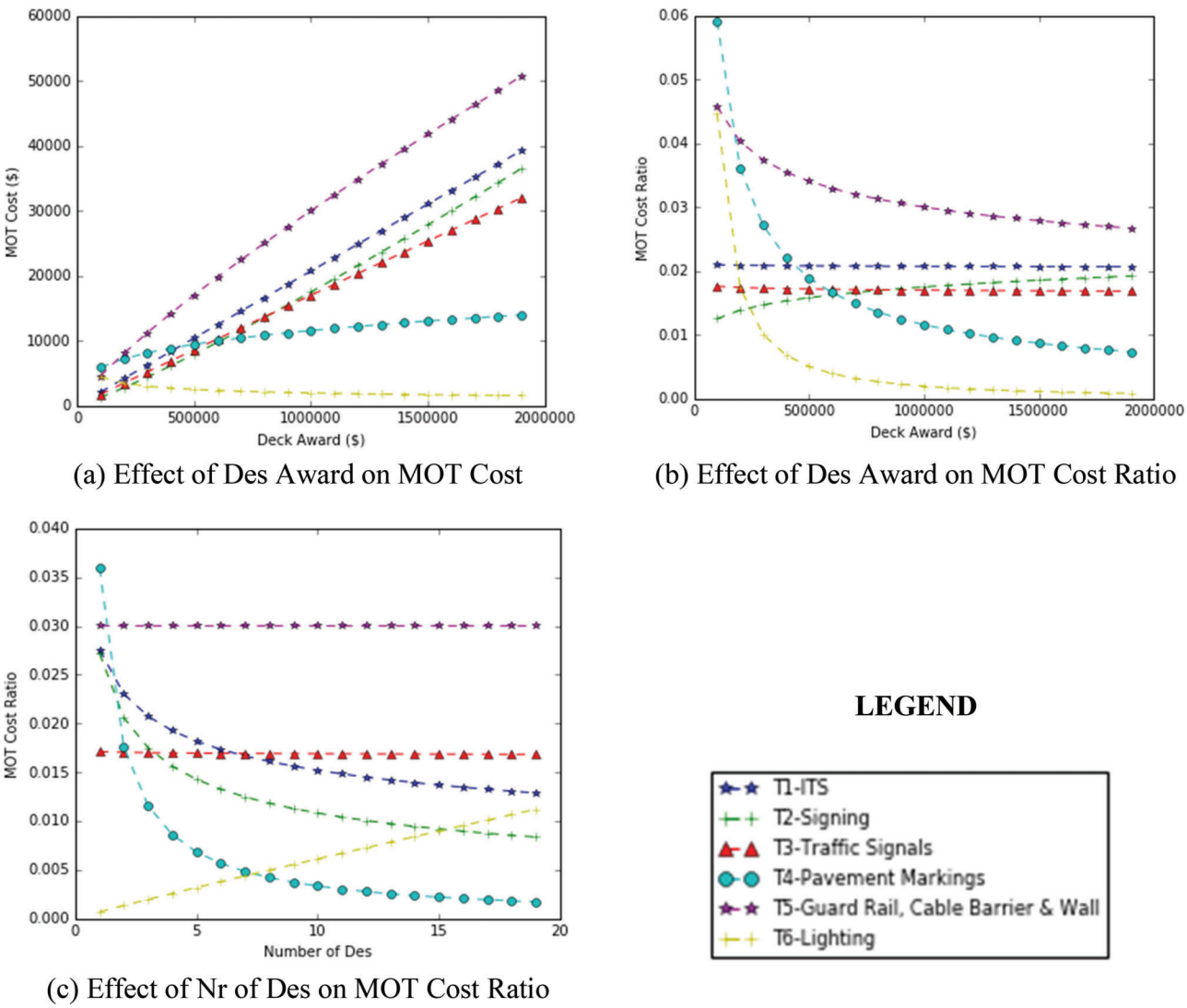


Figure 5.18 Effect of Des Award and Nr of Des on MOT cost for road work.

(MOT) cost. According to the results of the overall project cost model developed in Section 5.1, it was found that the project cost of all bridge work can be significantly reduced by project bundling, while this benefit was not found for most road project types. This is consistent with the results in the previous chapters. It is therefore believed that for road projects, having one longer section project is more cost-effective than having several short-section projects bundled in one contract. Another reason is that, based on the regression results for road work cost models, project similarity has a significant impact on the project cost. Projects that are bundled with similar project types are typically less expensive than projects bundled with very different project types. On the other hand, for road work, most projects are bundled with projects from other work categories according to the bundling strategy used in the past contract, which is discussed in greater detail in Chapter 6.

In Section 5.1.2, optimal threshold analysis and confidence bound estimation were carried out for bridge work. The optimal threshold is a threshold for the optimal number of des before which the unit cost of a project decreases as the number of des increases and after which the unit cost of the project starts increasing as more projects are bundled with it. This threshold exists due to the interaction between the effects of Nr of Des and Nr of Bids on the unit cost: the unit cost decreases as either Nr of Des or Nr of Bids increases, but the increase of Nr of Des lead to a decrease in the Nr of Bids. This interaction can be found for project types that have similar marginal effects for Nr of Des and Nr of Bids, that is, no one factor dominates the other. In our analysis, the optimal threshold was found for project types B3, B5, B6 and B7. According to the results of confidence bound estimation, B1 and B2 have a very small interval between the upper and lower bounds, indicating that the uncertainty associated with



(a) Effect of Des Award on MOT Cost

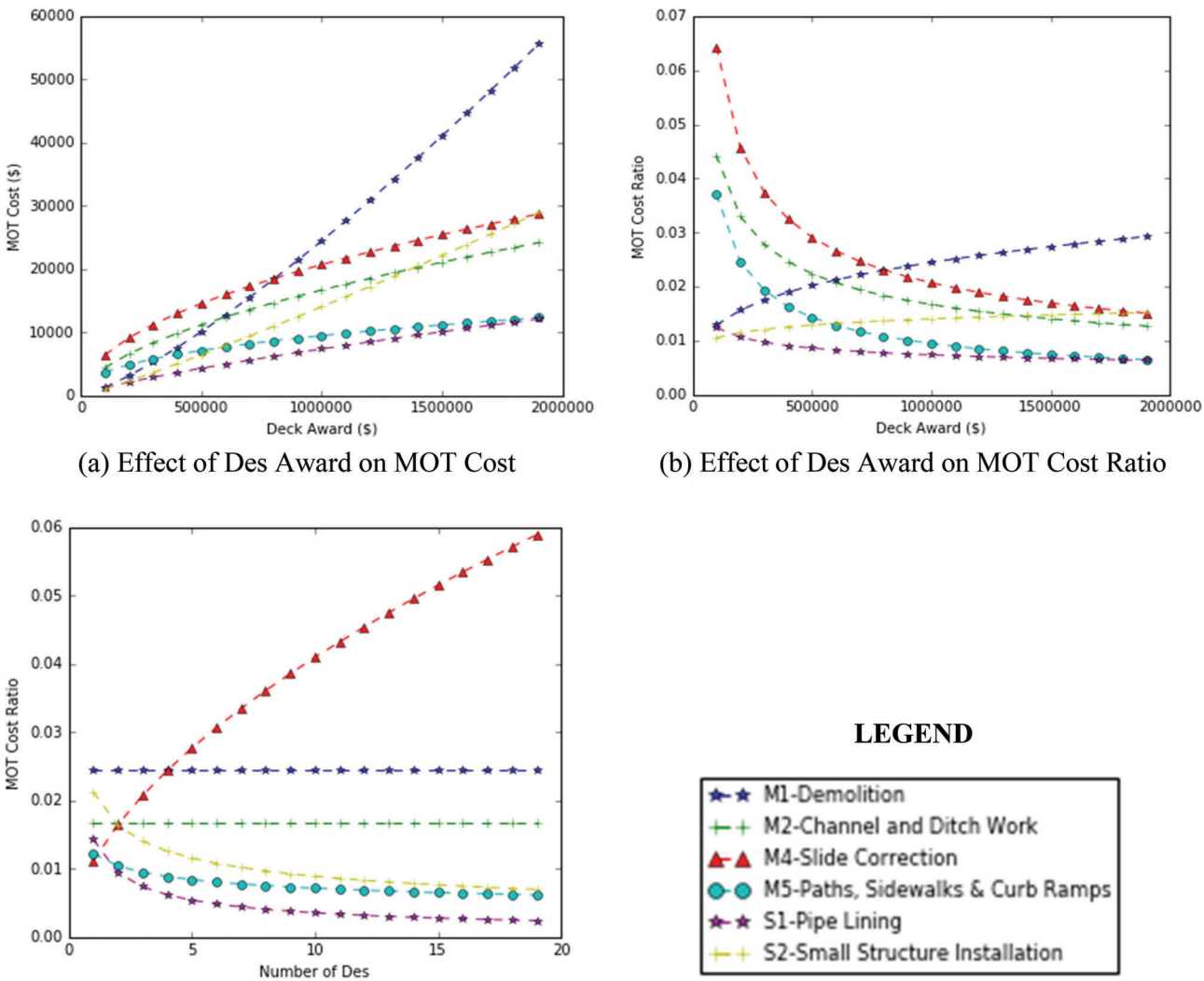
(b) Effect of Des Award on MOT Cost Ratio

(c) Effect of Nr of Des on MOT Cost Ratio

Figure 5.19 Effect of Des Award and Nr of Des on MOT cost for traffic work.

the number of bidders is therefore not expected to make much difference on the estimated unit cost. The interval between the upper and lower bounds is very wide for B3, B4, B5 and B6, indicating a great deal of uncertainty regarding the estimated cost. This means that the unit cost will be greatly affected by the uncertainties associated with the number of bidders.

In Section 5.2, regression models were developed for the maintenance of traffic (MOT) work. The regression results indicate that, for bridge work, the MOT cost for B1, B4, and B6 can be slightly reduced by project bundling, while the MOT cost for other project types might increase due to project bundling. The MOT cost for most road, traffic and small structure work was found to be more or less reduced by project bundling, and of the work categories, road work was found to benefit the most from project bundling in terms of MOT cost saving.



(a) Effect of Des Award on MOT Cost

(b) Effect of Des Award on MOT Cost Ratio

(c) Effect of Nr of Des on MOT Cost Ratio

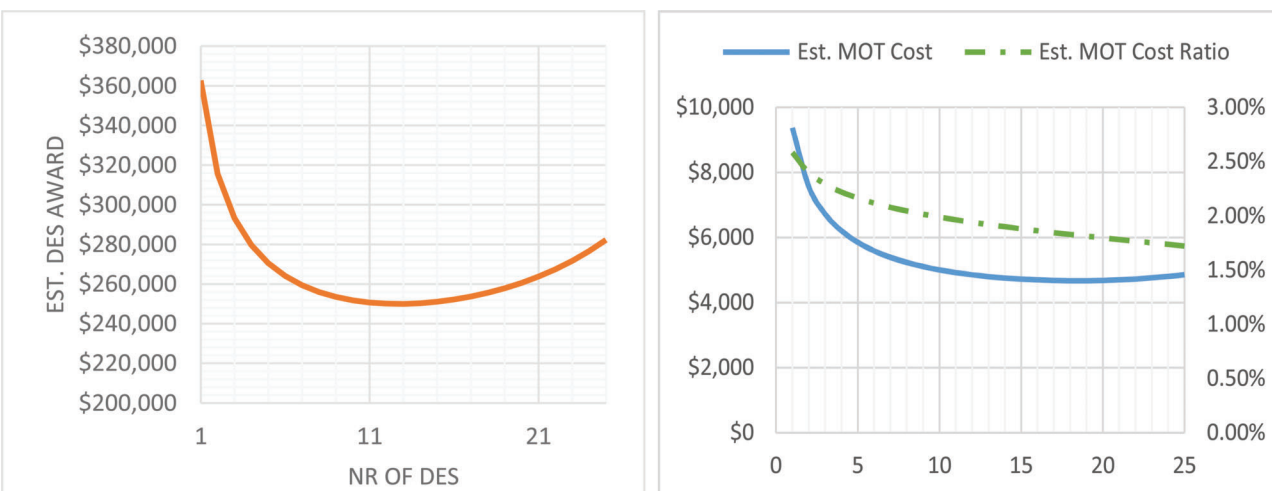
Figure 5.20 Effect of Des Award and Nr of Des on MOT cost for miscellaneous work.

TABLE 5.13
Project Information for Hypothetical Case Study

Evaluated Project	Bridge Deck Overlay (BDO)
Deck Area	6,000 (Assumed)
ADT on the bridge	10,000 (Assumed)
Average Similarity Distance (ASD)	0.3 (Assumed)
Nr of Des in the Contract	Range from 1 to 20
Nr of Bidders in the Contract	$Nr\ of\ Des = -3.631 * ln(Nr\ of\ Des) + 13.038$
Project Cost	Des Award $= e^{9.832} * Deck\ Area^{0.428} * Nr\ of\ Des^{-0.297} * Nr\ of\ Bids^{-0.311} * ADT^{0.01} * ASD^{0.032}$
MOT Cost	MOT Cost $= e^{-1.710} * Des\ Award^{0.848} * Nr\ of\ Des^{-0.138}$

TABLE 5.14
Hypothetical Case Study Results

Nr of Des	Est. Nr of Bids (Upper Bound)	Est. Des Award for the BDO Project	Est. MOT Cost for the BDO Project	MOT Cost Ratio for the BDO Project (%)
1	13.04	$362,711	$9,373	2.58
2	10.52	$315,590	$7,570	2.40
3	9.05	$293,214	$6,725	2.29
4	8.00	$279,669	$6,209	2.22
5	7.19	$270,568	$5,854	2.16
6	6.53	$264,118	$5,593	2.12
7	5.97	$259,427	$5,393	2.08
8	5.49	$255,992	$5,235	2.04
9	5.06	$253,509	$5,108	2.01
10	4.68	$251,781	$5,005	1.99
11	4.33	$250,675	$4,921	1.96
12	4.02	$250,103	$4,853	1.94
13	3.72	$250,001	$4,798	1.92
14	3.46	$250,329	$4,755	1.90
15	3.21	$251,060	$4,721	1.88
16	2.97	$252,178	$4,697	1.86
17	2.75	$253,680	$4,682	1.85
18	2.54	$255,570	$4,674	1.83
19	2.35	$257,862	$4,675	1.81
20	2.16	$260,579	$4,683	1.80
21	1.98	$263,756	$4,700	1.78
22	1.81	$267,439	$4,725	1.77
23	1.65	$271,690	$4,759	1.75
24	1.50	$276,593	$4,804	1.74
25	1.35	$282,256	$4,859	1.72



(a) Estimated Des Award (b) Estimated MOT Cost and MOT Cost Ratio

Figure 5.21 Hypothetical case study results.

6. BUNDLING STRATEGY EVALUATION

This chapter first evaluates past project bundling that has occurred among INDOT's past projects. This was done at the contract level and also at the project level. At the contract level, all combinations of project work category/project type in the previous bundled contracts are presented. The project-level analysis evaluated, for each project type, how often a project is bundled with the same or different project type. The second part of the chapter carries out scenario analysis to evaluate the cost savings associated with different project bundling strategies using the cost models developed in Chapter 5.

6.1 Bundling Strategies Used in Past Projects

6.1.1 Contract Level

Table 6.1 presents all 32 combinations of work categories in the study dataset. In the table, 32.38% of all the bundled contracts are from contracts with only bridge project types, and 11.91% are from contracts with only road project types. The most common combinations of bundled contracts with different work categories are bridge with road work (10.67%), traffic with road work (9.43%), bridge with traffic and road work (7.57%), and bridges with small-structures work (2.85%).

A similar analysis was carried out based on project type, and the results are presented in Table 6.2. There is a total of 235 different combinations of project types in all the bundled contracts, but only the most common combinations (those that occur more than 3 times) are presented due to limited space. A contract with Misc. Bridge Rehab & Repair only is the most frequent combination (9.43%) among all bundled contracts, followed by Bridge Deck Overlay only (7.94%). Some common combinations with different project types in bundled contracts include Intersection Improvement with Traffic Signals (3.97%), New Bridge with New Road Construction (3.85%), Bridge Replacement with Bridge Deck Overlay (1.99%) and New Bridge with Signing and New Road Construction (1.61%).

