"This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers. This material may be found at https://doi.org/10.1061/(ASCE)ME.1943-5479.0000855. "
ACT²: Time-Cost Tradeoffs of Alternative Contracting Methods

Kunhee Choi¹ M.ASCE¹, Junseo Bae², Yangtian Yin³, and Hyun Woo Lee, M.ASCE⁴.

ABSTRACT

Incentive/disincentive (I/D) and cost-plus-time (A+B) are the two most widely used alternative contracting methods (ACMs) for accelerating the construction of highway infrastructure improvement projects. However, little is known about their tradeoff effects on project schedule and cost performance. This study addresses this problem by creating and testing a stochastic decision support model called alternative contracting cost-time tradeoff (ACT²). This method was developed by a second order polynomial regression analysis and validated by the PRESS statistic and paired comparison tests. The results of a trend analysis based on a rich set of high-confidence project data show that I/D was effective at cutting the duration of projects, while I/D produced the largest cost growth as compared to pure A+B and conventional methods. This cost-time tradeoff effect was confirmed by the ACT² model, which determines the level of the cost-time tradeoff effect for different ACMs. This study will help state transportation agencies promote more effective application of ACMs by providing data-driven performance benchmarking results for ACMs when evaluating competing accelerating strategies and techniques.

¹ Associate Professor, Dept. of Construction Science, Texas A&M University, 3137 TAMU, Francis Hall 305, College Station, TX 77843-3137 (corresponding author), kchoi@tamu.edu
² Lecturer in Construction Management, School of Computing, Engineering and Physical Sciences, University of the West of Scotland, Paisley, PA1 2BE, UK, junseo.bae@uws.ac.uk
³ Ph.D. Candidate, Dept. of Construction Science, Texas A&M University, 3137 TAMU, Francis Hall 328, College Station, TX 77843-3137, yinyangt@tamu.edu
⁴ Associate Professor, Dept. of Construction Management, University of Washington, 120d Architecture Hall, Seattle, WA 98195, hyunwlee@uw.edu
INTRODUCTION

As the majority of the existing highway infrastructure systems were built during construction booms in the 1950’s and 1980’s and most feature a 20-year design life, this obsolescence issue of the US transportation infrastructure has created a major dual challenge for State Transportation Agencies (STAs) (Federal Highway Administration 2002; Lee et al. 2008; Napolitan and Zegras 2008; Uhlmeyer and Russell 2013). Specifically, badly deteriorating infrastructure systems need to be renewed, while at the same time the public inconvenience caused by construction work zones must be minimized. For these reasons, STAs are implementing a massive highway infrastructure rebuild (Choi and Kwak 2012). Such improvement projects are often undertaken in heavily trafficked urban areas, often causing intolerable inconvenience to motorists. The result is the average daily commuter spending 54 additional hours and burning 21 extra gallons of fuel each year, with an annual additional road user delay cost of $1,010 per commuter ($166 billions of wasted time and fuel annually in total) (Lasley 2019).

To lessen traffic inconvenience during construction under the presence of work zones, recently, these efforts at accelerating construction were promoted by the Federal Highway Administration’s Every Day Counts (EDC) initiative, which was designed to reduce project completion times (Federal Highway Administration 2012). In 2012, the Moving Ahead for Progress in the 21st Century Act (MAP-21) was initiated with many important provisions, including new regulations concerning acceleration of project delivery. Cutting the duration of project delivery and lessening traffic disruption during construction were noted as key challenges (Federal Highway Administration 2014). A prior study also reveals that the affected communities and commuters are willing to pay higher costs if they can anticipate that accelerated construction schedules will minimize their overall inconvenience (Choi et al. 2009). These new initiatives and
trends have brought to the fore the need for alternative contracting methods (ACMs) that can concurrently reduce construction duration and lessen unfavorable traffic impact on the traveling public and commercial enterprises.

**BACKGROUND**

Historically, cost has been regarded as the major component for determining a winning contract bid; that is, in the conventional project delivery mechanism, the contractor who turns in the lowest-cost bid wins the contract. However, in the early 1990s, some innovative states began considering alternative methods that offer the potential to deliver projects faster and limit negative traffic impact on the traveling public. In recent years, many STAs have adopted ACMs, including incentive/disincentive (I/D) and cost-plus-time (A+B) contracting methods (Choi et al. 2012; Choi et al. 2010; Choi et al. 2016; El-Rayes and Kandil 2005; Ellis and Pyeon 2005; Fick et al. 2010; Jiang et al. 2010; Shr and Chen 2006; Shr and Chen 2003; Sillars 2007). In particular, one alternative strategy of shortening the duration of construction is to offer an early completion incentive bonus to contractors procured through the Cost-plus-Time bidding process, commonly referred to as A+B. The A+B bidding strategy is very common, especially in local urban districts, and has become one of the most widely used ACMs for reducing construction time, especially in time-critical projects, often accompanied with I/D provisions for meeting the accelerated project delivery requirement and minimizing traffic delays (Choi et al. 2012). In A+B contracting, the winning bidder is the group that turns in the lowest total combined bid for the cost (A) and time (B) required to complete the project. The “B” value of the contract time determined by the contracting agency serves as the maximum allowable contract time and must be specified in the PS&E (i.e., Plans, Specs & Estimate) bid packages. The contractor’s bid for the “B” value
establishes the contract time in calendar days, after accounting for weather, holidays, and other non-workdays. In general, for the A+B bidding fixed completion date contracts are discouraged because the number of actual days the contractor bids and the completion date are likely to conflict. The use of A+B is a desirable alternative contracting strategy to accomplish early project completion (Actis et al. 2014), and takes advantage of contractors’ ingenuity by utilizing their realistic estimates of construction schedule. However, one notable disadvantage of A+B is that contractors often intentionally bid low on time and costs, which later results in the failure to complete the project on time and on budget (Chini et al. 2017; Choi et al. 2012; Christiansen 1987). A+B implementation experiences to date indicate that the effectiveness of A+B contracting is debatable largely due to inherent inaccuracy in letting contractors specify project duration during the bidding.

