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Decision support model for incentives/disincentives time–cost tradeoff

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ABSTRACT

Offering contractors a monetary incentive for early project completion provides agencies with an innovative means to expedite construction. To be effective, the incentive amount should exceed the contractor's additional cost (CAC) for completing the project early. Yet, estimating CAC poses a major challenge to agencies largely because of contractors' reluctance to disclose information about their profits. This study introduces a predictive, quantitative model that estimates realistic CACs by combining an existing schedule simulation technique with a regression method. An innovative, reliable tool called Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) was used for the simulation. Using CA4PRS, a set of contractors' time–cost tradeoff data was created and a linear regression analysis based on a second degree polynomial equation was performed to predict CAC growth rate by analyzing how the CAC interacts with the agency's specified schedule goal. The robustness of the proposed model was then validated through two case studies. This model can assist decision-makers in estimating better optimal incentive amounts.

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1. Introduction

1.1. Paradigm change in highway infrastructure construction

The aging of the transportation infrastructure in the U.S. has created an urgent challenge for State Highway Agencies (SHAs): they must renew badly deteriorated infrastructure systems while minimizing the impact and inconvenience that construction lane closures have on the traveling public. As a partial response to this challenge, the Obama administration's economic stimulus package included specific funding (about $80 billion) targeted for extensive transportation infrastructure rehabilitation and rebuilding projects [1]. Moreover, ‘improving transportation infrastructure’ has been identified as one of the fourteen *grand challenges for engineering in the 21st century* by the National Academy of Engineering [2].

From 1999 to 2001, approximately 30% of the highway construction projects in the United States were undertaken in urban areas [3]. The typical traffic disruptions incurred by these urban highway construction projects cause major inconveniences to the traveling public and commercial enterprises that rely on the roadways.

As a response to this growing challenge, many SHAs have changed their focus from development and construction of new facilities to maintenance and renewal of existing facilities [4,19]. Research into public perception has 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 [5].

1.2. Time-based incentives/disincentives for accelerated construction

To carry out transportation infrastructure improvements, SHAs 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 SHAs 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.

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 [6,7]. Indeed, incentive/disincentive (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 SHAs and contractors alike because they can establish win–win solutions for both parties [8,9]. 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.

1.3. Schedule simulations for building baseline schedule data

In the implementation of time-based I/D projects, the determination of contract time may be the most important factor that directly

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influences effectiveness. The Federal Highway Administration (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” [10].

In the time-based I/D contracting method, the contracting agency determines how long it will take to complete the project and the agency's contract completion time estimate is presented among the bid documents. In determining contract time, both historical information [11] and a Critical Path Method (CPM) analysis or a manual calculation is typically used as the basis for the average production performance of the contractor [4,6,12,13].

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. 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 [14]. Moreover, the related literature points out that systematic approaches to determining contract completion times have rarely been found in current industry practice.

Agency efforts to deliver projects in a timely manner have been facilitated by use of innovative software analysis programs and scheduling techniques like 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 (CA4PRS), which has come into use because of its ability to analyze schedules, costs, and work zone traffic impacts as shown in Fig. 1.

CA4PRS was developed in 1999 under the Federal Highway Administration (FHWA) pooled research fund with a multistate consortium (California, Minnesota, Texas, and Washington) to help agency decision-makers and contractors analyze schedules, costs, and work zone traffic impacts. The software has three main functions to estimate schedule, cost, and work zone. The CA4PRS 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, etc.), cross-section designs, construction windows (e.g., nighttime, weekend, extended 24/7 operations), and contractor logistics and resource constraints [15]. The CA4PRS 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 [16].

CA4PRS has been widely used in California and in three 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 [16]. As a result, there has been nationally growing acceptance of the program, including a recent arrangement by FHWA to provide free group licenses for all fifty states.

In the research described in this paper, CA4PRS generated the baseline schedule data to quantify the level of contractors' additional cost (CAC) growth for using additional resources. It was assumed that the simulation using CA4PRS would provide reliable baseline schedule data because its accuracy was validated by numerous highway renewal projects. It was specifically used for this study to estimate,

- how many closures (days) the project would take; and
- how many closures (days) a contractor can reasonably eliminate at each of four given resource levels.