6.1.2 Project Level

At the project level, we evaluated, for each project type, how a project is bundled with other project types by counting the frequency at which projects are bundled with same project type (or work category) and different project types (or work category). The results

TABLE 6.1
Combinations of Work Categories in all Bundled Contracts

Comb	Counts	Percent	Work 1	Work 2	Work 3	Work 4
1	261	32.38	Bridge			
2	96	11.91	Road			
3	86	10.67	Bridge	Road		
4	83	10.30	Small Structures			
5	76	9.43	Traffic	Road		
6	61	7.57	Bridge	Traffic	Road	
7	30	3.72	Traffic			
8	23	2.85	Bridge	Small Structures		
9	15	1.86	Miscellaneous			
10	15	1.86	Small Structures	Road		
11	10	1.24	Bridge	Traffic	Road	Utility
12	8	0.99	Road	Utility		
13	6	0.74	Miscellaneous	Road		
14	5	0.62	Traffic	Road	Utility	
15	4	0.50	Bridge	Traffic		
16	3	0.37	Traffic	Small Structures	Road	
17	3	0.37	Bridge	Traffic	Miscellaneous	Road
18	2	0.25	Bridge	Road	Utility	
19	2	0.25	Bridge	Miscellaneous	Road	
20	2	0.25	Bridge	Utility		
21	2	0.25	Traffic	Miscellaneous	Road	
22	2	0.25	Bridge	Miscellaneous		
23	2	0.25	Bridge	Small Structures	Road	
24	1	0.12	Traffic	Utility		
25	1	0.12	Bridge	Traffic	Small Structures	Road
26	1	0.12	Small Structures	Road	Utility	
27	1	0.12	Miscellaneous	Utility		
28	1	0.12	Traffic	Miscellaneous		
29	1	0.12	Bridge	Small Structures	Miscellaneous	
30	1	0.12	Small Structures	Utility		
31	1	0.12	Utility			
32	1	0.12	Bridge	Traffic	Utility	

TABLE 6.2
Combination of Project Types in All Bundled Contracts (with counts ≥4)

Counts	Percent	Project Type 1	Project Type 2	Project Type 3
76	9.43	B8-Misc. Bridge Rehab & Repair		
64	7.94	B6-Bridge Deck Overlay		
48	5.96	S1-Pipe Lining		
46	5.71	R4-Partial 3		
32	3.97	R11-Intersection Improvement	T3-Traffic Signals	
31	3.85	B1-New Bridge	R1-New Road Construction	
27	3.35	S2-Small Structure Installation		
27	3.35	B7-Thin Deck Overlay		
17	2.11	T3-Traffic Signals		
16	1.99	B2-Bridge Replacement	B6-Bridge Deck Overlay	
15	1.86	B4-Deck Replacement		
13	1.61	B1-New Bridge	T2-Signing	R1-New Road Construction
11	1.36	R3-Patch & Rehab Pavement		
10	1.24	B1-New Bridge		
9	1.12	B3-Superstructure Replacement		
8	0.99	M2-Channel and Ditch Work		
8	0.99	B2-Bridge Replacement	S2-Small Structure Installation	
7	0.87	B8-Misc. Bridge Rehab & Repair	B7-Thin Deck Overlay	
7	0.87	R11-Intersection Improvement		
7	0.87	T2-Signing	R2-Added Travel Lanes	
7	0.87	B4-Deck Replacement	B6-Bridge Deck Overlay	
6	0.74	B1-New Bridge	S2-Small Structure Installation	
5	0.62	R4-Partial 3	R3-Patch & Rehab Pavement	
4	0.50	T1-ITS		
4	0.50	R10-Pavement Replacement	B6-Bridge Deck Overlay	
4	0.50	M4-Slide Correction		
4	0.50	B8-Misc. Bridge Rehab & Repair	R4-Partial 3	
4	0.50	B6-Bridge Deck Overlay	R4-Partial 3	
4	0.50	R12-Interchange Work	B1-New Bridge	T2-Signing
4	0.50	S3-Small Str. Maintenance & Repair		
4	0.50	R12-Interchange Work	B2-Bridge Replacement	
4	0.50	T2-Signing	R5-Road Rehabilitation 3R/4R	
4	0.50	T3-Traffic Signals	T2-Signing	R2-Added Travel Lanes
4	0.50	T1-ITS		

are presented in Table 6.3 and Figures 6.1 and 6.2 for each project type. The results show that for bridge project types, B3- Superstructure Replacement, B4-Deck Replacement, B6-Bridge Deck Overlay, B7-Thin Deck Overlay and B8-Misc. Bridge Rehab & Repair were more likely to be bundled with projects in different work categories, while other bridge project types are more often to be bundled with projects in different work categories. For traffic work, only T1-ITS was more likely to be bundled with projects in the same work category. For miscellaneous work, only M1-Demolition and M3-Stormwater Improvements were more likely to be bundled with different project types. All small-structure projects are more often bundled with same project type. In addition, for utility work, all U1-Railroad Work is bundled with same project type, while all U2-Utility Relocation is bundled with different project types.

Among road project types, R3-Patch & Rehab Pavement, R4-Partial 3, R7-Sight Distance Correction and R9-Pavement, Other are found more often to be bundled with projects in the same work category, while other road project types are more likely to be bundled with projects in different work categories. According to the average cost comparison results in Chapter 4 and the regression model developed in Chapter 5, R3, R4, R7 and R9 are the only road project types that were found to benefit from project bundling. It can be reasonably inferred that, in general, project bundling can reduce cost for road projects mostly when the projects are bundled with same project type or projects in the same work category.

To demonstrate how the project unit cost is affected by different bundling strategies, the average cost approach was applied. This yielded, for each project type, the average unit cost of projects bundled with same work category and those bundled with different work categories. The analysis was carried out for bridge and road work only because adequate data were available for those work categories. The results are shown in Table 6.4.

For bridge work, as shown in Figure 6.3, the average unit cost of projects bundled with the same work category is slightly higher than those bundled with different work categories for project types B2-Bridge Replacement and B5-Bridge Widening. For other bridge project types, projects bundled with same work categories have,

TABLE 6.3
Number of Projects Bundled with Same and Different Project Type/Work Categories

Project Type	Total Count	Project Type Bundling: Bundled with Same Project Type (%)	Project Type Bundling: Bundled with Different Project Type (%)	Work Category Bundling: Bundled with Same Work Category (%)	Work Category Bundling: Bundled with Different Work Category (%)
B1-New Bridge	246	7.45	92.55	7.80	92.20
B2-Bridge Replacement	103	17.56	82.44	27.48	72.52
B3-Superstructure Replacement	37	48.78	51.22	73.17	26.83
B4-Deck Replacement	45	56.86	43.14	90.20	9.80
B5-Bridge Widening	40	13.64	86.36	20.45	79.55
B6-Bridge Deck Overlay	235	54.66	45.34	68.83	31.17
B7-Thin Deck Overlay	144	59.21	40.79	80.26	19.74
B8-Misc. Bridge Rehab & Repair	495	76.19	23.81	88.38	11.62
R1-New Road Construction	39	1.54	98.46	1.54	98.46
R2-Added Travel Lanes	37	10.64	89.36	10.64	89.36
R3-Patch & Rehab Pavement	40	80.77	19.23	94.23	5.77
R4-Partial 3R	138	59.24	40.76	68.79	31.21
R5-Road Rehabilitation (3R/4R)	26	2.78	97.22	5.56	94.44
R6-Wedge & Level Only	1	0.00	100.00	0.00	100.00
R7-Sight Distance Correction	5	12.50	87.50	75.00	25.00
R8-Shoulder Rehab & Repair	1	0.00	100.00	50.00	50.00
R9-Pavement, Other	1	33.33	66.67	66.67	33.33
R10-Pavement Replacement	59	23.53	76.47	32.35	67.65
R11-Intersection Improvement	58	19.35	80.65	22.58	77.42
R12-Interchange Work	31	8.57	91.43	11.43	88.57
S1-Pipe Lining	39	83.84	16.16	89.90	10.10
S2-Small Structure Installation	106	59.82	40.18	62.50	37.50
S3-Small Str. Maintenance & Repair	14	44.44	55.56	61.11	38.89
M1-Demolition	1	40.00	60.00	40.00	60.00
M2-Channel and Ditch Work	12	83.33	16.67	83.33	16.67
M3-Stormwater Improvements	1	0.00	100.00	0.00	100.00
M4-Slide Correction	7	68.75	31.25	68.75	31.25
M5-Paths, Sidewalks & Curb Ramps	1	66.67	33.33	66.67	33.33
T1-ITS	10	64.29	35.71	64.29	35.71
T2-Signing	74	4.39	95.61	7.89	92.11
T3-Traffic Signals	64	31.37	68.63	34.64	65.36
T4-Pavement Markings	5	40.00	60.00	50.00	50.00
T5-Guard Rail, Cable Barrier & Wall	6	30.00	70.00	40.00	60.00
T6-Lighting	12	23.53	76.47	35.29	64.71
U1-Railroad Work	1	100.00	0.00	100.00	0.00
U2-Utility Relocation	31	0.00	100.00	0.00	100.00

on average, slightly lower unit cost. This is mostly consistent with the results of the bridge cost regression models developed in Section 5.1.1.1 where the variable average similarity distance (ASD) is somewhat (not very) significant for bridge project types B1, B3, B4, B6 and B7 and has a direct relationship with project cost.

For most road projects (except R8-Shoulder Rehab & Repair), a significant difference was found between the unit cost of projects bundled with projects in the same work categories and those with different work categories, as shown in Figure 6.4. The analysis results suggest that a project that is bundled with same work category, on average, has a much lower unit cost compared to one bundled with different work categories. This is generally consistent with the results in Section 5.1.1.2, where the variable ASD is very significant and has a positive sign in most road project cost models. In other words, the higher the similarity (smaller ASD) between projects bundled in a contract, the lower the unit cost. This also explains why project bundling does not seem beneficial for most road project types as was found in the previous chapters. The reason is that, as evidenced from the historical records of past bundling, these projects are more likely to be bundled with different project types (lower similarity) (Table 6.3).

6.2 Bundling Scenarios Analysis

In this section, scenario analysis is carried out to evaluate the impact of different bundling strategies on project cost, using the project cost model developed in Chapter 5. Due to its greater data availability and superior cost models (that include all three major factors), bridge work was selected to illustrate the analysis. B8-Misc.

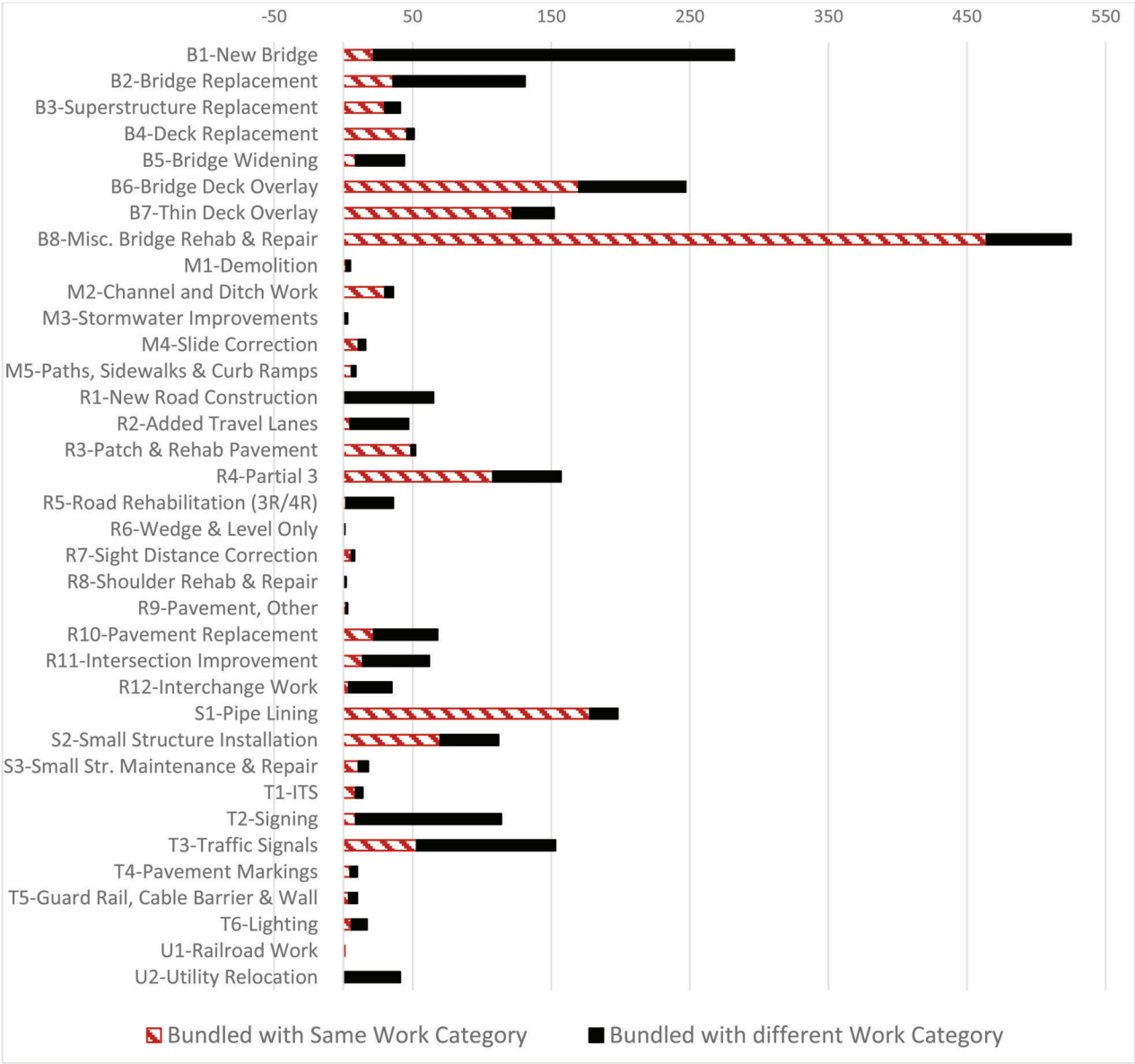


Figure 6.1 Number of projects bundled with same (and different) project type.

Bridge Rehab & Repair was excluded from analysis because B8 is a mix of many different project types. (See Section 4.1.) The analysis was conducted in two ways: (1) assuming past single projects are bundled and (2) assuming that the past bundled projects are either unbundled or rebundled with different bundling strategies. In Section 6.2.1, all the stand-alone bridge projects in three selected corridors were used for the analysis. This was done to compare the original project cost of these single projects with the new project cost estimated using the developed cost models, assuming projects are bundled with a specified bundling strategy. In Section 6.2.2, three bundled contracts were selected to compare the project cost under the old bundling strategy to the new project cost (assuming projects are unbundled or rebundled with revised bundling strategies).

6.2.1 Bundling of Past Single Projects Located along a Corridor

As shown in the corridor analysis in Section 4.6, from Year 2008 to 2017 there are many stand-alone projects in some corridors that might have instead been bundled into one contract. This section evaluates the expected cost savings from bundling the past single projects along a corridor using the cost model developed in Chapter 5.

6.2.1.1 Scenario Analysis along the I-69 Corridor. Ten stand-alone bridge projects completed along Interstate 69 at years 2008 to 2017 were analyzed. The information for these projects is listed in Table 6.5, including project type, Des ID, Letting Year, Des Award amount,

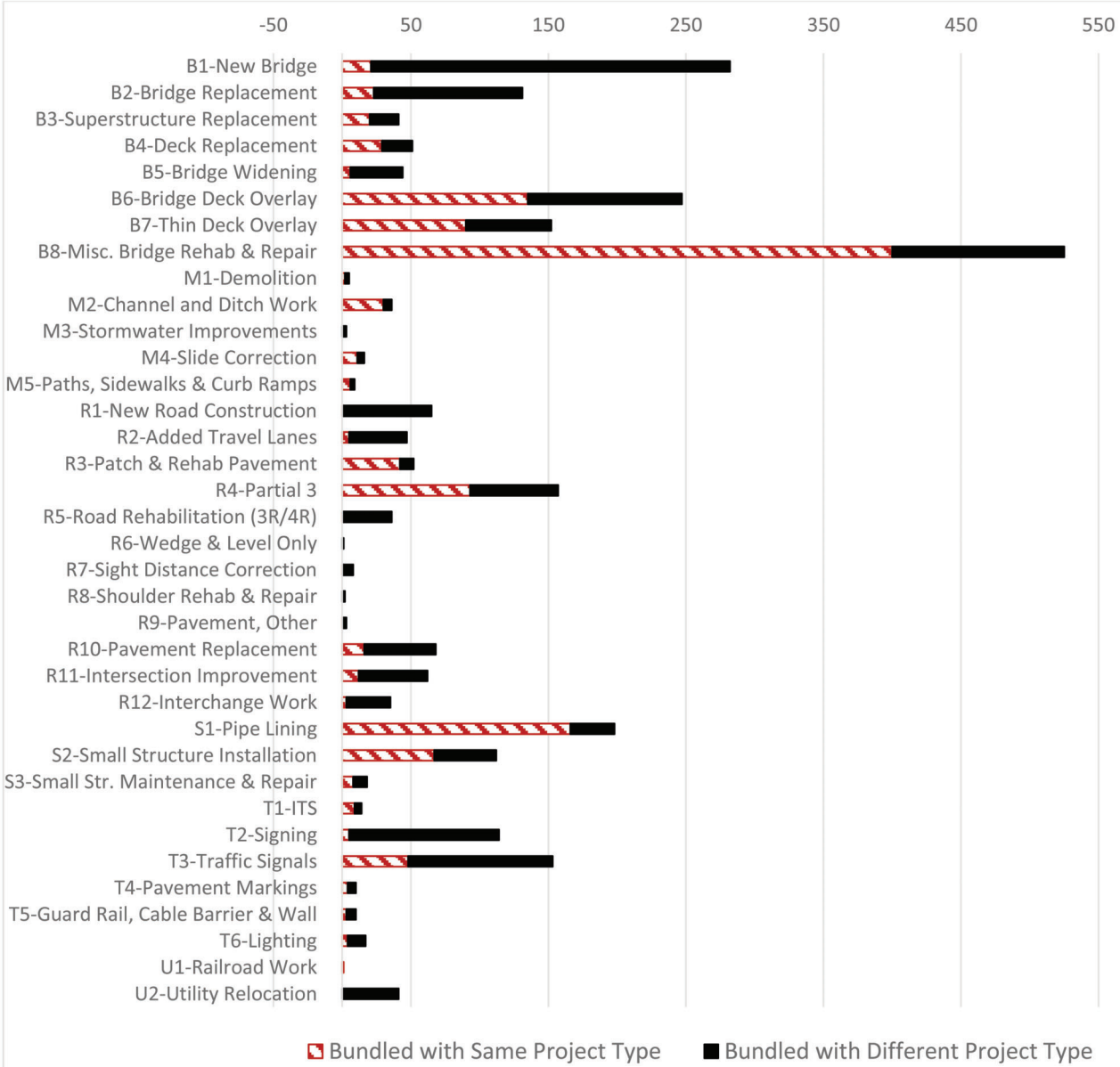


Figure 6.2 Number of projects bundled with same (and different) work category.

number of bidders, deck area, and ADT. The total cost of all these individual projects is the sum of all their Des Awards ($10,883,024). The objective is to apply developed project cost models to estimate the extent of cost savings achieved by bundling these single projects using specific bundling strategies.