Urban districts have used I/D contracting strategies either as a stand-alone method or in combination with alternative contracting methods. The system of I/D rewards contractors with monetary bonuses for early completion of projects and levies fines for schedule delays. In theory, to encourage competitive contractors to bid on projects, an agency must offer I/D amounts greater than the contractor’s additional cost of acceleration; this estimate must fall within the agency’s budget and still be sufficient to motivate the contractor to complete the project ahead of schedule. The maximum time allowed for the project must be estimated by the contracting agency to serve as the baseline for the I/D rates. In a conventional contracting arrangement, the general contractor and subcontractors have no input until they are selected. The agency’s engineers responsible for determining the contract completion time may lack experience in identifying long lead items and project constraints. The use of I/D provisions through an A + B bidding takes advantage of contractors’ ingenuity by utilizing their realistic estimates of construction schedules and costs. It
is also generally acknowledged that this bidding process eliminates unqualified contractors. However, A+B combined with I/D provisions is known to increase costs for both agencies and contractors, but agencies benefit from construction time saved for road users and the contractors benefit from incentive bonuses (Anderson and Damnjanovic 2008; Choi et al. 2016; Fick et al. 2010; Gransberg et al. 2016).

LITERATURE REVIEW

The literature review provided a comprehensive overview of ACMs with respect to their cost-time performance and interdependence on modeling (Choi and Kwak 2012; Choi et al. 2012; Choi et al. 2015; Ellis Jr et al. 2007; Fick et al. 2010; Ibrahim and Orabi 2016; Jiang et al. 2010; Minchin et al. 2016; Nahidi et al. 2017; Scott et al. 2006; Shr and Chen 2006; Strong et al. 2005). As depicted by Fig. 1, the existing body of knowledge pertinent to the scope of this study could be classified into three primary standpoints: (1) single – researching a sole aspect of performance measures either on time or cost; (2) parallel – researching the time and cost aspects of performance measures independently; and (3) intersectional – researching the interdependence of time and cost performance aspects.
Notably, the structured survey of pertinent literature (Fig. 1) conveyed the conclusion that the effectiveness of using ACMs such as I/D and A+B is controversial. For instance, a study by Scott et al. (2006) used 77 different A+B projects data (totaling $824 million) that were gathered from 20 different sources. Choi et al. (2012) reported that the main goal of agencies using I/D and A+B was to reduce the length of the project’s duration. Subsequently, Choi et al. (2015) examined the performance effects of ACMs change orders on the aspects of time and cost. The results showed that projects contracted with ACMs (i.e., A+B and I/D) were more prone to schedule and cost change orders than did conventionally contracted projects. However, this benefit comes with possible additional cost and an increased uncertainty (Choi et al. 2015; Minchin et al. 2016; Molenaar 2005; Scott et al. 2006). A previous study performed by the Construction Industry Institute (CII) on project delivery and contracting strategy (PDCS) selection (Anderson and Oyetunji 2003; Anderson 2003) produced an owner tool to select the most appropriate PDCS.
alternatives. The research confirmed that I/Ds were not a differentiator in PDCS selection. The conclusion was that I/Ds can be used effectively with any PDCS. The studies performed by El-Rayes (El-Rayes 2001; El-Rayes and Moselhi 2001) were aimed to develop a practical model to optimize the total cost-plus-time bid in A+B projects.

Some researchers have focused on time-cost tradeoff analysis by using a number of statistical and optimization models, such as regression modeling, integer programming, linear programming, dynamic programming and genetic algorithms. These optimization models attempted to minimize project time and cost for highway construction projects (Choi and Kwak 2012; El-Rayes 2001; El-Rayes and Moselhi 2001; Ibrahim and Orabi 2016; Jiang et al. 2010; Leu and Hwang 2001; Shr and Chen 2006). However, a summary of the comprehensive literature review shows that there is still very little known about the interdependence of cost and time under pure A+B and A+B combined with I/D clauses.

STATEMENTN OF PROBLEMS

To date, the existing body of knowledge pertinent to ACMs shows that both of the above-mentioned methods are increasingly common, but that there is still a large knowledge gap regarding the interdependence of cost-time performance and modeling. This is attributable to the following three reasons: 1) data relevant to ACMs are often not available or of poor quality; 2) in most states, A+B contracting has almost always been used in combination with I/D clauses (Bayraktar et al. 2004; Fick et al. 2010; Herbsman 1995; Scott et al. 2006), so very little definitive information about the effects of pure A+B is available; and 3) none of the existing studies investigating cost-time interdependence modeling analyzes how the originally installed project
cost interacts with an accelerated schedule, which often is affected by the choice of ACM. Below, each problem is described in detail.

**Problem I: How to Collect Quality Data?**

The effectiveness of project decisions is directly related to the ability of program and project managers to collect and interpret data. However, ACM data are often not available or of poor quality. For example, while I/D contracting has been used commonly in many STAs, percentage performance data are still relatively unavailable in the industry. Furthermore, when datasets are available, they often reflect different aspects of schedule, cost, and quality for projects that differ in type and scope. Therefore, many previous studies have more or less compared apples to oranges. In fact, the absence of comprehensive data hinders an STA’s ability to determine when to use a specific ACM and the particular type to apply.

