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16. Abstract

One innovative way of reducing construction duration is to reward contractors with an early completion incentive bonus and levy fines for delays. Although use of Incentive/Disincentive (I/D) is increasingly common, State Transportation Agencies (STAs) often struggle to select the most appropriate I/D rates due largely to the lack of the proper analytical methods. There is an immediate need to develop a holistic framework that is more general and applicable to a variety of transportation projects for the determination of optimal I/D rates.

The main objectives of this study are to create a new decision-support analytical framework of optimal I/D and test whether it can reasonably and realistically determine and justify the most economical I/D dollar amounts. This study blends existing schedule and traffic simulation techniques with a stochastic analysis by accounting for the integration of project schedule, Contractor's Additional Cost (CAC) of acceleration, and total savings to motorists and to the agency. STAs can arrive at an optimal I/D rate by employing a seven-stage methodology proposed in this study. These steps include two adjustment algorithms that are factored on the concepts of level-of-service and net present value. The study results revealed a strong tradeoff effect between schedule and cost, suggesting that CAC growth rate can be analyzed by how the CAC interacts with the agency's specified schedule goal. The robustness of the proposed seven-stage methodology was validated with two case studies performed on real-world construction projects.

The proposed work provides research communities and industry practitioners with the first holistic view to determine the most economical and realistic I/D dollar amounts for a given project—an optimal value that allows the agency to stay within budget while at the same time effectively motivating contractors to use their ingenuity to complete the projects earlier. It can help agency engineers and decision makers make better-informed decisions and allocate more realistic incentives, which will result in more favorable cost-benefit ratios and better use of public funds. It will significantly reduce the agency's expenses in the time and effort required for determining I/D rates.

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EXECUTIVE SUMMARY

Highway infrastructure improvement projects performed in heavily trafficked metropolitan areas frequently cause severe traffic inconvenience to the traveling public and commercial enterprises that rely on the roadways. Many State Transportation Agencies (STAs) are under increased pressure to minimize the work zone impacts occurred during lane closures. One innovative way of reducing construction duration is to offer contractors an early completion incentive bonus. The incentives/disincentives (I/D) provisions reward contractors with bonuses for early completion of projects and levy fines for delays. Indeed, I/D contracting has become one of agencies' favored alternative strategies to satisfy the public's expectation for early project completion, applied widely to numerous high-impact transportation infrastructure improvement projects in 36 states. In essence, the I/D contracting strategy is widely used and preferred by STAs and contractors alike because it can establish a win-win solution for both parties.

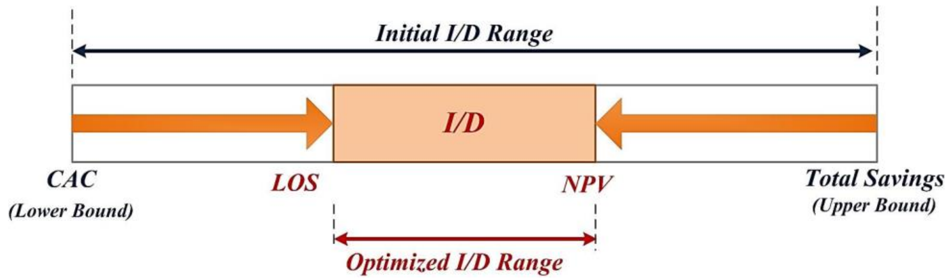
Gaps in Existing Knowledge and Practice

Research to date shows that early completion incentives are an effective means to motivate contractors to use ingenuity to complete the project ahead of schedule. Although use of I/D is increasingly common, very little is known about how to quantify realistic I/D rates. As a result, STAs often struggle to select the most appropriate I/D rates. The lack of the proper I/D analytical tools and standardized methods that can concurrently link project peculiarities, contractor's additional cost (CAC) of acceleration, and project impact on road users prevents STAs from realistically assessing the I/D dollar amounts.

In theory, to encourage competitive contractors to bid on projects, an agency must offer I/D amounts greater than the CAC of acceleration. In practice, however, I/D rates are determined based mainly on historical data and road user cost (RUC), resulting in frequent misapplications. It rarely considers what it would take the contractor, in terms of additional resources and associated indirect costs, to achieve those incentives. Critically, the I/D amounts should not only factor what it is worth to the traveling public, but also account for the contractor's additional commitments to achieve it. There is an immediate need to develop a holistic model for a variety of transportation projects to determine optimal I/D rates in a viable way to balance the agency benefits and the CAC.

Research Scope and Stepwise Methods

This research study assists STA engineers and decision makers to establish the most appropriate budgets and schedules by having advanced knowledge about the I/D consequences that are analyzed through the quantification of CAC and total savings to the agency and road users. To achieve this goal, this study creates and tests a novel decision-support analytical framework that can determine the most realistic and economical I/D rates and is applicable to a variety of transportation projects. This study blends existing schedule and traffic simulation techniques with a stochastic analysis to simultaneously capture project schedule for the I/D baseline, CAC as the I/D lower bound, and total savings (i.e., RUC + agency cost savings from early completion) to be served as the I/D upper bound. The quantified initial CAC provides a meaningful benchmarking point, representing the minimum level of I/D rate needed to minimally motivate contractors to pursue accelerated construction (or on-time completion). Throughout this study, however, researchers noticed that there could be a substantial gap between the lower bound of CAC and the upper bound of total savings, especially for heavily trafficked highway rehabilitation projects where time is deemed critical with high RUC. To reduce the gap to acceptable levels, this study adopts the concepts of Level-of-Service (LOS) and Net Present Value (NPV) to determine more economical and realistic I/D rates that mirror the agency's need of early project completion. The concept of LOS was applied to adjust the initial CAC upward to provide a more realistic minimum I/D range that is effective to motivate a contractor to complete the project ahead of schedule. The concept of NPV was adopted to adjust the initially estimated total savings to road users and to the agency downward in order for STAs to determine I/D rates that fall within an agency's budget. In a nutshell, the initially estimated CAC and total savings are intended to serve as the minimum and maximum range of daily I/D rates while the adjusted values of CAC and total savings are desired to determine an optimal, realistic I/D rate between the adjusted CAC and total savings.



The Constructability Analysis for Pavement Rehabilitation Strategies (CA4PRS) software has is reasonable in predicting optimum pavement construction production and can back-analyze historical I/D projects. CA4PRS was used in this study as a main analysis tool to create time-cost tradeoff data as well as to build RUC lookup tables. The Integrated Definition (IDEF0) function modeling technique was also adopted for this study to visualize stepwise approaches in sufficient details.

The objective of the study was achieved by conducting a seven-stage methodology, each of which is closely interwoven. These seven steps are recommended for the implementation of any new I/D project or provision. These steps can be summarized as follows.

Stage 1—Estimate the schedule baseline of I/D to quantify the probable number of days that can be saved by using an incentive schedule

This stage quantifies baseline schedule of I/D project including the number of closures and working days that can be saved with use of an incentive-driven accelerated construction approach. The estimated difference between the number of closures necessary to complete a project by using a conventional schedule and an incentive schedule determines the maximum probable number of closures and working days that can be saved by using an incentive schedule. This schedule estimate is essential in that the daily I/D and maximum incentive amounts are determined as a function of the time the project can save. CA4PRS deterministic schedule simulations were implemented to develop a database of schedule estimate lookup tables. This new approach using the state-of-the-art CA4PRS software should reduce the number of contractors who receive incentives without committing additional effort.

Stage 2 for the initial lower bound of I/D—Quantify the CAC of acceleration by developing predictive models

This stage computes the reasonable level of CAC of acceleration, which can effectively motivate contractors to pursue accelerated construction. Using the schedule simulation function of CA4PRS, a data set of the contractors' time-cost tradeoff is created on four different resource usage levels. A regression analysis is then performed to develop predictive models that determine contractors' most likely additional cost growth. In order to ensure that the quantifying model is applicable to a variety of transportation infrastructure improvement projects, the same processes were repeated for each of typical pavement rehabilitation strategies such as Jointed Portland Concrete Pavement (JPCP), Continuously Reinforced Concrete Pavement (CRCP), Hot Mix Asphalt (HMA), and Milling and Asphalt Concrete Overlay (MACO). Each strategy is referenced to typical cross-section designs to make the models applicable to a variety of highway rehabilitation projects. The quantifying models based on the time-cost tradeoff data (Tables 10–13) of each pavement strategy are shown in Equations (8)–(11).

Stage 3 and 4 for the initial upper bound of I/D—Computes total savings by accounting for the monetary values of the time saved by road users and to the contracting agency

These stages compute total savings to be used as the I/D upper bound. The monetary value of time saved by the traveling public from early project completion can be quantified by RUC lookup tables (Tables 16–18). To quantify the I/D upper bound, this study considers the new concept of total savings that extend the current practice to cover the monetary value of time realized in the agency cost (see Table 20), believing that the contracting agency can also save agency costs in proportion to the number of days the I/D project eliminates.

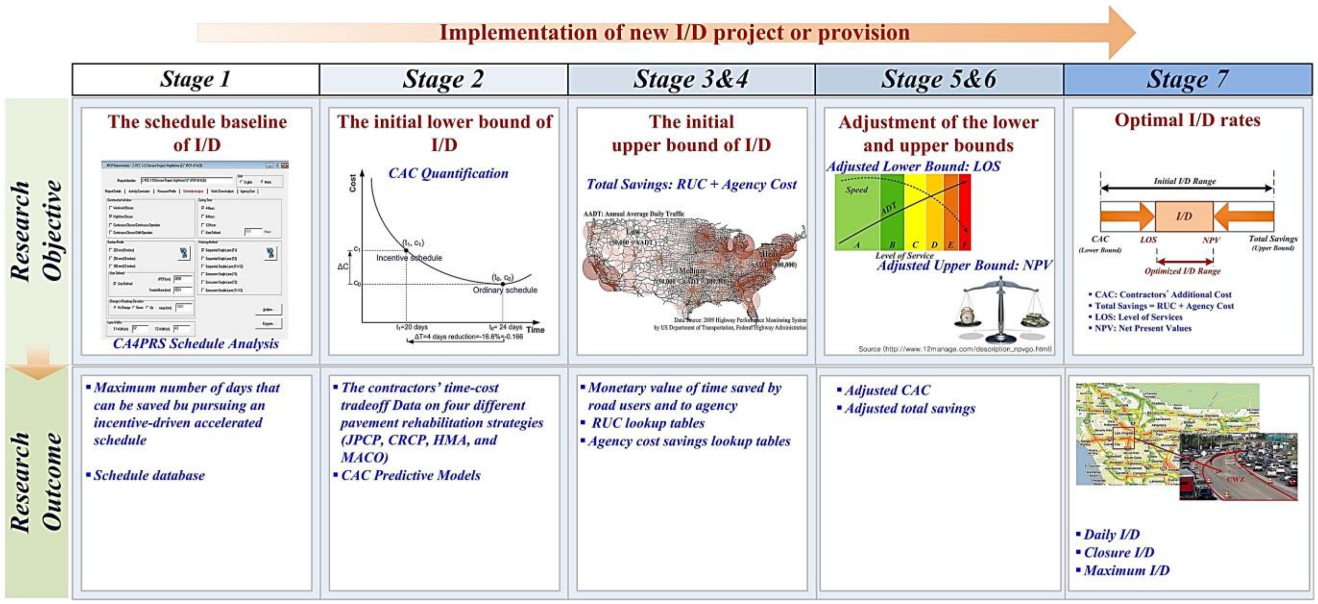
A series of CA4PRS work zone simulations were performed to generate the RUC tables. The agency cost savings were quantified by taking major saving factors into account.

Stage 5 and 6 for adjusting the lower and upper bounds of I/D—Adjust the initial CAC and total savings to quantify more realistic I/D rates

These stages adjust the initial CAC by applying the concept of LOS. The total savings derived from stages 3 and 4 are adjusted by adopting a NPV analysis technique in order to arrive at more realistic I/D rates by applying appropriate discount factors.

Stage 7—Determine optimal I/D rates through a validation study

In this stage, the final I/D dollar amounts are determined in three forms such as a closure I/D, a daily I/D, and a maximum I/D. A validation study was conducted on two long-life large-scale I/D rehabilitation projects completed in Southern California, with the goals of demonstrating the entire procedure to arrive at optima I/D rates and investigating how robust the proposed framework is in predicting the actual values of I/D amounts. The validation study confirmed the robustness of the proposed framework.



Conclusions and Contributions

This study presents a comprehensive framework that can be used to establish the optimized lower and upper bound for an I/D contract, an estimate that falls within an agency's budget and is still sufficient to motivate a contractor to complete the project ahead of schedule. It employs a holistic approach that integrates construction schedule, CAC, and total time value savings with a discounting algorithm. The proposed work can be used to justify whether incentives that will be paid to a contractor are recouped in the value of time saved by road users and the agency. The study results revealed a strong tradeoff effect between schedule and cost, suggesting that CAC growth rate can be determined by analyzing how the CAC interacts with the agency's specified schedule goal. The robustness of the proposed seven-stage methodology was tested and confirmed by conducting a validation study with two real-world construction projects.

The validation study reveals that both projects considered in this study were appropriate for application of an I/D provision since the estimated lower bound was smaller than the total time value savings. The validation study also proved the analytical capability of the model for highway rehabilitation projects in estimating realistic I/D amounts. Specifically, the contracting agency used a closure incentive of $100,000 for the I-710 project. The I/D amount ($100,000 per 55-hour weekend closure) set by the agency was close to the adjusted lower bound ($71,651 per closure) predicted by the model. However, in the post-construction meeting with the contractor, the agency acknowledged that the incentive amount paid to the contractor was not enough for the contractor to recoup the cost added for accelerating construction; the adjusted upper bound was $1.36 million per closure. Because this project had been time-critical, a larger incentive amount could have been put in place to more effectively motivate the contractor to complete the project earlier.

This research is the first of its kind and expected to be a significant leap forward over current ad-hoc approaches that rely heavily on STA engineers' intuition, historical data, and judgment, made primarily on the impact of I/Ds on road users. The proposed work provides research communities and industry practitioners with the first holistic view that they can use to determine the most economical and realistic I/D dollar amounts for a given project. Use of the proposed framework can help agency engineers and decision makers make better-informed decisions and allocate more realistic incentives when they consider the implementation of an I/D provision, which will result in more favorable cost-benefit ratios and better use of public funds. If the agency allocates an incentive smaller than the contractor's added cost, this may keep competitive contractors from submitting a bid. Use of the framework can also benefit contractors bidding on projects that include I/D provisions because it can provide them with advanced knowledge of the balanced time-cost tradeoff amount required for acceleration. Critically, it will significantly reduce the agency's expenses in the time and effort required for determining I/D rates.

Finally, the research team has recommended that pioneering STAs champion the use of the proposed work in an attempt to apply the proposed framework to time-sensitive pilot projects to test whether the proposed framework can reasonably determine and justify the most economical I/D dollar amounts.

NOMENCLATURE

AADT	Annual Average Daily Traffic
ACP	Asphalt Concrete Pavement
AADT	Annual Average Daily Traffic
CAC	Contractors' Additional Cost
Caltrans	California Department of Transportation
CA4PRS	Construction Analysis for Pavement Rehabilitation Strategies
COZEEP	Construction Zone Enhanced Enforcement Program
CRCP	Continuous Reinforced Concrete Pavement
FHWA	Federal Highway Administration
HMA	Hot Mixed Asphalt
I/D	Incentive/Disincentive
JPCP	Jointed Plain Concrete Pavement
LLPRS	Long Lasting Pavement Rehabilitation Strategies
LOS	Level of Service
MACO	Milling and Asphalt Concrete Overlay
NPV	Net Present Value
RUC	Road User Cost
STAs	State Transportation Agencies

DEFINITION OF TERMS

Lane-kilometer (mile)	The total length of all lanes calculated as centerline kilometer (mile) multiplied by the number of lanes
Value of Time (VOT)	The monetary equivalent of travel time wasted as a result of rehabilitation work
Road User Cost (RUC)	Monetary value of the estimated loss in dollars caused by delays in completing critical civil transportation projects
Contractor's Additional Cost (CAC)	A critical factor for competitive contractors to minimally motivate to pursue accelerated construction, defined as the minimum I/D rate
Total Savings	Total time savings to road users and the agency (i.e., the sum of RUC and agency cost)
Level of Service (LOS)	Letter designations *A* through *F* that measure and describe the operational effectiveness of a roadway section undergoing rehabilitation/renewal work
Net Present Value (NPV)	A standard method to evaluate the time value of money (cash flows) for long-term project, described as today's worth of a future amount of money, before interest earnings and charges

1 INTRODUCTION AND BACKGROUND

1.1 Highway Construction Paradigm Shift

The aging of the transportation infrastructure in the U.S. has created an urgent challenge for State Transportation Agencies (STAs)—they must renew badly deteriorated infrastructure systems while minimizing the impact and inconvenience that construction lane closures have on the traveling public. STAs are facing an immediate need for massive highway infrastructure rebuilding, as promoted by specific $80 billion funding targeted for extensive transportation infrastructure rehabilitation projects (Choi and Kwak 2012). Such highway infrastructure improvement projects performed in heavily trafficked metropolitan areas frequently cause severe traffic inconvenience to the traveling public and commercial enterprises that rely on the roadways, resulting in the average driver burning 67 hours and 32 extra gallons of fuel each year (Hasley 2013). Therefore, many STAs are under increased pressure to minimize the work zone impacts occurred during lane closures.

The Federal Highway Administration (FHWA) made a stride toward addressing this growing challenge by launching the Every Day Count initiative aimed at shortening project completion times (FHWA 2012). Research into public perception has also shown that the traveling public and affected businesses show a willingness to pay higher construction costs when they anticipate that shortened construction schedules will mitigate their overall inconvenience (Choi et al. 2009).

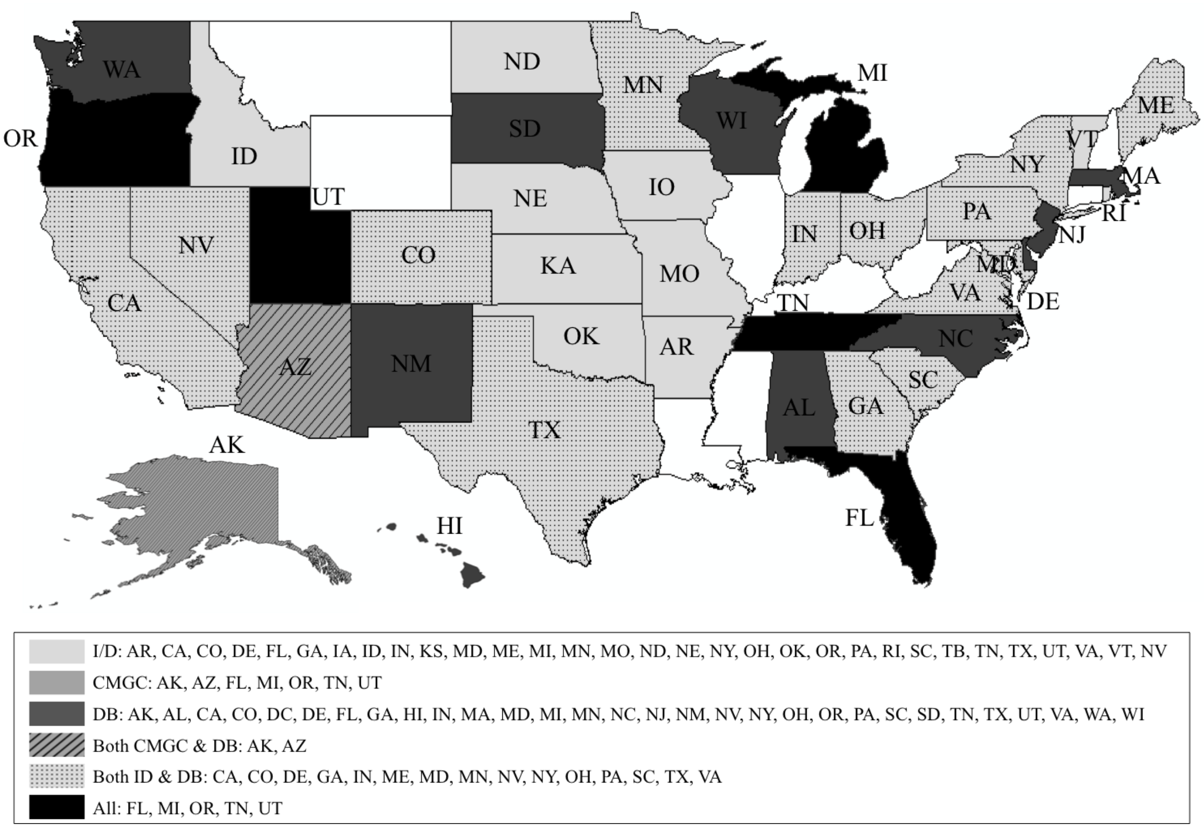


Figure 1. I/D and Alternative Project Delivery Methods versus States.

1.2 Alternative Accelerated Technical Concepts: Time-Based Incentive/Disincentive

Transportation infrastructure improvement projects in heavily-trafficked urban areas inconvenience the traveling public. Among the undesirable impacts for both STAs and the traveling public created by lane closures during construction are severe congestion, safety problems, and limited property access (Lee and Choi 2006). In particular, traffic disruptions at construction work zones (CWZs) on urban highway networks frequently create conflicts between STAs and the nearby communities.

To carry out transportation infrastructure improvements, STAs must close portions of highways while minimizing the impact of the necessary traffic changes on the traveling public and area businesses during the construction period. These apparently conflicting requirements demonstrate the challenge that STAs face: innovative contracting strategies that can both reduce construction duration and lessen unfavorable traffic impact to the traveling public and commercial enterprises that rely on these roadways. To mitigate these traffic disruption problems while responding to the challenge, the FHWA and the Transportation Research Board (TRB) have recommended experimenting with innovative approaches that have the potential to reduce construction time and diminish traffic disruption during construction.

One innovative way of reducing construction duration is to offer contractors an early completion incentive bonus that can motivate them to apply their ingenuity to completing projects early. STAs have experimented with I/D contracting strategies either as a stand-alone method or in a combination with other alternative accelerated technical concepts (e.g., cost-plus-time combined with I/Ds). I/D provisions help agencies balance the cost of road-user delay and project delivery expense. I/Ds have been used to accelerate construction under both the design-bid-build and design-build delivery methods. Even the contracting community has an interest in agencies setting I/Ds properly.

To motivate contractors to complete construction projects early on high-impact highway pavement construction projects, STAs have used I/D provisions. I/D contracting has become one of agencies' favored alternative strategies to satisfy the public's expectation for early project completion. Time-based I/D provisions are one of the most widely used strategies for reducing construction time preferred by STAs and contractors alike because they can establish win-win solutions for both parties (Ibarra et al. 2002; Sukumaran et al. 2006). The I/D contracting rewards contractors with bonuses for early completion of projects and levies fines for delays. The motivation behind the decision to use I/D provisions is to reduce the construction schedule on projects that cause significant cost impacts to the public as measured by road user cost (RUC). Adopting I/D provisions can help agencies save on road-user delay costs by cutting construction time, while contractors can increase profits by receiving an incentive bonus. Currently, I/D provisions have been applied widely to numerous high-impact transportation infrastructure improvement projects in 36 states, as depicted in Figure 1 (Choi et al. 2012).

2 RESEARCH OBJECTIVES AND METHODS

2.1 Gaps in Existing Knowledge

As shown in Figure 1, I/D contracting has been used widely in 36 states. Although use of I/D is increasingly common, very little is available for quantifying realistic I/D rates. As a result, STAs often struggle to select the most appropriate I/D rates. The lack of the proper I/D analytical tools to concurrently link project peculiarities, contractor's additional cost (CAC) of acceleration, and project impact on road users prevents STAs from realistically assessing the I/D dollar amounts.