The first bundling strategy scenario that was evaluated involves bundling all 10 single projects along the I-69 corridor into one new contract (see Table 6.6). In this case, the Nr of Des in the contract is 10. Two approaches were used to estimate the number of bidders under the new bundling strategy. The first approach uses the weighted average of Nr of Bids from the original contracts: $\mathrm{WANB_j} = \sum_{i=1}^{n_i} [\frac{\mathrm{DA_i}}{\sum_{k=1}^{N} DA_k} * B_i]$, where $\mathrm{WANB_j}$ is the weighted average number of bidders in new contract j, N is the total number of projects analyzed; n_j is the Nr of Des in the new contract j; $\mathrm{DA_i}$ is Des Award of the i-th project in the new contract j; and $\mathrm{B_i}$ is the actual number of bidders in the original contract. The second approach uses the upper-bound model developed in Section 4.3 to estimate the highest number of bidders, which gives an optimistic estimation on the project cost under the optimistic market competition. Under the Bundling Scenario 1, where all projects are bundled into one contract, the weighted *average* Nr of Bids is calculated as $\sum_{i=1}^{10} [\frac{\mathrm{DA_i}}{\sum_{k=1}^{10} DA_k} * B_i] = \frac{\$1,663,309}{\$10,883,024} * 3 + \frac{\$3,638,418}{\$10,883,024} * 3 + \ldots + \frac{\$186,721}{\$10,883,024} * 6 = 4.62$ and the *highest* number of bidders is

TABLE 6.4
Unit Cost Comparison Results

Project Type	Count: Bundled with Same Work Category	Count: Bundled with different Work Category	Unit Cost: Bundled with Same Work Category	Unit Cost: Bundled with different Work Category	Unit
B1	22	235	$239	$247	$/sqft
B2	31	78	$448	$401	$/sqft
B3	30	11	$179	$191	$/sqft
B4	45	4	$136	$145	$/sqft
B5	9	35	$214	$167	$/sqft
B6	170	76	$60	$86	$/sqft
B7	122	30	$16	$24	$/sqft
B8	457	60	$11	$31	$/sqft
R1	1	38	$1,249,502	$1,941,999	$/lane-mile
R2	1	36	$44,394	$2,726,358	$/lane-mile
R3	39	1	$18,363	$67,604	$/lane-mile
R4	95	43	$146,775	$151,848	$/lane-mile
R5	1	24	$222,600	$1,219,243	$/lane-mile
R7	3	1	$379,114	$1,632,142	$/lane-mile
R8	1	1	$441,535	$124,413	$/lane-mile
R10	19	39	$221,882	$1,070,051	$/lane-mile
R11	12	46	$839,670	$1,364,628	$/unit
R12	2	29	$495,660	$13,474,371	$/unit

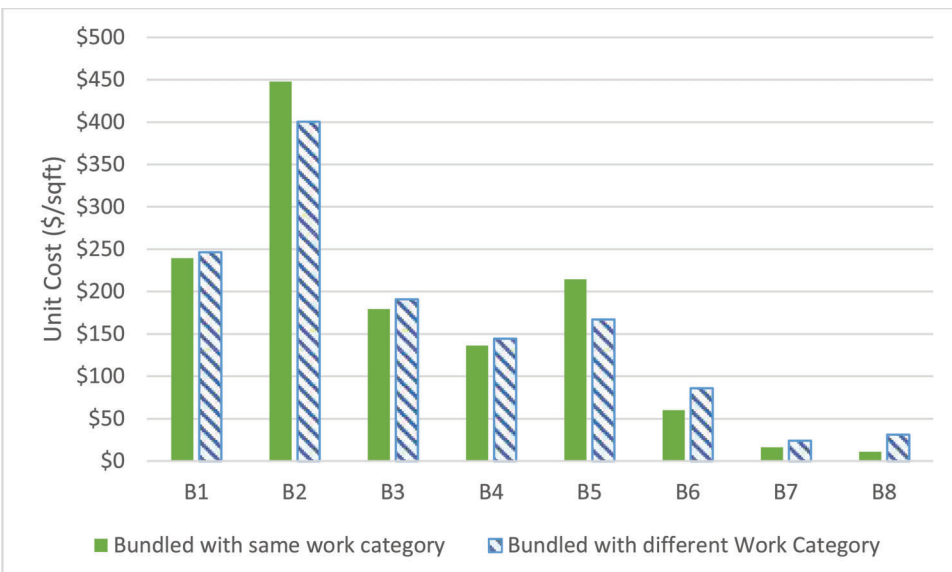


Figure 6.3 Unit cost comparison results for bridge work.

estimated as -3.631*ln(Nr of Des) + 13.038 = -3.631* ln(10) + 13.038 = 4.67. The upper-bound approach has a better statistical basis, but leads to "optimistic" lower costs. The weighted average approach uses actual number of bidders, which does not reflect changes that result from bundling, but should provide a frame of reference with which to judge the degree of "optimism" in the upper-bound estimates. As will be seen later in this chapter, the upper bound approach provides a good basis for comparing alternative bundling strategies.

The hypothetical project cost (Estimated Des Award) is estimated using the cost regression model for each bridge project type based on the new *Nr of Des* in the bundle and the estimated highest number of bidders. A sample calculation for Des 710141 (Project Type B4-Deck Replacement), using Equation 5.6 and the parameters for B4 in Table 5.1:

$$\text{Des Award (Average)} = 2096.448 * \text{Deck}_{\text{Area}}{}^{(0.746-1)}$$

$$* \; Nr\ of\ Des^{(-0.047)} * Nr\ of\ Bids^{-0.242} = 2096.448$$

$$* \; 23016^{(0.746-1)} * 10^{-0.047} * 4.62^{-0.242} = \$2{,}258{,}128$$

$$\text{Des Award (Optimistic)} = 2096.448 * 23016^{(0.746-1)}$$

$$* \; 10^{-0.047} * 4.67^{-0.242} = \$2{,}251{,}227$$

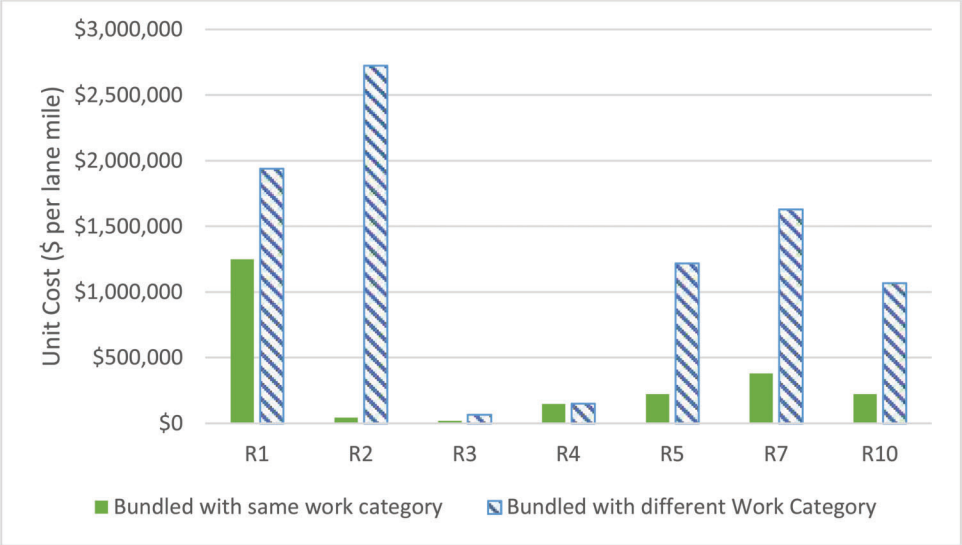


Figure 6.4 Unit cost comparison results for road work.

TABLE 6.5
Project Information for All Stand-Alone Bridge Projects on I-69

Project Type	Des ID	Nr of Des	Letting Year	Deck Area (sqft)	ADT	Nr of Bids	Des Award (2015$)
B4-Deck Replacement	0710141	1	2009	23016	24310	3	$1,663,309
B2-Bridge Replacement	0200934	1	2009	13139.16	33811	3	$3,638,418
B6-Bridge Deck Overlay	0800948	1	2012	4723.4	29009	3	$131,197
B3-Superstructure Replacement	0810271	1	2014	6246.6	45634	6	$1,130,886
B4-Deck Replacement	0810231	1	2012	5421	27117	6	$760,625
B6-Bridge Deck Overlay	1296558	1	2015	5538.5	30524	3	$615,790
B6-Bridge Deck Overlay	1296838	1	2015	7015	23454	3	$636,352
B3-Superstructure Replacement	1006468	1	2015	4382	45634	9	$1,928,500
B6-Bridge Deck Overlay	1006267	1	2015	4184	35470	2	$191,227
B6-Bridge Deck Overlay	1296734	1	2016	4280	35470	6	$186,721
	Sum of all Des Awards:						$10,883,024

TABLE 6.6
I-69 Cost Comparison Analysis for Bundling Scenario 1 (all projects bundled in a single contract)

		Observed Cost			Est. Average Cost			Est. Optimistic Cost	
Des ID	Nr of Des	Original Des Award (2015$)	Original Unit Cost ($/sqft)	WANB	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)	Est. Highest Nr of Bids*	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)
		Contract 1 (All Projects)							
710141	10	$1,663,309	$72	4.62	$2,258,128	$98	4.67	$2,251,227	$98
200934		$3,638,418	$277		$2,560,493	$195		$2,559,166	$195
800948		$131,197	$28		$222,649	$47		$221,775	$47
810271		$1,130,886	$181		$1,227,627	$197		$1,222,774	$196
810231		$760,625	$140		$767,887	$142		$765,541	$141
1296558		$615,790	$111		$238,469	$43		$237,533	$43
1296838		$636,352	$91		$263,158	$38		$262,125	$37
1006468		$1,928,500	$440		$981,106	$224		$977,227	$223
1006267		$191,227	$46		$211,814	$51		$210,982	$50
1296734		$186,721	$44		$213,880	$50		$213,041	$50
Total Cost		$10,883,024			$8,945,212			$8,921,390	
Cost Savings					$1,937,812			$1,961,634	

*Using the model for estimating the Nr of Bids.

TABLE 6.7
I-69 Cost Comparison Analysis for Bundling Scenario 2 (by letting year)

		Observed Cost		Est. Average Cost			Est. Optimistic Cost		
Des ID	Nr of Des	Original Des Award (2015$)	Original Unit Cost ($/sqft)	WANB	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)	Est. Highest Nr of Bids*	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)
		Contract 1 (Letting Year ≤2012)							
710141	4	$1,663,309	$72	3.37	$2,602,614	$113	8.00	$2,110,776	$92
200934		$3,638,418	$277		$2,887,372	$220		$2,786,704	$212
800948		$131,197	$28		$339,474	$72		$259,359	$55
810231		$760,625	$140		$885,032	$163		$717,780	$132
		Contract 2 (Letting Year >2012)							
810271	6	$1,130,886	$181	6.27	$1,217,293	$195	6.53	$1,201,753	$192
1296558		$615,790	$111		$265,710	$48		$262,342	$47
1296838		$636,352	$91		$293,219	$42		$289,502	$41
1006468		$1,928,500	$440		$972,847	$222		$960,427	$219
1006267		$191,227	$46		$236,010	$56		$233,018	$56
1296734		$186,721	$44		$238,312	$56		$235,291	$55
Total Cost		$10,883,024			$9,937,882			$9,056,951	
Cost Savings					$945,142			$1,826,073	

*Using the model for estimating the Nr of Bids.

The results suggest that, when all the unbundled projects are bundled in one contract, the total project cost (Des Award) reduces from $10,883,024 (sum of the individual standalone projects) to $9,056,951 under the average case with a total saving of $1,937,812, and to $8,921,390 under optimistic market conditions with a saving of $1,961,634.

Bundling all the projects into one contract can yield large savings on the total project cost (Des Award). However, in order to do this, some projects will need to be delayed and others will need to be implemented ahead of schedule. However, delaying a project too long beyond its originally scheduled letting date may lead to unacceptable deterioration of asset condition and/or cause unacceptably higher project cost and/or user costs in the subsequent years. Therefore, the next strategy involved bundling the projects by the contract letting year. Table 6.7 summarizes the results of bundling the four projects let before Year 2012 as one contract and the remaining six as another contract. The total project cost (Des Award) drops from $10,883,024 to $9,937,882 (average) and to $9,056,951 (optimistic), with total savings of $945,142 and $1,826,073. It was noticed that, although the overall saving in Scenario 2 is less than the saving in Scenario 1, when all projects are bundled in one contract, the unit cost of individual projects does not necessarily increase in Scenario 2. For example, the unit cost under the optimistic market condition of Des 710141 in Scenario 2 ($92) is slightly lower than it is in Scenario 1 ($98). This indicates that the size of the contract for the Scenario 1 bundling strategy might be so large that the cost of certain project types is higher than if they were bundled into smaller contracts, due to the changes in market competition (Nr of Bids).

Because the weighted average Nr of Bids is estimated using the value of *Nr of Bids* from the original contracts, it does not reflect the change of market competition due to the increased contract size (Nr of Des) under the new bundling strategy. The upper-bound model predicts the highest expected Nr of Bids under the best market condition. Therefore, in reality, the contract size (10 Des and $10,883,024 contract award) in Scenario 1 might be too large to attract a sufficient number of bidders. Bundling these projects as smaller multiple contracts might be necessary.

As indicated by the regression models developed in Section 5.1.1.1 for bridge work, project similarity is an influential variable on the project cost for some bridge project types. The higher the similarity between projects bundled in a contract, the lower the project cost. The third scenario is based on the similarity between different project types (similarity distance calculated in Section 4.4.2) to show whether there is a greater saving in project cost if projects with higher similarity are bundled together. As shown in Table 6.8, projects are bundled based on the similarity distance between project types. According to Table 4.7, B2, B3, and B4 have pairwise ASD values of 0.199 or lower, so the five B2-Bridge Replacement, B3-Superstructure Replacement, and B4-Deck Replacement projects are bundled into one contract. That leaves five B6-Bridge Deck Overlay projects. Under this scenario, the total project cost is reduced from $10,883,024 to $9,770,170 (a total saving of $1,112,854) in the average case, and to $8,834,707 (a total saving of $2,048,317) under the optimistic market condition. This indicates that bundling projects with higher similarity (compatibility) into a contract can lead to greater savings.

TABLE 6.8
I-69 Cost Comparison Analysis for Bundling Scenario 3 (projects bundled on the basis of their similarity)

		Observed Cost		Est. Average Cost			Est. Optimistic Cost		
Des ID	Nr of Des	Original Des Award (2015$)	Original Unit Cost ($/sqft)	WANB	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)	Est. Highest Nr of Bids*	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)
		Contract 1 (Replacement Work: B2, B3 and B4)							
710141	5	$1,663,309	$72	4.89	$2,300,813	$100	7.19	$2,095,647	$91
200934		$3,638,418	$277		$2,770,288	$211		$2,726,796	$208
810271		$1,130,886	$181		$1,297,529	$208		$1,149,796	$184
810231		$760,625	$140		$782,403	$144		$712,635	$131
1006468		$1,928,500	$440		$1,036,970	$237		$918,904	$210
		Contract 2 (Rehab Work: B6)							
800948	5	$131,197	$28	3.21	$306,328	$65	7.19	$238,323	$50
1296558		$615,790	$111		$328,094	$59		$255,258	$46
1296838		$636,352	$91		$362,061	$52		$281,684	$40
1006267		$191,227	$46		$291,420	$70		$226,725	$54
1296734		$186,721	$44		$294,264	$69		$228,937	$53
Total Cost		$10,883,024			$9,770,170			$8,834,707	
Cost Savings					$1,112,854			$2,048,317	

*Using the model for estimating the Nr of Bids.