**Problem II: How to Quantify the Likely Impact of an ACM on Cost and Schedule?**

With regards to the existing literature on the impact of pure A+B contracting, several research studies have been conducted with A+B project data (Bayraktar et al. 2004; Fick et al. 2010; Herbsman 1995; Scott et al. 2006). However, all existing studies on this topic were based on incentivized A+B contracting projects, so the performance impact of pure A+B remains unknown. Among STAs using A+B, it is very common that A+B is applied in association with I/D provisions (Bayraktar et al. 2004; Fick et al. 2010; Herbsman 1995; Scott et al. 2006). For instance, the Florida Department of Transportation (FDOT) enforces I/D to be accompanied with every A+B procured project (Chini et al. 2017; Ellis Jr et al. 2007; Minchin et al. 2016). Along the same line, common practice for the California Department of Transportation (Caltrans) is that all I/D projects are used in conjunction with A+B, while A+B can be implemented as a stand-alone method without I/D (Choi et al. 2012; Choi et al. 2015). To date, I/D outcomes indicate that the effectiveness of I/D
rewarding system is debatable, due largely to the inaccurate contract times and the values associated with road-user delay (Choi et al. 2013). To a significant extent, the contract time determination has resorted on the engineers’ experience and judgment (Choi and Kwak 2012).

Problem III: How to Link Cost and Schedule Interdependence to the Choice of ACM?

In spite of the common use of ACMs such as A+B and I/D, there has been very little research on their cost and schedule performance or the modeling of their interaction with the choice of ACM. This knowledge gap is largely attributable to the lack of available data. Very few systematic and repeatable research has been conducted on the particular effects of pure A+B; none of the existing studies investigate or model how cost interacts with an accelerated schedule driven by the adoption of ACMs.

RESEARCH OBJECTIVES

For the three reasons delineated above, the impact of I/D and pure A+B on cost and time performance remains largely unknown, and thus serves as the point of departure for this study. The lack of quantitative studies modeling a project’s characteristics and performance according to the ACM applied prevents STAs from accurately budgeting and realistically assessing when to implement such contracting strategies and which method to use. To address these problems, this study endeavors to assist STA engineers and decisionmakers in establishing the most appropriate budgets and schedules, helping them to obtain advanced knowledge of an ACM’s potential consequences as driven by the choice of ACM through the quantification of cost-time performance and interdependence modeling. To achieve this overarching goal, this research focuses on investigating the marginal cost-time impact of the selected ACMs and subsequently, creating and
testing a cost-time tradeoff decision-support model that predicts how the originally installed project cost is affected by schedule compression driven by the choice of an ACM.

**RESEARCH METHODS AND DATA COLLECTION**

The research objectives were achieved by conducting a four-stage methodology that articulates data stratification and analysis techniques (i.e., trend analyses, descriptive statistics, and hypothesis testing) and modeling frameworks where a balanced and viable tradeoff point between contract time and cost of ACMs is assessed and the model’s prediction accuracy is validated. More specifically, first, a rich set of 1,372 project data were obtained from Caltrans. The data included highly detailed information about key project indicators such as project summary, schedule, and cost, as well as information about the ACMs pursued for each project (see Table 1). Data were stratified for an unbiased analysis and modeling purpose, with regards to project type, size, and type of ACMs. Second, the stratified data were analyzed to investigate current trends in transportation infrastructure improvement projects. Third, the observed trends were statistically re-examined for scientific inference and generalization purposes. Whether or not the adoption of an ACM was effective at reducing the duration of a project and providing cost savings to the agency were tested by conducting multiple planned comparison tests. Lastly, an accelerated alternative contracting cost-time tradeoff (ACT²) model was created from a second order polynomial regression analysis with one-way ANOVA. The model’s validity and reliability were then tested and successfully proven by utilizing two well-known statistical validation techniques, the predicted error sum of square (PRESS) and paired difference tests.

This study is focused on the following three contracting strategies:
▪ Conventional: projects that were awarded through a typical unit price contract under a benchmarking design-bid-build project delivery method.

▪ Pure A+B: projects contracted solely through A+B bidding as a stand-alone method.

▪ I/D with A+B: projects contracted through A+B bidding with I/D provisions.

Problems with contracting related data collection from the highway construction industry are pervasive and can be grouped into two large categories: availability and quality. In response, the goal of the data collection for this study was to develop high-fidelity datasets that were representative, unbiased, and pertinent to the research goals. The research team was fortunate to have strong support from an STA servicing a leading state in ACM use. The original set of 6,000 datapoints were obtained from the Caltrans. A total of 1,372 projects completed in California in the past decade were unbiasedly selected after eliminating missing data through a rigorous data stratification process. As shown in Table 1, the studied data covered three primary areas such as project summaries, schedules, and costs.

<table>
<thead>
<tr>
<th>No.</th>
<th>Value type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EA number</td>
<td>6-digit unique project ID</td>
</tr>
<tr>
<td>2</td>
<td>District</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>County</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Route</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Postmiles</td>
<td>Lane-miles rebuilt</td>
</tr>
<tr>
<td>6</td>
<td>Location description</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Project type</td>
<td>Roadway 3R, capacity-added, bridge</td>
</tr>
<tr>
<td>8</td>
<td>Contractor</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Contracting type</td>
<td>Conventional, A+B only, I/D w/ A+B</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No.</th>
<th>Value type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Original project duration</td>
<td>Originally scheduled project duration</td>
</tr>
<tr>
<td>12</td>
<td>Contract SCO days</td>
<td>Days added due to change orders</td>
</tr>
<tr>
<td>13</td>
<td>Amended contract time</td>
<td>Equals 11+12</td>
</tr>
<tr>
<td>14</td>
<td>Actual project time</td>
<td>Days spent to complete project</td>
</tr>
<tr>
<td>15</td>
<td>Level of schedule changes</td>
<td>Equals 12/11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>No.</th>
<th>Value type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>Original contract amount</td>
<td>Awarded bid amount</td>
</tr>
<tr>
<td>22</td>
<td>Contract CCO amount</td>
<td>Costs added due to change orders</td>
</tr>
<tr>
<td>23</td>
<td>Amended contract amount</td>
<td>Equals 21+22</td>
</tr>
<tr>
<td>24</td>
<td>Actual project cost</td>
<td>Cost of completing the project</td>
</tr>
<tr>
<td>25</td>
<td>Level of cost changes</td>
<td>Equals 22/21</td>
</tr>
</tbody>
</table>
TREND ANALYSIS

Fig. 2 displays the current trend of infrastructure improvement projects; it indicates that the three major project types represent approximately 67.4% of all project establishments. When viewed as a percentage of all contract cost allotments, it becomes even clearer that the three major types (83.0%) are forming an ever-greater portion of infrastructure improvement projects. This number also suggests that the major types tend to feature larger project sizes than do other types.