2. Research scope and methods

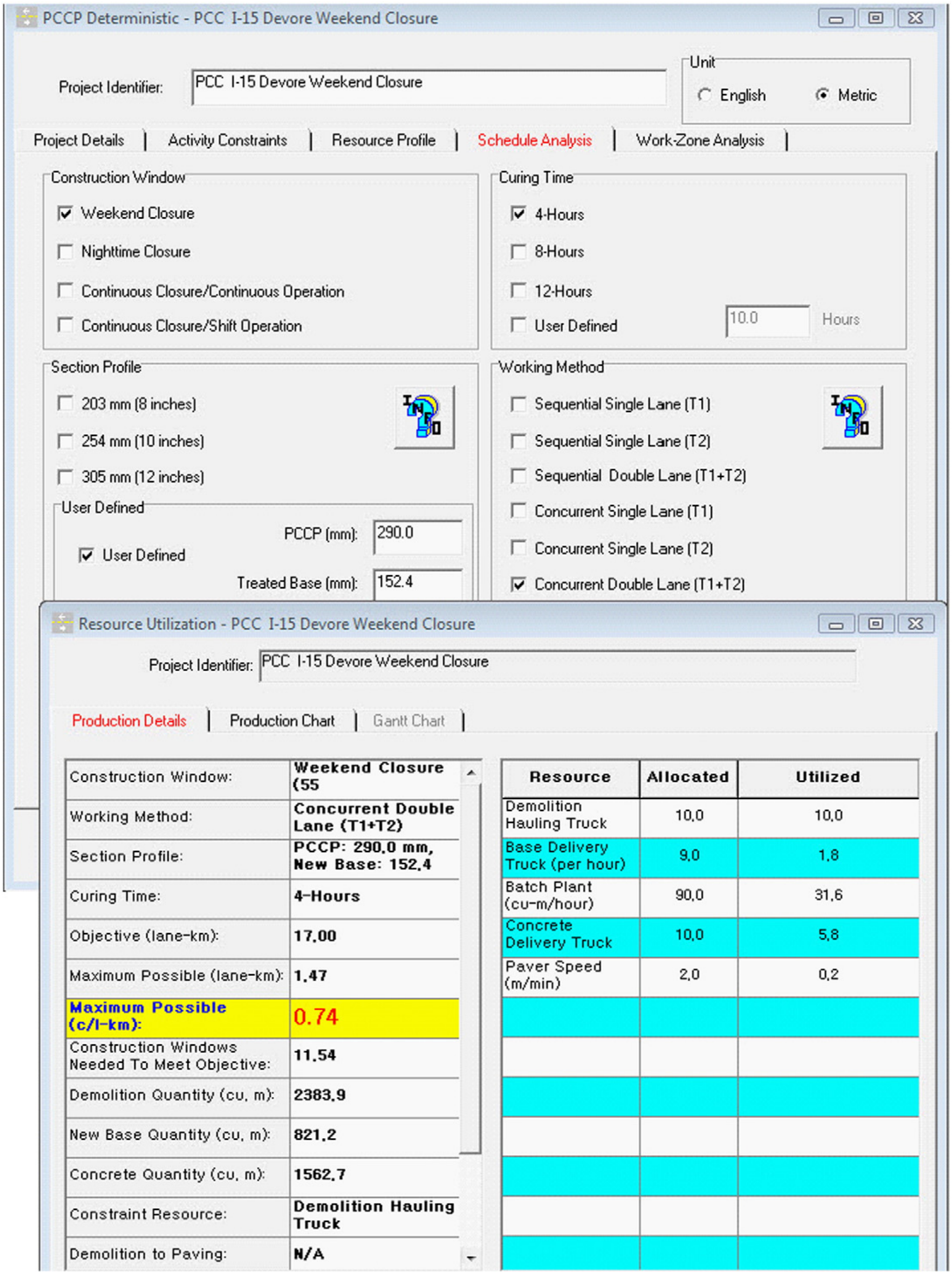
To effectively encourage contractors to complete projects earlier, the size of the incentive should exceed the CAC for expediting construction, which are defined in this study as the *lower bound*. An incentive amount smaller than the CAC would not only dissuade competitive contractors from bidding, it could also create a “winner's curse” for small-scale contractors. In addition, to be sound economically, incentive fees should be less than a portion of the decrease in total time savings (i.e., road user cost and agency cost) for cutting construction times, defined in this study as the *upper bound*. Therefore, incentive fees should satisfy the following relationship:

- CAC≤I/D≤Discounted total savings to road users and the contracting agency. (1)

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 SHAs have well-developed methods for establishing the I/D upper bound of Eq. (1) [17]. However, the lack of available data makes it extremely difficult to estimate the lower bound (i.e., 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. Even among researchers who reported success in obtaining contractors' final construction cost data in trying to estimate the level of CAC commitments, the final cost value was determined most likely to be the final cost paid at the end of construction, which includes increases to the original contract bid amount resulting from contract change orders issued during construction [18].