The amount of compensation specified in I/D contracts not only affects contractor project performance but also reflects how an agency spends taxpayer money. A contracting agency that wants to use the I/D contracting method must first determine the monetary value of the time saved by earlier project delivery. However, determining realistic incentive dollar amounts based on the value of time saved is a challenge because of the lack of standardized methods and computerized analytical tools. STAs have determined I/D rates mostly by their impacts on RUC, as measured as savings or delays (Choi et al. 2012). However, this often results in frequent misapplications and substantial losses of public resources. Determining I/D rates that promote early completion of projects, exceed contractors' additional cost of acceleration, and are below the total savings in the RUC is extremely difficult. Contractors' reluctance to disclose pertinent cost data is part of the problem, but the larger issue is that there is no systematic method or tool for helping STAs determine effective I/D rates (Choi and Kwak 2012). Although methods for determining daily I/D amounts and maximum incentive amounts have advanced over the years, many researchers and practitioners agree that currently available tools cannot concurrently capture project-specific peculiarities, RUC, and CAC (Gillespie 1998; FDOT 2000; Choi and Kwak 2012).

2.2 Research Objectives

This project creates and tests a novel decision-support analytical framework that determines the most realistic and economical I/D rates and is applicable to a variety of transportation projects. Early completion incentives have been shown to be an effective way to motivate contractors to use their ingenuity in order to complete the project ahead of schedule (Herbsman and Ellis 1995; Ibarra et al. 2002; Shr and Chen 2004; Ellis and Pyeon 2005; Shr and Chen 2006; Sillars and Leray 2006; Ellis et al. 2007; FDOT 2000; Fick 2010; Jiang et al. 2010; Choi and Kwak 2012; Choi et al. 2012; Pyeon and Lee 2012). 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. In practice, however, I/D rates are determined based mainly on RUC, resulting in frequent misapplications (Lee and Ibbs 2005; Choi et al. 2012; Pyeon and Lee 2012). It rarely considers what it would take the contractor, as translated into CAC for schedule acceleration with additional resources and associated costs to achieve those incentives and to avoid disincentives. Ideally, the I/D amounts should not only be quantified on what it is worth to road users (i.e., RUC), but also takes the contractor to achieve it (i.e., CAC). There is an immediate need to develop a model that is not only theoretically justified but also practically useful and applicable to real-world projects for the determination of optimal I/D rates that strike a balance between RUC and CAC. To achieve this, this study has the following six distinct tasks:

1. Gather preliminary information and identify gaps in knowledge.
2. Generate comprehensive time-cost tradeoff data from stochastic simulations sourced from real-world highway pavement rehabilitation projects.
3. Develop stochastic models for each typical type of pavements for estimating CAC (lower bound of I/D) by combining an existing schedule simulation technique with regression methods.
4. Develop a comprehensive lookup tables for the estimate of RUC (upper bound of I/D) from simulations.
5. Develop a novel algorithm to adjust the initial estimates of CAC and RUC by applying the concepts of level of service and net present value.
6. Validate research results with real-world highway rehabilitation projects.

2.3 Research Methods

To achieve the objectives, this study used simulation-based stochastic approaches that concurrently capture schedule (I/D baseline), CAC (I/D lower bound), and total savings (I/D upper bound) in RUC and agency cost by combining existing schedule and traffic simulations with a stochastic analysis. In this project, a novel analytical algorithm based on the concepts of Level of Service (LOS) and Net Present Value (NPV) was also developed to test the validity of the research hypothesis that the variables can be used to determine the most economical and realistic I/D rates by effectively adjusting the initial values of the lower and upper bounds (Figure 2).

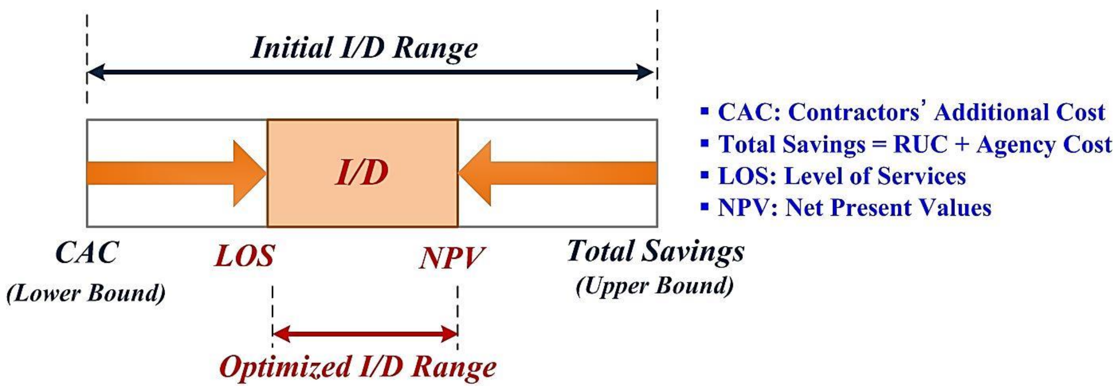


Figure 2. I/D Determination Principles.

Determining an optimal I/D dollar amount has typically been a daunting task for STAs, often adding cost to a project due to the missing link between what it is worth to the traveling public and what it additionally takes the contractor to accelerate construction for achieving early project completion. The main problem is a lack of holistic theoretical but practical algorithms specifically aimed at quantifying and validating I/D rates. Although the existing research provides valuable proof-of-concept studies, a rigorous theoretical and practical framework that captures time-cost tradeoff effects of I/D, savings to motorists and the agency, and adjustments concurrently is desperately needed for the determination of optimal I/D rates. Such a framework can translate into better use of public funds while advancing existing knowledge. This project aims to address this pressing need. The research methods of this study can be generally divided into the following activities, which are closely connected to each other:

1. **Baseline Schedule Estimation**: It quantifies the number of closures and working days by which the project can be shortened with use of an incentive-based accelerated schedule—with an expectation that the accelerated project will use 15 to 20 percent more resources than a conventional schedule. CA4PRS deterministic schedule simulations were used to develop a database of schedule estimate lookup tables by considering five critical factors that significantly affect project schedule, such as construction strategies (i.e., concrete, asphalt, and milling), project scope (i.e., lane-miles to be rebuilt), pavement design (i.e., cross-section design), construction windows (i.e., nighttime, weekday, weekend, and 24/7), and resource constraints (e.g., number of concrete delivery trucks per hour per team).
2. **Time-Cost Tradeoff Model for Quantifying CAC**: A series of Monte Carlo simulations with CA4PRS was carried out. Through the simulations, comprehensive schedule trend data were generated, which captures schedule compression effects on four different levels of resource use in the number of resources per hour per team, that is, ordinarily, a 5 percent increase, 15 percent increase, and 25 percent increase. Simulation results indicate that 25 percent increase on the ordinary level of resource use be a productivity ceiling point. Subsequently, changes in cost in response to schedule compression were then computed manually based on a widely accepted cost manual. By doing so, the research team was able to create a set of contractors' time-cost tradeoff data on the four different resource usage levels by analyzing how the CAC interacts with the agency's specified schedule goal. Lastly, the time-cost tradeoff relationship was plotted to determine the type of regression equation that best fits the data. The research team found that a quadratic curve function best describes the time-cost relationship, and an initial CAC regression model of Equation (2) was derived using the quadratic function. With the initial model, a regression analysis was then carried out to create a predictive model that determines the CAC of acceleration.
3. **Quantification of Total Savings to Road Users and to the Agency**: A rich set of lookup tables for quantifying the monetary value of time saved by road users (i.e., RUC) was generated from CA4PRS traffic simulations. The monetary savings to the agency were quantified by adding up three major reduction factors such as reductions in the costs of construction zone enhanced enforcement program (COZEEP), agency engineering cost (AEC), and moveable concrete barrier (MCB) rental.
4. **I/D Adjustment from Initial CAC and RUC**: To determine the most appropriate I/D rates for a given project, the concepts of level of service and net present value were applied to make a reasonable adjustment between initially estimated CAC and total savings.
5. **Validation of the Proposed I/D Framework with Real-World Projects**: The proposed framework was applied to two long-life I/D highway rehabilitation projects to check the robustness of the model in predicting the actual values of I/D amounts.

In order to ensure that the proposed framework is applicable to a variety of transportation infrastructure improvement projects across states in the United States, the same processes were repeated for each of typical pavement rehabilitation strategies such as JPCP, CRCP, HMA, and MACO. The proposed integration model produces three types of I/Ds such as closure I/Ds, daily I/Ds, and the maximum incentives. The research team believes that the proposed integration approach to determining an appropriate I/D rate can justify the I/D rate from a cost-benefit analysis standpoint. "Cost" is defined as the incentive fee that is subtracted from the CAC of acceleration. "Benefit" is defined as monetary savings to road users and to the agency from early project completion. To be an effective I/D rate, the additional cost commitment paid to the contractor must be recouped in the value of time saved by road users and the agency. The study results revealed a strong tradeoff effect between schedule and cost, suggesting that the level of CAC for acceleration can be captured as a function of reduced construction times with the proposed time-cost tradeoff models. The robustness of the proposed modeling framework was then validated through two case studies, applied to two highway pavement rehabilitation projects where time was deemed critical due to heavy traffic volumes. This research is expected to be a significant leap forward over current ad-hoc approaches that rely heavily on STA engineers' intuition, judgment, and historical data, thus lacking theoretical foundations. This provides research communities with the first view that they can use to determine the most economical and realistic I/D dollar amount for a given project.

The Constructability Analysis for Pavement Rehabilitation Strategies (CA4PRS) software has been reported to be reliable in predicting optimum pavement construction production (Choi and Kwak 2012; Lee and Ibbs 2005). This study adopts CA4PRS as a main analysis tool to create baseline time-cost tradeoff data as well as to build RUC lookup tables. In addition, to effectively visualize the processes of each analysis in sufficient detail, a process modeling technique was adopted for this study, which is widely used to depict, understand, and analyze processes. The research team also used the Integrated Definition (IDEF0) function modeling technique for demonstrating the optimal I/D determination processes in sufficient details, associated with each of the above listed five main research activities. The IDEF0 modeling technique has been proven to be an effective tool for visualizing the modeling processes (Anderson and Fisher 1997; Fisher 1997; MnDOT 2013).

2.3.1 Use of CA4PRS for Building Baseline Data

Agency efforts to deliver projects in a timely manner have been furthered by use of innovative software analysis programs and scheduling techniques such as Critical Path Method (CPM) or Program Evaluation and Review Technique (PERT). A more recent tool arising from these efforts is a state-of-the-art tool called Construction Analysis for Pavement Rehabilitation Strategies, which has come into use because of its ability to analyze schedules, costs, and work zone traffic impacts (Figure 3).

CA4PRS was developed under the FHWA pooled research fund with a multistate consortium (California, Minnesota, Texas, and Washington). The software has three main functions: schedule, cost, and work zone estimates. CA4PRS's schedule analysis estimates the duration of highway rehabilitation project in terms of total number of closures by considering the following critical factors that affect project duration: project scope (lane-mile to be rebuilt), construction strategies (e.g., concrete, asphalt concrete, milling), cross-section designs, construction windows (e.g., nighttime, weekend, extended 24/7 operations), and contractor logistics and resource constraints (Lee and Ibbs 2005). CA4PRS's work zone analysis, which is based on the Highway Capacity Manual demand capacity model, quantifies the impact of construction work zone closures on the traveling public in terms of road user cost and time spent in queue (Lee et al. 2008).

CA4PRS has been widely used in California and in four other states. Validation studies on several major highway rehabilitation projects in states including California, Washington, and Minnesota proved the scheduling reliability and accuracy of the software, and as a result, there has been nationally growing acceptance of the program including recent arrangements by FHWA of free group licenses for all 50 states.

CA4PRS played a pivotal role in this research in generating the baseline data for integration of schedule/time value savings/additional cost growth. It was used to estimate:

- How many closures the project would take.
- How much road user costs could be reduced by shortening construction time.
- How many closures (days) a contractor can reasonably eliminate under four given resource levels.

Since the scheduling reliability and accuracy of CA4PRS was validated with numerous highway renewal projects, it was assumed that the program's use would provide reliable baseline data.

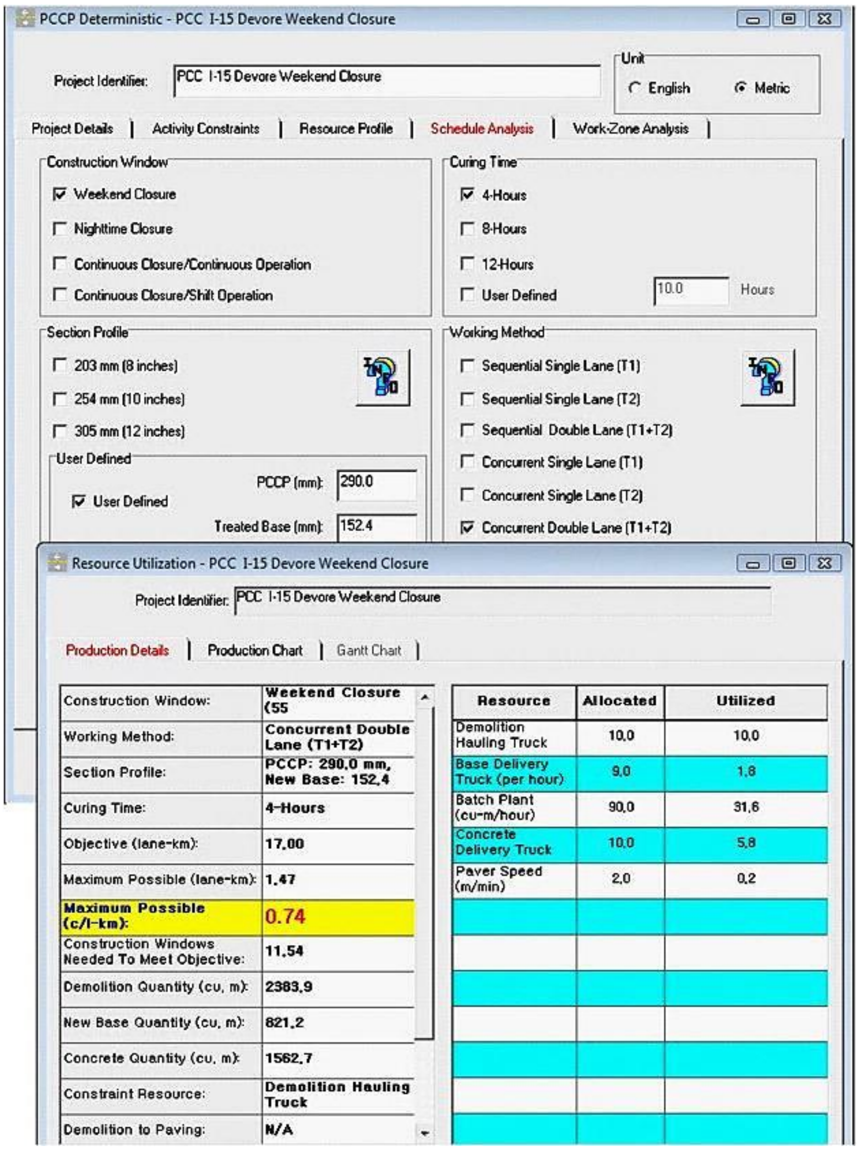


Figure 3. Input and Output Examples of the CA4PRS Schedule Estimate.

2.3.2 Use of IDEF0 Process Modeling Technique

The Integrated Definition function modeling technique was used for this study to highlight each of stepwise procedures aimed to arrive at optimal I/D rates. IDEF0 process modeling technique is a graphical description of the processes while showing logics of the modeling (Liu and Hu 2011). The IDEF0 modeling tool has been widely used to improve the communication process within the system and also to document, plan, analyze, design, and integrate algorithms, as it help to modify the logic and process.

Six different types of IDEF modeling tools are summarized below. Among six modeling techniques, this study adopts the IDEF0 technique for capturing the details of the I/D determination process.

- IDEF0: for function modeling.
- IDEF1: for information modeling.
- IDEF1x: for data modeling.
- IDEF3: for process modeling.
- IDEF4: for object-oriented design.
- IDEF5: for ontology description capture.

As depicted in Figure 4, the IDEF0 function modeling technique is based on the arrow syntax (Talluri and Yoon 2000). The figure demonstrates that the activity transforms inputs into outputs; inputs are shown by the entering arrow while the outputs are expressed by the exiting arrow on the right side of the activity box. Controls are defined as the factors that guide how the activity is performed while mechanisms describe what tools and methods are involved to perform the activity.

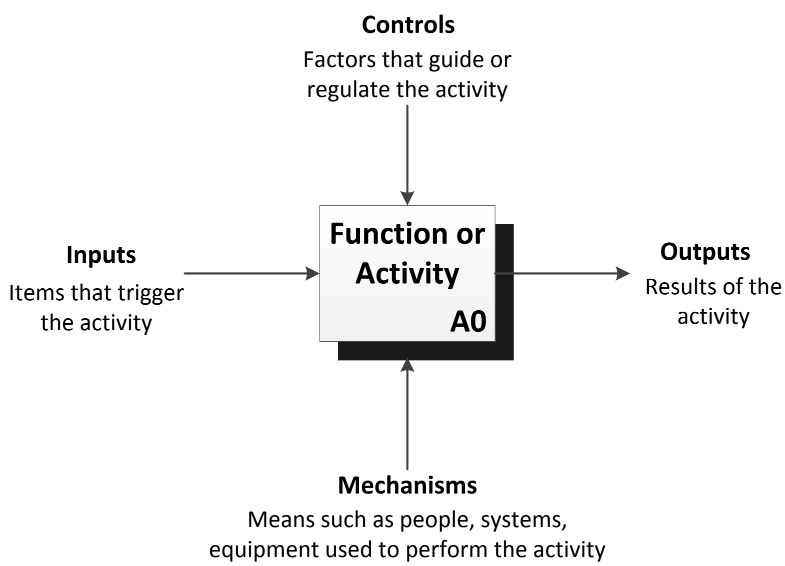


Figure 4. Basic IDEF0 Syntax.

IDEF0 modeling technique consists of several activities arranged in a top to bottom fashion. A simple hierarchical structure of an IDEF0 model is mentioned in Figure 5. This top-level function is decomposed into sub-function parts and is further decomposed until all of the relevant detail of the whole function is adequately visible (Waltman and Presley 1993). This process is called creating a child diagram.

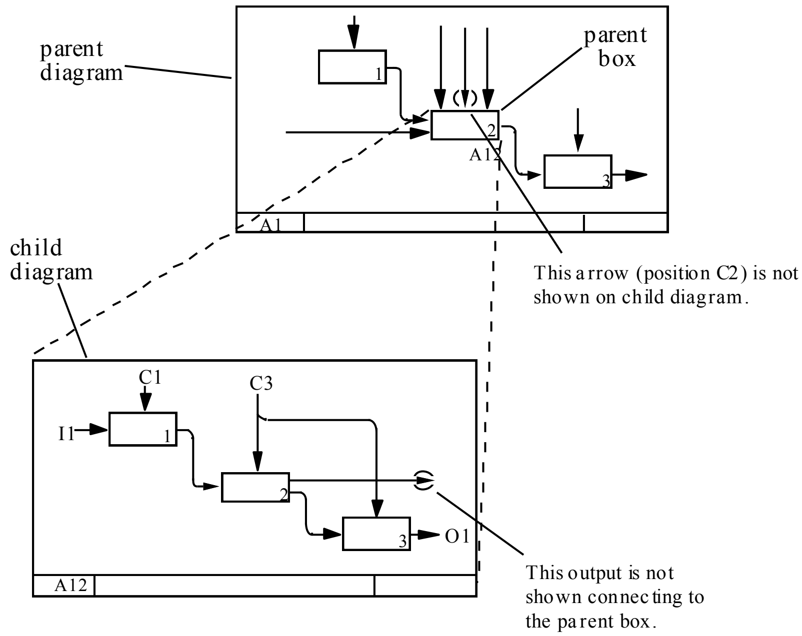


Figure 5. IDEF0 Model Decomposition Structure (Waltman and Presley 1993).

2.4 Research Assumptions and Limitations

There are three basic types of incentives: cost-based incentives, quality-based incentives, and time-based incentives. The decision-support modeling framework developed in this research is limited to the time-based incentives. Time-based incentives can be divided into two categories: linear incentives and escalating incentives. Shr and Chen defined these concepts as follows: "for the linear I/D, contractors receive or are charged the same daily amount regardless of the number of days completed early or late. For the escalating I/D, the earlier or later a job is completed, the greater the daily amount paid to or assessed against the contractor" (Shr and Chen 2004). This research will only take linear I/D into account under the following three research assumptions:

- All schedule and traffic simulation parameters are based on real-world highway pavement rehabilitation projects that were independently implemented and completed. Each simulation on generating schedule trend data and RUC lookup tables was also independently performed. All simulation data to be generated are assumed to be statistically independent.
- When estimating the CAC prediction model, contractors' individual production performance and work experiences were assumed to be identical.
- When validating the proposed framework, it was assumed that agency engineers were not biased in setting the original contract duration.

3 I/D DETERMINATION PRACTICE IN EXISTING KNOWLEDGE

Researchers conducted a thorough review of literature on the I/D determination to gain an insight into the crucial factors to consider in estimating an I/D rate. This literature review provided a comprehensive overview of crucial elements in the implementation of I/D provisions and a summary of case studies conducted by seven leading STAs to investigate the state-of-practice of I/D provisions.

The existing literature provides information about current industry practice on time-based I/D provisions and their effects on project acceleration and operations. The general themes emerged from the review include:

- The existing literature is outdated and insufficient. Besides, methodical research has not been conducted to frame the I/D determination procedures.
- Methods to determine daily I/D amount and contract time have advanced over the years, but they still have many limitations.
- Engineers' overestimation of contract time is noticeable in the studies to date and impedes the effective application of the time-based I/D contracting method.
- A daily I/D amount is calculated on a project-by-project basis using established construction engineering inspection costs, state-related traffic control and maintenance costs, detour costs, and road user costs.
- Engineering judgment has been used to adjust the calculated daily amount downward to a final daily I/D amount.
- Estimation of RUC may be done using acceptable state highway agency's policies and procedures.
- Most recent information should be used for calculating Vehicle Operating Cost.
- The daily incentive rate should never exceed the daily disincentive rate.
- A maximum of 5 percent has been specified as the incentive cap with no recommendation on the maximum disincentive amount.
- A daily I/D amount should provide a favorable benefit/cost ratio to the traveling public and be large enough to motivate the contractor.
- Theoretical frameworks or methods that can quantify optimal I/D rates by concurrently accounting for what it additionally takes the contractor and what it is worth to road users are missing entirely in existing knowledge and practice.

The following six sections summarize the key elements to be addressed when applying I/D provisions: the current state-of-practice in determining the value of time and contract completion time; and the impacts on contractors and agencies, costs and schedules, and administration and project operations.

3.1 I/D Selection Criteria

Several studies contain information on the selection criteria for determining whether or not to apply a time-based I/D provision (Christiansen 1987; Plummer et al. 1992; Jaraiedi et al. 1995; NYSDOT 1999; Livingstone et al. 2002; Ibarra et al. 2002; Rister and Wang 2004; Shr and Chen 2004; Choi et al. 2011; Choi et al. 2012). In general, the use of time-based I/D contracting method is limited to heavily trafficked, fast-track projects where achieving the earliest possible project completion is needed to minimize inconvenience to the traveling public. The selection criteria for employing a time-based I/D provision include:

- Heavy traffic volumes and anticipated high RUC increases due to construction.
- Major rehabilitation of a system already in use that will severely disrupt the current flow of traffic.
- Work that will complete a gap in the highway system.
- Limited access to detour routes.
- Significant impact on public safety and abutting businesses.
- Significant impact on emergency service.

Considering these criteria, time-based I/D provisions should be used carefully since they usually increase costs to the contracting agency and use public resources (Jaraiedi et al. 1995; Gillespie 1998; Sun et al. 2013). How candidate projects are selected and which criteria are the most important ones in the selection process will be further examined and evaluated through a continuous review of pertinent literature.

3.2 Determination of Project Completion Time

In the implementation of time-based I/D projects, the determination of contract time may be the most affecting factor that strongly influences the effectiveness of I/D. FHWA defines contract time for time-based I/D projects as "the time (completion date in a calendar-day basis) established for the contractor to complete critical work ahead of schedule on identified projects. This time is effective immediately when traffic is impacted by the project and normally ends when unrestricted traffic is permitted on the identified projects" (FHWA 1989).