![Fig. 2. Trend in infrastructure improvement projects](image)

It is noteworthy that among the three major types, roadway construction (i.e., 3R) represents 51.1% of all project establishments. This emphasis on the 3R type reinforces the observation that the trend in infrastructure improvement projects has begun to shift from building new roadways to rebuilding existing infrastructure. This high percentage of renewal projects focusing on existing roadways and the increased potential for growth in the near future implies that ACMs will play an instrumental role in shortening the duration of projects (especially in high-profile urban areas), consequently lessening the impact of traffic on the traveling public.
Fig. 3 displays the tendency to adopt ACMs more frequently for capacity-added projects such as the widening of existing lanes or addition of new lanes in live traffic conditions. These capacity-added projects, which are usually of a relatively large scale, are typically undertaken in heavily trafficked urban areas in order to meet the ever-growing traffic demand. At the same time, the large size of these projects requires agencies to close construction work zones for longer periods of time. These apparently conflicting constraints have brought to the fore the need for an ACM such as I/D to hasten project completion while minimizing public inconvenience.

![Fig. 3](image-url)

**Fig. 3.** Adoption of ACMs versus project type

Fig. 4 shows that the two ACMs selected for this study were implemented in 6.5% of all of the projects. When this usage was contrasted to the total project allotment cost, the percentage of utilizing those ACMs rose to 22.9%, meaning that ACMs were used more often in larger-than-usual projects.
Fig. 4. Adoption of ACMs versus project establishment and cost in overall

Fig. 5 confirms that I/D and A+B projects tended to be much larger than conventional projects in terms of average project size, as measured by the original contract amount. Following is more detailed information about the characteristics of I/D projects:

- I/D projects ($16.3 million) had the largest average project size when the original contract amount was compared, followed by A+B ($13.4 million) and conventional ($4.1 million) projects.

- The large size of I/D projects implies that the I/D strategy has primarily been adopted to relatively large-scale projects where time is of the essence.

- The average size of ACM projects ranges from $5 to $15 million, whereas conventional projects were around $5 million.

- The capacity-added projects had the largest project size.
Fig. 5. Average project size of ACMs versus project types

Fig. 6 displays daily contract dollar values for three contracting strategies. It was noted earlier that I/D more closely corresponded to use in larger-size projects than did A+B in terms of contract dollar value per project. As Fig. 5 shows, it is noticeable that the daily project size of A+B ($68,380) is larger than that of I/D ($63,512) in terms of contract dollar value per day, which results from the relatively shorter duration of A+B projects compared to I/D projects of similar project scope and size (A+B were 196 days on average, while I/D’s average was 257 days). Taken together, A+B projects seem to be subject to significant contractor underestimations of contract time when bidding on the “B” portion, likely because doing so makes a reward is more likely.
DISCRiPTiVe STATISTICS AND HypoThESIS TESTING

Key Performance Indicators for Assessment and Interpretation

Investigating cost-schedule effectiveness and modeling the interaction effect of selected ACMs were the primary objectives of this study. In considering these goals, trends in transportation projects by project type and ACM were first examined. To further document the cost-schedule effectiveness and model the interdependence tradeoff effect between cost and schedule performance, the following two project performance indicators (PPIs) were quantified from the project data examined. A series of planned hypothesis comparison tests were then performed from the computed PPIs prior to creating and testing the ACT² model.

- **Cost Performance Ratio (CPR)** = \([\frac{\text{final contract amount} - \text{original contract amount}}{\text{original contract amount}}]\) \(\quad (1)\)

- **Schedule Performance Ratio (SPR)** = \([\frac{\text{final contract time} - \text{original contract time}}{\text{original contract time}}]\) \(\quad (2)\)

**Fig. 6.** Average project size per day versus ACMs
The Cost Performance Ratio (CPR) was used to examine the level of cost growth. This is defined as the ratio of difference between the final and original contract amounts to the original contract amount. A positive ratio implies cost growth and a negative ratio means a reduction. The original contract amount consists of the cost of the bid items that the contractor specifies. The final contract amount is the final project cost expended for the bid items at the conclusion of the project, including total contract adjustments (e.g., incentive payments to contractors).

The Schedule Performance Ratio (SPR) is the ratio to evaluate the level of schedule accuracy. A negative value means that the project was finished sooner. A positive value implies that the project took longer. If the ratio equals zero, this denotes on-time project delivery. The amended contract time due to the occurrence of change orders was not considered for the purpose of this study. This was because the magnitude and frequency of contract change orders are likely to be affected by the choices of ACMs (i.e., accelerated construction). SPR was used to investigate whether the use of an ACM offers a decisive time-saving advantage over conventionally contracted projects.