TABLE 6.9
Project Information for All Stand-Alone Bridge Projects on I-70

Project Type	Des ID	Nr of Des	Letting Year	Deck Area (sqft)	ADT	Nr of Bids	Des Award (2015$)
B6-Bridge Deck Overlay	400966	1	2008	4332	48211	5	$322,606
B6-Bridge Deck Overlay	400967	1	2008	4230	38857	4	$330,065
B4-Deck Replacement	600089	1	2009	4534	2043	8	$824,937
B6-Bridge Deck Overlay	710871	1	2008	17082	148800	2	$960,086
B6-Bridge Deck Overlay	800956	1	2013	4699.2	36630	8	$414,351
B1-New Bridge	801047	1	2008	2240	35451	6	$2,618,773
B6-Bridge Deck Overlay	1173926	1	2016	12574.2	118670	1	$1,197,212
B6-Bridge Deck Overlay	1400344	1	2015	21364	99090	2	$343,145
B6-Bridge Deck Overlay	1173880	1	2015	5302	44760	2	$235,610
B7-Thin Deck Overlay	1401438	1	2016	51256.8	111240	1	$1,637,071
	Sum of all Des Awards:						$8,883,858

6.2.1.2 Scenario Analysis for I-70 Corridor. A similar analysis was conducted for all the stand-alone bridge projects along the I-70 corridor in Years 2008 to 2017, including B6-Bridge Deck Overlay, B7-Thin Deck Overlay, B4-Deck replacement and B1-New Bridge. The bridge information is listed in Table 6.9, and the original total project cost (Des Award) of the 10 single projects is $8,883,858.

The first bundling strategy evaluated is to bundle all the projects into one contract. Under this scenario, the number of des in the contract is 10, and the estimated highest number of bidders is 4.68. The new Des Award is predicted using the cost model developed for each project type. The total project cost under this scenario is reduced from $8,883,858 to $5,444,816 (average case) with a total saving of $5,444,816 and $3,380,108 (optimistic case) with a total saving of $5,368,03,749, as shown in Table 6.10.

Second, the bundling scenario where projects are bundled into two contracts based on the letting year was analyzed. As shown in Table 6.11, the five projects that were let before 2009 are bundled into Contract 1, and the other five projects are bundled into Contract 2. This yields total savings of $4,004,364 (average case) or $5,000,257 (optimistic case), compared to leaving all the projects unbundled. This is less than the savings under Scenario 1 if all projects are bundled in one contract.

We next evaluate how the cost will change if the projects were bundled by project similarity. As shown in Table 6.12, B1-New Bridge and B4-Deck Replacement (with high similarity) are bundled as a single contract, while B6-Thin Deck Overlay projects are bundled as a separate contract. The number of des in the two contracts are two and eight, respectively. The total project cost decreased from $8,883,858 to $4,563,282 (average

TABLE 6.10
Cost Comparison Analysis for Bundling Scenario 1 (all projects bundled as a single contract)

		Observed Cost		Est. Average Cost			Est. Optimistic Cost		
Des ID	Nr of Des	Original Des Award (2015$)	Original Unit Cost ($/sqft)	WANB	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)	Est. Highest Nr of Bids*	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)
		Contract 1 (All Projects)							
400966	10	$322,606	$74	4.38	$219,230	$51	4.68	$214,803	$50
400967		$330,065	$78		$216,538	$51		$212,165	$50
600089		$824,937	$182		$680,730	$150		$670,008	$148
710871		$960,086	$56		$398,859	$23		$390,803	$23
800956		$414,351	$88		$226,376	$48		$221,805	$47
801047		$2,618,773	$1,169		$483,925	$216		$481,961	$215
1173926		$1,197,212	$95		$349,050	$28		$342,001	$27
1400344		$343,145	$16		$437,150	$20		$428,322	$20
1173880		$235,610	$44		$238,856	$45		$234,032	$44
1401438		$1,637,071	$32		$188,327	$4		$184,209	$4
Total Cost		$8,883,858			$3,439,042			$3,380,108	
Cost Savings					$5,444,816			$5,503,749	

*Using the model for estimating the Nr of Bids.

TABLE 6.11
Cost Comparison Analysis for Bundling Scenario 2 (by letting year)

		Observed Cost		Est. Average Cost			Est. Optimistic Cost		
Des ID	Nr of Des	Original Des Award (2015$)	Original Unit Cost ($/sqft)	WANB	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)	Est. Highest Nr of Bids*	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)
		Contract 1 (Letting Year ≤2009)							
400966	5	$322,606	$74	5.37	$266,133	$61	7.19	$243,031	$56
400967		$330,065	$78		$262,865	$62		$240,047	$57
600089		$824,937	$182		$684,623	$151		$637,918	$141
710871		$960,086	$56		$484,191	$28		$442,161	$26
801047		$2,618,773	$1,169		$696,968	$311		$684,464	$306
		Contract 1 (Letting Year ≤2009)							
800956	5	$414,351	$88	1.91	$379,122	$81	7.19	$250,953	$53
1173926		$1,197,212	$95		$584,569	$46		$386,944	$31
1400344		$343,145	$16		$732,115	$34		$484,609	$23
1173880		$235,610	$44		$400,022	$75		$264,787	$50
1401438		$1,637,071	$32		$388,885	$8		$248,687	$5
Total Cost		$8,883,858			$4,879,494			$3,883,601	
Cost Savings					$4,004,364			$5,000,257	

*Using the model for estimating the Nr of Bids.

case) with a saving of $4,320,576, and to $3,724,534 (optimistic case) with a saving of $5,159,324. The cost saving for this scenario is slightly more than that for Scenario 2, where projects are bundled by letting year. The increase in the savings indicates the benefit of bundling projects with higher similarity. The reason why the savings did not increase significantly is that there are only two des bundled in Contract 1 under bundling Scenario 3, while there are five des under bundling Scenario 2. Due to the decreased number of des (economies of bundling), the unit cost of a project might increase in Scenario 3, even though it is bundled with a similar project type. For example, it can be found that, under the optimistic market condition, the estimated unit cost is $383 in Scenario 3 for Des 801047 where it is bundled with only one project (by similarity). This is larger than the estimated unit cost in Scenario 2 ($306), when Des 801047 is bundled with four other projects (by letting year).

6.2.1.3 Scenario Analysis for US 31 Corridor. Finally, a scenario analysis was conducted for the US 31 corridor. The stand-alone projects in this corridor from Year 2008 to 2017 include B2-Bridge Replacement, B3-Superstructure Replacement, B6-Bridge Deck Overlay and B7-Thin Deck Overlay. To be consistent with the

TABLE 6.12
Cost Comparison Analysis for Bundling Scenario 3 (projects bundled on the basis of their similarity)

		Observed Cost		Est. Average Cost			Est. Optimistic Cost		
Des ID	Nr of Des	Original Des Award (2015$)	Original Unit Cost ($/sqft)	WANB	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)	Est. Highest Nr of Bids*	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)
		Contract 1 (Replacement Work: B1 and B4)							
600089	2	$824,937	$182	6.48	$667,859	$147	10.52	$593,925	$131
801047		$2,618,773	$1,169		$883,359	$394		$857,202	$383
		Contract 2 (Rehab Work: B6)							
400966	8	$322,606	$74	2.24	$288,769	$67	5.49	$218,396	$50
400967		$330,065	$78		$285,223	$67		$215,714	$51
710871		$960,086	$56		$525,375	$31		$397,341	$23
800956		$414,351	$88		$298,182	$63		$225,515	$48
1173926		$1,197,212	$95		$459,767	$37		$347,721	$28
1400344		$343,145	$16		$575,813	$27		$435,487	$20
1173880		$235,610	$44		$314,620	$59		$237,947	$45
1401438		$1,637,071	$32		$264,315	$5		$195,287	$4
Total Cost		$8,883,858			$4,563,282			$3,724,534	
Cost Savings					$4,320,576			$5,159,324	

*Using the model for estimating the Nr of Bids.

TABLE 6.13
Project Information for the Stand-Alone Bridge Projects on the US 31 Corridor

Project Type	Des ID	Nr of Des	Letting Year	Deck Area (sqft)	ADT	Nr of Bids	Des Award (2015$)
B2-Bridge Replacement	0100317	1	2010	11576	33430	7	$3,490,106
B3-Superstructure Replacement	0600088	1	2009	22271.2	33430	5	$4,598,359
B6-Bridge Deck Overlay	1005959	1	2012	9286.8	6674	6	$606,901
B6-Bridge Deck Overlay	1173614	1	2014	24960	10170	2	$892,460
B6-Bridge Deck Overlay	1173783	1	2015	29242.72	5000	2	$1,746,500
B4-Deck Replacement	1005960	1	2013	2544.75	10683	5	$495,303
B7-Thin Deck Overlay	1401445	1	2017	34272	16975	4	$251,304
	Total Des Award (2015$)						$12,080,933

I-69 and I-70 corridor analyses, two B1-New Bridge projects (Des 0600358 and Des 0600358) on the new constructed corridor (Corridor 231) were deleted from the analysis. The bridge information is listed in Table 6.13. The original total project cost (Des Award) of the seven single projects is $12,080,933.

Again, the scenario where all projects were bundled into one contract was evaluated first. The analysis results are presented in Table 6.14. The number of des in the contract is seven, and the estimated highest number of bidders in this case is six. The new Des Award is predicted using the cost model developed for each project type. The total cost under this scenario is reduced from $12,080,933 to $7,361,410 (average case) or $7,067,895 (optimistic case), indicating a total saving of $4,719,522 or $5,013,038, respectively. It must be pointed out that the Des Award Estimates are computed using models that are based on data that were not collected with this purpose (bundling scenario analysis) in mind. For example, it was discovered that Des ID 100317 was a Bridge Replacement project, but the pay items associated with approach road work were included in the costs for that B1 project. This might explain at least part of the difference between Observed and Actual Des Awards. It is also a reminder that both dollar amounts should be treated as approximations.

The next scenario is to evaluate how the cost will change if projects were bundled by project similarity (see Table 6.15). Based on the similarity distance results in Table 4.15, B2-Bridge Replacement, B3-Superstructure Replacement, B4-Deck Replacement are bundled as a single contract, while B7-Thin Deck Overlay and B6-Bridge Deck Overlay are bundled as a separate second contract. The number of des in the two contracts are three and four, respectively, and the estimated expected highest number of bidders are nine and eight correspondingly. The total project cost decreased from $12,080,933 to $8,159,299 in the average case (with a saving of $3,921,633) and to $7,095,977 in the optimistic case (with saving of $4,984,955). The cost savings under this scenario are slightly less than those from Scenario 1, when all projects are bundled into one contract. How-

TABLE 6.14
US 31 Cost Comparison Analysis for Bundling Scenario 1 (all projects bundled as a single contract)

		Observed Cost			Est. Average Cost		Est. Optimistic Cost		
Des ID	Nr of Des	Original Des Award (2015$)	Original Unit Cost ($/sqft)	WANB	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)	Est. Highest Nr of Bids*	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)
		Contract 1 (All Projects)							
100317	7	$3,490,106	$301	4.9	$2,445,401	$211	5.97	$2,426,686	$210
600088		$4,598,359	$206		$2,880,580	$129		$2,716,398	$122
1005959		$606,901	$65		$335,633	$36		$316,633	$34
1173614		$892,460	$36		$514,597	$21		$485,466	$19
1173783		$1,746,500	$60		$546,788	$19		$515,835	$18
1005960		$495,303	$195		$446,711	$176		$426,907	$168
1401445		$251,304	$7		$191,700	$6		$179,969	$5
Total Cost		$12,080,933			$7,361,410			$7,067,895	
Cost Savings					$4,719,522			$5,013,038	

*Using the model for estimating the Nr of Bids.

TABLE 6.15
US 31 Cost Comparison Analysis for Bundling Scenario 2 (bundling based on project similarity)

		Observed Cost			Est. Average Cost		Est. Optimistic Cost		
Des ID	Nr of Des	Original Des Award (2015$)	Original Unit Cost ($/sqft)	WANB	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)	Est. Highest Nr of Bids*	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)
		Contract 1 (Replacement Work: B2, B3 and B4)							
100317	3	$3,490,106	$301	5.81	$2,682,551	$232	9.05	$2,634,320	$228
600088		$4,598,359	$206		$2,898,323	$130		$2,523,228	$113
1005960		$495,303	$195		$437,202	$172		$392,802	$154
		Contract 2 (Rehab Work: B6 and B7)							
1005959	4	$606,901	$65	2.84	$415,788	$45	8.00	$301,175	$32
1173614		$892,460	$36		$637,493	$26		$461,766	$19
1173783		$1,746,500	$60		$677,372	$23		$490,652	$17
1401445		$251,304	$7		$242,333	$7		$170,864	$5
Total Cost		$12,080,933			$8,159,299			$7,095,977	
Cost Savings					$3,921,633			$4,984,955	

*Using the model for estimating the Nr of Bids.

ever, as discussed earlier, the contract size (7 des and $12,080,933) in Scenario 1 might be too large to attract a sufficient number of bidders. Therefore, bundling these projects into two groups might be necessary, depending on the market competition.

To show the benefits of bundling projects by project similarity, a scenario involving projects randomly bundled into two contracts (with the same number of des in each contract) was created and evaluated (see Table 6.16). With a 3-project contract and a 4-project contract, the number of des and the estimated highest number of bidders can be controlled to the same value as the parameters in the previous scenario. Note that the total cost savings decreased from $3,921,633 and $4,984,955 (when projects are bundled based on similarity) to $3,887,182 and $4,809,459 (when projects are randomly bundled). This indicates bundling projects with higher similarity into one contract is more beneficial (in terms of cost savings) compared to randomly bundling without taking project compatibility into account.

6.2.2 Bundling Strategy Analysis

In this section, scenario analyses were carried out on contracts that were actually bundled in the past. The analysis seeks to ascertain how the project cost will change if these projects had been either unbundled or bundled using a different bundling strategy. From the dataset on historical contracts, Contracts 28973 (with eight bridge projects), 33066 (with four bridge projects) and 35537 (with seven bridge projects) were randomly selected.

The actual total project cost (Des Award) of all bridge projects in the three randomly selected bundled

TABLE 6.16
US 31 Cost Comparison Analysis for Bundling Scenario 3 (two random bundles, 3 des and 4 des)

		Observed Cost		Est. Average Cost			Est. Optimistic Cost		
Des ID	Nr of Des	Original Des Award (2015$)	Original Unit Cost ($/sqft)	Est. Nr of Bids	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)	Est. Nr of Bids*	Est. Des Award (2015$)	Est. Unit Cost ($/sqft)
		Contract 1 (Randomly Selected Projects)							
1005960	3	$495,303	$195	3.37	$510,096	$200	9.05	$401,754	$158
1005959		$606,901	$65		$486,388	$52		$357,870	$39
1173783		$1,746,500	$60		$792,387	$27		$583,016	$20
		Contract 2 (Randomly Selected Projects)							
600088	4	$4,598,359	$206	5.44	$2,967,735	$133	8.00	$2,629,452	$118
1401445		$251,304	$7		$246,118	$7		$216,067	$6
100317		$3,490,106	$301		$2,600,851	$225		$2,559,969	$221
1173614		$892,460	$36		$590,176	$24		$523,346	$21
Total Cost		$12,080,933			$8,193,751			$7,271,474	
Cost Savings					$3,887,182			$4,809,459	

*Using the model for estimating the Nr of Bids.

contracts is $19,082,148 (see Table 6.17). The estimated total Des Award using the cost estimation models is $17,354,061 (with the actual Nr of Bids) and $16,327,768 under the optimistic market condition (with highest Nr of Bids estimated using the upper bound model for bridge work). As discussed earlier, the gap between the actual cost ($19,082,148) and estimated cost ($17,354,061) arises from the discrepancy between the actual cost and the estimated cost from the developed model. Clearly, the models developed are not capable of capturing all the variations in the data, due to influential factors that were not included in the model, as evidenced by the some outliers in the data (unexpectedly high or low project cost). Several different bundling scenarios were evaluated in this section, and the cost under each bundling strategy was compared with the actual and estimated original cost.

The first scenario tests how the total project cost changes if all the bundled projects are unbundled. In this case, there would be 19 contracts, each containing only one project. The estimated highest number of bidders is 13 for each contract, based on the upper bound model. The estimated new Des Award is compared to the actual and predicted project cost under the original bundling strategies (See Table 6.18.) It is observed that the project unbundling leads to an increased total project cost of $3,789,948, compared to the estimated optimistic original cost (when projects were bundled into three contracts with the original strategy).

Note that the average model to estimate Nr of Bids is not used here, because no data for *Nr of Bids* data exists for the individual projects that were part of the bundles being studied. This is where the upper-bound model is of value. It is based on a large number of single- and multiple-project contracts. Although the cost estimates will be "optimistic" (lower than a least squares regression model would produce, if one could have been built), those optimistic costs do provide a reliable basis for the purpose of comparing alternative bundling strategies.

In the following sections, several different new bundling strategies were evaluated. The first bundling strategy is to bundle the 19 projects on the basis of project similarity (see Table 6.19). Project similarity is determined by the similarity distances calculated in Section 4.4.2. Projects with smaller similarity distances were assigned to the same contract. In this case, B1-New Bridge, B2-Bridge Replacement and B4-Deck Replacement are selected for Contract 1 (3 Des). B5-Bridge Widening (3 Des), B6-Bridge Deck Overlay (7 Des), and B7-Thin Deck Overlay (6 Des) are assigned to Contracts 2, 3 and 4, respectively. B6 and B7 have a good ASD=0.261 value in Table 4.7, but combining them would create a contract with 13 projects. The results showed that the new predicted project cost under this bundling strategy is $1,266,025, which is $5,055,974 lower than the cost in Scenario 1, and $1,266,025 lower than the estimated optimistic original cost, indicating the new bundling strategy is superior to both the unbundling strategy and original bundling strategy.