In the time-based I/D contracting method, the contracting agency determines how long it will take to complete the project. Estimation of contract completion time by the agency is presented as part of the bid documents. In determining contract time, a CPM analysis or a manual calculation is typically used as the basis for the average production performance of the contractor. Some researchers believe that an experienced competitive contractor can reduce construction time and receive an incentive bonus without an additional commitment of resources especially because of the previously noted tendency of agencies to overestimate contract time (Herbsman and Ellis 1995; Choi and Kwak 2012). Moreover, the related literature points out that systematic approaches to determining contract completion times have rarely been found in current industry practice.

3.3 Determination of Road User Cost

Although STAs have mostly determined I/D rates by their impacts on RUC, as measured as savings or delays (FDOT 2000; Choi et al. 2011; Pyeon and Lee 2012), there has not been a formally established standard calculation procedure. RUC considers the concept of opportunity cost, defined as time lost by motorists to traffic delays that could have been spent in recreation or work. It plays a pivotal role in work zone impacts assessment—used to identify impacts on service levels, determine lane-closure strategies, and identify I/D rates. In the A+B contracting method, the daily RUC serves to help the contractor determine the monetary value of time (B) when making a bid. In the I/D contracting method, daily RUC is used as the basis for determining an appropriate I/D amount.

The RUC is comprised of the following three elements: (1) the travel time change due to delays during construction, (2) the average number of passengers per vehicle, and (3) the hourly cost per passenger (Shr and Chen 2004). Externalities such as air-quality cost and vehicle noise factors have rarely been reflected in the calculation of RUC (Gillespie 1998). The bottom line for determining daily I/D rates is that the rates must reflect an overriding time-saving benefit for the traveling public (Herbsman et al. 1995; Plummer et al. 1992; Sun et al. 2013). In other words, to be effective, the I/D amount should be greater than the increases in the contractor's additional costs and smaller than total RUC (Rister and Wang 2004). Even if there is a high RUC, most states have refused to use an amount equal to RUC as an incentive because of budget limitations. Therefore, how effectively the initial RUC can be discounted is important for the effective use of the time-based I/D contracting method.

The most widely used state-of-practice software for calculating RUC is the *Highway Capacity Software* (*HCS*). This is based on the Highway Capacity Manual (HCM) and *MicroBENCOST* (Gillespie 1998). *QUEWZ*, *QuickZone*, and *HCS* are being widely used for the calculation of queue length and work zone delays (Benekohal et al. 2003). *MicroBENCOST* emerged as an alternative to *QUEWZ*, which has been used since the early 1980s. *MicroBENCOST* was based on the 1985 HCM and the 1977 AASHTO "Red Book," with special emphasis on the calculation of vehicle operating cost (TTI 1993). Developed in 1995, *HCS* is a computer version of the HCM for calculating RUC (University of Florida 1995). The FHWA recently developed the Microsoft Excel spreadsheet-based *QuickZone* as an estimating tool for work zone delays (FHWA 2005). *QuickZone* was developed to evaluate traveler delays due to construction. It provides a complete and realistic view of total construction costs based on the estimation and quantification of work-zone delays and the resulting user costs (FHWA 2005).

3.4 Determination of Daily I/D Amount

Methods for determining the daily I/D amounts have evolved over the years and they vary from one state to another. Even though I/D amounts are determined by RUCs in some innovative states, the majority of STAs still use a percentage of the total project cost to determine them (Benekohal et al. 2003). The same value is typically used for both the daily incentive and disincentive with some exceptions (Plummer et al. 1992; Jaraiedi et al. 1995; Benekohal et al. 2003).

The work of Plummer et al. shows a conventional way to manually determine the initial I/D amounts (Plummer et al. 1992). According to the study, 5 percent of total project cost is first determined to serve as the maximum incentive amount. (FHWA also recommends a cap of 5 percent of the total project cost be used as the maximum incentive [Ibarra et al. 2002].) To calculate the (maximum possible) daily I/D amount, the initial maximum incentive amount is divided by the number of days that are saved by using the I/D fast-track schedule. After the determination of the daily I/D amount, the maximum number of days for the incentive payment should be determined by the difference in the number of days required to complete the project using an accelerated schedule versus an I/D schedule (Jaraiedi et al. 1995). The maximum number of days is limited to 30 percent of the engineer's time estimate for that phase (NYSDOT

1999). The maximum incentive amount is then capped by multiplying the daily incentive dollar amount. In general, the maximum incentive amount is limited to 5 percent of the total construction cost (Herbsman et al. 1995; Arditi et al. 1997; Shr and Chen 2004). The critical problem in this conventional way of manually determining I/D amounts is that it does not reflect time savings to road users, an accurate construction schedule and production rate, and the specific needs for early completion due to the heavy traffic volumes through the CWZ.

The daily I/D amount has increased over time from a range of $1,000 to $5,000 and $2,500 to $5,000 (Herbsman et al. 1995) to a range of $5,000 to $20,000 (Yakowenko 2000; Sun et al. 2013). The daily I/D amount is usually higher in urban areas than in rural areas due to higher urban RUCs (Benekohal et al. 2003). In most states, where the time-based I/D provisions have been implemented, the initial daily I/D amount is adjusted downward to provide a favorable benefit-cost ratio for the contractors and the traveling public.

3.5 Pros and Cons of I/D Contracting

Generally, time-based I/D provisions increase costs for both agencies and contractors, but agencies benefit by the time saved by road users and the contractors benefit from incentive bonuses. The research experience of Herbsman and Ellis indicates that 99 percent of the contractors in 35 states who contracted with I/D provisions on highway infrastructure projects received an incentive bonus (Herbsman et al. 1995; Herbsman and Ellis 1995), which supports the assertion that overestimation of contract completion time is prevalent.

Following is a list of pros and cons of the I/D contracting method compared with the conventional contracting method:

1. Pros

- I/D contracting reduces construction time significantly (Christiansen, 1987; Jaraiedi et al., 1995; Choi et al. 2012). For example, 100 percent of I/D projects in Missouri in 2011 were completed on time or sooner, significantly higher on-time completion rate that non-I/D projects (Sun et al. 2013).
- I/D contracting minimizes inconvenience to the traveling public and affected enterprises (Lee and Choi 2006).
- I/D contracting improves construction labor productivity by 25 to 30 percent and shortens schedules by 15 to 25 percent (Ibbs and Abu-Hijleh 1989).
- I/D contracting lowers agency risks by transferring them to the contractor (disincentive clause) (Arditi and Yasamis 1998).
- I/D contracting provides a better definition of project objectives and a better definition of project design (Ibbs and Abu-Hijleh 1989).
- I/D contracting improves safety performance (Ashley and Workman 1985).
- I/D contracting results in higher project bids because contractors expect to receive incentive bonuses (Arditi et al. 1997; Sun et al. 2013), an advantage for agencies trying to reduce costs to the public.

2. <u>Cons</u>

- Increased cost to the contracting agency, if not effectively implemented (Jaraiedi et al. 1995; Sun et al. 2013).
- Higher frequency and magnitude of change orders (Arditi et al. 1997).
- Higher probability of budget overflows (Arditi et al. 1997).
- More vulnerable to legal disputes between agency and contractor (Ashley and Workman 1985; Arditi et al. 1997; Gillespie 1998; Ibarra et al. 2002).
- Difficulty in administration (Ashley and Workman 1985).
- Greater effort required in project coordination and administration (Christiansen 1987).

3.6 Case Studies

3.6.1 California

California Department of Transportation (Caltrans) is one of the leading STAs when it comes to I/D provisions. Prior to 1994, Caltrans used the I/D provisions in the Ventura Improvement Project, where the goal was to reconstruct and rehabilitate three heavily trafficked portions of the existing freeway (US 101). The project also included three bridge reconstructions. The general contractor for each portion was eligible to receive an incentive bonus of $6,000 per day if the work was completed in 120 days or less, and was subject to a disincentive to pay the same amount if the work took longer than 120 days (Gillespie 1998).

To expedite the rebuilding of the portions of the Los Angeles highway system damaged by the Northridge earthquake in 1994, Caltrans used record-breaking incentive payments for the earliest possible completion of construction. For example, in the rehabilitation of I-10 in Los Angeles, the contractor completed the project 66 days ahead of schedule and received an incentive bonus of $200,000 per day (Gillespie 1998).

In 1998, Caltrans, which oversees a 78,000 lane-km state highway system, began implementing its Long-life Pavement Rehabilitation Strategies (LLPRS) program to rebuild approximately 2,800 lane-km of deteriorated high-volume urban freeways with pavements designed to last more than 30 years with minimal maintenance (Caltrans 1998). In general, the LLPRS projects are constructed as fast-track projects with the implementation of time-related I/D provisions in the belief that the extra expense of incentive fees will be paid off in the time savings of road users traveling through CWZs. The fast-track concepts of the time-based I/D provisions have been validated and successfully implemented in the following three experimental time-critical LLPRS projects.

3.6.1.1 I/D Pilot Project: I-10 Concrete Rehabilitation in Pomona

Various I/D provisions were used in the rehabilitation of I-10 Pomona pilot-project, where 2.8 lane-km of deteriorated truck-lane was rebuilt during one 55-hour weekend closure with around-the-clock operations. In this project, an incentive payment was to be made to the contractor in the amount of $600 per lane-meter for each lane-meter replaced in excess of 2,000 lane-meters during the weekend closure. A disincentive would be assessed in the amount of $250 per lane-meter for each lane meter less than 2,000 lane-meters. The incentives were capped at $500,000. The contractor was awarded a $500,000 incentive payment for completing more than 2.0 lane-km of the contractual threshold (Lee et al. 2008).

3.6.1.2 I/D Demonstration Project: I-710 Asphalt Rehabilitation in Long Beach

Caltrans included time-based I/D provisions in the I-710 project contract to achieve faster delivery of construction with less traffic disruption during lane closures. Deteriorating PCC pavement was replaced with a long-life asphalt concrete pavement in eight 55-hour weekend closures. The I/D provisions specified that the contractor was eligible to receive an incentive bonus of $100,000 per weekend closure if the project was completed earlier than Caltrans' initial plan of 10 weekend closures. Conversely, the contractor was subject to a disincentive in the same amount. An incentive cap of $500,000 was the specified maximum incentive amount; there was no specified upper limit on the disincentive amount. Motivated by the I/D clauses, the contractor committed additional resources, completed the project two weekends early, and received a $200,000 incentive bonus (Lee et al. 2008).

3.6.1.3 I/D Implementation Project: I-15 Fast-Track Concrete Rehabilitation in Devore

Detailed I/D provisions were applied on the I-15 Devore urban highway reconstruction project in October 2004, as the first large-scale I/D implementation project. Motivated by the I/D provision, the contractor completed a 4.5-km stretch of badly damaged concrete truck lanes in only two 215-hour (about 9 days) one-roadbed continuous closures, with 24/7 construction operations (Lee and Choi 2006). Due to high traffic volume during closures and the public desire for early completion, three levels of time-based incentive provisions were specified in the contract to ensure the earliest possible completion of closures: (1) I/D clauses in a closure and daily basis, (2) late opening disincentives for the segment with the three-lane section, and (3) cost plus time (A+B) contracting for the entire project. Two types of I/D provisions were specified for the extended closures: primary incentives for the total number closures and secondary incentives for the total closure days (Choi et al. 2009).

The contractor was eligible for a closure incentive bonus of $300,000 if a one-roadbed continuous closure was completed in a time period equal to or less than two units of a specified time segment (111 hours per unit), and was subject to a closure disincentive without a limit if the closure took longer than three units of this time segment (an extra time segment was given for flexibility). In addition to this closure incentive requirement, the contractor was eligible to receive a daily incentive (secondary) bonus of $75,000 if the reconstruction was completed in fewer than 19 days (a total of 456 hours), and was subject to a daily disincentive penalty without a limit. A late lane-opening penalty of $5,900 per 15-minute period without limitation was to be charged if the closure was not completely opened to traffic by 5 a.m. Friday to accommodate the highest weekday commuter and weekend leisure traffic volumes headed to Las Vegas. The final incentive amount was adjusted downward because of state budget limitations, and $600,000 was used as the incentive cap (Lee et al. 2008).

3.6.2 Florida

The Florida Department of Transportation (FDOT) realized that overestimation of contract completion times had prevailed in industry practice because engineers' experiences and average contractor performance rates had been widely used in determining the duration of projects. In response, FDOT reduced contract times by 20 percent without experiencing any major delays in project completion dates (Herbsman et al. 1995).

In 1996, the Florida Legislature authorized the department to use alternative contracting techniques with the goals of controlling time and cost increases on construction projects. Accordingly, since 1996, the FDOT has maintained the Alternative and Innovative Contracting Program to promote the use of innovative contracting methods of highway construction to minimize the inconvenience to the traveling public, adjacent businesses, and communities (FDOT 2000). Based on a report issued by the Office of Inspector General in FDOT, a total of 61 I/D contracting projects were completed from the years 1996 to 2000, and approximately $7.3 million were paid as incentive bonuses for early project completion (FDOT 2000).

3.6.3 Michigan

The Michigan Department of Transportation (MDOT) often uses time-based I/D provisions in association with an A+B (cost-plus-time) bidding procedure (Gillespie 1998) because the contract completion time estimated by the winning bidder would be more realistic than the contract time estimated by the contracting agency (Arditi and Yasamis 1998). To be considered for an I/D clause, the following conditions are taken into account: (1) substantial road user cost savings are expected; (2) total additional user costs are expected to be at least 5 percent of the project cost, with a daily incentive of $5,000 for major projects; and (3) by implementing an I/D provision the duration of lane closure can be shortened by at least 15 days (Gillespie 1998).

3.6.4 Other States

In Illinois from 1989–1993, all 28 highway construction projects that used time-based I/D provisions were completed ahead of schedule. About 79 percent of the contractors for these 28 projects received the maximum incentive payment. The average incentive amount paid per project was 4.71 percent of the contract amount (Arditi et al. 1997).

In Kentucky from 1999 to 2002, approximately 32 highway construction projects were implemented with time-based I/D provisions. For these 32 highway projects, about $10.8 million was paid out in incentive bonuses and $21,500 was collected as disincentives (Rister and Wang 2004).

According to a survey conducted by Iowa Department of Transportation, 35 states responded that they had adopted I/D provisions for their highway rehabilitation/reconstruction projects. Of these 35 states, 32 said that contractors had received an incentive payment and 22 states responded they had paid the maximum incentive amount (Plummer et al. 1992).

In Ohio from 2004 to 2007, 95 I/D projects were completed with average costs of $6.1 million—and I/D contracts had shown to be effective in satisfying the public’s expectation for early project completion (Caruso 2010). In 2010, Ohio Department of Transportation paid out incentives of more than $2.8 million on completed projects, including $792,666 for a bridge project on I-280 in Lucas County and $700,000 for a roadway widening project on Rt. 22 in Hamilton County (Caruso 2010).

4 STAGE 1: BASELINE SCHEDULE ESTIMATE

4.1 Overall Decision-Support Framework

This study helps STA engineers and decision makers to establish the most appropriate budgets and schedules by understanding the I/D consequences that are analyzed through the estimations of CAC and total savings. The proposed work would assist STAs with the implementation of the integrated I/D decision-support framework that not only captures total savings to road users and to the agency but also accounts for contractor's additional commitments. Critically, it will significantly reduce the agency's expenses in the time and effort required for determining I/D rates. To achieve these goals, a seven-stage decision-support framework was created, tested, and validated, as depicted by the IDEF0 function modeling technique in Figure 6 and Figure 7.

- **Stage 1** serves as the baseline of I/D: This stage estimates baseline schedules for quantifying the probable number of days that can be saved by using an incentive schedule.
- **Stage 2** serves as the initial lower bound of I/D: This stage quantifies the level of CAC of acceleration by developing predictive models.
- **Stage 3** serves as the initial upper bound of I/D: This stage computes total savings by accounting for the monetary value of the time saved by road users (i.e., RUC).
- **Stage 4** serves as the initial upper bound of I/D: This stage computes total savings by accounting for the monetary value of the time to the contracting agency by completing the project ahead of schedule achieved by I/D provisions.
- **Stage 5** serves as the final lower bound of I/D: This stage adjusts the initial CAC based on the concept of LOS in order to arrive at more realistic I/D rates by applying appropriate discount factors.
- **Stage 6** serves as the final upper bound of I/D: This stage adjusts the total savings derived through stages 3 to 4 based on the concept of NPV in order to arrive at more realistic I/D rates by applying appropriate discount factors.
- **Stage 7** determines an optimal I/D between the final lower and upper bounds: This stage results in the estimates of three types of incentives such as closure I/Ds, daily I/Ds, and I/D cap rates.

Over the years, computer tools for determining daily I/D amounts and maximum incentive amounts have advanced, but these tools still have crucial limitations insofar as they cannot concurrently account for project-specific peculiarities, CAC, and total savings in RUC and agency cost. In addition, a reasonable adjustment algorithm of those defining parameters is currently lacking. All the tools currently available have the following critical limitations:

- None of the tools provide reliable estimates of the number of days that can be saved by using an incentive schedule, even though this quantity is crucial for determining the daily I/D amount and the maximum incentive amount. In general, the time-saved estimate is manually input by an agency engineer who bases it on judgment and personal experience rather than on a validated method.
- None of tools and methods provide an integrated systematic approach to concurrently quantifying what it is worth to the traveling public and what it takes to the contractor.

- None of tools consider an adjustment mechanism to determine an optimal I/D value between discounted CACs of acceleration and total savings, i.e., how effectively the initial estimates can be adjusted downward to the final daily I/D amount is not taken into consideration.

Recognizing the above-mentioned limitations, the proposed framework intends to fully address those limitations by employing an integrated analysis of (1) construction schedule, (2) contractor's additional cost commitment, (3) total time value savings, and discounting algorithm. In doing so, STAs can determine the most realistic, economical I/D dollar amounts that fall within an agency's budget and are still sufficient to motivate a contractor to complete the project ahead of schedule. This will also help the contracting agencies make better-informed decisions when implementing I/D provisions while facilitating agencies' creation of more realistic incentive budgets, which will result in more favorable cost-benefit ratios and better use of public funds.

The primary applications of the model proposed in this study are limited to urban highway pavement maintenance and renewal projects, which represent, according to the data analysis, 51 percent of all project establishments over the past eight years in California (Choi et al. 2012).

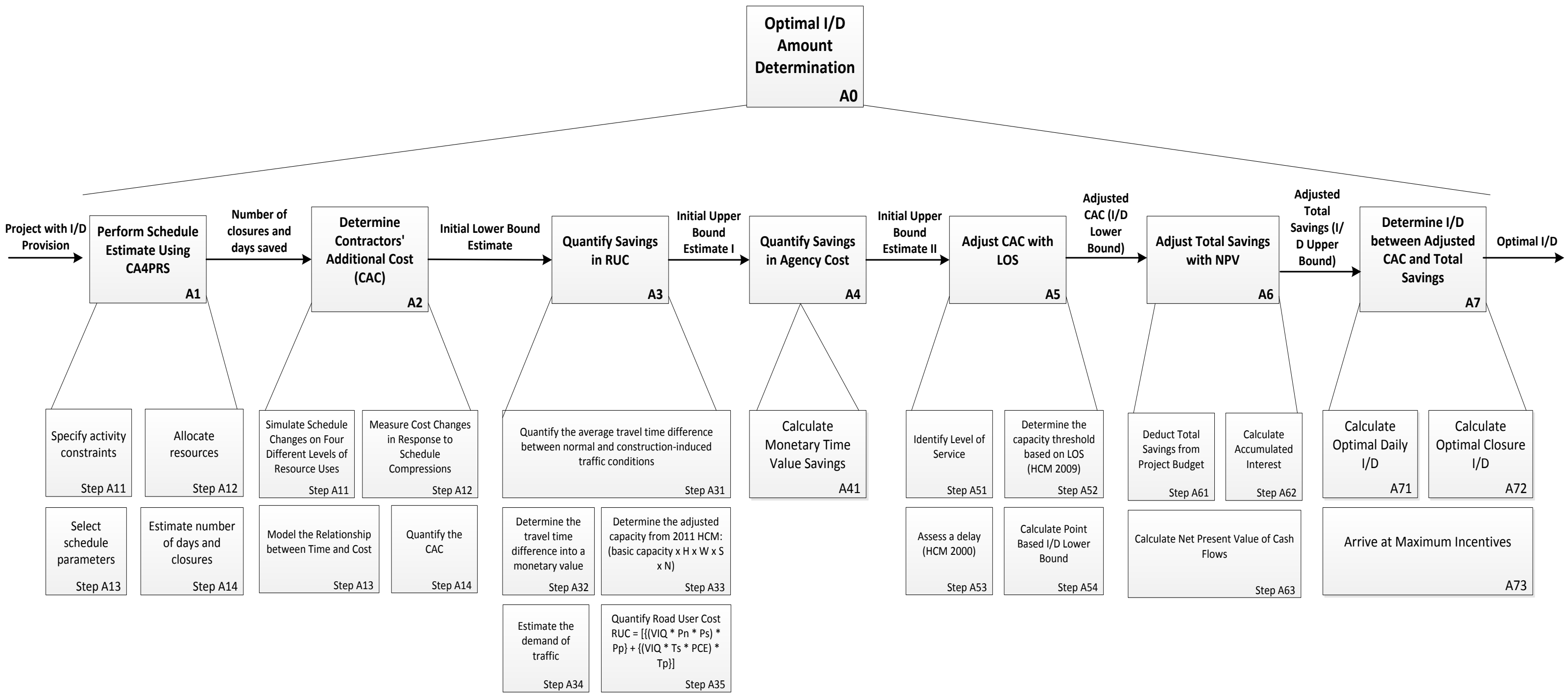


Figure 6. Overall Framework to Arrive at Optimal I/D Rates.

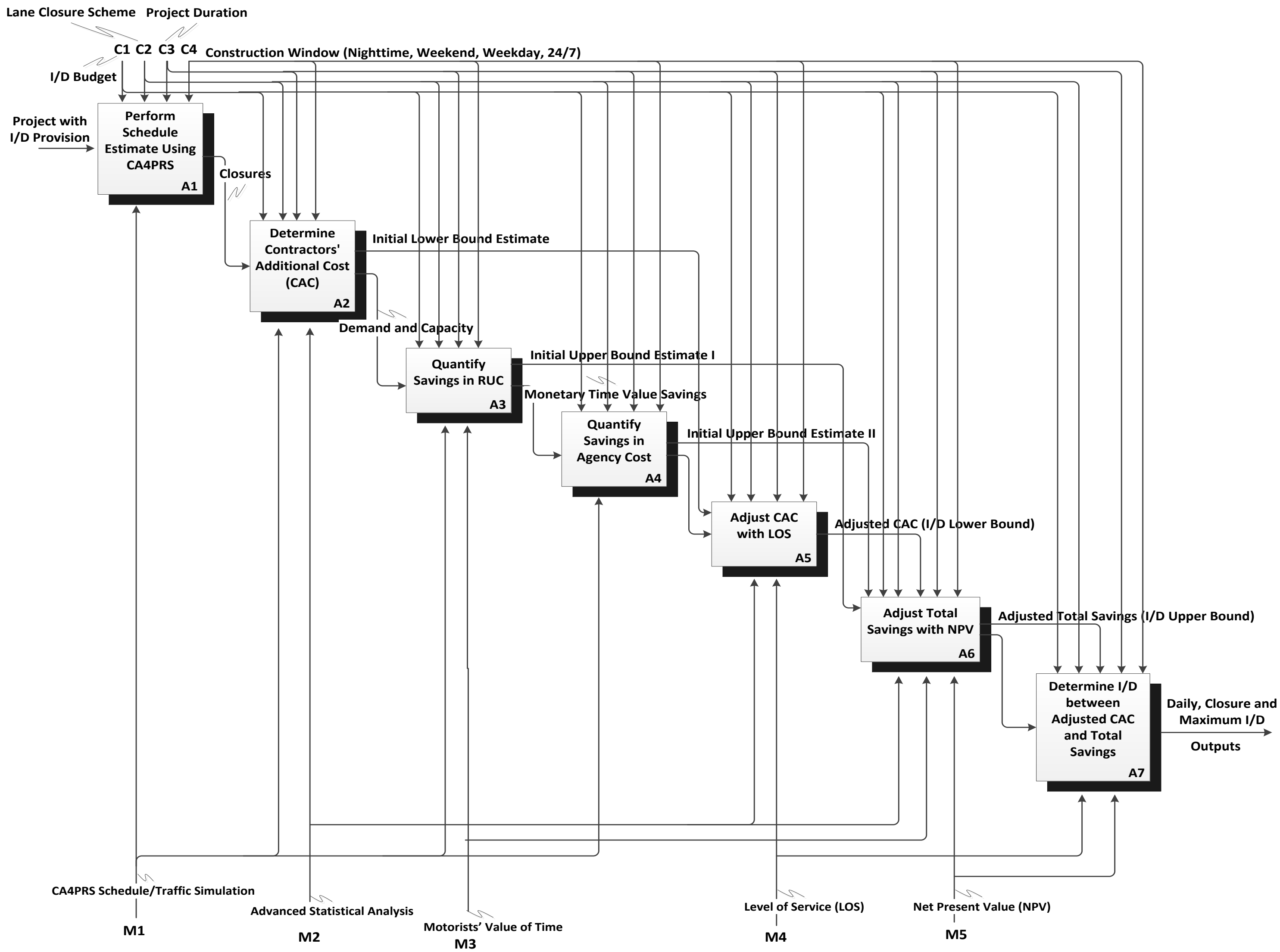


Figure 7. Seven-Stage Optimal I/D Determination Procedure.