**Descriptive Statistical Analysis**

Of the 1,372 projects surveyed, 7.2% were delivered using A+B, 3.6% used I/D, and 89.2% employed a conventional contracting strategy. The samples were unbiased towards any of these three project contracting strategies. Each contracting strategy was categorized as one of these three types. Fig. 7 shows the percentage distribution of the three major project types by contracting strategy, indicating that both ACMs were awarded more to bridge and capacity-added projects.
Fig. 7. Contracting strategies by project type

Fig. 8 shows the distribution of schedules and CPR by contracting strategy. In the cost-time tradeoff analysis, when it came to schedule performance, I/D projects shortened the duration of construction by cutting the original schedule by 15.8% on average, while A+B and conventional projects incurred schedule delays by 12.0% and 5.4%. Conversely, in terms of cost performance analysis, the I/D contracting strategy had the largest overall cost performance change rate (16.7%), while the conventional contracting strategy was the smallest of the three (6.4%). This demonstrates that a schedule reduction effort forced by I/D provisions causes additional resource commitment in order to reduce the schedule of a project, as shown in Fig 8. Therefore, this study may convey the fact that the adoption of I/D is preferable for shortening construction time because I/D projects have demonstrated the power of including an I/D provision, which serves as an effective means of achieving on-time project completion, sometimes even surpassing the agency’s goal.

However, this comes with a cost: I/D projects yield additional cost growth, even though they support shorter project duration. This cost-time tradeoff effect seen in I/D projects was scientifically tested to support this general conclusion.
While I/D with A+B was found to be an effective means of schedule compression, A+B as a stand-alone contracting method demonstrated a critical problem. Before this study, it was believed that the use of A+B would result in a schedule savings effect similar to what is seen in incentive contracts. However, this initial analysis showed that in both measurements A+B resulted not only in a noticeable schedule delay, but also a significant cost growth worse than what conventional contracting produces. This abnormal behavior required a more rigorous scientific investigation. The following section describes the effort implemented for this purpose.
Hypothesis Testing: Project Schedule and Cost Performance versus ACM

In order to make a scientific inference about the schedule-cost tradeoff effect of I/D and the abnormal performance observations seen with A+B in the previous trend analysis and descriptive statistics, a planned comparison hypothesis test was carried over to examine if the means of one contracting group were significantly higher than those of other groups (i.e., one-tailed). This process is determined by setting an error threshold, called a significance level, \( \alpha \). The significance level is defined as “the probability that the researcher is willing to take of incorrectly rejecting a true null hypothesis” (Gerstman, 2003). For instance, in the significance level of 0.01, the researcher is willing to take one percent probability of incorrectly rejecting a true null hypothesis. The predetermined significance level (\( \alpha = 0.05 \) for this study) is then compared to a \( p \)-value computed through test statistics. If the \( p \)-value is less than or equal to the alpha level, the null hypothesis is rejected. If the \( p \)-value is larger than the alpha level, the null hypothesis is retained. The primary reason for selecting this testing method over an ANOVA \( F \)-test was because the rejection of the null hypothesis would not specifically verify which mean was significantly different from the others.

Research Hypotheses Used for Planned Comparison

To investigate the difference in schedule-cost performances of the three ACM groups, six different hypotheses were established for planned statistical comparisons by reviewing literature (Choi et al. 2012; Choi et al. 2010; Choi et al. 2016; El-Rayes and Kandil 2005; Ellis and Pyeon 2005; Fick et al. 2010; Jiang et al. 2010; Shr and Chen 2006; Shr and Chen 2003; Sillars 2007):

1) Schedule performance

- Hypothesis 1: ACMs would reduce the duration of projects significantly more than would conventional contracting (ACMs vs. Conventional).
Hypothesis 2: Conventional contracting would shorten construction time significantly more than would A+B (Conventional vs. A+B).

Hypothesis 3: I/D would reduce the project duration significantly more than would conventional contracting (ID vs. Conventional).

Hypothesis 4: Adoption of I/D would reduce the project duration significantly more than would A+B (I/D vs. A+B).

2) Cost performance

Hypothesis 5: ACMs would incur a project cost growth significantly more than would conventional contracting (ACMs vs. Conventional).

Hypothesis 6: I/D would increase project cost significantly more than would A+B contracting (I/D vs. A+B).

Analysis of Hypotheses Test Results for Schedule-Cost Performance

Before conducting hypotheses testing, the research team was aware that the data needed to satisfy certain preliminary assumptions to produce unbiased results. These included issues such as data normality, homogeneity of variances, and homoscedasticity, each of which was examined before testing. It was observed that the data did have a normality issue in terms of the cost-performance ratio data, and this normality problem was resolved by transforming the data. The research team believes that even if this was deemed to be an important issue, these assumptions and their testing were beyond the scope of this work, and a detailed description of this assumption testing procedure was not necessary.
Table 2 shows the outcomes of the planned comparisons test performed to quantify the schedule-cost performance built for the ACMs studied. The $t$-statistic of -.673 ($p = .251$) for Hypothesis 1 yields that there was no significant proof to confirm that ACMs would shorten the duration of projects significantly more than conventional contracting. Therefore, the planned Hypotheses 2 and 3 were conducted to further examine the effect that a specific ACM would have on schedule compression. The significance of Hypothesis 2 ($p = .058$) reveals that there was no significant evidence to prove that conventionally contracting projects performed better than did A+B projects, yet it was very close to the threshold level ($p = .050$). In contrast, the significance ($p < .05$) of Hypotheses 3 and 4 affirms that I/D performed significantly better than did other contracting projects. These results taken together suggest that I/D would be an effective means for reducing construction times, while A+B projects were ineffective for cutting down the completion time of a project (which in certain cases could be worse than conventional projects).