In the third scenario evaluated, the projects are still bundled into four contracts, but by random selection, to be compared with Scenario 2 where projects were bundled by their similarity (see Table 6.20). To distinguish the impact of project similarity from the effect of contract size, the number of projects in each contract was kept as same as that in Scenario 2. For example, Des 1172943, 1296125 and 1296397 were randomly assigned to the first contract. The number of des in the first contract is 3 and the estimated number of bidders is 9. Compared with the estimated optimistic original cost ($16,327,768), the total project cost is $930,017 higher, indicating that, based on the cost estimation model, this bundling strategy is not superior to the original bundling strategy in terms of the total cost. Also, the cost was found to increase significantly from $15,061,743 under Strategy 2 (where the projects were bundled based on their similarity) to $17,257,785 (where

TABLE 6.17
Project Information for Bridge Projects from Three Contracts

Contr. ID	Des ID	Project Type	Deck Area (sqft)	Act. Nr of Bids	Observed Des Award (2015$)	Est. Des Award (2015$)	Est. Highest Nr of Bids*	Est. Optimistic Des Award (2015$)
28973	0201046	B5	4411	4	$1,434,718	$781,981	5.49	$731,432
	0201049	B5	4411		$1,483,604	$781,981		$731,432
	0300462	B6	3440		$270,489	$228,871		$210,064
	0300475	B6	3440		$231,569	$228,871		$210,064
	0300485	B6	2520		$259,761	$200,328		$183,867
	0300488	B6	2520		$222,714	$200,328		$183,867
	1400667	B7	7525		$158,200	$116,005		$104,354
	1400668	B7	9450		$208,407	$125,690		$113,065
33066	1172943	B1	65556	6	$7,908,410	$8,584,568	8.00	$8,149,076
	1172944	B2	12167		$3,424,164	$2,678,337		$2,646,932
	1297418	B6	6696.5		$364,139	$333,779		$300,265
	1297419	B5	7555.5		$591,187	$1,063,505		$975,716
35537	1296142	B6	4120	4	$409,445	$255,896	5.97	$221,922
	0800879	B4	7676		$752,555	$1,071,920		$964,811
	1296034	B6	7788		$838,235	$330,854		$286,928
	1296097	B7	3520		$110,345	$87,469		$73,995
	1296113	B7	4025		$91,112	$90,237		$76,337
	1296125	B7	4484		$97,445	$87,776		$74,255
	1296397	B7	6270		$225,647	$105,663		$89,386
Sum of Total Des Award ($)					$19,082,148	$17,354,061		$16,327,768

*Using the model for estimating the Nr of Bids.

TABLE 6.18
Cost Comparison Analysis for Bundling Strategy 1* (unbundling of bundling projects)

Project Type	Des ID	Nr of Des	Est. Highest Nr of Bids†	Est. Optimistic Des Award (2015$)	Est. Optimistic Unit Cost
	Scenario 1: Single Project Contracts				
B5-Bridge Widening	0201046	1	13	$764,498	$173
B5-Bridge Widening	0201049			$764,498	$173
B6-Bridge Deck Overlay	0300462			$259,564	$75
B6-Bridge Deck Overlay	0300475			$259,564	$75
B6-Bridge Deck Overlay	0300485			$227,194	$90
B6-Bridge Deck Overlay	0300488			$227,194	$90
B7-Thin Deck Overlay	1400667			$175,505	$23
B7-Thin Deck Overlay	1400668			$190,156	$20
B1-New Bridge	1172943			$10,796,169	$165
B2-Bridge Replacement	1172944			$3,051,679	$251
B6-Bridge Deck Overlay	1297418			$349,521	$52
B5-Bridge Widening	1297419			$1,051,548	$139
B6-Bridge Deck Overlay	1296142			$278,930	$68
B4-Deck Replacement	0800879			$836,028	$109
B6-Bridge Deck Overlay	1296034			$360,635	$46
B7-Thin Deck Overlay	1296097			$123,736	$35
B7-Thin Deck Overlay	1296113			$127,652	$32
B7-Thin Deck Overlay	1296125			$124,170	$28
B7-Thin Deck Overlay	1296397			$149,474	$24
Total Cost				$20,117,716	
Savings	-$3,789,948 (compared to Est. optimistic original cost)				

*Each project is a contract (no project is bundled).
†Using the model for estimating the Nr of Bids.

TABLE 6.19
Cost Comparison Analysis for Bundling Strategy 2

Bundling Strategy	Project Type	Des ID	Nr of Des	Est. Highest Nr of Bids*	Est. Optimistic Des Award (2015$)	Est. Optimistic Unit Cost
	Scenario 2: Bundled into 4 Contracts by Project Similarity					
Contract 1 (B1, B2 and B4)	B1-New Bridge	1172943	3	9	$7,203,955	$110
	B2-Bridge Replacement	1172944			$2,724,353	$224
	B4-Deck Replacement	0800879			$867,848	$113
Contract 2 (B5)	B5-Bridge Widening	0201046	3	9	$716,805	$162
	B5-Bridge Widening	0201049			$716,805	$162
	B5-Bridge Widening	1297419			$985,947	$130
Contract 3 (B6)	B6-Bridge Deck Overlay	0300462	7	6	$185,217	$54
	B6-Bridge Deck Overlay	0300475			$185,217	$54
	B6-Bridge Deck Overlay	0300485			$162,119	$64
	B6-Bridge Deck Overlay	0300488			$162,119	$64
	B6-Bridge Deck Overlay	1297418			$249,408	$37
	B6-Bridge Deck Overlay	1296142			$199,036	$48
	B6-Bridge Deck Overlay	1296034			$257,339	$33
Contract 4 (B7)	B7-Thin Deck Overlay	1400667	6	7	$87,797	$12
	B7-Thin Deck Overlay	1400668			$95,127	$10
	B7-Thin Deck Overlay	1296097			$61,899	$18
	B7-Thin Deck Overlay	1296113			$63,858	$16
	B7-Thin Deck Overlay	1296125			$62,117	$14
	B7-Thin Deck Overlay	1296397			$74,775	$12
Total Cost					$15,061,743	
Savings	$1,266,025 (compared to Est. optimistic cost original cost) $5,055,974 (compared to Strategy 1: unbundling)					

*Using the model for estimating the Nr of Bids.

TABLE 6.20
Cost Comparison Analysis for Bundling Strategy 3

Bundling Strategy	Project Type	Des ID	Nr of Des	Est. Highest Nr of Bids*	Est. Optimistic Des Award (2015$)	Est. Optimistic Unit Cost
	Scenario 3: Bundled into 4 Contracts by Random Selection					
Contract 1 (3 Projects Randomly Selected)	B1-New Bridge	1172943	3	9	$9,223,781	$141
	B7-Thin Deck Overlay	1296125			$100,918	$23
	B7-Thin Deck Overlay	1296397			$121,483	$19
Contract 2 (3 Projects Randomly Selected)	B6-Bridge Deck Overlay	0300475	3	9	$236,305	$69
	B5-Bridge Widening	1297419			$985,947	$130
	B4-Deck Replacement	0800879			$913,845	$119
Contract 3 (7 Projects Randomly Selected)	B6-Bridge Deck Overlay	0300462	7	6	$207,975	$60
	B6-Bridge Deck Overlay	0300485			$182,038	$72
	B7-Thin Deck Overlay	1400667			$109,548	$15
	B7-Thin Deck Overlay	1400668			$118,693	$13
	B6-Bridge Deck Overlay	1297418			$280,052	$42
	B7-Thin Deck Overlay	1296113			$79,679	$20
	B7-Thin Deck Overlay	1296097			$78,835	$20
Contract 4 (6 Projects Randomly Selected)	B5-Bridge Widening	0201046	6	7	$692,248	$157
	B5-Bridge Widening	0201049			$692,248	$157
	B6-Bridge Deck Overlay	0300488			$182,038	$72
	B2-Bridge Replacement	1172944			$2,538,153	$209
	B6-Bridge Deck Overlay	1296142			$223,492	$54
	B6-Bridge Deck Overlay	1296034			$288,958	$37
Total Cost					$17,257,785	
Savings	-$930,017 (compared to Est. optimistic original cost) -$2,196,043 (compared to Strategy 2: four contracts by similarity)					

*Using the model for estimating the Nr of Bids.

projects are randomly bundled). This means it is generally more cost-effective to bundle projects if they are more compatible with each other.

The next scenario, involving the bundling of projects into three contracts by project similarity, was then evaluated. B5-Bridge Widening, B1-New Bridge, and B2-Bridge Replacement projects are bundled in Contract 1, and B6-Bridge Deck Overlay and B7-Thin Deck Overlay projects are bundled in Contracts 2 and 3, respectively (see Table 6.21). The total project cost under this bundling strategy is reduced by $1,846,206, compared to the estimated optimistic original cost. Also, compared with Scenario 2 where projects were also bundled by project similarity, but into four contracts, there is an additional saving of $580,181 due to the increased contract size.

In order to show the benefit of bundling projects by project similarity in terms of cost savings, the next scenario involved bundling of projects by random selection into three contracts (with same contract sizes as in Scenario 4) (see Table 6.22). The total project cost (Des Award) under this scenario is $15,193,676 (a reduction of $1,134,092 compared to the estimated optimistic original cost). However, the cost is increased by $712,114 from the previous scenario, where the projects were bundled into contracts with the same number of des, but a higher average project similarity than in the current scenario. In addition, compared to Scenario 2 (where projects were bundled into four contracts based on their similarity), there is a small increase of $131,933 in the total project cost. This means that, although the number of des per contract is higher in Scenario 5 compared to Strategy 2, the overall cost is not decreased, because the effect of project bundling on cost savings is outweighed by the cost increase due to the lower similarity between the constituent projects in a contract.

In the next two scenarios, the projects are bundled into two contracts using a random selection strategy. In Scenario 6, projects are bundled into two contracts with unbalanced number of des (to allow a comparison with Scenario 8) (see Table 6.23). Six projects are bundled into Contract 1 and 13 projects are bundled into Contract 2. The total cost is $14,985,185 under this scenario, indicating a saving of $1,846,206 compared to the estimated optimistic original cost. Scenario 6 is also compared with Scenario 5 (where projects are also randomly bundled to form three contracts). A cost saving of $208,491 is observed. This saving is mainly from the increased number of des per contract (the "economies of bundling" effect).

To allow a comparison with the unbalanced bundling in Scenario 6, projects are bundled into two contracts with 10 and 9 number of des, respectively, by random selection in Scenario 7 (see Table 6.24). The total project cost is reduced from $14,985,185 in Scenario 6 to $14,195,652, a decrease of $285,910. This means that, based on the developed overall project cost model, the

TABLE 6.21
Cost Comparison Analysis for Bundling Strategy 4

Bundling Strategy	Project Type	Des ID	Nr of Des	Est. Highest Nr of Bids*	Est. Optimistic Des Award (2015$)	Est. Optimistic Unit Cost
	Scenario 4: Bundle into 3 Contracts by Project Similarity					
Contract 1	B5-Bridge Widening	0201046	6	7	$692,248	$157
(B1, B2 and B5)	B5-Bridge Widening	0201049			$692,248	$157
	B1-New Bridge	1172943			$6,829,773	$104
	B2-Bridge Replacement	1172944			$2,538,153	$209
	B5-Bridge Widening	1297419			$952,169	$126
	B4-Deck Replacement	0800879			$930,942	$121
Contract 2 (B6)	B6-Bridge Deck Overlay	0300462	7	6	$185,217	$54
	B6-Bridge Deck Overlay	0300475			$185,217	$54
	B6-Bridge Deck Overlay	0300485			$162,119	$64
	B6-Bridge Deck Overlay	0300488			$162,119	$64
	B6-Bridge Deck Overlay	1297418			$249,408	$37
	B6-Bridge Deck Overlay	1296142			$199,036	$48
	B6-Bridge Deck Overlay	1296034			$257,339	$33
Contract 3 (B7)	B7-Thin Deck Overlay	1400667	6	7	$87,797	$12
	B7-Thin Deck Overlay	1400668			$95,127	$10
	B7-Thin Deck Overlay	1296097			$61,899	$18
	B7-Thin Deck Overlay	1296113			$63,858	$16
	B7-Thin Deck Overlay	1296125			$62,117	$14
	B7-Thin Deck Overlay	1296397			$74,775	$12
Total Cost					$14,481,562	
Savings	$1,846,206 (compared to Est. optimistic original cost)					
	$580,181 (compared to Strategy 2: four contracts by similarity)					

*Using the model for estimating the Nr of Bids.

TABLE 6.22
Cost Comparison Analysis for Bundling Strategy 5

Bundling Strategy	Project Type	Des ID	Nr of Des	Est. Highest Nr of Bids*	Est. Optimistic Des Award (2015$)	Est. Optimistic Unit Cost
	Scenario 5: Bundled into 3 Contracts by Random Selection					
Contract 1 (Randomly Selected 6 Projects)	B5-Bridge Widening	0201046	6	7	$692,248	$325
	B5-Bridge Widening	0201049			$692,248	$336
	B6-Bridge Deck Overlay	0300475			$209,465	$67
	B6-Bridge Deck Overlay	1296142			$225,093	$99
	B7-Thin Deck Overlay	1296113			$80,753	$23
	B7-Thin Deck Overlay	1296125			$78,550	$22
Contract 2 (Randomly Selected 6 Projects)	B6-Bridge Deck Overlay	0300462	7	6	$209,918	$79
	B6-Bridge Deck Overlay	0300485			$183,739	$103
	B6-Bridge Deck Overlay	0300488			$183,739	$88
	B7-Thin Deck Overlay	1400667			$108,219	$21
	B7-Thin Deck Overlay	1400668			$117,254	$22
	B2-Bridge Replacement	1172944			$2,508,591	$281
	B6-Bridge Deck Overlay	1297418			$282,668	$54
Contract 3 (Randomly Selected 7 Projects)	B1-New Bridge	1172943	6	7	$7,262,201	$121
	B5-Bridge Widening	1297419			$952,169	$78
	B4-Deck Replacement	0800879			$942,961	$98
	B6-Bridge Deck Overlay	1296034			$291,028	$108
	B7-Thin Deck Overlay	1296097			$78,275	$31
	B7-Thin Deck Overlay	1296397			$94,557	$36
Total Cost					$15,193,676	
Savings	$1,134,092 (compared to Est. optimistic original cost) -$131,933 (compared to Strategy 2: four contracts by project similarity) -$712,114 (compared to Strategy 4: three contracts by project similarity)					

*Using the model for estimating the Nr of Bids.

TABLE 6.23
Cost Comparison Analysis for Bundling Strategy 6

Bundling Strategy	Project Type	Des ID	Nr of Des	Est. Highest Nr of Bids*	Est. Optimistic Des Award (2015$)	Est. Optimistic Unit Cost
	Scenario 6: Bundle into 2 Contracts by Random Selection (unbalanced)					
Contract 1 (Randomly Selected 6 Projects)	B5-Bridge Widening	0201049	6	7	$692,248	$157
	B6-Bridge Deck Overlay	0300485			$183,343	$73
	B1-New Bridge	1172943			$7,262,201	$111
	B6-Bridge Deck Overlay	1296142			$225,093	$55
	B4-Deck Replacement	0800879			$942,961	$123
	B7-Thin Deck Overlay	1296125			$78,550	$18
Contract 2 (Randomly Selected 13 Projects)	B5-Bridge Widening	0201046	13	4	$723,931	$164
	B6-Bridge Deck Overlay	0300462			$198,137	$58
	B6-Bridge Deck Overlay	0300475			$198,137	$58
	B6-Bridge Deck Overlay	0300488			$173,428	$69
	B7-Thin Deck Overlay	1400667			$90,870	$12
	B7-Thin Deck Overlay	1400668			$98,456	$10
	B2-Bridge Replacement	1172944			$2,372,437	$195
	B6-Bridge Deck Overlay	1297418			$266,805	$40
	B5-Bridge Widening	1297419			$995,749	$132
	B6-Bridge Deck Overlay	1296034			$275,290	$35
	B7-Thin Deck Overlay	1296097			$64,066	$18
	B7-Thin Deck Overlay	1296113			$66,093	$16
	B7-Thin Deck Overlay	1296397			$77,392	$12
Total Cost					$14,985,185	
Savings	$1,342,583 (compared to Est. optimistic original cost) $208,491 (compared to Strategy 5: three contracts by random selection)					

*Using the model for estimating the Nr of Bids.