4.2 Stage 1: Baseline Schedule Estimate

As noted earlier, use of the CA4PRS deterministic schedule simulations is the basis for proceeding to the next levels of analysis. This stage quantifies the number of closures and working days by which the project can be shortened with use of an incentive-based accelerated schedule—with an expectation that the accelerated project will use 15 to 20 percent more resources than a conventional schedule.

Many researchers have reported that competitive highway construction contractors possess adequate resources (e.g., extra labor and equipment) to meet incentive-based schedules (Herbsman et al. 1995; Lee et al. 2008). Further, because schedules are usually overestimated by the contracting agencies in current practice, it is believed that contractors easily perform expedited work and received an incentive bonus without additional effort. For these reasons, it is essential to accurately estimate project duration in order to arrive at the most realistic I/D amount.

It has been reported that CA4PRS provides accurate schedule estimates of highway renewal projects (Lee and Ibbs 2005); therefore the program was used to develop a database of schedule estimate lookup tables by considering five critical factors that significantly affect project schedule (Figure 8):

- Rehabilitation strategy: concrete, asphalt, and milling.
- Project scope: lane-miles to be rebuilt.
- Pavement design: cross-section design.
- Construction window: nighttime versus weekend closures.
- Resource constraints.

This stage of baseline schedule estimates incorporates the database to produce reliable schedule estimates—including the number of closures and working days that can be saved—by comparing the effort required to use a conventional schedule strategy and an incentive schedule strategy. The estimated difference between the number of closures necessary to complete a project by using a conventional schedule and an incentive schedule determines the maximum probable number of closures and working days that can be saved by using an incentive schedule. This schedule estimate is essential in that the daily I/D and maximum incentive amounts are determined as a function of the time the project can save. This new approach using state-of-the-art CA4PRS software should reduce the number of contractors who receive incentives without committing additional effort.

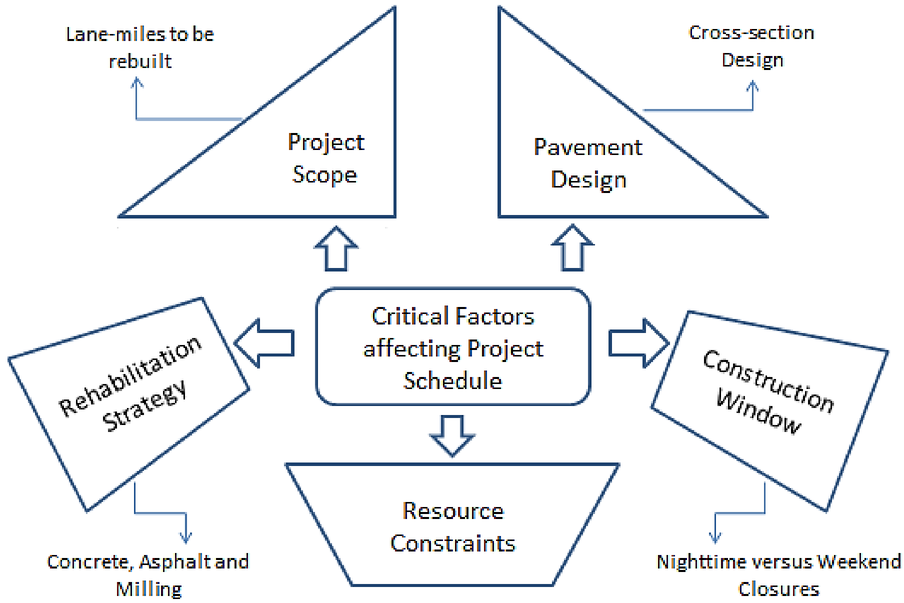


Figure 8. Factors Affecting Project Schedule.

The computational procedure of this module is shown in Figure 9, which describes how the module arrives at the maximum probable number of working days that can be saved. Figure 9 describes how CA4PRS estimates two different contracting strategies, first estimating the number of closures required for completing a given project with the specified scope (lane-miles). The conventional schedule was estimated on the basis of competitive contractors’ average resource usage levels, average resource capacity, and average labor productivity. The incentive schedule reflects an accelerated construction schedule that commits additional resources, namely, 15 percent more for a strategy that uses concrete and 20 percent more for strategies that use asphalt concrete and milling. Labor productivity for the incentive and conventional schedules were assumed to be equivalent. Second, the estimated number of closures on the 55-hour weekend window was converted into working days because current STAs’ practice calls for use of working days rather than calendar days when determining I/D project completion times. The number of weekend closures was multiplied by 2.29 for the conversion to working days. Last, the maximum probable number of days that can be saved was then calculated using the difference in the number of days required to complete the project with a conventional schedule and with an I/D schedule (Tables 1−5).

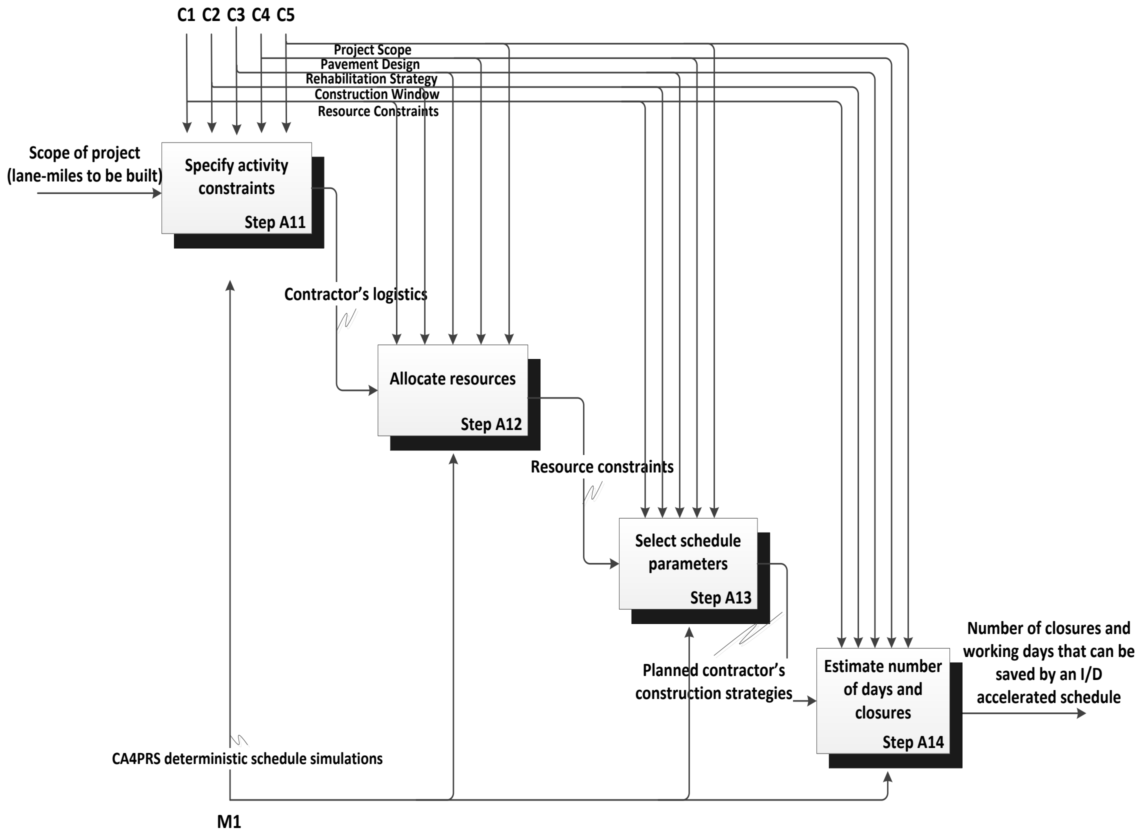


Figure 9. IDEF0 Flowchart for Estimate Baseline Schedules Using CA4PRS.

Table 1. Schedule Estimate of Concrete Rehabilitation Strategies for Nighttime Construction.

Scope (lane-mi)	Ordinary Schedule 8-Hrs Window		Incentive Schedule 8-Hrs Window		Number of Closures Saved	
	8"	12" with 6" base	8"	12" with 6" base	8"	12" with 6" base
	A	**B**	**C**	**D**	**E**	**F**
1	19	28	17	24	2	4
2	38	56	33	49	5	7
3	57	83	50	73	7	10
4	76	111	66	97	10	14
5	94	139	82	121	12	18
6	113	166	99	145	14	21
7	132	194	115	169	17	25
8	151	222	131	193	20	29
9	170	249	148	217	22	32
10	188	277	164	241	24	36
11	207	305	180	265	27	40
12	226	332	197	289	29	43
13	245	360	213	313	32	47
14	264	388	229	337	35	51
15	282	415	246	361	36	54
16	301	443	262	385	39	58
17	320	470	278	409	42	61
18	339	498	295	433	44	65
19	358	526	311	457	47	69
20	376	553	327	481	49	72

1. Column (E) = Column (A) – Column (C)
2. Column (F) = Column (B) – Column (D)

Table 2. CA4PRS Schedule Estimate with 55-Hour Weekend Construction.

Scope (lane-mile)	Ordinary Schedule 55-Hrs Window				Incentive Schedule 55-Hrs Window				Number of Closures and Days Saved			
	8"		12" with 6" base		8"		12" with 6" base		8"		12" with 6" base	
	Closures	Days	Closures	Days	Closures	Days	Closures	Days	Closures	Days	Closures	Days
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
1	0.8	2	1.6	4	0.7	2	1.4	3	0.1	0	0.2	1
2	1.5	3	3.1	7	1.3	3	2.7	6	0.2	0	0.4	1
3	2.3	5	4.7	11	2	5	4.1	9	0.3	0	0.6	2
4	3	7	6.3	14	2.6	6	5.4	12	0.4	1	0.9	2
5	3.8	9	7.8	18	3.3	8	6.8	16	0.5	1	1	2
6	4.6	11	9.4	22	4	9	8.2	19	0.6	2	1.2	3
7	5.3	12	10.9	25	4.6	11	9.5	22	0.7	1	1.4	3
8	6.1	14	12.5	29	5.3	12	10.9	25	0.8	2	1.6	4
9	6.8	16	14.1	32	5.9	14	12.2	28	0.9	2	1.9	4
10	7.6	17	15.6	36	6.6	15	13.6	31	1	2	2	5
11	8.4	19	17.2	39	7.3	17	15	34	1.1	2	2.2	5
12	9.1	21	18.8	43	7.9	18	16.3	37	1.2	3	2.5	6
13	9.9	23	20.3	47	8.6	20	17.7	41	1.3	3	2.6	6
14	10.6	24	21.9	50	9.2	21	19	44	1.4	3	2.9	6
15	11.4	26	23.4	54	9.9	23	20.4	47	1.5	3	3	7
16	12.2	28	25	57	10.6	24	21.7	50	1.6	4	3.3	7
17	12.9	30	26.6	61	11.2	26	23.1	53	1.7	4	3.5	8
18	13.7	31	28.1	64	11.9	27	24.5	56	1.8	4	3.6	8
19	14.4	33	29.7	68	12.6	29	25.8	59	1.8	4	3.9	9
20	15.2	35	31.3	72	13.2	30	27.2	62	2	5	4.1	10

1. Column (I) = Column (A) – Column (E)
2. Column (J) = Column (B) – Column (F)
3. Column (K) = Column (C)– Column (G)
4. Column (L) = Column (D)– Column (H)

Table 3. Schedule Estimate of Concrete Rehabilitation Strategies for 72-Hour Weekday Construction.

Scope (lane-mile)	**Ordinary Schedule 55-Hrs Window**				**Incentive Schedule 55-Hrs Window**				**Number of Closures and Days Saved**			
	8"		12" with 6" base		8"		12" with 6" base		8"		12" with 6" base	
	Closures	Days	Closures	Days	Closures	Days	Closures	Days	Closures	Days	Closures	Days
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
1	0.3	1	0.7	2	0.3	1	0.6	2	0	0	0.1	0
2	0.7	2	1.4	4	0.7	2	1.2	4	0	0	0.2	0
3	1	3	2.2	7	1	3	1.8	5	0	0	0.4	2
4	1.3	4	2.9	9	1.3	4	2.4	7	0	0	0.5	2
5	1.6	5	3.6	11	1.6	5	3	9	0	0	0.6	2
6	2	6	4.3	13	2	6	3.6	11	0	0	0.7	2
7	2.3	7	5.1	15	2.3	7	4.2	13	0	0	0.9	2
8	2.6	8	5.8	17	2.6	8	4.8	14	0	0	1	3
9	3	9	6.5	20	2.9	9	5.4	16	0.1	0	1.1	4
10	3.3	10	7.2	22	3.3	10	6	18	0	0	1.2	4
11	3.6	11	7.9	24	3.6	11	6.6	20	0	0	1.3	4
12	3.9	12	8.7	26	3.9	12	7.2	22	0	0	1.5	4
13	4.3	13	9.4	28	4.3	13	7.8	23	0	0	1.6	5
14	4.6	14	10.1	30	4.6	14	8.4	25	0	0	1.7	5
15	4.9	15	10.8	32	4.9	15	9	27	0	0	1.8	5
16	5.3	16	11.5	35	5.2	16	9.6	29	0.1	0	1.9	6
17	5.6	17	12.2	37	5.6	17	10.2	31	0	0	2	6
18	5.9	18	13	39	5.9	18	10.8	32	0	0	2.2	7
19	6.2	19	13.7	41	6.2	19	11.4	34	0	0	2.3	7
20	6.6	20	14.4	43	6.5	20	12	36	0.1	0	2.4	7

1. Column (I) = Column (A) – Column (E)
2. Column (J) = Column (B) – Column (F)
3. Column (K) = Column (C)– Column (G)
4. Column (L) = Column (D)– Column (H)

Table 4. Schedule Estimate of Asphalt Concrete Rehabilitation Strategy: Nighttime versus Weekend.

Scope (lane-mile)	Ordinary Schedule				Incentive Schedule				Number of Closures and Days Saved			
	Nighttime		55-hours		Nighttime		55-hours		Nighttime		55-hours	
	Closures	Days	Closures	Days	Closures	Days	Closures	Days	Closures	Days	Closures	Days
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
5	71	71	1.5	3	60	60	1.3	3	11	11	0.2	0
10	142	142	3.1	7	119	119	2.6	6	23	23	0.5	1
15	213	213	4.6	11	178	178	3.8	9	35	35	0.8	2
20	284	284	6.1	14	237	237	5.1	12	47	47	1	2
25	355	355	7.7	18	296	296	6.4	15	59	59	1.3	3
30	426	426	9.2	21	355	355	7.7	18	71	71	1.5	3
35	497	497	10.7	25	415	415	8.9	20	82	82	1.8	5
40	568	568	12.3	28	473	473	10.2	23	95	95	2.1	5
45	639	639	13.8	32	533	533	11.5	26	106	106	2.3	6
50	710	710	15.3	35	592	592	12.8	29	118	118	2.5	6
55	781	781	16.8	39	651	651	14	32	130	130	2.8	7
60	852	852	18.4	42	710	710	15.3	35	142	142	3.1	7
65	923	923	19.9	46	770	770	16.6	38	153	153	3.3	8
70	994	994	21.4	49	829	829	17.9	41	165	165	3.5	8
75	1065	1065	24.5	56	888	888	19.1	44	177	177	5.4	12
80	1136	1136	25	57	947	947	20.4	47	189	189	4.6	10

1. Column (I) = Column (A) – Column (E)
2. Column (J) = Column (B) – Column (F)
3. Column (K) = Column (C)– Column (G)
4. Column (L) = Column (D)– Column (H)

Table 5. Schedule Estimate of Milling and Asphalt Concrete Overlay Rehabilitation Strategy: Nighttime versus Weekend.

Scope (lane-mile)	Ordinary Schedule				Incentive Schedule				Number of Closures and Days Saved			
	Nighttime		55-hours		Nighttime		55-hours		Nighttime		55-hours	
	Closures	Days	Closures	Days	Closures	Days	Closures	Days	Closures	Days	Closures	Days
	A	**B**	**C**	**D**	**E**	**F**	**G**	**H**	**I**	**J**	**K**	**L**
5	18	18	2.3	5	16	16	2.1	5	2	2	0.2	0
10	35	35	5	11	32	32	4.2	10	3	3	0.8	1
15	52	52	6.9	16	48	48	6.3	14	4	4	0.6	2
20	70	70	9.2	21	64	64	8.4	19	6	6	0.8	2
25	87	87	11.5	26	80	80	10.4	24	7	7	1.1	2
30	104	104	13.8	32	96	96	12.5	29	8	8	1.3	3
35	121	121	16.1	37	110	110	14.6	33	11	11	1.5	4
40	139	139	18.4	42	127	127	16.7	38	12	12	1.7	4
45	156	156	20.7	47	143	143	18.8	43	13	13	1.9	4
50	173	173	22.9	52	159	159	20.9	48	14	14	2	4
55	190	190	25.2	58	175	175	23	53	15	15	2.2	5
60	208	208	27.5	63	191	191	25.1	58	17	17	2.4	5
65	225	225	29.8	68	207	207	27.1	62	18	18	2.7	6
70	242	242	32.1	74	222	222	29.2	67	20	20	2.9	7
75	260	260	34.4	79	238	238	31.3	72	22	22	3.1	7
80	277	277	36.7	84	254	254	33.4	77	23	23	3.3	7

1. Column (I) = Column (A) – Column (E)
2. Column (J) = Column (B) – Column (F)
3. Column (K) = Column (C)– Column (G)
4. Column (L) = Column (D)– Column (H)

5 STAGE 2: QUANTIFICATION OF CONTRACTORS' ADDITIONAL COST OF ACCELERATION

5.1 Systematic CAC Quantification Procedures

A contracting agency that wants to use the I/D contracting method must first determine the monetary value of the time saved when a project is delivered early, and most STAs have well-developed methods for estimating the time value. However, the lack of available data makes it extremely difficult to estimate CAC growth in exchange for shortened construction times. This is due to contractors' reluctance to disclose data that contain information about their profits, and as well as the extreme difficulty contracting agencies have in tracking information about individual CAC growth.

To tackle this issue, this study proposes a new approach for quantifying the reasonable level of CAC of acceleration, which can effectively motivate contractors to pursue accelerated construction. For this purpose, this study combines an existing schedule simulation with a regression method to develop predictive models for each of four typical pavement rehabilitation strategies (i.e., JPCP, CRCP, HMA, MACO), each of which is also referenced to typical cross-section designs to make the models applicable to a variety of highway rehabilitation projects.

The main idea of this stage is to capture the relationship between shortened construction time and contractor's additional cost growth for acceleration by modeling "time-cost tradeoff" effects on four different levels of resource use, namely, 5 percent increase, 15 percent increase, and 25 percent increase in the number of resources per hour per team. CA4PRS was selected for the simulation because its schedule simulation is based on contractors' actual production performance data, and its simulation results have been tested and validated on numerous highway rehabilitation projects throughout California and other four states (Lee et al. 2008).

Figure 10 shows the main analytical procedures to arrive at the CAC quantifying models that represent each of the four typical rehabilitation strategies. To generate schedule data for this research project, a number of stochastic schedule simulations with CA4PRS were performed based on contractors' actual construction plans sourced from four real-world construction projects. These projects represent the typical characteristics and conditions of each pavement rehabilitation strategy while providing detailed, reliable construction plans including pavement design, lane-closure tactics, resource logistics, etc. Changes in cost in response to schedule compression were then calculated based on a cost manual published and updated annually by Caltrans. A set of contractors' time-cost tradeoff data were created on the four different resource usage levels by calculating changes in cost in response to schedule compression. Finally, the relationship between time and cost was plotted to identify an appropriate initial regression equation and a regression analysis was then carried out to model the time-cost tradeoff relationship. The robustness of the proposed model was validated through two case studies presented in the following chapter.

It was assumed that in a well-planned I/D contract the incentive amount would be sufficient to motivate a contractor to use additional resources to complete a project early. Following this assumption, four different resource usage levels were considered to quantify the CAC growth rates in the following procedures:

1. Identify critical factors affecting JPCP rehabilitation production performance.
2. Perform schedule estimates using a series of CA4PRS stochastic schedule simulations with four different resource usage levels (Tables 6−9).
3. Determine the unit price ($/hour) of all resources used.
4. Calculate CACs using Equation (1).
5. Quantify the interaction between CAC rates and specified schedule compression rates to generate time-cost tradeoff data (Tables 10−13).
6. Draw a scatter plot of CAC growth rates over schedule compression rates to confirm that a quadratic model fits the regression data.
7. Conduct a regression analysis to determine coefficients of Equation (2) for the quadratic regression equation selected for this study.
8. Derive a quadratic equation to reflect CAC growth as a function of the schedule compression the agency sets.
9. Develop a final quantifying equation by substituting the coefficients into the quadratic equation developed in Step 8.
10. Repeat Steps 2–9 for other rehabilitation strategies such as CRCP, HMA, and MACO.

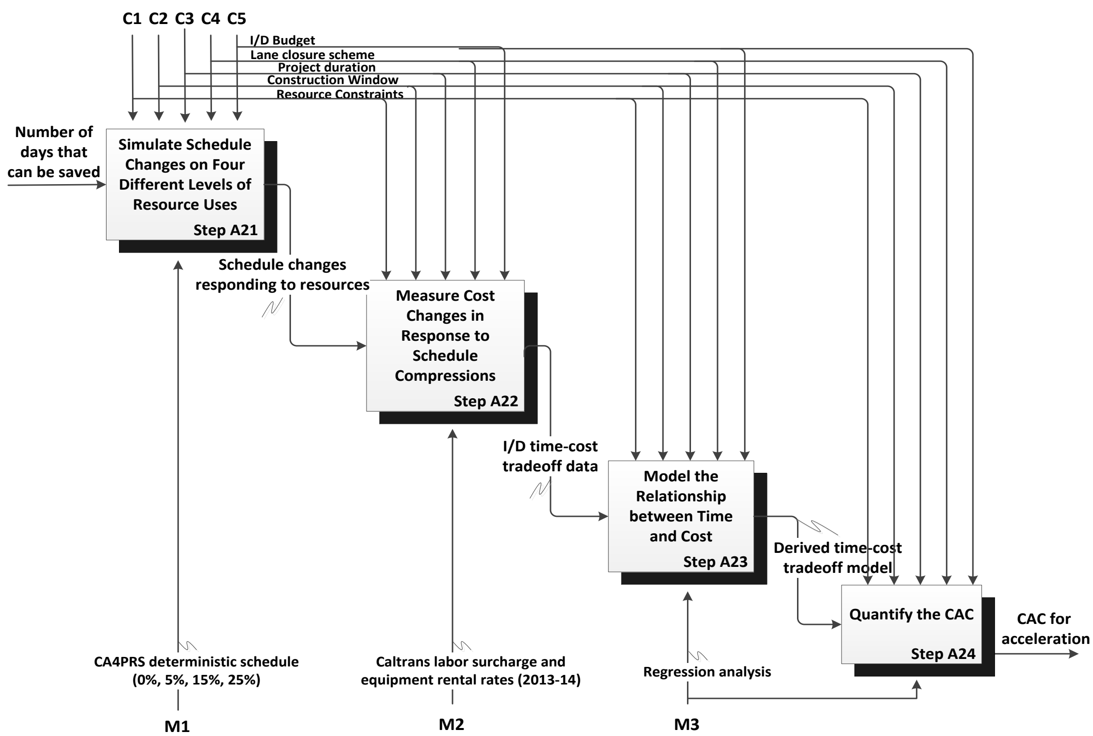


Figure 10. Stage 2: CAC Quantification for the Initial I/D Lower Bound before Adjustment.