With regards to cost performance measurements by ACM, the research team conducted two planned comparisons: Hypothesis 5 to test whether ACMs were different from conventional contracting and Hypothesis 6 to examine if the adoption of I/D would incur a significant project cost growth. The $t$-statistic of 2.543 ($p = .015/2 = .0075$) for Hypothesis 5 shows that ACMs projects would increase project cost significantly more than the conventional projects. The significance of Hypothesis 6 ($p = .413/2 = .207$) shows that there was no significant evidence proving the validity of the research hypothesis that the adoption of I/D increased project cost significantly greater than did pure A+B.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hypothesis</th>
<th>Value</th>
<th>Std. Error</th>
<th>$t$-value</th>
<th>Sig. (1-tailed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td>ACMs vs. Conventional</td>
<td>-.098</td>
<td>.145</td>
<td>-.673</td>
<td>.251</td>
</tr>
<tr>
<td></td>
<td>Conventional vs. A+B</td>
<td>-.130</td>
<td>.082</td>
<td>-1.573</td>
<td>.058*</td>
</tr>
</tbody>
</table>
While hypothesis testing could be an effective means of examining the marginal cost-time effects of different contracting strategies, its main usage in the context of this study is limited to examining the difference in schedule and cost performance of three contracting project groups. It cannot be used to capture a circularly tradeoff effect between cost and time by the choice of an ACM. It is imperative to know how the project cost behaves as project duration reduces or increases by the choice of an ACM. This kind of hands-on knowledge helps STAs make better-informed decisions when choosing ACMs for early project completion by having advanced understanding about a balanced and viable tradeoff point between contract time and cost. In light of this, the natural logical next step is to develop a cost-time tradeoff decision-support model that predicts how the originally installed project cost is affected by schedule compression driven by the choice of an ACM.

**COST-TIME TRADEOFF MODELING**

**FORMULATION OF ACT²**

In addition to the statistical investigations of separate schedule and cost performances of ACMs conducted in this study, existing research efforts have shed little light on the profound impact of the choice of ACM on the project cost-time interaction effect. This study addresses these problems by creating and testing a stochastic decision support model called alternative contracting cost-time tradeoff (ACT²). The proposed ACT² provides a new focus on the transformational relationship...
between cost and time as affected by the choice of ACM; this can be seen in the theoretical curved form shown in Fig. 9.

The ACT\textsuperscript{2} is a decision support mechanism for an ACM model that can predict how schedule compression is driven by the implementation of an ACM, placing a premium on the originally installed project cost. To delineate this uniqueness, modeling the ACT\textsuperscript{2} involved incorporating computed project performance indicators (i.e., CPR and SPR) and the choice of ACM into a second order polynomial regression analysis. As seen in Eq. (3), dummy variable was embedded to numerically define the categorical variables for the two types of ACM and the conventional contracting, creating dichotomous variables (i.e., 0 and 1).

\[ \text{CPR} = \beta_0 + \beta_1 \cdot \text{SPR} + \beta_2 \cdot \text{SPR}^2 + \beta_3 \cdot I_1 + \beta_4 \cdot I_2 \]  

(3)

where the continuous dependent variable CPR is the cost performance indicator; SPR is the schedule performance ratios; and the variables $I_1$ and $I_2$ refer to the vector containing three dummy coded indicators: for conventional, set $I_1 = 0, I_2 = 0$; for pure A+B, set $I_1 = 1, I_2 = 0$; for I/D with A+B, set $I_1 = 0, I_2 = 1$. 

![Theoretical time-cost tradeoff curve](image)  
Fig. 9. Theoretical time-cost tradeoff curve
Development of ACT²

To produce unbiased results of ACT², preliminary assumptions were firstly examined and verified, on aspects of normality, homogeneity of variances, and homoscedasticity. Based on statistically validated study data, a second order polynomial regression analysis with a one-way ANOVA test was then implemented to test whether SPR in response to the choice of ACM placed significant stressors on CPR, as compared to what was seen with conventional contracting. Table 3 is a summary of the one-way ANOVA analysis results and the second order polynomial regression. The F-ratio of 9.04 is significant at the .0001 level, suggesting that the proposed regression model would be adequate. The adjusted R² value of 0.458 indicates that 45.8% of the variability in the CPR could be explained by the independent variables, which can be translated into moderate predictive accuracy of the regression. As a R²-value itself cannot determine whether the estimated coefficients and prediction are biased, the robustness of the regression analysis result was assessed further by scientifically examining residuals. To this end, Kolmogorov-Smirnov test was conducted by setting the null hypothesis that the residuals were normally distributed. The test result confirmed that the data would be from the normal distribution with the p-value over .01 (p = 0.1072). Therefore, the robustness of the data was confirmed.

Table 3. Summary of ANOVA and Polynomial Regression Analysis

<table>
<thead>
<tr>
<th>Sum of Squares</th>
<th>df</th>
<th>Mean Square</th>
<th>F-ratio</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANOVA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Regression</td>
<td>.15296</td>
<td>4</td>
<td>.03824</td>
<td>9.04</td>
</tr>
<tr>
<td>Residual</td>
<td>1.97096</td>
<td>466</td>
<td>.00423</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>2.12392</td>
<td>470</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>Coefficient</th>
<th>Std. Error</th>
<th>t-value</th>
<th>P-value</th>
<th>VIF</th>
<th>Adjusted R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>.05158</td>
<td>.00332</td>
<td>15.55</td>
<td>&lt;.0001</td>
<td>0</td>
<td>0.458</td>
</tr>
<tr>
<td>SPR</td>
<td>.04290</td>
<td>.00914</td>
<td>4.69</td>
<td>&lt;.0001</td>
<td>3.36</td>
<td></td>
</tr>
</tbody>
</table>


The Variance Inflation Factor (VIF) is an index for measuring the impact of collinearity on an estimated regression coefficient (Ott and Longnecker 2010). The model’s VIF in Eq. (4) ranged from 1.00 to 3.36, indicating that there was no multicollinearity issue in the model. With five significant coefficients, the following equation was derived (Eq. (4)):

$$CPR = 0.05158 + 0.0429 \cdot SPR - 0.01 \cdot SPR^2 + 0.02928 \cdot I_1 + 0.04196 \cdot I_2$$  