TABLE 6.24
Cost Comparison Analysis for Bundling Strategy 7

Bundling Strategy	Project Type	Des ID	Nr of Des	Est. Highest Nr of Bids*	Est. Optimistic Des Award (2015$)	Est. Optimistic Unit Cost
	Scenario 7: Bundle into 2 Contracts by Random Selection (balanced)					
Contract 1 (Randomly Selected 10 Projects)	B5-Bridge Widening	0201049	10	5	$705,956	$160
	B6-Bridge Deck Overlay	0300475			$199,834	$58
	B6-Bridge Deck Overlay	0300485			$174,913	$69
	B6-Bridge Deck Overlay	0300488			$174,913	$69
	B7-Thin Deck Overlay	1400667			$96,177	$13
	B2-Bridge Replacement	1172944			$2,424,112	$199
	B5-Bridge Widening	1297419			$971,024	$129
	B7-Thin Deck Overlay	1296097			$67,808	$19
	B7-Thin Deck Overlay	1296113			$69,954	$17
	B7-Thin Deck Overlay	1296125			$68,046	$15
Contract 2 (Randomly Selected 9 Projects)	B5-Bridge Widening	0201046	9	5	$717,872	$163
	B6-Bridge Deck Overlay	0300462			$206,186	$60
	B7-Thin Deck Overlay	1400668			$109,878	$12
	B1-New Bridge	1172943			$6,333,280	$97
	B6-Bridge Deck Overlay	1297418			$277,643	$41
	B6-Bridge Deck Overlay	1296142			$221,569	$54
	B4-Deck Replacement	0800879			$1,003,645	$131
	B6-Bridge Deck Overlay	1296034			$286,472	$37
	B7-Thin Deck Overlay	1296397			$86,371	$14
Total Cost					$14,195,652	
Savings	$2,132,116 (compared to Est. optimistic original cost)					
	$285,910 (compared to Strategy 6: three contracts by random selection)					

*Using the model for estimating the Nr of Bids.

total project costs can be reduced by bundling projects into contracts with a more balanced size (a more equal number of des).

In Scenario 8, projects are again bundled into 2 contracts, this time based on the similarity between projects and not by random selection (see Table 6.25). This strategy is found to be the best strategy (under the optimistic market condition) so far, with the lowest total project cost of $13,041,827. The total cost saving associated with this bundling strategy is $3,285,941, compared to the estimated optimistic cost under the original bundling strategy. In addition, the cost is reduced by $1,943,358 and $1,153,825, compared to the two random-selection based Scenarios 6 (unbalanced) and 7 (balanced), respectively.

The last bundling strategy that was evaluated is to bundle all projects as a single contract. As presented in Table 6.26, the total project cost is reduced from the estimated optimistic cost of $16,327,768 under the original strategy to $13,677,940. Also, a significant reduction of $6,439,775 was found between Scenario 2 (where all bundled projects are unbundled) and the current scenario (where all unbundled projects are bundled into one contract). In real practice, however, this contract might be too large, because it consists of 19 Des and contains some expensive projects (new bridge and replacement work). Furthermore, in terms of cost-effectiveness, bundling all projects into one contract is not as helpful as bundling projects into two contracts (Scenario 8), due to the reduced market competition and lower project similarity. The cost savings amount for Scenario 9 is $636,113 less than that for Scenario 8. Specifically, when the Nr of Des in the contract increased to 19,

- the market competition was significantly reduced (to an expected maximum of 2 bidders by the upper-bound model), and
- the average similarity distance when all projects were bundled into one contract was much higher than when projects were bundled into two contracts based on their similarity, because some projects are quite different.

It can be observed that the effects of reduced market competition and lower project similarity dominate the effect of bundling, and therefore lead to an overall higher project cost (estimated optimistic cost).

Figure 6.5 compares the total project costs under the different bundling strategies. It can be seen that the cost is reduced the most dramatically from Scenario 1 to Scenario 2 (where all unbundled projects are bundled in a single contract), and from Scenario 2 (bundling projects into four contracts based on randomly selection) to Scenario 3 (bundling projects into 4 contracts based on project similarity). From Scenario 4 to Scenario 9, the general trend of the total project cost is still decreasing as the number of des in a contract increases, albeit with a smaller slope. The best bundling strategy is found in Scenario 8, where projects are bundled into two contracts based on project similarity. This indicates the

TABLE 6.25
Cost Comparison Analysis for Bundling Strategy 8

Bundling Strategy	Project Type	Des ID	Nr of Des	Est. Highest Nr of Bids*	Est. Optimistic Des Award (2015$)	Est. Optimistic Unit Cost
	Scenario 8: Bundle into 2 Contracts by Project Similarity					
Contract 1 (B1, B2 and B5)	B5-Bridge Widening	0201046	6	7	$692,248	$157
	B5-Bridge Widening	0201049			$692,248	$157
	B1-New Bridge	1172943			$5,587,754	$85
	B2-Bridge Replacement	1172944			$2,538,153	$209
	B5-Bridge Widening	1297419			$952,169	$126
	B4-Deck Replacement	0800879			$892,705	$116
Contract 2 (B6 and B7)	B6-Bridge Deck Overlay	0300462	13	4	$174,823	$51
	B6-Bridge Deck Overlay	0300475			$174,823	$51
	B6-Bridge Deck Overlay	0300485			$153,021	$61
	B6-Bridge Deck Overlay	0300488			$153,021	$61
	B7-Thin Deck Overlay	1400667			$71,859	$10
	B7-Thin Deck Overlay	1400668			$77,858	$8
	B6-Bridge Deck Overlay	1297418			$235,411	$35
	B6-Bridge Deck Overlay	1296142			$187,867	$46
	B6-Bridge Deck Overlay	1296034			$242,897	$31
	B7-Thin Deck Overlay	1296097			$50,662	$14
	B7-Thin Deck Overlay	1296113			$52,266	$13
	B7-Thin Deck Overlay	1296125			$50,840	$11
	B7-Thin Deck Overlay	1296397			$61,201	$10
Total Cost					$13,041,827	
Savings	$3,285,941 (compared to Est. optimistic original cost) $1,943,358 (compared to Strategy 6: unbalanced) $1,153,825 (compared to Strategy 7: balanced)					

*Using the model for estimating the Nr of Bids.

TABLE 6.26
Cost Comparison Analysis for Bundling Strategy 9

Bundling Strategy	Project Type	Des ID	Nr of Des	Est. Highest Nr of Bids*	Est. Optimistic Des Award (2015$)	Est. Optimistic Unit Cost
	Scenario 9: Bundle All Projects into One Contract					
Contract 1 (All Projects)	B5-Bridge Widening	0201046	19	2	$838,812	$190
	B5-Bridge Widening	0201049			$838,812	$190
	B6-Bridge Deck Overlay	0300462			$221,980	$65
	B6-Bridge Deck Overlay	0300475			$221,980	$65
	B6-Bridge Deck Overlay	0300485			$194,297	$77
	B6-Bridge Deck Overlay	0300488			$194,297	$77
	B7-Thin Deck Overlay	1400667			$96,768	$13
	B7-Thin Deck Overlay	1400668			$104,847	$11
	B1-New Bridge	1172943			$5,126,922	$78
	B2-Bridge Replacement	1172944			$2,334,824	$192
	B6-Bridge Deck Overlay	1297418			$298,911	$45
	B5-Bridge Widening	1297419			$1,153,765	$153
	B6-Bridge Deck Overlay	1296142			$238,542	$58
	B4-Deck Replacement	0800879			$1,215,278	$158
	B6-Bridge Deck Overlay	1296034			$308,416	$40
	B7-Thin Deck Overlay	1296097			$68,224	$19
	B7-Thin Deck Overlay	1296113			$70,384	$17
	B7-Thin Deck Overlay	1296125			$68,464	$15
	B7-Thin Deck Overlay	1296397			$82,416	$13
Total Cost					$13,677,940	
Savings	$2,649,828 (compared to Est. optimistic original cost) $6,439,777 (compared to Scenario 1: unbundle all projects) -$636,113 (compared to Strategy 8: best strategy)					

*Using the model for estimating the Nr of Bids.

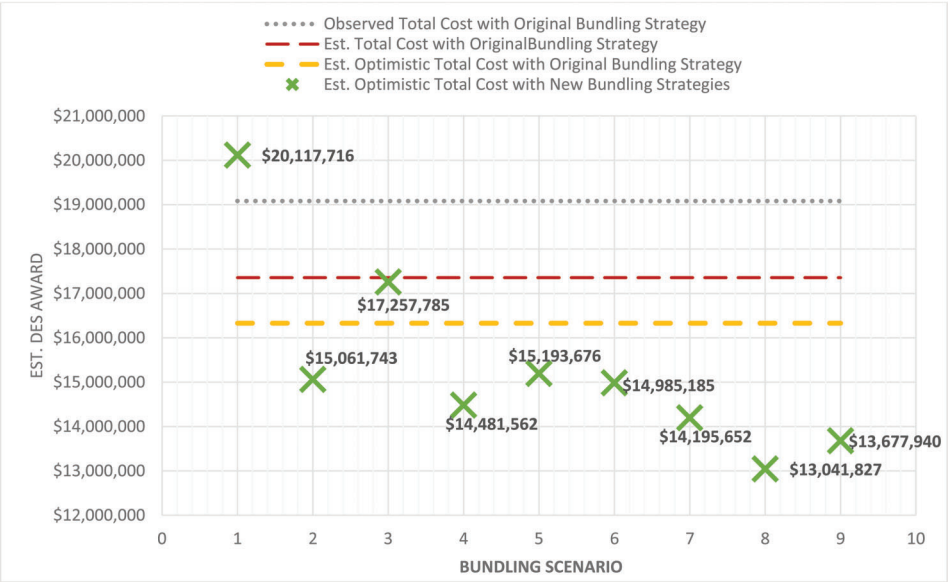


Figure 6.5 Bundling strategy analysis results. (See Tables 6.18–6.26 for scenario details.)

least total project cost (under the optimistic market condition) among all the strategies evaluated. When the contract size continues to increase (from Scenario 8 to Scenario 9), there is an increase of $636,113 in the project cost (estimated optimistic cost). This increase is caused by the effect of reduced market competition and reduced project similarity on the project cost. In addition, the contract in Scenario 9 (19 Des and $13,677,940 Contract Award) might be too large in real practice.

6.3 Chapter Summary

This chapter began by summarizing and evaluating past bundling strategies used in the practice. At a contract level, combinations of project types (or work categories) in all the bundled contracts were extracted from the dataset. Some most common combinations of different work categories include bridge with road work, traffic with road work, bridge with traffic and road work, and bridge with small structures work. Also, the most common combinations of different project types include Intersection Improvement with Traffic Signals, New Bridge with New Road Construction, Bridge Replacement with Bridge Deck Overlay, and New Bridge with Signing and New Road Construction.

At a project level, investigations were conducted on whether a project in the dataset is more likely to be bundled with same project type (work category) or with different project types (work categories). The average cost approach was used to compare the average unit cost of projects bundled with the same work category and with different work categories for bridge and road work. The results show a significant difference between the unit costs for road work: the average unit cost of projects bundled with same work category is significantly lower than projects bundled with a different work category. According to past bundling strategies, road project types are more likely than bridge projects to be bundled with projects in different work categories. This explains why bundling does not always show cost savings for certain project types. It is therefore recommended in the future to bundle road projects with projects that have higher similarity (compatibility), if possible.

This chapter next evaluated various bundling strategies that can be used in the future, based on the developed cost models. Section 6.2.1 analyzed the cost savings achieved by bundling past single projects along a corridor into one contract. Section 6.2.2 on the other hand, evaluated how the project cost would change if the past bundled projects were either unbundled or were rebundled using new bundling strategies. It was found that project cost generally decreases as more projects are bundled into a contract, and that the reduction of project cost is most significant when the number of des in a contract increases from 1 to 2, or from 2 to 3. When the number of des passes a certain threshold, the cost for some project types starts to increase. In scenario analysis (Section 6.2.2), Scenario 8 (bundling projects into 2 contracts of 6 and 13 projects) was found to be the best strategy (under the optimistic market condition) among all strategies tested, and the total project cost starts to increase when the contract becomes larger (Scenario 9). In comparing Scenario 6 and Scenario 7, it was found that bundling projects into contracts with more balanced sizes (a more equal number of des) is superior to bundling projects into the same number of contracts with less balanced sizes. In addition to the number of des, project similarity is an important factor to be considered in project bundling. In Section 6.2, by comparing the project cost when projects are bundled by random selection and when

projects are bundled by project similarity, a significant cost saving was found for the latter. The results in this chapter show the impact (on the project cost) of how projects are bundled, and the importance of carefully selecting an appropriate bundling strategy for a given situation.

7. IMPLICATIONS AND CONCLUSIONS

7.1 Overview of the Research Study

This study explores the effects of various factors of the cost of bundled and unbundled projects, including the economies of scale, economies of bundling, economies of competition, and the similarity between bundled projects. The main objective is to investigate the possible benefits of project bundling. To what extent does bundling lead to savings in project cost? Do the savings depend on the types of projects being bundled? Are there any other issues that could affect the decision to bundle projects into multi-project contracts?

The report is organized into seven chapters. Chapter 1 presents the problem statement, objectives, and the scope of the study. Chapter 2 contains a literature review, including a synthesis of bundling methodologies that have been used by several states and localities. Chapter 3 provides data statistics and the distributions of the cost categories and factors in the dataset. Chapter 4 compares the unit project cost of single and bundled projects using an average cost approach, and conducts preliminary investigations on the potential influential variables for overall project cost and maintenance of traffic cost. In addition, relationship models between market competition and contract size are established using both deterministic and probabilistic approaches. The similarity between different project types is quantified based on the cost compositions of project pay items using a Euclidean distance method. Chapter 4 also presents the corridor analysis that compared the costs of stand-alone project and bundled projects along the same corridor. Chapter 5 developed statistical models for the overall project cost and MOT cost for each project type, followed by marginal effects and sensitivity analyses. Threshold analysis and confidence bound estimation were then carried out to determine the optimal contract size and to measure the uncertainty (arising from fluctuating market conditions) on the estimated project cost. Chapter 6 summarized and analyzed past bundling strategies, and evaluated various bundling strategies that, in the future, can be considered by INDOT, on the basis of the cost models developed in this report.

7.2 Findings and Conclusions

This study yielded the following findings:

1. *Economies of scale*—the decline in unit cost as the project size increases—were observed and documented for all project types analyzed in this study. This is true for both single-project contracts and multiple-project contracts.
2. *Economies of bundling*—the reduction in project cost as more projects are bundled into a contract—were found for all Bridge project types, and most Traffic, Small Structure and Miscellaneous project types. For Road project types, however, the reduction in project cost due to project bundling was only found for four project types (R3, R4, R7 and R9), but was not seen for other Road project types. This indicates that, for most Road work, having one big project in a contract is more cost-effective than bundling several small projects into one contract. In practice, R3, R4, R7 and R9 were the Road project types most likely to be bundled by INDOT with projects in the same work category, based on the data examined. It is therefore reasonable to infer that Road work can benefit from project bundling when the project is bundled with similar project types.
3. *Economies of competition*—contract prices reflect increased market competition—is a significant influential variable in overall project cost models for most Bridge project types. If the highway agency can encourage a larger number of bidders, lower project costs can be expected.
4. *The relationship between market competition and contract size*—the notion that a larger contract can lead to less competition—was investigated and modeled using both deterministic and probabilistic methods. It was found that, although the highest number (upper bound) of bidders generally decreases as the contract size (measured in terms of number of des) increases, the average (mostly likely) number of bidders is not necessarily higher when the contract is very small. According to the probabilistic model used in this study, the average number of bidders tends to be the highest when the number of des is 2 to 4.
5. *Optimal contract size under optimistic market condition*—larger contracts lend themselves to economies of scale, but they can discourage all but the largest firms from bidding on the work. As a result, there appears to be a threshold of contract sizes (measured in this study in terms of the number of des) beyond which the estimated optimistic unit project cost (under the best market condition) might start increasing. In Section 5.1.3, the optimal thresholds (the most appropriate Nr of Des) were determined, based on the deterministic upper-bound model developed for the number of bidders, for Bridge project types B3-Superstructure Replacement, B5-Bridge Widening, B6-Bridge Deck Overlay and B7-Thin Deck Overlay.
6. *Uncertainty in the estimated project cost*—Due to the uncertainty of market competition, the project cost estimated using the overall project cost models can vary to a certain degree, depending on the marginal effect of the number of bidders on project cost. In Section 5.1.3.2, the 95% confidence bound on the project cost was estimated for Bridge work using the probabilistic Beta distribution model developed for the number of bidders. From the results of confidence bound estimation, B1- New Bridge and B2 - Bridge Replacement were each found to have a very small interval between the upper and lower bounds, indicating that uncertainty about the number of bidders will not make much difference in the estimated unit cost. The interval between the upper and lower bounds is very wide for B3-Superstructure Replacement, B4-Deck Replacement, B5-Bridge Widening and B6-Bridge Deck Overlay, indicating high uncertainty regarding the estimated cost. This suggests that the project unit cost will be greatly affected by the uncertainties associated with the number of bidders. It is worth mentioning that INDOT

has limited direct control on the number of bidders for a contract.

7. *Project similarity (compatibility)*—The similarity between different project types is quantified as "similarity distance," based on their constituent pay items using a Euclidean distance method described in Section 4.4.2. It was verified that project types in the same work category have a better (smaller) similarity distance compared to those in different work categories. In addition, within the same work category, a project type can have a smaller degree of similarity distance with certain project types compared to other types. For example,

   - B1-New Bridge and B2-Bridge Replacement are more similar to each other—with a much smaller similarity distance (0.14)—than to other project types.
   - B3-Superstructure Replacement and B4-Deck Replacement are found to be the most similar project types, with a distance of 0.074.
   - B6-Bridge Deck Overlay is found to be most similar to B7-Thin Deck Overlay, with a similarity distance of 0.261.
   - The similarity between B8-Misc. Bridge Rehab & Repair and all other bridge projects is strong, because this project type itself is a mix of several different project types. (See Appendix.)