5.2 Quantification of Contractor's Time-Cost Tradeoff Effect

5.2.1 Contractor's Schedule Compression Data within Resource Constraints

Tables 6−9 show the result of the CA4PRS stochastic schedule simulations. Because construction strategies, cross-section design, construction window, and contractor's resource constraints turned out to be the four most important factors directly affecting rehabilitation production (Lee and Ibbs 2005), they were taken into account in the schedule simulations using CA4PRS. Each strategy such as JPCP, CRCP, HMA and MACO, shown respectively through Tables 6 to 9, is based on actual I/D projects where project scope (lane-miles to be rebuilt) and project size (original contract amount) were similar.

Conventional lane closures for 7 or 10 hours during at nighttime defined as the *nighttime* in Table 6 have been implemented widely because daytime closures may cause intolerable severe traffic delays during construction. The disadvantage of nighttime closures includes slow construction processes, safety of motorists and construction crews, and higher construction costs. The 55-hour weekend closures have been implemented for projects where peak traffic volumes are significantly lower on weekends than on weekdays (Lee and Choi 2006) The extended closures with 24/7 around-the-clock operations have been applied to large-scale rehabilitation projects where time is of essence. Unlike the short-term conventional nighttime closures that limit the pavement service lives of no more than 15 years, the weekend and extended closures allow long-life pavements lasting 30+ years with minimal maintenance. However, a multi-faceted public outreach program with detailed traffic management plans should be carefully planned and implemented for those projects to minimize traffic inconvenience caused by construction work being performed during the extended weekend and 24/7 lane closures because they are likely to cause major traffic inconvenience to the traveling public and commercial enterprises that rely on these roadways.

Table 6. CA4PRS Schedule Estimate vs. Additional Resource Usage for JPCP.

Strategies	Cross-section profile	Construction window	Schedule estimate versus additional resource usage							
			Ordinary usage		5%		15%		25%	
			Closures	Days	Closures	Days	Closures	Days	Closures	Days
JPCP	8"	Nighttime	143.45	143.45	136.56	136.56	125.96	125.96	118.18	118.18
		Weekend	10.14	23.22	9.66	22.12	8.91	20.40	8.36	19.14
		Extended	3.85	30.80	3.50	28.00	3.21	25.68	2.96	23.68
	10"	Nighttime	210.00	210.00	199.28	199.28	182.78	182.78	170.68	170.68
		Weekend	18.71	42.85	17.76	40.67	16.29	37.30	15.21	34.83
		Extended	4.74	37.92	4.31	34.48	3.95	31.60	3.86	30.88
	12" with 6" ACB	Nighttime	229.77	229.77	218.10	218.10	200.14	200.14	186.97	186.97
		Weekend	20.47	46.88	19.43	44.49	17.83	40.83	16.66	38.15
		Extended	5.41	43.28	4.92	39.36	4.51	36.08	4.21	33.68

Table 7. CA4PRS Schedule Estimate vs. Additional Resource Usage for CRCP.

Strategies	Cross-section profile	Construction window	Schedule estimate versus additional resource usage							
			Ordinary usage		5%		15%		25%	
			Closures	Days	Closures	Days	Closures	Days	Closures	Days
CRCP	8"	Nighttime	717.55	717.55	704.68	704.68	682.28	682.28	660.19	660.19
		Weekend	20.06	45.94	19.17	43.90	17.57	40.24	17.57	40.24
		Extended	12.53	100.24	11.95	95.60	11.29	90.32	11.26	90.08
	10"	Nighttime	1125.34	1125.34	1109.30	1109.30	1081.41	1081.41	1057.98	1057.98
		Weekend	41.66	95.40	39.67	90.84	36.22	82.94	34.90	79.92
		Extended	23.48	187.84	22.36	178.88	20.42	163.36	19.01	152.08
	13" with 3" ACB	Nighttime	1158.98	1158.98	1138.15	1138.15	1101.93	1101.93	1071.46	1071.46
		Weekend	45.26	103.65	43.24	99.02	41.66	95.40	39.67	90.84
		Extended	24.71	197.68	23.77	190.16	23.48	187.84	22.36	178.88

Table 8. CA4PRS Schedule Estimate vs. Additional Resource Usage for HMA.

Strategies	Cross-section profile	Construction window	Schedule estimate versus additional resource usage							
			Ordinary usage		5%		15%		25%	
			Closures	Days	Closures	Days	Closures	Days	Closures	Days
HMA (Simultaneous Paving)	8"	Nighttime	63.32	63.32	60.30	60.30	55.06	55.06	50.66	50.66
		Weekend	5.65	12.94	5.39	12.34	5.09	11.66	5.08	11.63
		Extended	1.06	7.42	1.01	7.07	0.95	6.65	0.95	6.65
	10"	Nighttime	80.12	80.12	76.45	76.45	69.23	69.23	63.78	63.78
		Weekend	7.09	16.24	6.76	15.48	6.38	14.61	6.37	14.59
		Extended	1.31	9.17	1.25	8.75	1.18	8.26	1.18	8.26
HMA (Pre-paving)	8"	Nighttime	41.92	41.92	38.94	38.94	35.65	35.65	34.63	34.63
		Weekend	3.76	8.61	3.56	8.15	3.25	7.44	3.14	7.19
		Extended	0.76	5.32	0.72	5.04	0.66	4.62	0.63	4.41
	10"	Nighttime	51.78	51.78	49.15	49.15	44.87	44.87	43.38	43.38
		Weekend	4.64	10.63	4.42	10.12	4.05	9.27	3.92	8.98
		Extended	0.93	6.51	0.89	6.23	0.81	5.67	0.78	5.46

Table 9. CA4PRS Schedule Estimate vs. Additional Resource Usage for MACO.

Strategies	Cross-section profile	Construction window	Schedule estimate versus additional resource usage							
			Ordinary usage		5%		15%		25%	
			Closures	Days	Closures	Days	Closures	Days	Closures	Days
HMA (Simultaneous Paving)	8"	Nighttime	63.32	63.32	60.30	60.30	55.06	55.06	50.66	50.66
		Weekend	5.65	12.94	5.39	12.34	5.09	11.66	5.08	11.63
		Extended	1.06	7.42	1.01	7.07	0.95	6.65	0.95	6.65
	10"	Nighttime	80.12	80.12	76.45	76.45	69.23	69.23	63.78	63.78
		Weekend	7.09	16.24	6.76	15.48	6.38	14.61	6.37	14.59
		Extended	1.31	9.17	1.25	8.75	1.18	8.26	1.18	8.26
HMA (Pre-paving)	8"	Nighttime	41.92	41.92	38.94	38.94	35.65	35.65	34.63	34.63
		Weekend	3.76	8.61	3.56	8.15	3.25	7.44	3.14	7.19
		Extended	0.76	5.32	0.72	5.04	0.66	4.62	0.63	4.41
	10"	Nighttime	51.78	51.78	49.15	49.15	44.87	44.87	43.38	43.38
		Weekend	4.64	10.63	4.42	10.12	4.05	9.27	3.92	8.98
		Extended	0.93	6.51	0.89	6.23	0.81	5.67	0.78	5.46

The simulation results show that the duration of a project is shortened as the contractor uses more resources. The following four real-world projects represent each different strategy. A brief project overview of each strategy and the assumptions made in conducting the schedule estimates are given below.

- **Jointed Plain Concrete Pavement** strategy is based on the I-15 Devore Project where the project scope was to rebuild a 10.7 lane-mile stretch of badly damaged concrete truck lanes (project size: $18 million). JPCP is the most commonly used pavement strategy among currently available rigid pavement alternatives. JPCP has been used in 43 states across the nation with a well-established design procedure (WSDOT 2011). JPCP can typically offer a design life expectancy of 20 to 25 years depending on design requirements and traffic volumes (MoDOT 2004). JPCP requires both transverse and longitudinal contraction joints for crack control. The distance between two joints, mainly depending on slab thickness, usually ranges from 12 ft (3.7 m) to 20 ft (6.1 m) without reinforcing steel (WSDOT 2011). Dowel bars and tie bars transfer load transversely and longitudinally, respectively. If there is a crack in the middle of a slab, only aggregate interlock transfers load across the joint.
- **Continuously Reinforced Concrete Pavement** strategy is based on the I-5 Stockton Project in Stockton, CA, where the scope of the project was to rebuild 21.0 lane-mile stretch of badly deteriorated highway lanes (project size: $45 million). CRCP is known to support long-term performance and reduced maintenance, especially for high-volume pavements, because it requires no transverse joints (Caltrans 2011). CRCP is commonly used for the interstate systems of Illinois, Texas, and North Dakota (WSDOT 2011), with a life expectancy of 30 years and even up to 50 years (AISI 2012). CRCP requires only continuous reinforcing steel, so only longitudinal joints are installed. CRCP is a pre-stressed concrete pavement, which can resist greater loads using smaller cross-section area and longer spans. CRCP can be applied in both wet and dry conditions due to less water penetration.
- **Hot-Mix Asphalt** strategy is based on the I-710 Long Beach Project where the project scope was to rehabilitate approximately 16.4 lane-mile of a six-lane highway segment (project size: $16.7 million). HMA is another type of paving material in which the surface mixture is prepared by heating the aggregate in excess of 300°F. Advantages include: it can be easily installed in much less time, and at the same time provides same durability, strength, and life at almost the same cost (Lee et al. 2008). Typical thickness of the HMA strategy ranges from 6 inches to 10 inches.
- **Milling and Asphalt Concrete Overlay** strategy is based on the I-15 Baker Project where the project scope was to rehabilitate an aging 43.5 lane-mile stretch of two lanes (project size: $20 million). MACO removes deteriorated pavement surfaces by milling and replacing them with new asphalt concrete overlays. The MACO strategy is applied to pavements where a minimum level of maintenance is needed (Labi et al. 2005). Typical thickness of the MACO strategy ranges from 3 inches to 6.5 inches (Labi et al. 2005).

For the construction window and lane closure tactics, a sequential single-lane closure with a four-hour curing time was assumed for a nighttime construction window. A concurrent double-lane closure with a 12-hour curing time was assumed for weekend (55-hour) and extended (24/7) construction windows.

5.2.2 Contractor's Time-Cost Tradeoff versus Resource Changes

Caltrans Labor Surcharge and Equipment Rental Rates 2013–14 manual was used to calculate the additional cost growth by taking into account the unit price information of all the resources used. The unit prices of all the major resources on the basis of the latest manual are $88.70 with overtime rate of 0.86 (Truck), $139.67 with overtime rate of 0.88 (Paver), $413.38 with overtime rate of 0.90 (Milling Machine), and $688 with overtime rate of 0.59 (Batch Plant).

Unit price as mentioned above includes the labor costs, and the labor surcharge rate includes all the miscellaneous factors such as payroll data, fringe benefits, and taxes. The surcharge rate for the year 2013–14 is 12 percent for regular time and 11 percent for overtime, as per the Caltrans manual.

To estimate the initial CAC growth rates of acceleration with more resources, the unit price (hourly rate) information of all the major resources was needed. This information was found in the Caltrans publication, Labor Surcharge and Equipment Rental Rates (Caltrans 2013). Caltrans updates this publication annually and revises changes to fuel costs, interest rates, producer price indices, sales tax, and freight rates. The following unit prices are some examples of major resources from the latest version of the manual published in 2013:

- Truck: $88.70 with overtime rate of 0.86.
- Paver: $139.67 with overtime rate of 0.88.
- Milling machine: $413.38 with overtime rate of 0.90.
- Batch plant: $688.00 with overtime rate of 0.59.

These four also reflect major resources used in CA4PRS simulations. The unit prices include the labor costs required to provide the above listed items. The labor surcharge compensates the contractor for statutory payroll items including workers' compensation, social security, fringe benefits, federal unemployment, state unemployment, and state training taxes (Caltrans 2013). The published surcharge rates for year 2012 were 12 percent for regular time and 11 percent for overtime. Multiple shift hours are paid at the same rate as overtime hours. The unit prices, however, do not include the operator costs of equipment due to the lack of such data.

Contractor's expected cost growth = unit price ($/hour) × number of additional resources × labor surcharge rate × working hours per day × days needed to complete the project × overtime rate × number of shifts × overhead cost (15%) (1)

The initial CAC rates were quantified based on Equation (1). Tables 10−13 present the contractor's time-cost tradeoff data created for this study, containing the dependent (cost) and independent (schedule) variables used for the regression analysis, with three different resource usage levels.

Table 10. Contractor's Time-Cost Tradeoff Data for JPCP.

Strategies	Cross-section profile	Construction window	Time-cost tradeoff versus additional resource usage					
			5%		15%		25%	
			Schedule Compression	Cost Growth	Schedule Compression	Cost Growth	Schedule Compression	Cost Growth
JPCP	8"	Nighttime	4.80	0.40	12.19	1.21	17.62	2.01
		Weekend	4.73	0.63	12.13	1.07	17.55	1.52
		Extended	9.09	0.68	16.62	1.37	23.12	1.61
	10"	Nighttime	5.10	0.42	12.96	1.22	18.72	2.01
		Weekend	5.08	0.59	12.93	1.23	18.71	1.51
		Extended	9.07	0.71	16.67	1.47	18.57	1.72
	12" with 6" ACB	Nighttime	5.07	0.43	12.90	1.24	18.63	2.00
		Weekend	5.08	0.56	12.89	1.38	18.61	1.49
		Extended	9.06	0.74	16.64	1.56	22.18	1.82

Table 11. Contractor's Time-Cost Tradeoff Data for CRCP.

Strategies	Cross-section profile	Construction window	Time-cost tradeoff versus additional resource usage					
			5%		15%		25%	
			Schedule Compression	Cost Growth	Schedule Compression	Cost Growth	Schedule Compression	Cost Growth
CRCP	8"	Nighttime	1.79	0.16	4.92	0.48	7.99	1.11
		Weekend	4.44	0.41	12.41	0.16	12.41	2.58
		Extended	4.63	0.33	9.90	1.13	10.14	1.85
	10"	Nighttime	1.43	1.25	3.90	0.38	5.99	2.76
		Weekend	4.78	0.44	13.06	0.14	16.23	3.38
		Extended	4.77	0.34	13.03	1.49	19.04	3.67
	13" with 3" ACB	Nighttime	1.80	0.45	4.92	0.57	7.55	2.89
		Weekend	4.46	0.67	7.95	0.45	12.35	3.06
		Extended	3.80	0.89	4.98	1.56	9.51	4.13

Table 12. Contractor's Time-Cost Tradeoff Data for HMA.

Strategies	Cross-section profile	Construction window	Time-cost tradeoff versus additional resource usage					
			5%		15%		25%	
			Schedule Compression	Cost Growth	Schedule Compression	Cost Growth	Schedule Compression	Cost Growth
HMA (Simultaneous Paving)	8"	Nighttime	4.78	0.42	13.04	1.27	15.22	2.12
		Weekend	4.60	0.42	9.91	1.27	10.09	2.10
		Extended	4.72	0.34	10.38	1.19	10.38	1.89
	10"	Nighttime	4.58	4.00	13.59	1.32	20.39	2.84
		Weekend	4.65	0.42	10.01	1.28	10.16	2.11
		Extended	4.58	0.33	9.92	1.14	9.92	1.81
HMA (Pre-paving)	8"	Nighttime	7.11	0.62	14.96	1.46	17.39	2.43
		Weekend	5.32	0.49	13.56	1.74	16.49	3.43
		Extended	5.26	0.38	13.16	1.51	17.11	3.12
	10"	Nighttime	5.08	4.44	13.34	1.29	16.22	2.26
		Weekend	4.74	0.49	12.72	1.63	15.52	3.22
		Extended	4.30	0.31	12.90	1.48	16.13	2.94

Table 13. Contractor's Time-Cost Tradeoff Data for MACO.

Strategies	Cross-section profile	Construction window	Time-cost tradeoff versus additional resource usage					
			5%		15%		25%	
			Schedule Compression	Cost Growth	Schedule Compression	Cost Growth	Schedule Compression	Cost Growth
MACO (Simultaneous Paving)	4"	Nighttime	1.81	0.79	5.42	2.61	7.98	3.35
		Weekend	1.86	0.96	5.54	3.23	8.32	3.87
		Extended	1.84	0.93	5.58	2.99	8.34	3.99
	6"	Nighttime	1.74	0.77	5.20	2.51	8.05	3.65
		Weekend	2.28	1.18	5.45	3.18	8.12	3.89
		Extended	2.31	1.71	5.49	2.94	8.16	4.13
MACO (Pre-paving)	4"	Nighttime	2.14	0.94	5.12	2.47	8.23	4.32
		Weekend	2.29	1.18	5.49	3.20	8.15	5.67
		Extended	2.35	1.19	5.52	2.96	8.21	5.48
	6"	Nighttime	4.74	2.09	13.01	4.67	19.95	10.46
		Weekend	4.74	2.45	12.56	5.13	17.58	12.23
		Extended	4.79	2.43	13.00	5.87	17.93	11.96

5.2.3 Modeling Contractor's Time-Cost Tradeoff Effect

A well-known trade-off effect exists between construction cost and schedule. As Figure 11 shows, there is a normal point beyond the tradeoff between cost and schedule. For example, to shorten the duration of a project by as much as ΔT (from t_0 to t_1), a contractor would need to make an additional cost commitment of ΔC (from c_0 to c_1). The additional cost increase for shortening construction time involves a direct cost increase covering 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.

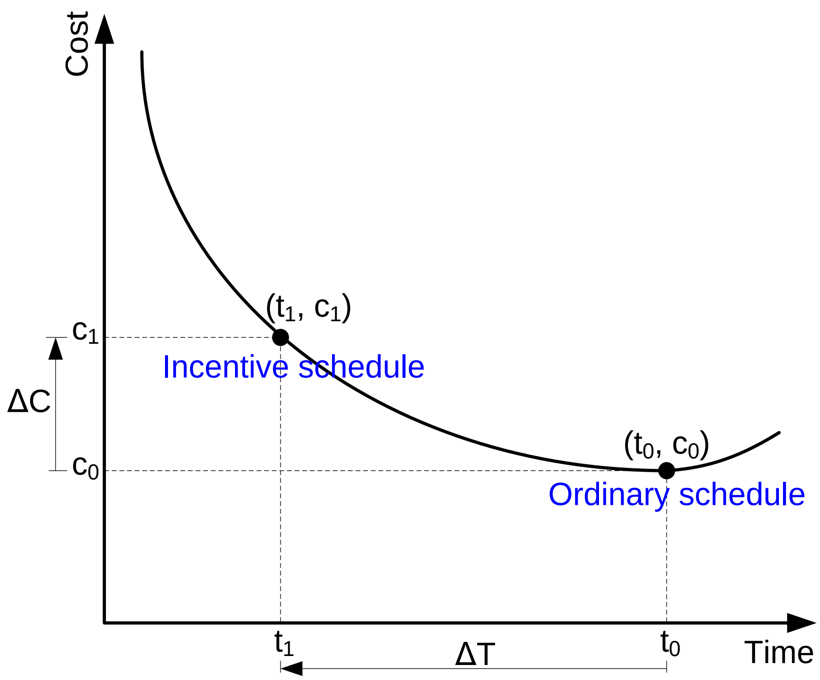


Figure 11. Time-Cost Tradeoff Effect in Theory (adapted from Shr and Chen 2004).

Meanwhile, a delay in the project schedule from the normal point also increases the project cost due largely to increased indirect costs, such as office overhead, overtime payments, running rental equipment longer than originally contracted, etc. (Plummer et al. 1992). The plots in Figure 12 that are based on time-cost tradeoff data (Tables 10−13) illustrate contractors' cost growth as a function of reduced construction time. It can be observed from the plots that there is a conspicuous trade-off relationship between schedule and cost. Contractors' cost growth can be projected using the following quadratic regression equation:

$$Cost = \beta_0 + \beta_1\,(Time) + \beta_2\,(Time)^2 \qquad (2)$$

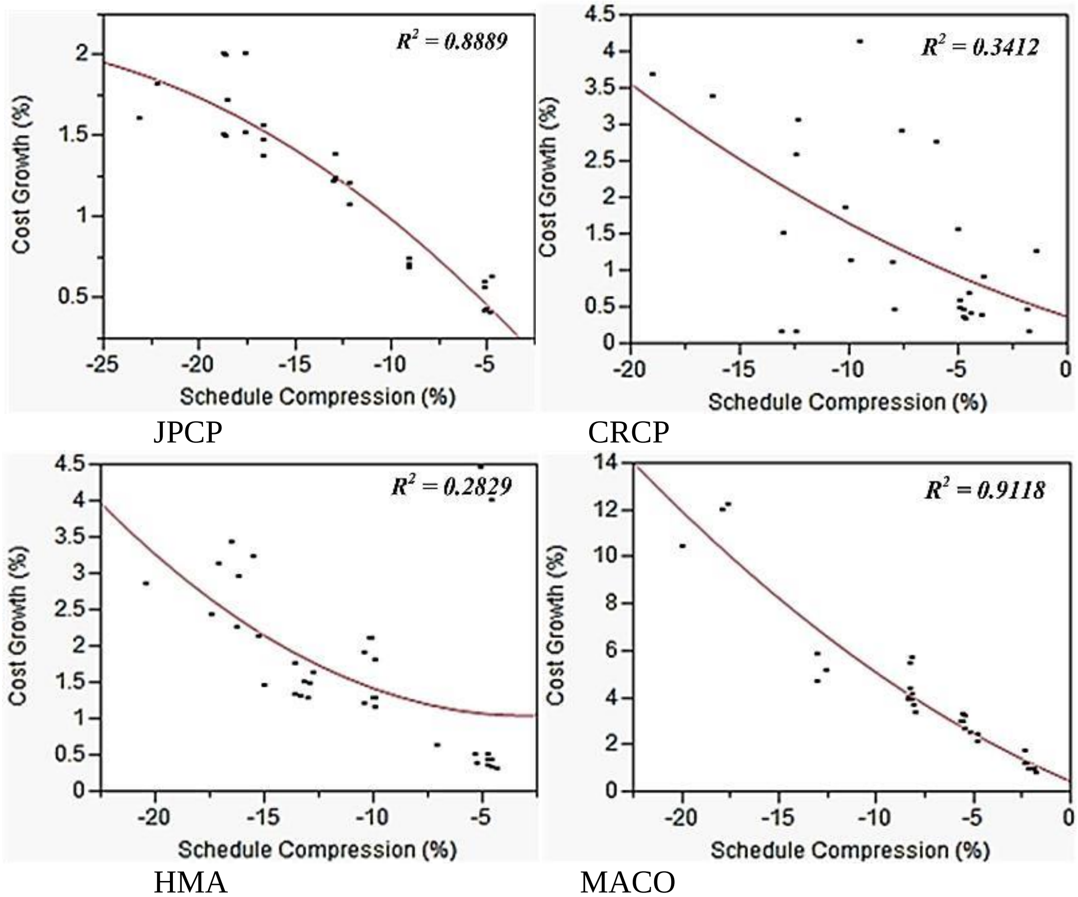


Figure 12. Time-Cost Tradeoff Curves.