As seen in Eq. (4), the coefficients $\beta_0, \beta_1, \beta_2, \beta_3, \text{ and } \beta_4$ were derived by conducting a second order polynomial regression analysis. Based on the concept of well-known cost-time tradeoff shown in Fig. 9, it is reasonable to assume that an additional cost commitment of $\Delta C$ would be required to accelerate the project schedule by $\Delta T$. To confirm the suitability of the derived regression equation, two project performance indicators that encompassed CPR and SPR were expressed as functions of the contractor’s cost change amount ($\Delta C$) and changes in construction duration ($\Delta T$), respectively.

$$CPR = \frac{C_1 - C_0}{C_0} = \frac{(C_0 + \Delta C) - C_0}{C_0} = \left(\frac{\Delta C}{C_0}\right)$$  

$$SPR = \frac{T_1 - T_0}{T_0} = \frac{(T_0 - \Delta T) - T_0}{T_0} = -\left(\frac{\Delta T}{T_0}\right)$$  

where: $C_1 = C_0 + \Delta C$; and $T_1 = T_0 - \Delta T$

As shown in Eqs. (5) and (6) derived from the aforementioned theoretical curve, CPR appears to have a mathematically positive relationship with $\Delta C$, while SPR holds a negative relationship with $\Delta T$. 

<table>
<thead>
<tr>
<th>SPR$^2$</th>
<th>-0.00955</th>
<th>0.00262</th>
<th>-3.65</th>
<th>0.003</th>
<th>3.36</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_1$</td>
<td>0.02928</td>
<td>0.01150</td>
<td>2.55</td>
<td>0.0112</td>
<td>1.01</td>
</tr>
<tr>
<td>$I_2$</td>
<td>0.04196</td>
<td>0.01658</td>
<td>2.53</td>
<td>0.0117</td>
<td>1.00</td>
</tr>
</tbody>
</table>
$\Delta T$. In turn, $\Delta C$ implies cost growth against to the original contract amount ($C_0$), while $-\Delta T$ delineates the accelerated contract time compared to the original contract time ($T_0$).

By combining the definition of $\Delta C$ and $\Delta T$ with the derived polynomial regression equation, the final ACT$^2$ model is derived to capture the effect of alternative contracting over conventional contracting for highway rehabilitation projects (Eq. (7)).

$$\left( \frac{\Delta C}{C_0} \right) = 0.05158 - 0.0429 \cdot \left( \frac{\Delta T}{T_0} \right) + 0.01 \cdot \left( \frac{\Delta T}{T_0} \right)^2 + 0.02928 \cdot I_1 + 0.04196 \cdot I_2 \quad (7)$$

**DISCUSSIONS USING GRAPHICAL REPRESENTATION OF ACT$^2$**

As described above, the goal of this study was to better understand how the choice of ACM could affect the performance of highway rehabilitation projects. To quantitatively capture the potential cost-time tradeoff effects by choice of ACM, changes in contract time and cost were incorporated into the ACT$^2$ prediction algorithm. It is apparent from the cost-time tradeoff curves in Fig. 10 that cutting the duration of a project comes with an additional cost commitment. As compared to the conventional contracting method, ACMs involve a higher interaction rate by holding the level of schedule acceleration. In I/D contracting ($I_1 = 0$, $I_2 = 1$), prediction of the cost performance change rate increases by about 4.2% over the conventional method, while A+B ($I_1 = 1$, $I_2 = 0$) increases by about 3% by holding the schedule change rate.
The developed ACT\(^2\) provided a new focus on the transformational relationship between cost and time under ACMs. Main findings achieved from ACT\(^2\) comply with past research on this topic and current applications of ACMs for accelerated highway rehabilitation projects. Both ACMs encourage contractors to maximize efficiency crews and equipment and to use time saving methods to accelerate the project. In turn, the additional cost increase for shortening construction time involves an increase of direct project costs, such as the use of (1) extra crews (regular plus overtime) and equipment, (2) faster-setting materials, and (3) adoption of methods to expedite delivery of construction materials.

By having a closer look into the cost-time interdependency under ACMs, an increase in cost performance change rate under I/D is 1.2\% higher than A+B, by holding the schedule change rate. Even though A+B seems slightly more efficient on the aspect of cost performance, it is noteworthy that the use of I/D provisions would be recommended to strike a balance between

\[
\frac{\Delta C}{C_0} = 0.05158 - 0.04429 \cdot \frac{\Delta T}{T_0} + 0.01 \cdot \left( \frac{\Delta T}{T_0} \right)^2 + 0.02928 \cdot I_1 + 0.04196 \cdot I_2
\]
STAs and contractors’ interests. STAs would benefit construction time saved by including I/D provision in an A+B bidding system, while overcoming a key disadvantage of A+B bidding – the possibility of underestimating construction duration in order to win the bid from a contractor’s side. Meanwhile, contractors can still benefit from incentive bonuses, despite relatively higher project bids than A+B without I/D. In turn, main findings of this study will help STAs promote effective applications of the most widely-used ACMs properly.

**ROBUSTNESS VALIDATION OF ACT²**

When establishing a quantitative model, checking the robustness of the model through a validation study is crucial to ensure that it is repeatable and verifiable. To assure the robustness of ACT², two different validation methods were employed: (1) Predicted Error of Square Statistic (PRESS) and (2) measured-to-predicted paired comparison.