8. *The effect of project similarity*—higher similarity between projects bundled in a contract can lead to lower project cost—has been identified as an important factor included in the overall project cost regression models for most project types. Also, the effect of project similarity on reducing project cost has been found to be most significant for Road work.
9. *Maintenance of Traffic (MOT) Cost*—MOT can be a major component of project cost. For some project types, MOT as a percentage of the total Des Award is very high (e.g., 23.7% for Thin Deck Overlay). The results of the regression models developed for MOT cost in Section 5.2 indicate that, for Bridge work, the MOT cost for B1-New Bridge, B4-Deck Replacement, and B6-Bridge Deck Overlay can be slightly reduced by project bundling, while the MOT cost for other project types might increase due to project bundling. The MOT cost for most Road, Traffic, and Small Structure project types was found to be generally reduced by project bundling. Of all work categories, Road work was found to benefit the most from project bundling in terms of MOT cost savings.
10. *Past bundling strategy*—According to the current dataset, the most frequent combinations of work categories in the past bundled contracts include Bridge with Road work, Traffic with Road work, Bridge with Traffic and Road work, and Bridge with Small Structures work. The most common combinations of different project types include Intersection Improvement with Traffic Signals, New Bridge with New Road Construction, Bridge Replacement with Bridge Deck Overlay, and New Bridge with Signing and New Road Construction.
11. *Bundling strategy for the future*—According to the scenario analysis results in Section 6.2, the project cost generally decreases as projects are bundled into a contract, and the reduction in project cost is typically most significant when the number of des in a contract increases from 1 to 2. The project cost might start increasing when the contract becomes too large; therefore, identifying the appropriate number of projects to bundle is important when developing bundling strategies. In addition, when comparing the project cost after projects are bundled by random selection and after projects are bundled by project similarity, a significantly greater cost saving was found for the latter. Therefore, bundling projects using a carefully designed bundling strategy is critical in achieving reduced overall contract costs.

7.3 Limitations and Recommendations for Future Research

The various statistical models established in this research study can be applied to estimate market competition, project cost, maintenance of traffic cost, and the overall contract cost. However, there are some limitations involved in the application of these models. At a future time, when more project cost data are available, this study can be extended to address these limitations.

1. The models developed in Chapter 4 to predict the number of bidders for a contract are based only on the number of des, due to the lack of data on other influential variables. The upper bound model established in this study can provide an estimate of the highest number of bidders expected for a contract with a certain number of des, and can be therefore used to estimate an "optimistic" project unit cost under specified market conditions. The upper bound models were useful in comparing various bundling scenarios, to identify the bundling strategy that yields the highest cost savings under the specified market condition. In the future, when more variables (in addition to the number of des) that influence the number of bidders in a contract become available, a model based on all data points—not just those that form an upper bound on number of bidders—can be developed to replace the upper bound model. This would allow analysis of bundling scenarios under the average, rather than optimistic, market condition. That approach would predict the most likely number of bidders (rather than the expected highest number) and the average expected project unit cost instead of the lowest expected cost.
2. In seeking to bundle projects, an agency may defer a project to a later year when its prospective kin project becomes eligible for implementation. However, delaying a project too long beyond its originally scheduled letting date may allow unacceptable deterioration in asset condition and/or cause unacceptably high project cost and/or user costs in the subsequent years. The model developed in this study does not consider the change in cost caused by shifting the letting dates of projects to be bundled. Future research could help identify an appropriate methodology to quantify the extra cost caused by delaying a project, and investigating the trade-off between the cost reduced by project bundling and the cost increase due to project delay.
3. It was believed that contracts containing projects that are located closer to each other would benefit more from project bundling. However, the cost models developed in this study do not contain an explicit geographic "distance" term, because the distance variable was neither significant nor intuitive when tested using regression models. A reason

for this might be the lack of variability in the values of the factor in the observed data; projects bundled into a contract are often located along the same corridor. Therefore, there is inadequate data in the current dataset on contracts that contain projects that are located farther apart. As a result, the average geographic distance between projects bundled in different contracts does not vary enough to make a distinguishing difference in project costs. At a future time, if more data with more widely dispersed projects become available, the effect of the geographic distance variable can be determined.

4. The cost model developed in this study includes only agency costs. However, user cost is also a consideration in infrastructure maintenance and rehabilitation decisions. In a future study, in addition to measuring the effectiveness of project bundling in terms of agency cost savings, the analysis could quantify the impact of project bundling in terms of roadway user costs. User costs associated with work zones may differ for different bundling strategies, due to differences in the duration and location of bundled projects. If bundling multiple projects into a single contract can lead to significant reductions in road user costs, this would be further justification for a sound bundling strategy.
5. The cost model developed in the current study can predict, at a project level, the cost of each individual project by type. In estimating the overall contract cost, the project-level cost model can be applied to determine the expected project cost (Des Award) for each project in the contract, and summed to yield the total contract award. By doing this, the impacts of different project combinations on project costs are largely ignored. In realizing this problem, the study proposed including the average similarity between bundled projects as an influential variable in the cost model, while a better way to take different project combinations into account may be to build a mixed cost model, at a contract level, for estimating directly the overall cost for a contract that involves different project types. This approach was not pursued in the current study, because the current dataset has 235 different combinations of project types in the past bundled contracts, only ten of them have more than ten observations, and most combinations only appear once. This makes it infeasible to develop a uniform model that can take all these combinations into account. As INDOT undertakes more bundled projects, and as the number of observations for each combination becomes larger in the future, it may be possible for a future study to build a contract-level mixed cost model to guide bundling decisions. A possible way to do this is to consider each contract as an observation, and to use a binary variable (0 or 1) for each project type.
6. This study provides guidance in determining appropriate bundling strategies. In Chapter 6, bundling strategies were compared and selected through conducting several scenario analyses. This method, however, does not consider all the possible combinations of project candidates for bundling. Due to the large number of projects eligible for bundling, enumeration for computing the cost savings for all strategies of project combinations would be time-consuming, if not impractical. Therefore, an important task for the future is to develop an efficient optimization model (solved using an appropriate heuristic) to identify the project combination that minimizes the overall project cost or maximizes the total cost savings, with an acceptable time of computation. By considering constraints on geographic proximity, project type similarity, project letting schedule and contract size (e.g., overall contract cost, number of projects bundled in the contract), some project combinations could be screened out as candidates. As a result, instead of exhaustive enumeration, a method that produces an "optimal" bundling strategy from a reduced set of combinations would present the decision makers with choices that otherwise might not be known.

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APPENDIX

Work Type	Work Category	Project Type
New Bridge, Steel Construction	Bridge	B1-New Bridge
New Br, Comp. Steel Construction	Bridge	B1-New Bridge
New Br, Comp.Steel Beam-Simple Span	Bridge	B1-New Bridge
New Br, Comp.Stl.Gdr.(Wld Plt,Smpl.Span)	Bridge	B1-New Bridge
New Br, Comp.Cont.Steel Beam	Bridge	B1-New Bridge
New Br, Comp. Cont.Stl.Grdr (Wld.Plate)	Bridge	B1-New Bridge
New Br, Comp.Cont.Steel Box Girder	Bridge	B1-New Bridge
New Br, Steel Truss	Bridge	B1-New Bridge
New Br, Steel Deck Truss	Bridge	B1-New Bridge
New Br, Steel Thru Truss	Bridge	B1-New Bridge
New Br, Steel Girder	Bridge	B1-New Bridge
New Br, Welded Girder Rigid Frame	Bridge	B1-New Bridge
New Br, Welded Steel Thru Girder	Bridge	B1-New Bridge
New Bridge, Concrete Construction	Bridge	B1-New Bridge
New Br, Comp. Cont. Conc. Constr.	Bridge	B1-New Bridge
New Br, Comp.Cont.Pres.Conc Box Beam	Bridge	B1-New Bridge
New Br, Comp.Cont.Pres.Conc.I-Beam	Bridge	B1-New Bridge
New Br, Comp.Cont.Pres.Conc.Bulb T-Beam	Bridge	B1-New Bridge
New Br, Comp.Cont.Precast Conc.Beam	Bridge	B1-New Bridge
New Br, Post Tension Conc. Construction	Bridge	B1-New Bridge
New Br, P.T.Comp.Cont.Pres.Conc.Bulb T	Bridge	B1-New Bridge
New Br, P.T.Comp.Cont.Pres.Conc.I-Beam	Bridge	B1-New Bridge
New Br, P.T. Conc.Box Girder	Bridge	B1-New Bridge
New Br, Conc Beam Construction	Bridge	B1-New Bridge
New Br, Pres.Conc.Box Beam-Simple Span	Bridge	B1-New Bridge
New Br, Pres.Conc. I-Beam (Simple Span)	Bridge	B1-New Bridge
New Br, Cont.Pres.Conc.Box Beam	Bridge	B1-New Bridge
New Br, Reinforced Concrete Construction	Bridge	B1-New Bridge
New Br, Rc Box—Under Fill	Bridge	B1-New Bridge
New Br, Cont. Rc Slab	Bridge	B1-New Bridge
New Br, Rc Slab (Simple Span)	Bridge	B1-New Bridge
New Br, Rc Slab—Under Fill	Bridge	B1-New Bridge
New Bridge, Other Construction	Bridge	B1-New Bridge
New Br, Pipe Arch or Culvert	Bridge	B1-New Bridge
New Br, Cast In Place Box Culvert	Bridge	B1-New Bridge
New Br, Pipe Arch	Bridge	B1-New Bridge
New Br, Precast 3 Sided Culvert	Bridge	B1-New Bridge
New Br, Precast Box Culvert	Bridge	B1-New Bridge
New Br, Special	Bridge	B1-New Bridge
New Bridge Special Construction	Bridge	B1-New Bridge
New Br, Timber Bridge	Bridge	B1-New Bridge
New Br, Covered Bridge	Bridge	B1-New Bridge
New Bridge, Other	Bridge	B1-New Bridge
Bridge Replacement, Steel	Bridge	B2-Bridge Replacement
Bridge Repl, Comp Steel Construction	Bridge	B2-Bridge Replacement
Br Repl, Comp.Steel Beam (Simple Span)	Bridge	B2-Bridge Replacement
Br Repl, Comp.Stl.Gdr.(Wld Plt,Smpl.Spn)	Bridge	B2-Bridge Replacement
Br Repl, Comp.Cont.Steel Beam	Bridge	B2-Bridge Replacement
Br Repl, Comp.Cont.Stl.Grdr(Wld Plate)	Bridge	B2-Bridge Replacement
Br Repl, Comp.Cont.Steel Box Girder	Bridge	B2-Bridge Replacement
Br Repl, Steel Truss	Bridge	B2-Bridge Replacement
Br Repl, Steel Deck Truss	Bridge	B2-Bridge Replacement
Br Repl, Steel Thru Truss	Bridge	B2-Bridge Replacement
Br Repl, Steel Girder	Bridge	B2-Bridge Replacement
Br Repl, Welded Girder Rigid Frame	Bridge	B2-Bridge Replacement
Br Repl, Welded Steel Thru Girder	Bridge	B2-Bridge Replacement
Bridge Replacement, Concrete	Bridge	B2-Bridge Replacement
Br Repl, Comp. Cont. Conc. Construction	Bridge	B2-Bridge Replacement
Br Repl, Comp.Cont.Pres.Conc.Box Beam	Bridge	B2-Bridge Replacement
Br Repl, Comp.Cont.Pres.Conc. I-Beam	Bridge	B2-Bridge Replacement

APPENDIX
(Continued)

Work Type	Work Category	Project Type
Br Repl, Comp.Cont.Pres.Conc.Bulb T-Beam	Bridge	B2-Bridge Replacement
Br Repl, Comp.Cont.Precast Conc. Beam	Bridge	B2-Bridge Replacement
Br Repl, Post Tension Conc. Construction	Bridge	B2-Bridge Replacement
Br Repl, P.T.Comp.Cont.Pres.Conc.T-Bulb	Bridge	B2-Bridge Replacement
Br Repl, P.T.Comp.Cont.Pres.Conc.I-Beam	Bridge	B2-Bridge Replacement
Br Repl, P.T. Conc. Box Girder	Bridge	B2-Bridge Replacement
Bridge Repl, P.T. Conc. Slab	Bridge	B2-Bridge Replacement
Br Repl, Conc. Beam Construction	Bridge	B2-Bridge Replacement
Br Repl, Pres.Conc.Box Beam(Smpl.Span)	Bridge	B2-Bridge Replacement
Br Repl, Pres.Conc.I-Beam(Simple Span)	Bridge	B2-Bridge Replacement
Br Repl, Cont. Pres. Conc. Box Beam	Bridge	B2-Bridge Replacement
Br Repl, Cont, Pres. Conc. Blub T-Beam(SMPL)	Bridge	B2-Bridge Replacement
Br Repl, Reinforced Conc. Construction	Bridge	B2-Bridge Replacement
Br Repl, Rc Box—Under Fill	Bridge	B2-Bridge Replacement
Br Repl, Cont. Rc Slab	Bridge	B2-Bridge Replacement
Br Repl, Rc Slab (Simple Span)	Bridge	B2-Bridge Replacement
Br Repl, Rc Slab—Under Fill	Bridge	B2-Bridge Replacement
Bridge Replacement, Other Construction	Bridge	B2-Bridge Replacement
Bridge Replacement, Pipe Arch or Culvert	Bridge	B2-Bridge Replacement
Br Repl, Cast In Place Box Culvert	Bridge	B2-Bridge Replacement
Br Repl, Pipe Arch	Bridge	B2-Bridge Replacement
Br Repl, Precast 3 Sided Culvert	Bridge	B2-Bridge Replacement
Br Repl, Precast Box Culvert	Bridge	B2-Bridge Replacement
Bridge Replacement, Special	Bridge	B2-Bridge Replacement
Br Repl, Covered Bridge	Bridge	B2-Bridge Replacement
Br Repl, Timber Bridge	Bridge	B2-Bridge Replacement
Bridge Replacement	Bridge	B2-Bridge Replacement
Small Structure Replacement with Bridge	Bridge	B2-Bridge Replacement
Replace Superstructure	Bridge	B3-Superstructure Replacement
Bridge Deck Reconstruction	Bridge	B4-Deck Replacement
Bridge Deck Replacement	Bridge	B4-Deck Replacement
Bridge Widening	Bridge	B5-Bridge Widening
Bridge Deck Replacement & Widening	Bridge	B5-Bridge Widening
Bridge Deck Reconstruction & Widening	Bridge	B5-Bridge Widening
Bridge Deck Overlay	Bridge	B6-Bridge Deck Overlay
Bridge Thin Deck Overlay	Bridge	B7-Thin Deck Overlay
Bridge Rehabilitation or Repair	Bridge	B8-Misc. Bridge Rehab & Repair
Bridge Deck Patching	Bridge	B8-Misc. Bridge Rehab & Repair
Bridge Deck Sealing	Bridge	B8-Misc. Bridge Rehab & Repair
Bridge Deck Barrier Wall	Bridge	B8-Misc. Bridge Rehab & Repair
Raise Bridge/Lower Pavement	Bridge	B8-Misc. Bridge Rehab & Repair
Raise Bridge	Bridge	B8-Misc. Bridge Rehab & Repair
Raise Bridge	Bridge	B8-Misc. Bridge Rehab & Repair
Bridge Painting	Bridge	B8-Misc. Bridge Rehab & Repair
Substructure Repair and Rehabilitation	Bridge	B8-Misc. Bridge Rehab & Repair
Bridge Maintenance and Repair	Bridge	B8-Misc. Bridge Rehab & Repair
Repair or Replace Joints	Bridge	B8-Misc. Bridge Rehab & Repair
Straighten Beam	Bridge	B8-Misc. Bridge Rehab & Repair
Railing Replace or Repair	Bridge	B8-Misc. Bridge Rehab & Repair
Repairs to Approach Slab	Bridge	B8-Misc. Bridge Rehab & Repair
Remove & Replace Beam	Bridge	B8-Misc. Bridge Rehab & Repair
Bridge Cleaning	Bridge	B8-Misc. Bridge Rehab & Repair
Truss Reconstruction or Repair	Bridge	B8-Misc. Bridge Rehab & Repair
Arch Reconstruction or Repair	Bridge	B8-Misc. Bridge Rehab & Repair
Covered Bridge Rehabilitation	Bridge	B8-Misc. Bridge Rehab & Repair
Repair/Replace Cathodic Protection	Bridge	B8-Misc. Bridge Rehab & Repair
Scour Protection (Erosion)	Bridge	B8-Misc. Bridge Rehab & Repair
District Wide Bridge Maintenance	Bridge	B8-Misc. Bridge Rehab & Repair
Demolition	Miscellaneous	M1-Demolition
Bridge Removal	Miscellaneous	M1-Demolition
Demolition, Remove Buildings, Foundations	Miscellaneous	M1-Demolition
Remove Bridge Abutments	Miscellaneous	M1-Demolition

APPENDIX
(Continued)