Table 14 shows that the quadratic equation of contractors' cost growth rate is adequate. F-ratio of each pavement strategy is large enough. (The corresponding p-value is less than 0.001.) The estimated regression coefficients in Table 14 indicate that schedule compression results in an increase in project cost.

Table 14. A Regression Summary Table of Four Pavement Strategies.

Model		Coefficient	Std. Error	t-value	R^2 value	F-ratio
JPCP	Intercept	−0.1803	0.1822	0.3325	0.8889	95.09*
	Time	−0.1378	0.0317	0.0002		
	$(\text{Time})^2$	−0.0021	0.0012	0.0991		
CRCP	Intercept	0.365	0.6898	0.6014	0.3412	6.2156*
	Time	−0.096	0.1719	0.5803		
	$(\text{Time})^2$	0.0032	0.0089	0.7279		
HMA	Intercept	1.1133	0.1035	0.2062	0.2829	6.5115*
	Time	0.0469	0.0062	0.7942		
	$(\text{Time})^2$	0.0077	0.0012	0.3491		
MACO	Intercept	0.4414	0.4397	0.3227	0.9118	170.5328*
	Time	−0.3507	0.1106	0.0033		
	$(\text{Time})^2$	0.0112	0.0055	0.0479		

*p<0.001

5.2.4 Modeling CAC Predictive Models

By performing a regression analysis, the coefficients β_0, β_1, and β_2 of Equation (2) were estimated. Figure 11 clearly shows that contractors would require committing extra costs by ΔC (i.e., $c_0 - c_1$) to shorten the duration by ΔT (from t_0 to t_1). From Equation (2), a time function can be defined as follows:

$$f = \beta_0 + \beta_1 t + \beta_2 t^2 \tag{3}$$

where f denotes CAC.

Since the CAC increase is expressed as a function of shortening time by ΔT, the following relationship can be derived from Figure 11:

$$\text{CAC } (\Delta C) = f(t_1) - f(t_0) = f(t_1) - f(t_1 + \Delta T) \tag{4}$$

where $t_0 = t_1 + \Delta T$.

The following equation is derived by combining Equations (3) and (4):

$$\Delta C \text{ in total} = -\,\Delta T\,(2\beta_2\, t_1 + \beta_1 + \beta_2\,\Delta T) \tag{5}$$

The negative sign implies that cost decreases as time increases. In Equation (5), the symbol ΔT represents the difference in the number of days necessary to complete the project using conventional and incentive schedules. In other words, ΔT reflects the agency goal of schedule reduction. The symbol t_1 represents days necessary to complete the project by using an incentive schedule.

To convert the total extra cost increase to a daily basis, Equation (5) needs to be divided by the number of days saved (i.e., ΔT), which cancels out ΔT. Thus, the daily CAC growth rate equals $2\beta_2 t_1 + \beta_1 + \beta_2 \Delta T$.

Based on coefficients generated through the regression analysis shown in Table 14, the following equations for the JPCP strategy are derived to predict the level of the CAC to the original contract amount:

$$\Delta C = -0.1378 - 0.0042t_1 - 0.0021\Delta T \text{ for roadway renewal projects with JPCP} \quad (6)$$

where, $t_1 = t_0 - \Delta T$

Using the definition of t_1, the final equation is derived:

$$\Delta C = -0.1378 - 0.0042t_0 + 0.0021\Delta T \quad (7)$$

As previously stated, the daily incentive amount should range from an increase in the contractor's daily additional cost to the portion of daily road user cost savings. By repeating these procedures for other pavement strategies, following CAC predictive models are derived (Figure 12):

$$\text{JPCP: } (-0.1378 - 0.0042t0 + 0.0021\Delta T) \leq \text{Daily I/D} \leq \text{Discounted total savings} \quad (8)$$

$$\text{CRCP: } (-0.096 + 0.0064\, t0 - 0.0032\, \Delta T) \leq \text{Daily I/D} \leq \text{Discounted total savings} \quad (9)$$

$$\text{HMA: } (0.0469 + 0.0154\, t0 - 0.0077\, \Delta T) \leq \text{Daily I/D} \leq \text{Discounted total savings} \quad (10)$$

$$\text{MACO: } (-0.662 + 0.0224\, t0 - 0.0112\, \Delta T) \leq \text{Daily I/D} \leq \text{Discounted total savings} \quad (11)$$

How to estimate the upper bound of I/D is described in the following chapter.

6 STAGES 3 AND 4: QUANTIFICATION OF TOTAL SAVINGS

The proposed seven-stage research activities are closely interwoven. Previous stages provide information needed to proceed to the next step because the CAC growth rates and the maximum probable numbers of closures and days that can be saved provide the basis for estimating the total time value savings to road users and to the agency. The quantification of total savings takes the schedule information and then quantifies the total monetary value of the time saved by use of I/D.

6.1 Stage 3: Determining Monetary Value of Time Saved by Road Users

Although STAs have mostly determined I/D rates by their impacts on RUC, as measured by the monetary value of time saved by road users, it appears that there has not been a formally established standard calculation procedure. RUC considers the concept of *opportunity cost*, defined as time lost by motorists to traffic delays that could have been spent in recreation or work. It plays a pivotal role in work zone impact assessments—used to identify impacts on service levels, determine lane-closure strategies, and identify I/D.

This research attempts to extend the current practice of I/D upper bound estimate by including savings realized by the contracting agency. RUC lookup tables that capture major components of RUC were created by performing a series of CA4PRS work zone traffic simulations. The research team believes that this approach can bring a breakthrough in automatic determination of RUC in a viable way to improve the ability of STA engineers to quickly and more efficiently produce RUC estimations in the project scoping process.

The CA4PRS work zone simulation quantifies the impact of construction work zone closures on the traveling public in terms of road user cost and time spent in queue. This quantification is based on the Highway Capacity Manual demand-capacity model. The remainder of this section is organized to describe the concepts of the demand-capacity model, major components of RUC, and its estimation using the work zone simulations. Figure 13 shows the main analytical procedures to arrive at the initial RUC lookup tables. In Section 6.2, the new approach to determining total savings to the agency is described.

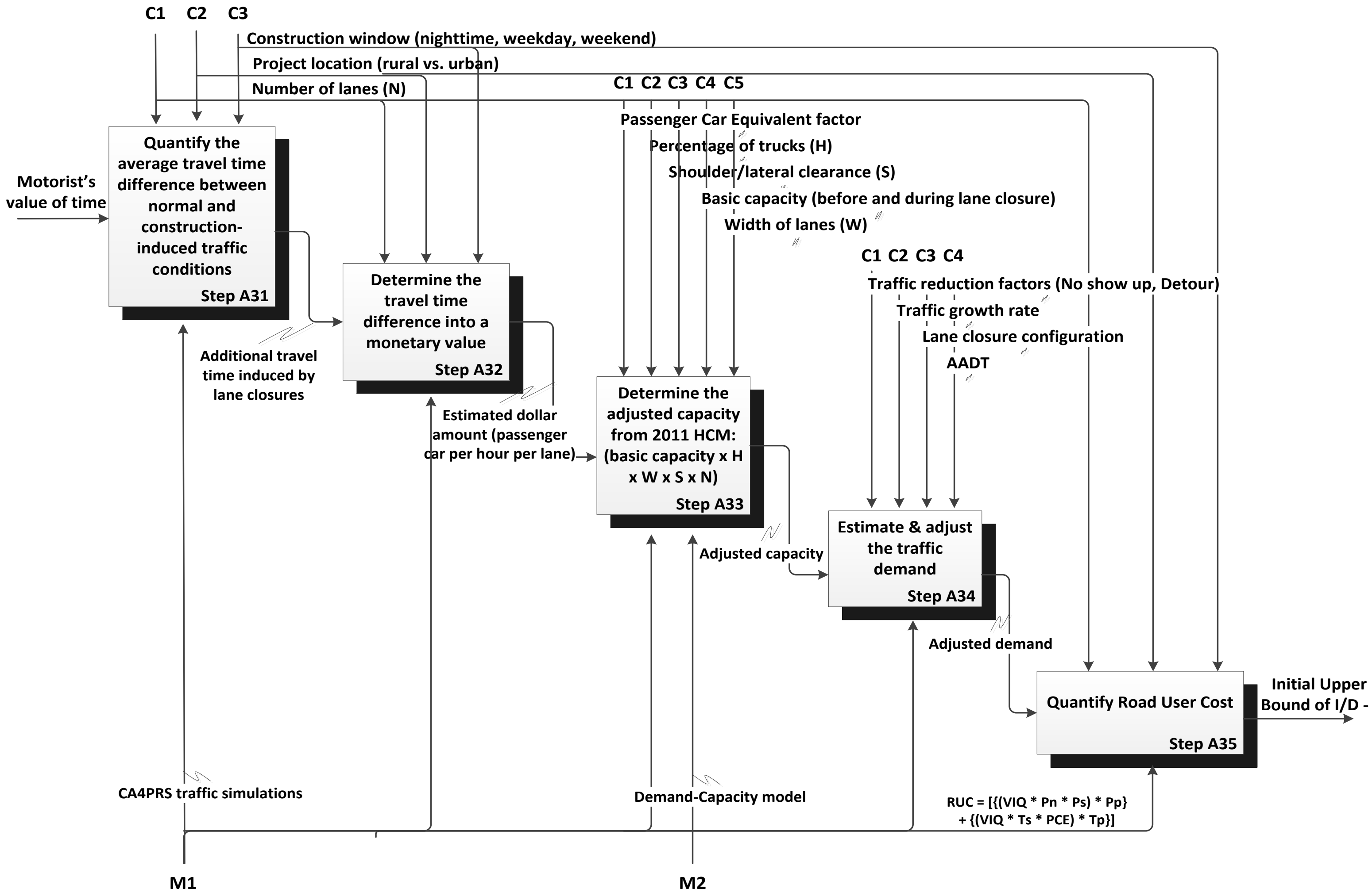


Figure 13. Stage 3: RUC Quantification for the Initial I/D Upper Bound before Adjustment.

6.1.1 Components of Road User Cost

In practice, the determination of RUC incorporates the concept of demand-capacity model to determine RUC, based on the *Highway Capacity Manual 2010* (TRB 2010). *Demand* is defined as hourly traffic volumes at a certain point of interest, which is unknown and thus requires the logical quantification presented in this section. *Capacity* is defined as the maximum possible traffic service flow, which can be selected from the manual. In general, it is assumed that in normal conditions capacity ranges from 2,200 to 2,300 pcphpl (passenger car per hour per lane) and that in construction conditions it ranges from 1,500 to 1,600 pcphpl. Using a passenger car equivalent (PCE) factor, it is generally assumed that a truck is equal to 1.5 passenger vehicles (2.5 for a rolling setting and 4.5 for a mountain setting). Capacity varies because of the following factors:

- Project location where the project is taken place.
- Percentage of heavy vehicles (H): $H = 100 / [100 + P(PCE-1)]$, where P = percentage of trucks.
- Width of lanes (W): W=1.00 if width is 12.0 feet, W=0.95 if width is 11.0 feet, and W=0.90 if width is 0.90.
- Shoulder and lateral clearance (S): S=1.00 if both shoulders are available, S=0.95 if one shoulder is available, and S= 0.90 if now shoulder is available.
- Number of lanes opened to traffic (N).

Adjusted capacity can be calculated by taking into account the above mentioned factors:

- Adjusted capacity = basic capacity $\times$ H $\times$W $\times$S $\times$N.

The RUC is not tangible, but when considering the concept of opportunity cost that motorists could be spent doing something else for recreation or work, its value as time saved by completing the project early becomes important to road users. The four major factors to account for when estimating RUC are: (1) additional travel time (time lost due to construction lane closures), (2) the average number of motorists per vehicle, (3) the monetary value of time to motorists in the vehicle, and (4) the percentage of trucks at a construction work zone. The travel-time changes arise from differences in average travel time at the work zone in two different traffic conditions, i.e., traffic conditions before construction and its predicted condition during construction, when normal flow is disrupted by lane closures for construction. The value of motorists' wasted time (cost per hour) on the roadway should be considered as a key parameter in the calculation of RUC. Different pay rates should also be applied to passenger cars and trucks.

6.1.2 Analytical Procedure for Quantifying Road User Cost

Based on the understanding of the major RUC components discussed earlier, the RUC was computed using the following procedure in this study:

1. Input the average travel time in normal traffic conditions.
2. Input the average travel time in conditions with construction-induced traffic disruption.

3. Calculate the difference in the average travel time at the work zone in two different traffic conditions.
4. Convert the predicted travel time delay into a monetary value using Table 15.
5. Apply Equation (11) to determine the initial daily RUC.

Table 15. Monetary Value of Time by Major States (updated from Ibarra et al. 2002).

State	Average Time Value Automobiles ($)	Average Truck Value Trucks ($)
California	11.51	27.83
Florida	11.12	22.36
Georgia	11.65	N/A
New York	9.00	21.14
North Carolina	8.70	N/A
Ohio	12.60	26.40
Oregon	16.31	29.00
Pennsylvania	12.21	24.18
Texas	11.97	21.87
Virginia	11.97	21.87
Washington	12.51	50.00

As Table 15 shows, the hourly time value varies among states; for instance, in California the hourly value of time to road users is $11.51 per passenger vehicle and $27.83 per truck. These travel time values are based on those established by the Caltrans Division of Transportation Planning and the Division of Traffic Operations. An adjustment factor based on an average vehicle occupancy rate of 1.1 persons per passenger vehicle is applied to passenger vehicles.

As noted above, the first step for estimating RUC is to measure the difference in average travel time at the construction work zone in two different traffic conditions. Most of the state highway agencies that use I/D provisions perform a preconstruction traffic sensitivity analysis to estimate expected traffic delay times, as part of transportation management plans. Subsequently, the expected average travel delay time is directly input or selected by the agency engineers who will use the model. The predicted travel time delay is then converted into a monetary value per passenger (per hour), taking account of the project location and the rate of inflation at the time of construction. This approach uses the dollar value of time to road users that is described in Table 15. For example, if a 30-minute delay is predicted at a one-lane highway rehabilitation project undertaken in California in the year 2008, the hourly value of time is cut to half, about $5.76 per passenger car and $13.92 per truck.

Next, the following equation is applied to calculate the time value to road users:

$$RUC = [(VIQ * P_n * P_s) * P_p) + ((VIQ * T_s * PCE) * T_p] \quad (11)$$

where,
VIQ = anticipated number of vehicles in queue due to a construction delay (vehicles per hour per lane).
P_n = average number of passengers per passenger vehicle.

P_s = monetary time value per passenger for passenger vehicles.
P_p = percentage of passenger vehicles driving through the CWZ.
T_s = average pay rate per hour for trucks.
PCE = passenger car equivalent factor.
T_p = percentage of trucks driving through the CWZ.

Due to the budget limitations of STAs, the time value to road users should be adjusted downward by applying a realistic discount factor in an economically rational manner under the appropriate circumstances as is considered in the next chapter.

6.1.3 Quantification of Road User Cost with CA4PRS Simulations

The most recent version of CA4PRS has capability of doing work zone analysis in terms of road user cost and time spent in queue. The work zone analysis module of CA4PRS is also based on the demand-capacity model described in an earlier section.

Using the latest version of CA4PRS, RUC lookup tables were created for this study to serve as the initial upper bound of I/D. It is believed that this alternative way of using CA4PRS can considerably reduce the effort, time, and future development costs of a prototype computer software system.

As Tables 16−18 show, the lookup tables are designed to capture the following crucial affecting factors when estimating RUC: (1) levels of traffic (AADT: Annual Average Daily Traffic), (2) construction working windows (nighttime versus extended), (3) percentage of trucks (5 percent, 10 percent, and 15 percent), and (4) lane closure scheme (partial closure versus full closure). However, this current RUC lookup tables are limited to urban highway renewal projects where the project scope is rebuilding of a portion of a typical four-by-four lane freeway in both directions.

The following assumptions in the CA4PRS analysis were used to develop a RUC lookup database:

- **Number of lanes opened to traffic during lane closures:** Four-by-two lane closures were assumed for the partial closure scheme, and counter-flow traffic that closed one direction completely was assumed for the full-closure scheme.
- **Changes in roadway capacity:** In normal conditions capacity was assumed as about 2,150 pcphpl and in conditions with construction-induced traffic disruption it was assumed to be approximately 1,500 pcphpl.
- **Passenger car equivalent (PCE) factor:** A PCE of 1.50 was assumed, which means that a truck is equivalent to 1.5 passenger vehicles.
- **Traffic pattern:** It was assumed for the weekend construction project that both directions have the same level of traffic volume because most I/D projects have this type of traffic pattern. Further, it turns out that changing a traffic pattern produces similar values of RUC. Traffic patterns assumptions made on weekday and weekend lane closures are depicted by Figure 14.
- **Motorists travel pattern adjustments:** Three percent no-shows (detour reduction) were assumed for the nighttime construction with partial-closures and 5 percent no-shows and

5 percent detours were assumed for the weekday and weekend construction with full-closures.

- **Motorists' additional travel time for diversions:** This was not taken into consideration because the detour routes can flow freely even during peak commute hours.
- **Lane width:** It was assumed that the width of lane is reduced to 11 feet from 12 feet due to the lane closures.
- **Externalities:** Vehicle operating cost (e.g., fuel, tires, and mileage-dependent depreciation) resulting from construction work being performed was not taken into consideration due to its complexity in measurements.

Regarding motorists travel pattern adjustments, a research study concluded that demand around the construction work zone can be reduced by 10 percent to 20 percent with implementation of a public outreach program, which has now become an essential part of a transportation management plan (Lee and Choi 2006).

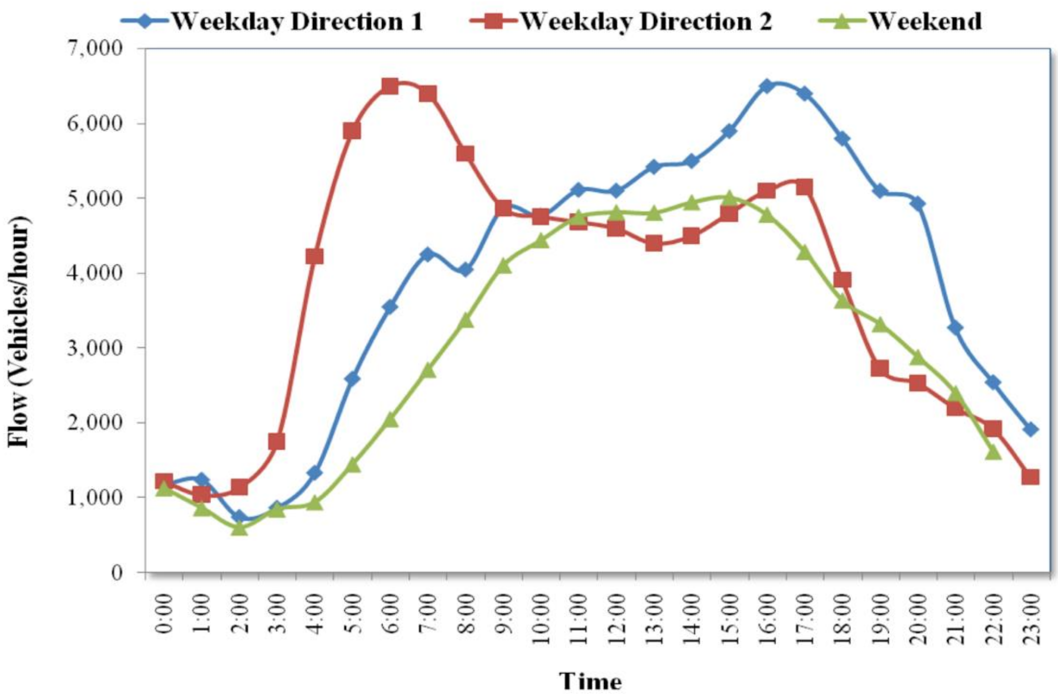


Figure 14. Typical Weekday and Weekend Traffic Patterns Based on *CA4PRS* Hourly Traffic Distribution Tables.

Under the assumptions listed above, the following factors significantly affecting the value of RUC were included as CA4PRS inputs:

- Average number of passengers in passenger vehicles: 1.10.
- Monetary value of time to road users: $11.51 for passenger cars and $27.83 for trucks.
- Percentage of trucks: 5 percent, 10 percent, and 15 percent conditions.
- Closure tactics: 8-hour nighttime closures versus 55-hour one roadbed continuous closures on weekends.
- Number of lanes opened to traffic: sequential single lane versus concurrent double lane.

Table 16. RUC Calculation for a 4 by 4 Urban Freeway: Nighttime Construction Project with Partial Closure.

Partial Closure: 8-hour Nighttime Construction* Two Lane Closed in One Direction

AADT	5% Trucks	10% Trucks
50,000	549	590
55,000	605	649
60,000	660	709
65,000	714	767
70,000	769	826
75,000	824	886
80,000	879	945
85,000	934	1,003
90,000	990	1,063
95,000	1,044	1,122
100,000	1,099	1,181
105,000	1,154	1,240
110,000	1,209	1,299
115,000	1,264	1,358
120,000	1,318	1,418
125,000	1,374	1,476
130,000	1,429	1,535
135,000	1,484	1,595
140,000	1,539	1,653
145,000	1,593	1,712
150,000	1,648	1,772
155,000	2,084	2,770
160,000	2,814	3,587
165,000	3,590	4,462
170,000	4,412	5,408
175,000	5,319	6,439
180,000	6,297	7,575
185,000	7,375	8,844
190,000	8,577	14,466
195,000	14,330	23,215
200,000	22,632	38,727

Table 17. RUC Calculation for a 4 by 4 Urban Freeway: Weekend Construction Project with Full Closure.

Extended Full Closure: 55-hour Weekend Construction* Counter Flow Traffic (One Direction Closed Completely)

AADT	5% Trucks		10% Trucks	
	Per Day	Per Closure	Per Day	Per Closure
50,000	5,208	11,935	5,584	12,797
55,000	5,730	13,131	6,142	14,075
60,000	6,250	14,323	6,250	14,323
65,000	6,772	15,519	7,250	16,615
70,000	7,292	16,711	7,818	17,916
75,000	7,813	17,905	8,376	19,195
80,000	8,334	19,099	8,934	20,474
85,000	8,854	20,290	9,492	21,753
90,000	9,375	21,484	10,051	23,034
95,000	9,896	22,678	10,609	24,312
100,000	13,788	31,598	22,965	52,628
105,000	38,298	87,766	67,217	154,039
110,000	112,762	258,413	201,051	460,742
115,000	280,932	643,803	425,126	974,247
120,000	526,347	1,206,212	725,545	1,662,707
125,000	823,566	1,887,339	1,065,467	2,441,695
130,000	1,148,759	2,632,573	1,419,503	3,253,028
135,000	1,489,249	3,412,862	1,792,609	4,108,062
140,000	1,840,156	4,217,024	2,180,459	4,996,885
145,000	2,211,146	5,067,210	2,580,652	5,913,994
150,000	2,587,398	5,929,454	2,993,502	6,860,109
155,000	2,980,721	6,830,819	3,421,222	7,840,300
160,000	3,382,703	7,752,028	3,852,581	8,828,831
165,000	3,788,026	8,680,893	4,287,627	9,825,812
170,000	4,196,736	9,617,520	4,726,411	10,831,359
175,000	4,608,877	10,562,010	5,178,043	11,866,349
180,000	5,037,978	11,545,366	5,661,729	12,974,796
185,000	5,492,116	12,586,099	6,149,647	14,092,941
190,000	5,950,137	13,635,731	6,641,860	15,220,929
195,000	6,412,096	14,694,387	7,138,426	16,358,893
200,000	6,878,045	15,762,186	7,639,408	17,506,977

Table 18. RUC Calculation for a 4 by 4 Urban Freeway: Weekday Construction Project with Full Closure.