**PRESS: Predicted Error of Square Statistic**

The typical means of validation with new validation data often imposes a challenge on researchers, requiring them to obtain additional secondary data (Choi et al. 2013; Choi et al. 2015). Recognizing such a potential hardship at the onset of the study, this research was proactively designed to test the model’s robustness by performing the PRESS statistic, an effective alternative validation means that clearly reveals the predictability and reliability of a model (Choi et al. 2013; Choi et al. 2015; Holiday et al. 1995; Ott and Longnecker 2010; Tarpey 2000). In addition, to re-affirm the reliability and accuracy of the model, the predicted dependent variable means were compared to holdout data (i.e., measured responses) stored from the original sample datasets, based on paired difference tests.
PRESS is the predicted sum of squares, calculated by deleting one observation, fitting the
model, and then predicting the value of the deleted observation using the model (Choi et al. 2013;
Choi et al. 2015). SSE is the sum of residuals from a regression model. When the value of the
PRESS statistic is approximate to that of SSE, it is concluded that the model is robust in predicting
the intended attribute. The PRESS statistic of a regression model can be expressed as follows (Eq.
(8)):

\[ \text{PRESS} = \sum_{i=1}^{n} (y_i - \hat{y}_i^*)^2 \]  

(8)

where \( y_i \) is a prediction for the \( i^{th} \) observation in the regression model; and \( \hat{y}_i^* \) is a prediction of
a new subset model for the \( i^{th} \) observation, which is fitted leaving out the \( i^{th} \) observation. The
PRESS validation result revealed that the comparison ratio of the PRESS statistic and SSE was
1.0224 (\( \text{PRESS/SSE} = 2.01506/1.97096 \)), which implies that the ACT\(^2\) model is robust in
predicting cost performance change rate and schedule performance for the contracting strategies
examined.

**Paired Difference: Prediction of the ACT\(^2\) Model versus Measured Response**

A statistical comparison of model prediction with measured responses was constructed to confirm
the validation issue. Two paired datasets were used to consider identical observations of schedule
performance change rate, and the paired difference test was used to compare the dependent
variable (i.e., cost performance change rate). In other words, these represented conditions before
and after applying the ACT\(^2\) model. The null hypothesis that the difference between the pairs was
zero was established (Eq. (9)).

\[ y_{di} = y_i - \hat{y}_i = 0 \]  

(9)
where $y_{dl}$ is the sample mean (or median) difference; $y_i$ is a measured response of the $i^{th}$ observation; and $\hat{y}_i$ is a prediction of the $i^{th}$ observation.

Hypothesis testing was performed using the student’s $t$-test and Wilcoxon signed-rank test. In general, a $t$-test is used to examine if two sets of data are significantly different from one another when the datasets are normally distributed. As the result, the $t$-test produced a $p$-value of .9985 ($t$-statistic = -.00185), which provided the significant evidence that there was no difference between the measured data reserved from the original sample and the prediction.

The Wilcoxon signed-rank test was further conducted to confirm the hypothesis test result; this is a nonparametric test comparing the rank difference between pairs, specifically comparing the median difference between pairs that come from the same population and thus are available and useful, even if the data cannot be assumed to be normally distributed. The result of the signed-rank test ($W$-statistic = -528) also confirmed that there was insufficient evidence to conclude that there was difference ($p = .8584$).

CONCLUSIONS

Many STAs have adopted ACMs such as I/D and A+B to accelerate construction and rebuild aging transportation infrastructure. However, little is known about their specific impact on project performance aspects such as time, cost, and cost-time interdependency. The lack of systematic studies supported scientifically by logical quantitative measures has hampered efforts to assess the effectiveness of ACMs. This study addressed this issue by investigating the likely impacts of ACMs on project performance, based on a large volume of project data and rigorous statistical testing, modeling, and validation. To this end, this study developed and tested a new decision support system called ACT\textsuperscript{2} to capture the effects of ACMs on project time and cost performances.
Data on a total of 1,372 highway rehabilitation projects completed in California were gathered and sorted with respect to project type and size. The stratified data were then leveraged to analyze the current ACM trends, the conclusions from which provided the groundwork for subsequent hypothesis testing, modeling, and validation studies. The results of the schedule analysis reveal that I/D was effective at significantly reducing project duration, while pure A+B led to substantial schedule delays that were worse than what was produced by the conventional contracting method. Meanwhile, the results of the cost analysis showed that I/D led to the largest cost growth. It was also seen that projects contracted solely according to A+B underwent levels of cost growth similar to that of I/D projects, confirming a tradeoff effect between time and cost. Through second order polynomial regression analyses, the ACT^2 model was developed and validated by the PRESS statistic and paired comparison tests. From a practical standpoint, it can be used to conduct a cost-time tradeoff analysis when choosing among ACMs, particularly for I/D and A+B contracting methods. The ACT^2 model clearly yields a cost-time tradeoff effect. More specifically, the predicted additional cost increase for I/D contracting was 4.20% on average, as compared to benchmark conventional projects, while A+B had a 3% higher increase than the same.

This study is intended to assist STAs in promoting the more effective application of the two most widely used ACMs. The outcomes of this study will help STAs make better-informed decisions when choosing ACMs for early project completion by having advanced understanding about a balanced and viable tradeoff point between contract time and cost of ACMs. Use of the model will also facilitate a more realistic allocation of contract time and cost by capturing the effects of ACMs on contract time and cost performances.

Despite the robust study approach and validated study findings, the following limitations are acknowledged in terms of endogeneity (Antonakis et al. 2010 and Antonakis 2017), with
respect to the causal relationships found by this study. First, the effect of omitted selection bias was not considered in this study by assuming independence among all project data and no bias in project selection or team selection. Second, the effect of omitted variable bias was not considered by assuming no hidden confounding variables that may affect the validity of the study. Therefore, following Antonakis et al. (2010), future research is suggested to further validate the study findings by applying a quasi-experimental method as a way to overcome the noted endogeneity issues.

**DATA AVAILABILITY STATEMENT**

The data generated and analyzed during this research are available from the corresponding author by request. Information about the journal’s data sharing policy can be found here: [http://ascelibrary.org/doi/10.1061/%28ASCE%29CO.1943-7862.0001263](http://ascelibrary.org/doi/10.1061/%28ASCE%29CO.1943-7862.0001263).
REFERENCES