Work Type	Work Category	Project Type
Bridge Channel Correction	Miscellaneous	M2-Channel and Ditch Work
Debris Removal From Channel	Miscellaneous	M2-Channel and Ditch Work
Channel Clearing and Protection	Miscellaneous	M2-Channel and Ditch Work
Channel Realign and Reshape	Miscellaneous	M2-Channel and Ditch Work
Drainage Ditch Correction	Miscellaneous	M2-Channel and Ditch Work
Ditch Relocation	Miscellaneous	M2-Channel and Ditch Work
Paved Side Ditch Installation	Miscellaneous	M3-Stormwater Improvements
Paved Side Ditch Repair	Miscellaneous	M3-Stormwater Improvements
Sewer/Curb/Gutter Construction	Miscellaneous	M3-Stormwater Improvements
Sewer/Curb/Gutter Const/Reconstr	Miscellaneous	M3-Stormwater Improvements
Slotted Drain or Inlet Replacement	Miscellaneous	M3-Stormwater Improvements
Storm Sewer Repair or Replacement	Miscellaneous	M3-Stormwater Improvements
Other Sewer/Curb/Gutter Construction	Miscellaneous	M3-Stormwater Improvements
Slide Correction	Miscellaneous	M4-Slide Correction
Bike/Pedestrian Facilities	Miscellaneous	M5-Paths, Sidewalks & Curb Ramps
Construct ADA Approved Sidewalk Ramps	Miscellaneous	M5-Paths, Sidewalks & Curb Ramps
Roadside Maintenance	None	Do Not Include
Roadside Maintenance, Tree Remov/Trimmng	None	Do Not Include
Roadside Maintenance, Mowing	None	Do Not Include
Roadside Maintenance, Herbicide Treatment	None	Do Not Include
Brush Control	None	Do Not Include
Roadside Facilities	None	Do Not Include
Weigh Stations Constr/Reconstr.	None	Do Not Include
Reconstruct Weigh Station	None	Do Not Include
Construct Weigh Station	None	Do Not Include
Rest Area & Parking Area Constr/Reconstr	None	Do Not Include
Rest Area Modernization	None	Do Not Include
Rest Area Construction	None	Do Not Include
Parking Area Reconstruction	None	Do Not Include
Access Control	None	Do Not Include
Roadside Work, Other	None	Do Not Include
Enhancement	None	Do Not Include
Historical Site Preservation	None	Do Not Include
Outdoor Advertising Control	None	Do Not Include
Scenic Easements	None	Do Not Include
Buildings	None	Do Not Include
Canals/Locks & Dams	None	Do Not Include
Environmental Mitigation	None	Do Not Include
Mitigate Runoff Pollution	None	Do Not Include
Noise Abatement	None	Do Not Include
Other Roadside Maintenance	None	Do Not Include
Fence Replacement or Repair	None	Do Not Include
Roadside Maintenance, Mech.Sweeping	None	Do Not Include
Landscaping	None	Do Not Include
Beautification/Wildflowers	None	Do Not Include
Erosion Control	None	Do Not Include
Pumping/Lift Stations	None	Do Not Include
Sign or Billboard Removal	None	Do Not Include
Bridge Inspections	None	Do Not Include
Underwater Bridge Inspections	None	Do Not Include
Single Location Bridge Inspection	None	Do Not Include
Other Type Project (Miscellaneous)	None	Do Not Include
Protective Buying	None	Do Not Include
Relinquishments/Road Transfer	None	Do Not Include
Transit Operating	None	Do Not Include
Transit Purchase Vehicles	None	Do Not Include
Transit Misc Equipment	None	Do Not Include
Transit Communications Equipment	None	Do Not Include
Transit Facilities	None	Do Not Include
Transit Commuter Rail Capital	None	Do Not Include
Transit Preventative Maintenance	None	Do Not Include
Transit Planning	None	Do Not Include

APPENDIX
(Continued)

Work Type	Work Category	Project Type
Transit-Rider Amenities (Bus Shelters, Benches, etc.)	None	Do Not Include
Lower Pavement	Road	R10-Pavement Replacement
Lower Pavement	Road	R10-Pavement Replacement
Pavement Replacement	Road	R10-Pavement Replacement
Pavement Replacement, New PCC	Road	R10-Pavement Replacement
Pavement Replacement, HMA	Road	R10-Pavement Replacement
Pavement Replacement, Composite	Road	R10-Pavement Replacement
Pavement Replacement, Small Town	Road	R10-Pavement Replacement
Pavement Replacement, Small Town, HMA	Road	R10-Pavement Replacement
Pavement Replacement, Small Town, PCCP	Road	R10-Pavement Replacement
Radii Improvement	Road	R11-Intersection Improvement
Intersect. Improv. w/Added Turn Lanes	Road	R11-Intersection Improvement
Intersect. Improv. w/New Signals	Road	R11-Intersection Improvement
Other Intersection Improvement	Road	R11-Intersection Improvement
Intersection Improvement, Roundabout	Road	R11-Intersection Improvement
New Interchange Construction	Road	R12-Interchange Work
New Interchange, Multi-Level	Road	R12-Interchange Work
Interchange Modification	Road	R12-Interchange Work
Interchange Modification, Multi-Level	Road	R12-Interchange Work
New Road, Grading Only	Road	R1-New Road Construction
New Road, Paving Only	Road	R1-New Road Construction
New Road, PCC Paving Only	Road	R1-New Road Construction
New Road, HMA Paving Only	Road	R1-New Road Construction
New Road, Composite Paving Only	Road	R1-New Road Construction
New Road, Aggregate Paving Only	Road	R1-New Road Construction
New Road Construction	Road	R1-New Road Construction
New Road Construction, PCC	Road	R1-New Road Construction
New Road Construction, HMA	Road	R1-New Road Construction
New Road Construction, Composite	Road	R1-New Road Construction
New Road Construction, Aggregate	Road	R1-New Road Construction
Added Travel Lanes	Road	R2-Added Travel Lanes
Added Travel Lanes, PCC	Road	R2-Added Travel Lanes
Added Travel Lanes, HMA	Road	R2-Added Travel Lanes
Added Travel Lanes, Composite	Road	R2-Added Travel Lanes
Added Travel Lanes, Construct Turn Lanes	Road	R2-Added Travel Lanes
Truck/Auxiliary Lane Construction	Road	R2-Added Travel Lanes
Dual Lane Existing Route	Road	R2-Added Travel Lanes
Auxiliary Lane Construction	Road	R2-Added Travel Lanes
Auxiliary Lanes	Road	R2-Added Travel Lanes
Auxiliary Lanes, Passing	Road	R2-Added Travel Lanes
Auxiliary Lanes, Accel & Decel or Turn Lanes	Road	R2-Added Travel Lanes
Auxiliary Lanes, Two-way Left Turn Lanes	Road	R2-Added Travel Lanes
Auxiliary Lanes, Truck Climbing Lanes	Road	R2-Added Travel Lanes
Patch and Rehab Pavement	Road	R3-Patch & Rehab Pavement
Patch and Rehab Bituminous Pavement	Road	R3-Patch & Rehab Pavement
Asphalt Patching	Road	R3-Patch & Rehab Pavement
Crack Sealing	Road	R3-Patch & Rehab Pavement
Drainage Inspection and Cleaning	Road	R3-Patch & Rehab Pavement
Patch and Rehab PCC Pavement	Road	R3-Patch & Rehab Pavement
PCCP Patching	Road	R3-Patch & Rehab Pavement
Profiling, PCCP	Road	R3-Patch & Rehab Pavement
PCCP Cleaning and Sealing Joints	Road	R3-Patch & Rehab Pavement
Undersealing	Road	R3-Patch & Rehab Pavement
Retrofit Joint Load Transfer	Road	R3-Patch & Rehab Pavement
Partial 3-R	Road	R4-Partial 3
Resurface over Asphalt Pavement	Road	R4-Partial 3
HMA Overlay, Preventive Maintenance	Road	R4-Partial 3
HMA Overlay, Structural	Road	R4-Partial 3
HMA Overlay, Functional	Road	R4-Partial 3
Surface Treatment, PM	Road	R4-Partial 3
Surface Treatment, Thin HMA Overlay	Road	R4-Partial 3
Surface Treatment, Chip Seal	Road	R4-Partial 3

APPENDIX
(Continued)

Work Type	Work Category	Project Type
Surface Treatment, Microsurface	Road	R4-Partial 3
Surface Treatment, Ultrathin Bonded Wearing Course	Road	R4-Partial 3
Resurface PCC Pavement (Partial 3/R Standards)	Road	R4-Partial 3
Crack & Seat PCCP & HMA Overlay	Road	R4-Partial 3
Concrete Pavement Restoration (CPR)	Road	R4-Partial 3
HMA Functional Overlay on PCCP	Road	R4-Partial 3
Road Rehabilitation (3R/4R Standards)	Road	R5-Road Rehabilitation (3R/4R)
Road Reconstruction (3R/4R Standards)	Road	R5-Road Rehabilitation (3R/4R)
Crack & Seat Composite Pavement & HMA Overlay	Road	R5-Road Rehabilitation (3R/4R)
Crack & Seat PCCP & HMA Overlay	Road	R5-Road Rehabilitation (3R/4R)
Repair PCCP & HMA Overlay	Road	R5-Road Rehabilitation (3R/4R)
Rubblize PCCP & HMA Overlay	Road	R5-Road Rehabilitation (3R/4R)
PCCP on PCC Pavement	Road	R5-Road Rehabilitation (3R/4R)
Rubblize Composite & HMA Overlay	Road	R5-Road Rehabilitation (3R/4R)
Wedge and Level	Road	R6-Wedge & Level Only
Sight Distance Improvement	Road	R7-Sight Distance Correction
Horizontal Sight Correction	Road	R7-Sight Distance Correction
Vertical Sight Correction	Road	R7-Sight Distance Correction
Curve Correction	Road	R7-Sight Distance Correction
Shoulder Rehabilitation and Repair	Road	R8-Shoulder Rehab & Repair
Pavement, Other	Road	R9-Pavement, Other
Institution & Park Road Maintenance	Road	R9-Pavement, Other
Scenic and Historic Highways	Road	R9-Pavement, Other
Bridge Rehab-Pipe Lining	Small Structures	S1-Pipe Lining
Small Structure Pipe Lining	Small Structures	S1-Pipe Lining
Small Structure Replacement	Small Structures	S2-Small Structure Installation
Small Structure—New	Small Structures	S2-Small Structure Installation
Box Culvert Replacement	Small Structures	S2-Small Structure Installation
Culvert Clean and Repair	Small Structures	S3-Small Str. Maintenance & Repair
Small Structure Paved Invert	Small Structures	S3-Small Str. Maintenance & Repair
Small Structure Maint and Repair	Small Structures	S3-Small Str. Maintenance & Repair
Intelligent Transportation Systems (ITS)	Traffic	T1-ITS
ITS Traveler Information Systems	Traffic	T1-ITS
New Dynamic Message Sign (Dms)	Traffic	T1-ITS
Modernize Dynamic Message Sign (Dms)	Traffic	T1-ITS
New Highway Advisory Radio (Har)	Traffic	T1-ITS
Modernize Dynamic Message Sign (Har)	Traffic	T1-ITS
Software Dev and App for Dyn. Mess Sign	Traffic	T1-ITS
ITS Traffic Management Systems	Traffic	T1-ITS
Traffic Management Facility Construction	Traffic	T1-ITS
Traffic Mgmt Facility Modernization	Traffic	T1-ITS
Work Zone Traffic Management Systems	Traffic	T1-ITS
Software Dev and App for Traf.Mess. Sys.	Traffic	T1-ITS
ITS Traffic Monitoring Systems	Traffic	T1-ITS
New Traf Flow Detection Devices/Hardware	Traffic	T1-ITS
Mod Traf Flow Detection Devices/Hardware	Traffic	T1-ITS
Software Dev and App for Traf. Flow Det.	Traffic	T1-ITS
ITS Communications Systems	Traffic	T1-ITS
New Communication Towers	Traffic	T1-ITS
Modernized Communications Towers	Traffic	T1-ITS
New Fiber Optic Systems	Traffic	T1-ITS
Modernized Fiber Optic Systems	Traffic	T1-ITS
New Wireless Communications Systems	Traffic	T1-ITS
Modernized Wireless Communication System	Traffic	T1-ITS
Software Dev and App ror Wireless System	Traffic	T1-ITS
ITS Operations and Maintenance Contracts	Traffic	T1-ITS
ITS Devices Maintenance Contracts	Traffic	T1-ITS
ITS Program Contracted Services	Traffic	T1-ITS
ITS Program Equipment	Traffic	T1-ITS
Signs, Lighting, Signals and Markings	Traffic	T2-Signing
Signing	Traffic	T2-Signing
Signing Installation/Repair	Traffic	T2-Signing

APPENDIX
(Continued)

Work Type	Work Category	Project Type
New Sign Installation	Traffic	T2-Signing
Sign Modernization (Series of Units)	Traffic	T2-Signing
Overhead Sign Install	Traffic	T2-Signing
Overhead Sign Repair	Traffic	T2-Signing
Un-Signalized Intersection Sign & Marking Visibility Imp	Traffic	T2-Signing
Curve Sign and Marking Visibility Improvements	Traffic	T2-Signing
Traffic Signals	Traffic	T3-Traffic Signals
Traffic Signals, New or Modernized	Traffic	T3-Traffic Signals
New Signal Installation	Traffic	T3-Traffic Signals
Traffic Signals Modernization	Traffic	T3-Traffic Signals
Install Loop Detector	Traffic	T3-Traffic Signals
Closed Loop Interconnect System	Traffic	T3-Traffic Signals
Freeway Traffic Control System	Traffic	T3-Traffic Signals
New Flasher Installation	Traffic	T3-Traffic Signals
Flashers, Modernize	Traffic	T3-Traffic Signals
Traffic Signal Maintenance	Traffic	T3-Traffic Signals
Traffic Signal Repair	Traffic	T3-Traffic Signals
Pedestrian Flashing Beacons, Installed	Traffic	T3-Traffic Signals
Traffic Signal Visibility Improvements	Traffic	T3-Traffic Signals
Traffic Hardware Modernization	Traffic	T3-Traffic Signals
Pavement Markings	Traffic	T4-Pavement Markings
Line, Paint	Traffic	T4-Pavement Markings
Line, Thermoplastic	Traffic	T4-Pavement Markings
Raised Pavement Markings, New	Traffic	T4-Pavement Markings
Raised Pavement Markings, Refurbished	Traffic	T4-Pavement Markings
Line, Preformed Plastic	Traffic	T4-Pavement Markings
Traffic, Other	Traffic	T4-Pavement Markings
Safety Revisions	Traffic	T4-Pavement Markings
Centerline & Edge Line Rumble Stripes Installation	Traffic	T4-Pavement Markings
Centerline Rumble Stripes Installation	Traffic	T4-Pavement Markings
Edge Line Rumble Stripes Installation	Traffic	T4-Pavement Markings
Install New Guard Rail	Traffic	T5-Guard Rail, Cable Barrier & Wall
Guardrail, Maintenance or Repair	Traffic	T5-Guard Rail, Cable Barrier & Wall
Guardrail, Maintenance	Traffic	T5-Guard Rail, Cable Barrier & Wall
Replace Guard Rail	Traffic	T5-Guard Rail, Cable Barrier & Wall
Repair Guard Rail	Traffic	T5-Guard Rail, Cable Barrier & Wall
Guard Rail Attenuators, New or Modernize	Traffic	T5-Guard Rail, Cable Barrier & Wall
Barrier Wall	Traffic	T5-Guard Rail, Cable Barrier & Wall
New Barrier Wall	Traffic	T5-Guard Rail, Cable Barrier & Wall
Repair or Replace Barrier Wall	Traffic	T5-Guard Rail, Cable Barrier & Wall
Glare Screen and/or Extensions	Traffic	T5-Guard Rail, Cable Barrier & Wall
Median Construction	Traffic	T5-Guard Rail, Cable Barrier & Wall
Install New Cable Rail Barriers	Traffic	T5-Guard Rail, Cable Barrier & Wall
Cable Rail Barrier Maintenance or Repair	Traffic	T5-Guard Rail, Cable Barrier & Wall
Lighting	Traffic	T6-Lighting
Lighting Installation/Maintenance	Traffic	T6-Lighting
Install New Continuous Lighting	Traffic	T6-Lighting
Modernize Continuous Lighting	Traffic	T6-Lighting
Install Lighting	Traffic	T6-Lighting
Repair or Replace Lighting	Traffic	T6-Lighting
Lighting Maintenance	Traffic	T6-Lighting
Tower Lighting	Traffic	T6-Lighting
Railroad Work	Utility	U1-Railroad Work
Railroad Crossing	Utility	U1-Railroad Work
Railroad Protection	Utility	U1-Railroad Work
Railroad Protection & Surface	Utility	U1-Railroad Work
Railroad Crossing Removal	Utility	U1-Railroad Work
Utility Relocation	Utility	U2-Utility Relocation
Pavement Replacement, Concrete	Road	R10-Pavement Replacement
Bridge Deck Overlay and Widening	Bridge	B5-Bridge Widening
HMA Overlay Minor Structural	Road	R10-Pavement Replacement
Small Structure, Replacement	Small Structures	S2-Small Structure Installation

APPENDIX
(Continued)

Work Type	Work Category	Project Type
Guard Rail Work	Traffic	T5-Guard Rail, Cable Barrier & Wall
New Bridge Construction	Bridge	B1-New Bridge
Interchange Work	Road	R12-Interchange Work
Intersection Improvement	Road	R11-Intersection Improvement
Road Construction	Road	R1-New Road Construction
QC/QA PCC Thin Overlay	Road	R11-Intersection Improvement
Pavement Repair or Rehabilitation	Road	R11-Intersection Improvement
Small Structures & Drains Construction	Small Structures	S3-Small Str. Maintenance & Repair

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

Further information about JTRP and its current research program is available at: http://www.purdue.edu/jtrp

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