Extended Full Closure: 72-hour Weekday Construction* Counter Flow Traffic (One Direction Closed Completely)

AADT	5% Trucks		10% Trucks	
	Per Day	Per Closure	Per Day	Per Closure
50,000	5,208	15,624	5,584	16,752
55,000	5,730	17,190	6,142	18,426
60,000	6,250	18,750	6,700	20,100
65,000	6,771	20,313	7,259	21,777
70,000	7,292	21,876	7,817	23,451
75,000	7,813	23,439	8,376	25,128
80,000	8,334	25,002	11,993	35,979
85,000	18,653	55,959	26,283	78,849
90,000	36,717	110,151	49,675	149,025
95,000	65,343	196,029	94,277	282,831
100,000	126,389	379,167	175,151	525,453
105,000	216,444	649,332	283,134	849,402
110,000	329,857	989,571	423,533	1,270,599
115,000	506,031	1,518,093	673,626	2,020,878
120,000	763,178	2,289,534	971,842	2,915,526
125,000	1,064,916	3,194,748	1,326,539	3,979,617
130,000	1,412,261	4,236,783	1,742,541	5,227,623
135,000	1,826,961	5,480,883	2,267,442	6,802,326
140,000	2,284,979	6,854,937	2,793,000	8,217,000
145,000	2,791,654	8,374,962	3,292,015	9,876,045
150,000	3,312,240	9,936,720	3,849,620	11,548,860
155,000	3,836,114	11,508,342	4,418,417	13,255,251
160,000	4,376,824	13,130,472	5,040,521	15,121,563
165,000	4,969,943	14,909,829	5,679,247	17,037,741
170,000	5,569,840	16,709,520	6,322,571	18,967,713
175,000	6,173,958	18,521,874	6,970,556	20,911,668
180,000	6,782,354	20,347,062	7,623,267	22,869,801
185,000	7,395,086	22,185,258	8,289,514	24,868,542
190,000	8,022,295	24,066,885	8,972,350	26,917,050
195,000	8,663,094	25,989,282	9,660,298	28,980,894
200,000	9,308,577	27,952,731	10,353,433	31,060,894

6.2 Stage 4: Determining Monetary Value of Time Saved to Agency

Through the I/D contracting strategy, contractors are motivated to accomplish internal milestones faster and/or to complete entire projects sooner than originally scheduled. By shortening construction times, the contracting agency can also save agency costs in proportionate to the number of days the I/D project eliminates. The savings include reductions in the costs of COZEEP, AEC, and MCB rental. Agency cost savings were quantified by accounting for these three major cost saving factors. Table 19 shows a list of agency cost saving factors and presents methods to quantify their monetary value. Table 20 shows monetary time values saved to the agency, made in the basis of the CA4PRS cost estimate outline.

Table 19. Agency Cost Saving Calculation.

Factors	Rates	Methods
COZEEP	▪ $700/day/officer ▪ Number of officers - 2.5/day for nighttime - 4.5/day for extended closure ▪ Overtime rate of 1.2	▪ CHP cost/day x # number of days saved x overtime rate x 3 shifts for extended closure
AEC	▪ $320/day/staff ▪ Number of staff - 3/day for nighttime - 4/day for extended closure with 3 shifts ▪ Overtime rate - 1.1 for nighttime - 1.5 for extended closure	▪ Staffing cost/day x # of staff/day x number of days x overtime rate x 3 shifts for extended closure
MCB*	▪ Barrier cost - $60/meter for the first month - $11/meter for the second month ▪ Transformer cost - $30,000 for the first month - $15,000 for the second month	▪ Center-lane-meter to set up x appropriate monthly rates

*MCB cost applies to the extended closure only.

Table 20. Total Savings to the Contracting Agency Realized by Early Project Completion.

Days Saved	Nighttime Construction		Total Savings ($)	Extended Construction		Total Savings ($)
	COZEEP ($)	AAC($)		COZEEP ($)	AAC ($)	
A	B	C	D	E	F	G
1	2,100	1,056	3,156	11,340	5,760	17,100
2	4,200	2,112	6,312	22,680	11,520	34,200
3	6,300	3,168	9,468	34,020	17,280	51,300
4	8,400	4,224	12,624	45,360	23,040	68,400
5	10,500	5,280	15,780	56,700	28,800	85,500
6	12,600	6,336	18,936	68,040	34,560	102,600
7	14,700	7,392	22,092	79,380	40,320	119,700
8	16,800	8,448	25,248	90,720	46,080	136,800
9	18,900	9,504	28,404	102,060	51,840	153,900
10	21,000	10,560	31,560	113,400	57,600	171,000
11	23,100	11,616	34,716	124,740	63,360	188,100
12	25,200	12,672	37,872	136,080	69,120	205,200
13	27,300	13,728	41,028	147,420	74,880	222,300
14	29,400	14,784	44,184	158,760	80,640	239,400
15	31,500	15,840	47,340	170,100	86,400	256,500
16	33,600	16,896	50,496	181,440	92,160	273,600
17	35,700	17,952	53,652	192,780	97,920	290,700
18	37,800	19,008	56,808	204,120	103,680	307,800
19	39,900	20,064	59,964	215,460	109,440	324,900
20	42,000	21,120	63,120	226,800	115,200	342,000
21	44,100	22,176	66,276	238,140	120,960	359,100
22	46,200	23,232	69,432	249,480	126,720	376,200
23	48,300	24,288	72,588	260,820	132,480	393,300
24	50,400	25,344	75,744	272,160	138,240	410,400
25	52,500	26,400	78,900	283,500	144,000	427,500
26	54,600	27,456	82,056	294840	149,760	444,600
27	56,700	28,512	85,212	306,180	155,520	461,700
28	58,800	29,568	88,368	317,520	161,280	478,800
29	60,900	30,624	91,524	328,860	167,040	495,900
30	63,000	31,680	94,680	340,200	172,800	513,000

Column (D) = Column (B) + Column (C)
Column (G) = Column (E) + Column (F)

7 STAGES 5 AND 6: ADJUSTMENTS OF INITIAL CAC AND TOTAL SAVINGS

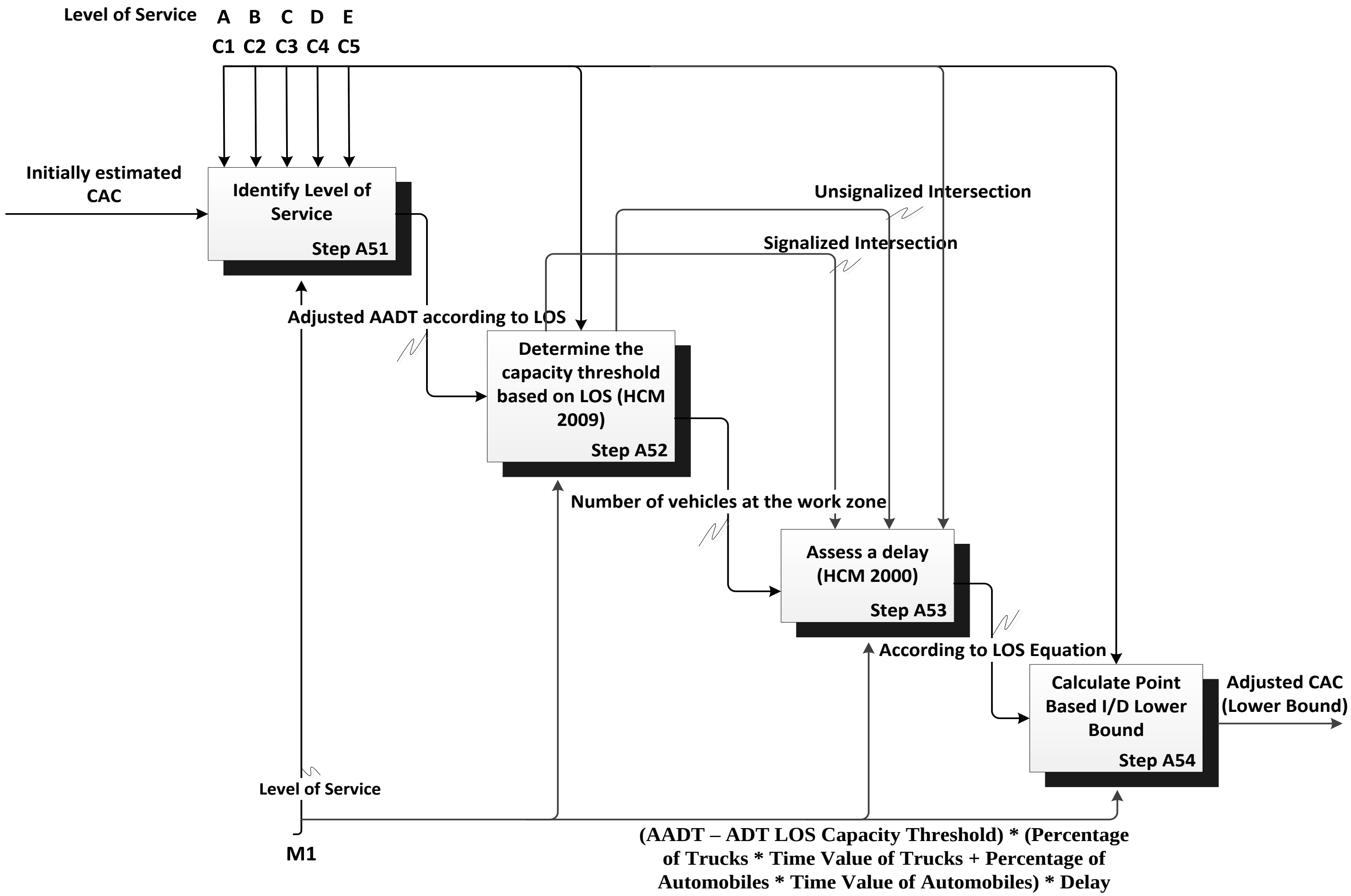


Figure 15. IDEF0 Framework for Determining Adjusted I/D Lower Bound Using Level of Service.

7.1 CAC Adjustment with the Concept of Level-of-Service

7.1.1 Level-of-Service Standards

To quantitatively analyze the effect of land-use changes and effectively monitor traffic congestion, the state of California mandates that LOS must be included in the Congestion Management Program (CMP) process (Alameda County Transportation Commission 2012). Hence, the congestion management agency is required to evaluate whether local governments satisfy the LOS standards in their CMP.

The LOS measures and describes the operational effectiveness of a roadway section undergoing rehabilitation/renewal work. Specifically, Letter designations A through F describe traffic conditions that represent speed, travel time, volume and capacity, traffic interruptions, comfort, convenience, and safety (Alameda County Transportation Commission 2012). LOS A is the best performing service, which indicates free flow of traffic with little or no delay, whereas LOS F is the worst service accompanied by traffic flows exceeding the capacity, thereby resulting in long queues and delays (TRB 2010). LOS in the Highway Capacity Manual includes following definitions of letter designations (TRB 2010):

- A: Free flow operations at average travel speeds.
- B: Reasonably unimpeded operations by maintaining LOS A.
- C: Stable flow, but restricted to maneuver through lanes.
- D: Approaching unstable flow with decreasing speeds as traffic volume slightly increases.
- E: Unstable flow operations at capacity.
- F: Arterial flow at extremely low speeds below one-third to one-quarter of the free flow speed.

7.1.2 Level-of-Service Definition

Annual Average Daily Traffic (AADT), contained in Tables 16–18, is the total volume of traffic accompanying any roadway/highway throughout the year divided by 365 days. Table 21 highlights different types of LOS thresholds as specified in the Highway Capacity Manual (TRB 2010). Average Daily Traffic (ADT) is the total number of vehicles passing through a given point measured over a course of time period ranging from 2 to 365 days.

Table 21. LOS Definitions for Roadway Segments.

Roadway Classification	Number of Lanes	ADT Level of Service Capacity Threshold				
		A	B	C	D	E
Minor Arterial	2	9,000	10,700	12,000	13,500	15,000
Collector Street	2	5,250	6,125	7,000	7,875	8,750
Local Street	2	-	-	3,000	4,000	5,000

7.1.3 Level-of-Service versus Delay

Table 22 shows the different levels of delay and LOS for signalized and unsignalized intersections. Signalized intersections use various intersection characteristics such as traffic volumes, lane geometry, and signal phasing to estimate the average control delay per vehicle (TRB 2010). On the other hand, unsignalized intersections incorporate all-way stop-controlled and side-street stop-controlled evaluations (TRB 2010).

Table 22. Intersection Level of Service Criteria.

Level of Service	Signalized Intersection Control Delay per Vehicle (Seconds)	Unsignalized Intersection Control Delay per Vehicle (Seconds)
A	≤ 10.0	≤ 10.0
B	> 10.0 and ≤ 20.0	> 10.0 and ≤ 15.0
C	> 20.0 and ≤ 35.0	> 15.0 and ≤ 25.0
D	> 35.0 and ≤ 55.0	> 25.0 and ≤ 35.0
E	> 55.0 and ≤ 80.0	> 35.0 and ≤ 50.0
F	> 80.0	> 50.0

This study uses signalized intersections to calculate the discounting factors to determine point based I/D amount.

7.1.4 Contractor's Additional Cost Adjustment

Savings associated with LOS for any given roadway profile can be calculated using the equation given below:

(AADT – ADT LOS Capacity Threshold) × (Percentage of Trucks ×Time Value of Trucks + Percentage of Automobiles ×Time Value of Automobiles) ×LOS Delay (20)

The I/D amount calculated from CAC is then added to the savings generated from LOS to arrive at point based estimates of I/D for the lower bound.

7.2 Total Savings Adjustment Based on Net Present Value

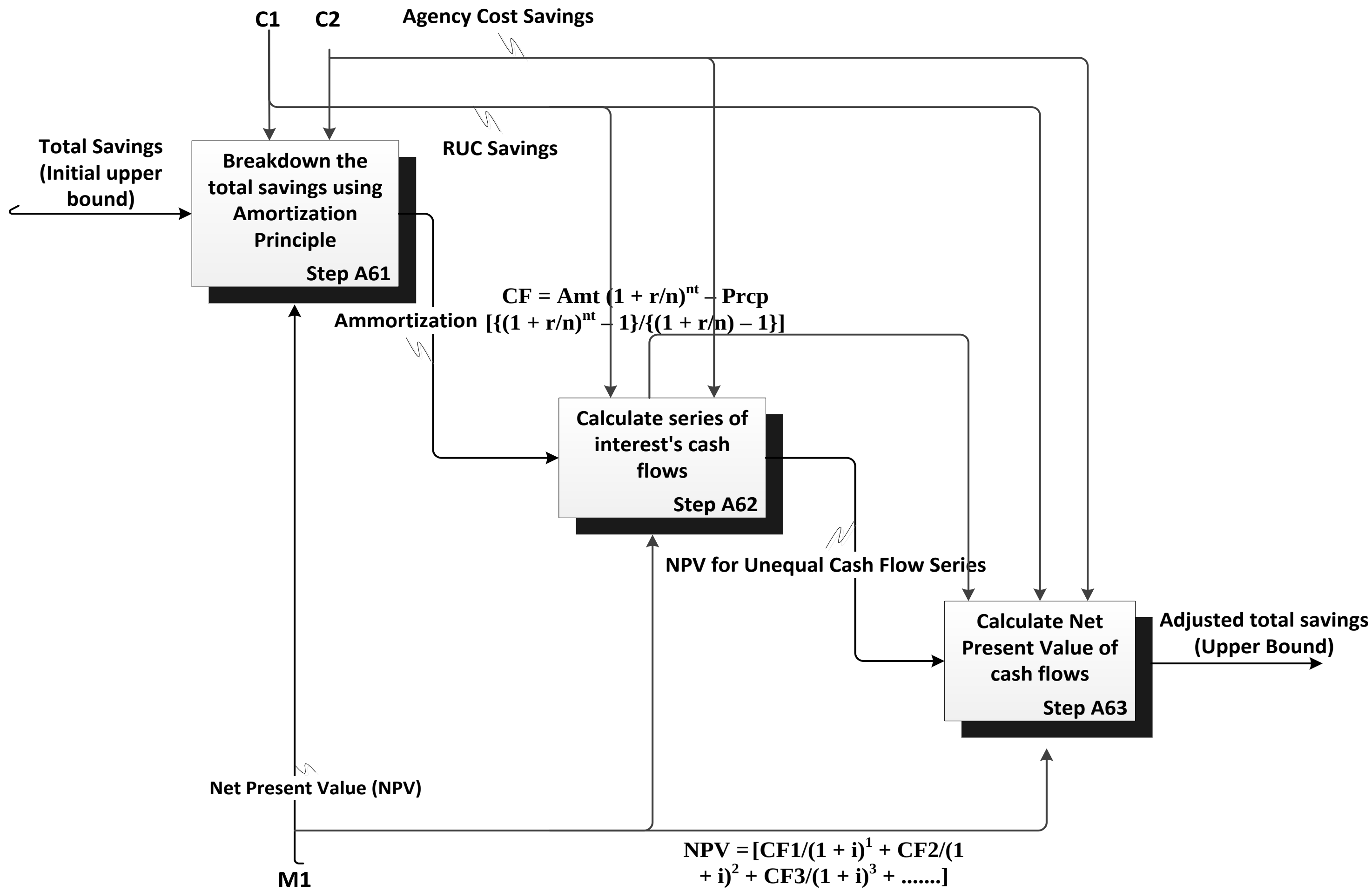


Figure 16. IDEF0 Framework for Determining Adjusted Upper Bound Using Net Present Value.

7.2.1 Use of Net Present Value Analysis for Adjusting the Upper Bound

NPV describes today's worth of a future amount of money before interest earnings and charges. For this study, NPV of the interests accumulated over a loan period is considered as the baseline for adjusting the initial upper bound. STAs are benefited from completing the project early, resulting in a reduction in RUC and agency cost. If the agency can have advanced knowledge of the savings from the NPV perspective, this reduction can be used to adjust the initial upper bound (i.e., total savings to road user and to the agency from early project completion). For the adjustment, initial total savings (i.e., total savings in road user cost and agency cost times maximum probable number of days derived from the previous stages) are incorporated in a NPV cash-flow analysis stream.

7.2.2 Accumulated Interests

The quantified total savings are assumed to be the amount that the contracting agency needs to borrow from project funding agencies. These total savings can be assumed to be a loan amount required to pay interests accrued exponentially over the loan period. The following equation can be used for the cash flow analysis:

$$\text{CF} = \text{Amount}\,(1 + r/n)^{nt} - \text{Principal}\,[\{(1 + r/n)^{nt} - 1\}/\{(1 + r/n) - 1\}] \tag{21}$$

where,
CF = Cash Flow (Total balance after t years).
Amount = Total amount borrowed.
n = number of payments.
Principal = Principal amount paid per payment.
r = rate of interest.

7.2.3 Net Present Value of Cash Flow

The interest accrued each year can be used to create a series of cash flows. NPV of the total cash flows (Interest payments each year) can be calculated using the following equation:

$$\text{NPV} = [\text{CF1}/(1 + i)^1 + \text{CF2}/(1 + i)^2 + \text{CF3}/(1 + i)^3 + \ldots\ldots] \tag{22}$$

where,
i is the rate of return per period.
CF1 is the cash flow during the first period.
CF2 is the cash flow during the second period.
CF3 is the cash flow during the third period, and so on...

In general, the NPV of the interest payments accrued each year is designed to decrease the initial amount of total savings of the I/D upper bound.

8 VALIDATION STUDIES: MODEL PRACTICALITY AND ROBUSTNESS

Accelerated construction on the nation's aging highway infrastructure has become a major issue in recent years as it is increasingly recognized that the economic health of the U.S. is tied to the condition of its transportation infrastructure. To address this issue, Caltrans initiated the Long-Life Pavement Rehabilitation Strategies (LLPRS) program in 1998 to rebuild 2,800 lane-km of high-volume urban freeway with premium pavements. Most LLPRS projects are large-scale and located in heavily trafficked urban areas; 80 percent are within the Los Angeles Basin and 15 percent of them are in the San Francisco Bay Area (Choi and Kwak 2012). The practicality and robustness of the proposed I/D determination framework in predicting realistic I/D amounts were tested and validated in the following two LLPRS projects that have been already completed and are deemed to be experimental with the use of detailed I/D provisions.

8.1 Case Study I: I-15 Devore Concrete I/D Project (EA 0A4234)

The scope of I-15 Devore project (Caltrans project ID: EA 0A4234), which has been selected for use as an example of the proposed model, was the rehabilitation of a heavily trafficked 2.67-mile stretch of badly damaged concrete truck lanes on I-15 in Devore in Southern California. Key information about the rehabilitation project includes:

- Project size: approximately $18 million.
- Lane-miles to be rebuilt: 10.7 lane-mile.
- Construction window: extended weekday closures with around-the-clock operations.
- Lane closure scheme: concurrent double-lane closure with counter-flow traffic.
- Cross-section design: 11.4-in doweled slabs of Type III Portland concrete cement and a 5.9-in asphalt concrete (AR-8000 binder) base.
- AADT: approximately 100,000 vehicles.
- Percentage of trucks at the construction work zone: 10 percent.

8.1.1 Step 1: Estimate the Schedule Baseline of I/D with the Probable Number of Days That Can Be Saved by Using an Accelerated Schedule

Given the project's scope, pavement design, and construction working methods, Table 3 shows that the project would require 7.9 72-hour weekday closures (24 working days) with a conventional contracting strategy and 6.6 closures (20 working days) with an I/D accelerated construction strategy. Four working days (1.3 closures) is the estimated maximum probable number of days that I/D use could eliminate for this project.

8.1.2 Step 2: Quantify the Initial I/D Lower Bound of CAC

Based on the probable number of days that I/D use could eliminate, the schedule compression rate ΔT is set to −0.166 (16.6 percent reduction of t_0), as shown in Figure 17. The contractor's daily additional cost growth rate (ΔC) is estimated as follows using Equation (8):

$$– 0.1378 – 0.0042\, t_0 + 0.0021\Delta T = – 0.1378 – 0.0042\,(1) – 0.0021(.166)$$

$$\mathbf{= 0.1423\% = \$25{,}614/day\ (\$76{,}842/closure)}$$

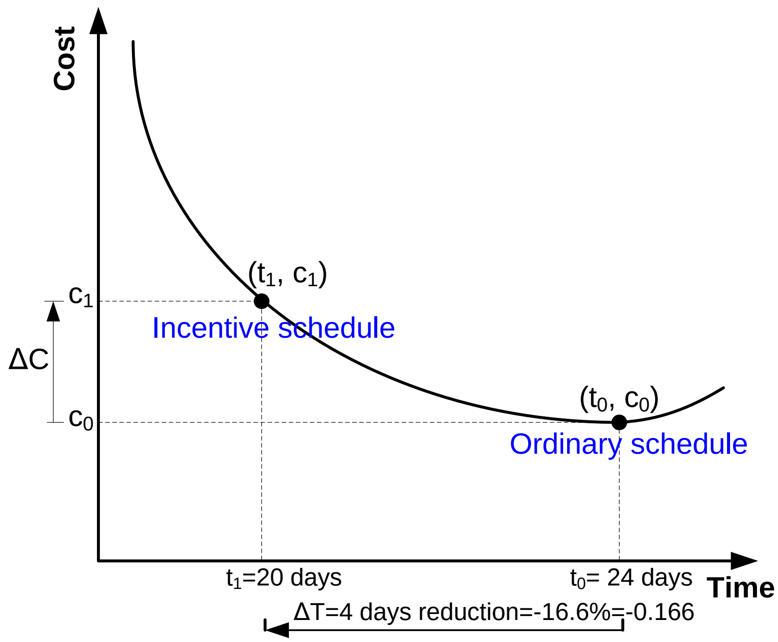


Figure 17. Calculation of ΔT for the I-15 Devore Project.

8.1.3 Step 3 and 4: Compute the Initial I/D Upper Bound of Total Savings

According to the RUC lookup table (refer to Table 18 as this project uses weekday construction under full closure), for this project's given AADT (100,000) and percentage of trucks (10 percent), the expected daily monetary saving to road users is estimated to be $175,151. The expected closure-based monetary saving to road users is $525,453. The expected savings in the agency cost by completing the project five days early is estimated to be $68,400 ($205,200 per closure), based on the monetary value calculation in Table 20.

This analysis reveals that the project is an appropriate one for use of an I/D provision because the estimated lower bound is smaller than the total time value savings in both the daily- and closure-based measurements, as shown in Table 26 below.

Table 23. Initial Lower and Upper Bounds of I/D (I-15).

	ΔC (JPCP) (Initial Lower Bound)	Savings to road users	Savings to the agency	Total Savings (Initial Upper Bound)
Daily I/D	$25,614	$175,151	$68,400	$243,551
Closure I/D	**$76,842**	$525,453	$205,200	**$730,653**

Table 26 shows the initial lower and upper bounds for determining I/D dollar amount for the given project. The maximum incentive amount in this range is within 5 percent of the agency's budget for this project.

8.1.4 Step 5: Adjust the Initial I/D Lower Bound by Applying the Concept of LOS

The AADT for this project is known as 100,000. Due to the given traffic volume, the level E of LOS would be suitable for the project. From Table 21 and 22, the capacity threshold is estimated to be 15,000 and signalized intersection control delay per vehicle is between 55–80 seconds. To adjust the initial CAC growth rate derived through stage 2, 68 seconds (i.e., mean value) was computed as the delay time for this project. Therefore, the difference between AADT and ADT capacity thresholds implies that 85,000 vehicles could possibly avoid a work zone traffic delay of 68 seconds when passing through any given point in the construction work zone.

In addition, based on Table 15, the average time value for automobile and trucks is $11.51 and $27.83 per hour, respectively. The percentage of trucks at the construction work zone is 10 percent. Given this information, the following adjustment can be made on the initial CAC growth rate by applying Equation (20):

(AADT – ADT LOS Capacity Threshold) × (Percentage of Trucks × Time Value of Trucks + Percentage of Automobiles × Time Value of Automobiles) × Delay
= (100,000 – 15,000) × (0.1 × 27.83 + 0.9 × 11.51) × 68 / (60 × 60) = $21,100

This amount implies that the contractor is eligible to get an addition incentive bonus of $21,000 if he maintains the LOS E. Table 24 shows daily and closure I/D dollar amounts for the lower bond of CAC before and after adjustment is made.

Table 24. I-15 Devore Project: Point based Estimates of I/D for LOS E.

	Initial CAC before adjustment	Final CAC after Adjustment
Daily I/D	$25,614	$46,714
Closure I/D	$76,842	**$140,142**

The initial CAC growth rate of acceleration was determined in the second stage, and the CAC growth rate is adjusted afterward in that stage by applying the concept of LOS, generally being upward in a viable way to further motivate the contractor to pursue accelerated construction. The initial CAC amount still provides a meaningful benchmarking point—the minimum I/D rate so that the contractor could be minimally motivated. The adjusted CAC amount is desired to more effectively motive the contractor, depending on project's need of early completion that is reflected by LOS. In this regard, the initial CAC is served as the minimum I/D rate and the adjusted CAC is served as the realistic I/D lower bound.

8.1.5 Step 6: Adjust the Initial I/D Upper Bound by Applying the Concept of NPV

Initial daily total savings = $243,551
Initial total savings for 4 days (maximum probable days saved) = $974,204

$974,204 reflects the total monetary value that can be saved by completing the project 4 days earlier, which was identified as the maximum probable number of days that can be saved by using an accelerated I/D schedule. In the NPV analysis, this amount is assumed to be the money that the contracting agency needs to borrow from project funding agencies (e.g., loan amount required to pay interests accrued exponentially over the loan period). This can be interpreted as agency savings in terms of interest payments accumulated over the loan period.

In the NPV adjustment, the research team considers this loan amount of $974,204 with an interest rate of 5 percent over a 10-year period. Table 25 shows the breakdown structure of the principal amount and the interest charges. The generated cash flow stream can then be used to calculate the NPV of the interest payments accumulated over a period of 10 years at an interest rate of 5 percent. The adjusted NPV upper bound of this project is estimated to be **$287,436/closure and $71,859/day**.

Table 25. Breakdown Structure of the Loan Amount (I-15 Devore Project).

Year	Principal	Interest	Balance
2013	77,454	48,710	974,204
2014	81,326	44,838	896,750
2015	85,393	40,771	815,424
2016	89,662	36,502	730,031
2017	94,146	32,018	640,369
2018	98,853	27,311	546,223
2019	103,795	22,369	447,370
2020	108,985	17,179	343,575
2021	114,434	11,730	234,590
2022	120,156	6,008	120,156

8.1.6 Step 7: Determine Optimal I/D Rates

As stated earlier, most agencies would not want to use an amount equivalent to the total time value savings (upper bound) due to budget constraints. It would also be ineffective to set the same amount of total time value savings as the upper limit even if the agency has an adequate budget for an incentive payment. The model developed in this study provides a reasonable range-based estimate of I/D amounts between the lower and upper limits that are sufficient to motivate contractors to apply their ingenuity for accelerated construction while fall within the agency's budget. The most realistic I/D amount for the given project was determined by adjusting the initial I/D range through step 5 and step 6.

$$\mathbf{\$46{,}714} \leq \text{Daily I/D} \leq \mathbf{\$71{,}759}$$

$$\mathbf{\$140{,}142} \leq \text{Closure I/D} \leq \mathbf{\$287{,}436}$$

$$\mathbf{\$186{,}856} \leq \text{Maximum I/D} \leq \mathbf{\$287{,}036}$$

Following the proposed seven-step framework in an algorithmic order, two types of I/Ds are determined: one for completion of an internal project milestone within a specified number of closures (closure I/D), and another for completion of an entire project sooner than originally scheduled (daily I/D). The maximum incentive amount is then calculated by multiplying the maximum probable number of days the project can eliminate by the daily I/D amount. If the maximum incentive amount at the end of the analysis falls outside the agency budget, the total time savings (upper bound) and daily incentive amount should be adjusted until they are changed to an economically rational maximum incentive amount that can be offered that will still motivate the contractor to complete the project ahead of schedule. The initial I/D range is adjusted to the optimal lower and upper bounds of closure I/D (Figure 18).

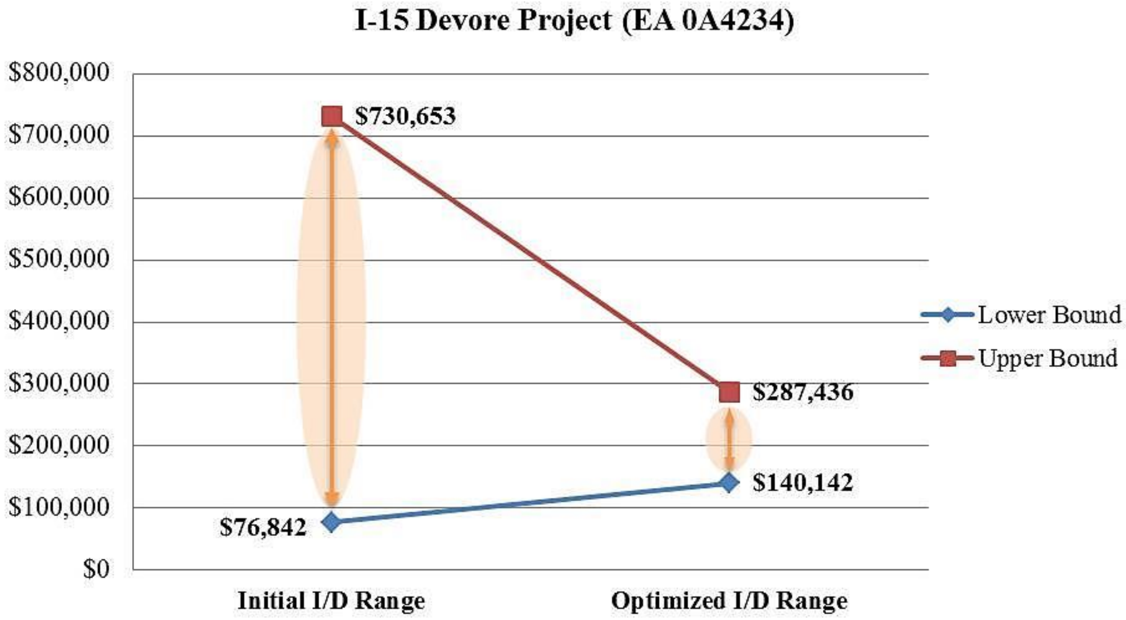


Figure 18. Initial and Optimized Range of Closure I/D for I-15 Devore Project.

When Caltrans implemented this I/D project in 2004, the agency used a daily incentive bonus of $75,000, an acceptable amount that could properly motivate the contractor to accomplish an early project completion.

8.2 Case Study II: I-710 Long Beach Project (EA 1384U4)

The I-710 Long Beach Project in Los Angeles was the first large-scale asphalt concrete pilot project for evaluating the Caltrans LLPRS with a detailed I/D provision. The construction corridor represents one of the most heavily traveled portions of I-710. The scope of I-710 Long Beach Project (Caltrans Project ID: EA 1384U4) was to rehabilitate a 16.4 lane-mile section of I-710 near the Port of Long Beach during a series of 55-hour weekend closures. The project consisted of three full-depth asphalt concrete (FDAC) replacement sections (1.0 mile total) under freeway overpasses, and two sections (1.7 mile total) with crack, seat, and overlay (CSOL) of existing PCC slabs with asphalt concrete (AC). Key information about the rehabilitation project includes:

- Project size: approximately $16.7 million.
- Lane-miles to be rebuilt: 16.4 lane-mile.
- Construction window: extended closures (55-hour weekend) with around-the-clock operations.
- Lane closure scheme: concurrent double-lane closure with counter-flow traffic.
- AADT: approximately 120,000 vehicles.
- Percentage of trucks at the construction work zone: 5 percent.

8.2.1 Step 1: Estimate the Schedule Baseline of I/D with the Probable Number of Days That Can Be Saved by Using an Accelerated Schedule

Given the project's scope, pavement design, and construction working methods, Table 2 shows that the project would require 10.4 extended weekend closures (24 working days) with a conventional contracting strategy and 8.6 closures (20 working days) in an I/D contracting strategy. Four working days (1.8 closures) is the estimated maximum probable number of days that I/D use could eliminate.

8.2.2 Step 2: Quantify the Initial I/D Lower Bound of CAC

Based on the probable number of days that I/D use could eliminate, the schedule compression rate ΔT is set to be −0.166 (16.6 percent reduction of t_0) shown in Figure 19. The contractor's daily additional cost growth rate (ΔC) is estimated as follows using Equation (9):

$$– 0.096 + 0.0064\, t_0 – 0.0032\Delta T = – 0.096 + 0.0064\,(1) + 0.0032(0.166)$$
$$\mathbf{= 0.0891\% = \$14{,}880/day\ (\$34{,}075/closure)}$$

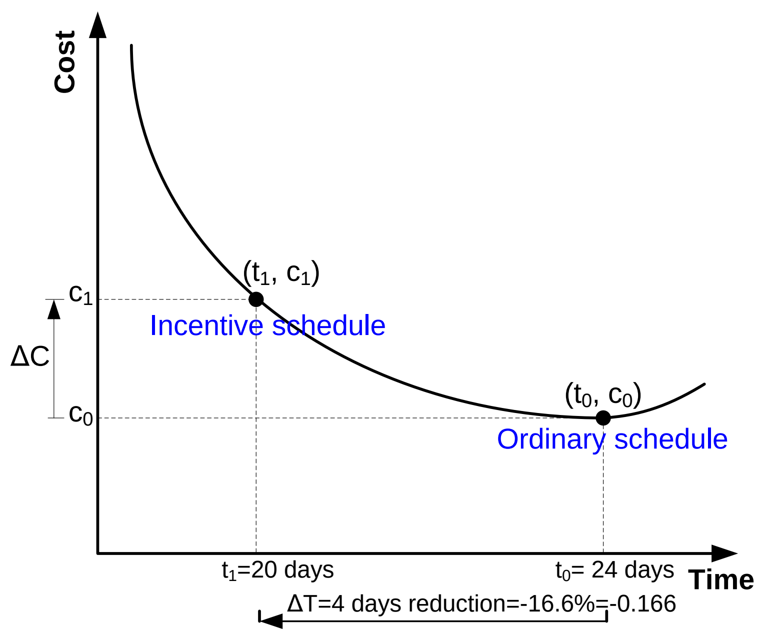


Figure 19. Calculation of ΔT for the I-710 Long Beach Project.

8.2.3 Step 3 and 4: Compute the Initial I/D Upper Bound of Total Savings

According to the RUC lookup table (refer to Table 17 as this project uses weekend construction under full closure), for this project's given AADT and percentage of trucks, the expected daily monetary saving to road users is estimated to be \$526,347. The expected closure-based monetary saving to road users is \$1,206,212, and the expected savings in agency cost by completing the project four days early is estimated to be \$68,400 (\$156,750 per closure), based on monetary value calculation in Table 20. This analysis reveals that the project is an appropriate one for use of an I/D provision because the estimated lower bound is smaller than the total time value savings in both the daily- and closure-based measurements.

Table 26. Initial Lower and Upper Bounds of I/D (I-710).

	∆C (CRCP) (Initial Lower Bound)	Savings to road users	Savings to the agency	Total Savings (Initial Upper Bound)
Daily I/D	$14,880	$526,347	$68,400	$594,747
Closure I/D	**$34,075**	$1,206,212	$156,750	**$1,362,962**

Table 27 shows the results of initial lower and upper bound estimates for I-710 Long Beach Project through step 1 to step 4.

8.2.4 Step 5: Adjust the Initial I/D Lower Bound by Applying the Concept of LOS

The AADT for this project is known as 120,000. Due to the given traffic volume, the level D of LOS would be suitable for this project. From the Table 21 and 22, the capacity threshold is estimated to be 13,500 and signalized intersection control delay per vehicle is between 35–55 seconds. To adjust the initial CAC growth rate derived through stage 2, 45 seconds (i.e., mean value) was computed as the delay time for this project. Therefore, the difference between AADT and ADT capacity thresholds implies that 106,500 vehicles could possibly avoid a work zone traffic delay of 45 seconds when passing through any given point in the construction work zone.

In addition, based on Table 15, the average time value for automobile and trucks is $11.51 and $27.83 per hour, respectively. The percentage of trucks at the construction work zone is 5 percent. Given this information, the following adjustment can be made on the initial CAC growth rate by applying Equation (20):

(AADT – ADT LOS Capacity Threshold) × (Percentage of Trucks × Time Value of Trucks + Percentage of Automobiles × Time Value of Automobiles) × Delay
$= (120{,}000 - 13{,}500) \times (0.05 \times 27.83 + 0.95 \times 11.51) \times 45 / (60 \times 60) = \$16{,}409$

This amount implies that the contractor is eligible to get an addition incentive bonus of $16,409, if he maintains the LOS D. Table 30 shows daily and closure I/D dollar amounts for the lower bound of CAC before and after adjustment is made.

Table 27. I-710 Long Beach Project: Point Based Estimates of I/D for LOS D.

	Initial CAC through Step 2	Final CAC after Adjustment
Daily I/D	$14,880	$31,289
Closure I/D	$34,075	$71,651

As noted earlier in the first case study on I-15 Devore Project, the initial CAC is served as the minimum I/D rate and the adjusted CAC is intended to serve as the realistic I/D rate.

8.2.5 Step 6: Adjust the Initial I/D Upper Bound by Applying the Concept of NPV

Initial daily total savings = $594,747
Initial total savings for 4 days (maximum probable days saved) = $2,378,988

$2.38 million reflects the total monetary value that can be saved by completing the project 4 days earlier, which was identified as the maximum probable number of days that can be saved by using an accelerated I/D schedule. In the NPV analysis, this amount is assumed to be the money that the contracting agency needs to borrow from project funding agencies (e.g., loan amount required to pay interests accrued exponentially over the loan period). This can be interpreted as agency savings in terms of interest payments accumulated over the loan period.

In the NPV adjustment, the research team considers this loan amount of $2,378,988 with an interest rate of 2 percent over a 15-year period. Table 28 shows the breakdown structure of the principal amount and the interest charges. The generated cash flow stream can then be used to calculate the NPV of the interest payments accumulated over a period of 15 years at an interest rate of 2 percent. The adjusted NPV upper bound of this project is estimated to be **$398,201/closure and $99,550/day**.

Table 28. Breakdown Structure of the Loan Amount (I-710 Long Beach Project).

Year	Principal	Interest	Balance
2013	137,566	47,580	2,378,988
2014	140,318	44,828	2,241,422
2015	143,124	42,022	2,101,104
2016	145,986	39,160	1,957,980
2017	148,906	36,240	1,811,994
2018	151,884	33,262	1,663,088
2019	154,922	30,224	1,511,204
2020	158,020	23,965	1,356,282
2021	161,181	27,126	1,198,262
2022	164,404	20,742	1,037,081
2023	167,692	17,454	872,677
2024	171,046	14,100	704,985
2025	174,467	10,679	533,939
2026	177,957	7,189	359,472
2027	181,516	3,630	181,515

8.2.6 Step 7: Determine optimal I/D rates

The most realistic I/D amount for the given project was determined by adjusting the initial I/D range through step 5 and step 6.

$$\mathbf{\$34{,}075} \leq \text{Daily I/D} \leq \mathbf{\$99{,}550}$$

$$\mathbf{\$71{,}651} \leq \text{Closure I/D} \leq \mathbf{\$398{,}201}$$

$$\mathbf{\$136{,}300} \leq \text{Maximum I/D} \leq \mathbf{\$398{,}200}$$

The estimated maximum incentive amount at the end of the analysis falls inside the agency budget. The initial I/D range is adjusted to the optimal lower and upper bounds of closure I/D (Figure 20).

When Caltrans implemented this I/D project in 2003, the agency used an incentive of $100,000 per weekend closure, which is close to the predicted value ($71,651) of I/D lower bound. Conversely, the contractor was subject to a disincentive in the same amount; there was no specified upper limit on the disincentive amount. An incentive cap of $500,000 was the specified maximum incentive amount, which is acceptable because the maximum incentive amount in this range is within 5 percent of the agency's budget for this project. The contractor completed the project two weekends early and received a $200,000 incentive. However, in the post-construction meeting, Caltrans received feedback from the contractor pointing out that the incentive payment was not sufficient to commit additional resources. The model developed in this study confirms the fact that even though the incentive amount of $100,000 was acceptable based on the analysis, it was not sufficient for the contractor to add additional resources to affect the earliest possible completion, as the actual incentive amount paid to the contractor turned out to be close to the adjusted lower bound.

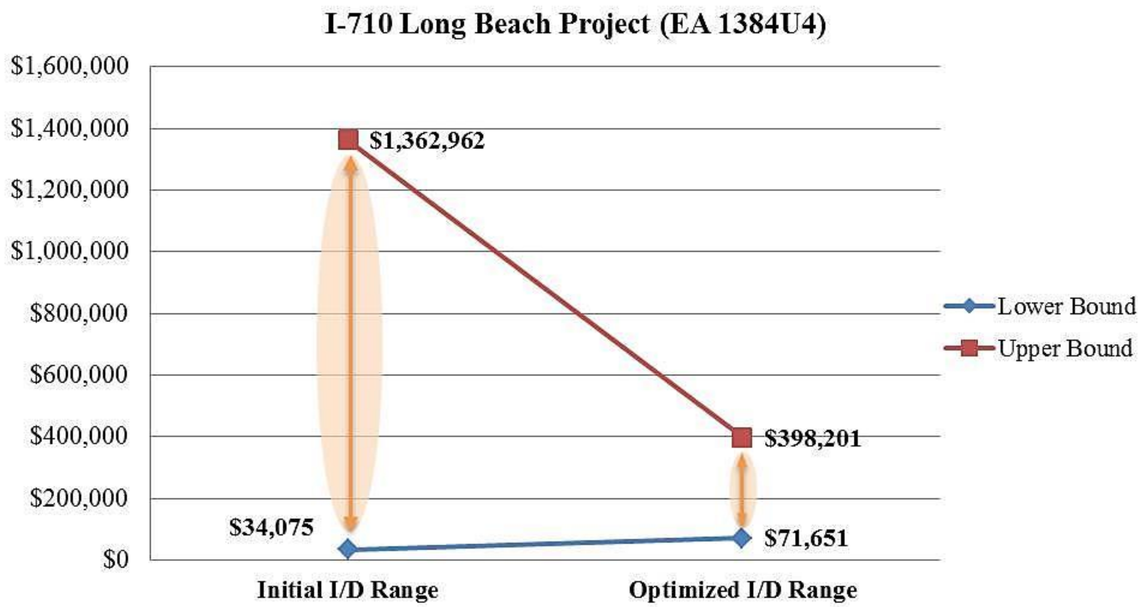


Figure 20. Initial and Optimized Range of Closure I/D for I-710 Long Beach Project.

9 SUMMARY, CONCLUSIONS, AND FUTURE STUDY

The I/D contracting strategy has been widely adopted by STAs to complete critical civil transportation improvement projects ahead of their assigned schedule in order to minimize inconvenience to motorists which in turn results in significant cost savings in terms of road user cost and agency cost. Use of I/Ds are intended to motivate contractors to use their ingenuity to complete the projects earlier by employing additional resources, resulting in additional cost growth. Therefore, incentives should be greater than the contractor's additional cost for expediting construction, and at the same time in order to sound economical, incentives should be less than the total savings as measured by their impacts on road users and the contracting agency. Several research studies to date have reported that determining I/D rates that promote early completion of projects, exceed contractors' additional cost of acceleration, and are below the total savings is extremely difficult due largely to the lack of systematic methods and tools for helping STAs determine effective I/D rates.

To tackle these issues, this study aims to create a novel decision-support modeling framework and test whether it can reasonably determine and justify the most economical I/D dollar amounts from simulation and stochastic modeling data, for the purpose of significantly reducing the cost the agency spends and the time it takes to develop. To achieve this objective, a simulation-based stochastic approach was adopted to concurrently capture schedule, contractors' additional cost of acceleration, and total savings to road users and to the agency by combining existing schedule and traffic simulations with a stochastic analysis. These monetary values were then adjusted toward more realistic I/D rates by applying the concepts of LOS and NPV. The robustness of the proposed seven-stage framework was tested and validated using case studies of two I/D completed rehabilitation projects that were deemed experimental at their time of construction.

The results of the validation study on the two real-world projects reveal that both projects selected for this study were appropriate for application of an I/D provision since the estimated lower bound was smaller than the total time value savings. The validation study also proved the analytical capability of the model for highway rehabilitation projects in estimating realistic I/D amounts. Specifically, the contracting agency used a closure incentive of $100,000 for the I-710 project. The I/D amount ($100,000 per 55-hour weekend closure) set by the agency was close to the adjusted lower bound ($71,651 per closure) predicted by the model. However, in the post-construction meeting with the contractor, the agency acknowledged that the incentive amount paid to the contractor was not enough for the contractor to recoup the cost added for accelerating construction; the adjusted upper bound was $1.36 million per closure. Because this project had been time-critical, a larger incentive amount could have been put in place to more effectively motivate the contractor to complete the project earlier.

The proposed work provides the research community and industry practitioners with the first view and systematic estimation method that they can use to determine the most economical and realistic I/D dollar amount for a given project—an optimal value that allows the agency to stay within budget while effectively motivating contractors to complete projects ahead of schedule. It will also significantly reduce the agency's expenses in the time and effort required for determining I/D dollar amounts. Use of the proposed framework would establish a win-win solution for state highway agencies and contractors alike. It can help agency engineers and decision makers make better-informed decisions and allocate more realistic incentives when they consider the implementation of an I/D provision. Use of the framework can also benefit contractors bidding on projects that include I/D provisions because it can provide them with advanced knowledge of the balanced time-cost tradeoff amount required for acceleration.

The proposed framework provides the missing link between contractor's additional cost commitments of expediting construction and total benefits received by saved days. For instance, the proposed integration approach to determining an appropriate I/D rate can be used to justify the I/D rate from a cost-benefit standpoint. This, in turn, will enable the future development of novel, automated applications for the I/D contracting method. Therefore, the proposed framework and discoveries sought in this project are expected to serve as a grounding work for a new decision-support computer model for I/D contracting. In the future study, the proposed discounting algorithm that balances the upper and lower bounds needs to be fine-tuned and further developed. Finally, the research team has recommended that pioneering STAs conduct pilot studies to test whether the proposed framework can reasonably determine and justify the most economical I/D dollar amounts for each type of highway pavement rehabilitation projects.

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