To overcome the limitation stemming from the absence of methods for establishing the I/D lower bound, this study proposes a new approach for quantifying a lower bound amount that can effectively motivate contractors to pursue accelerated construction. This study combines an existing schedule simulation with a regression method to develop a predictive, quantitative model. The model aims at estimating the I/D lower bound by modeling the relationship of “time–cost tradeoff” on four different levels of resource use; that is, ordinary, 5% increase, 15% increase, and 25% 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 three sponsoring states [16]. To generate schedule data for research described in this paper, the schedule simulation with CA4PRS was performed based on contractors' actual construction plans sourced from real-world construction projects. Three highway pavement rehabilitation projects recently completed in California were selected because these projects were large-scale I/D pilot projects with 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 the Department of California Transportation (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 determine 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 then validated through two case studies.

It is assumed that in a well-planned I/D contract the incentive amount will be sufficient to motivate a contractor to use additional resources to complete a project early. Following this assumption, four



Project Identifier: PCC I-15 Devore Weekend Closure

Unit: ○ English ● Metric

Construction Window
☑ Weekend Closure
☐ Nighttime Closure
☐ Continuous Closure/Continuous Operation
☐ Continuous Closure/Shift Operation

Curing Time
☑ 4-Hours
☐ 8-Hours
☐ 12-Hours
☐ User Defined 10.0 Hours

Section Profile
☐ 203 mm (8 inches)
☐ 254 mm (10 inches)
☐ 305 mm (12 inches)
User Defined
☑ User Defined
PCCP (mm): 290.0
Treated Base (mm): 152.4

Working Method
☐ Sequential Single Lane (T1)
☐ Sequential Single Lane (T2)
☐ Sequential Double Lane (T1+T2)
☐ Concurrent Single Lane (T1)
☐ Concurrent Single Lane (T2)
☑ Concurrent Double Lane (T1+T2)

Project Identifier: PCC I-15 Devore Weekend Closure

Construction Window:	**Weekend Closure (55**
Working Method:	**Concurrent Double Lane (T1+T2)**
Section Profile:	**PCCP: 290.0 mm, New Base: 152.4**
Curing Time:	**4-Hours**
Objective (lane-km):	**17.00**
Maximum Possible (lane-km):	**1.47**
Maximum Possible (c/l-km):	0.74
Construction Windows Needed To Meet Objective:	**11.54**
Demolition Quantity (cu. m):	**2383.9**
New Base Quantity (cu. m):	**821.2**
Concrete Quantity (cu. m):	**1562.7**
Constraint Resource:	**Demolition Hauling Truck**
Demolition to Paving:	**N/A**

Resource	Allocated	Utilized
Demolition Hauling Truck	10.0	10.0
Base Delivery Truck (per hour)	9.0	1.8
Batch Plant (cu-m/hour)	90.0	31.6
Concrete Delivery Truck	10.0	5.8
Paver Speed (m/min)	2.0	0.2

Fig. 1. Input and output screen example of the CA4PRS schedule simulation.

different resource usage levels were considered to quantify the CAC growth rates in the following procedures:

1. Identify critical factors affecting rehabilitation production performance;
2. Perform schedule estimates using CA4PRS simulations with four different resource usage levels (Table 1);
3. Determine the unit price ($/h) of all resources used;
4. Calculate CACs using Eq. (2);
5. Quantify the interaction between CAC rates and specified schedule compression rates (Table 2);
6. Draw a scatter plot of CAC growth rates over schedule compression rates to confirm that the regression data is fit into a quadratic shape;
7. Conduct a linear regression analysis to determine coefficients (β_0, β_1, and β_2);
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; and
10. Conduct a case study to check the robustness of the equation in predicting the actual values of incentive/disincentive amounts.

Table 1
CA4PRS schedule estimate versus additional resource usage.

Strategies	Cross-section profile	Construction window	Schedule estimate versus additioanl resource usage							
			Ordinary usage		5%		15%		25%	
			Closures	Days	Closures	Days	Closures	Days	Closures	Days
PCCP	8 in.	Nighttime	142.00	142.00	136.00	136.00	118.00	118.00	113.00	113.00
		Weekend	6.88	15.76	6.55	14.99	5.98	13.69	5.50	12.59
		Extended	3.13	25.04	2.98	23.81	2.72	21.75	2.50	20.00
	12 in. with 6 in. ACB	Nighttime	227.14	227.14	216.32	216.32	197.51	197.51	181.71	181.71
		Weekend	20.06	47.17	19.41	44.91	17.91	41.01	16.48	37.74
		Extended	6.83	54.64	6.51	52.05	5.94	47.51	5.46	43.70
ACP	6 in. (3 × 2 lift)	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
MACO	6 in.	Nighttime	126.24	126.24	120.25	120.25	109.82	109.82	101.06	101.06
		Weekend	17.92	41.04	17.07	39.09	15.67	35.88	14.77	33.82
		Extended	13.16	39.48	12.53	37.59	11.45	34.35	10.80	32.40

The research results and decision-support model presented in this paper will help SHAs make better-informed decisions when choosing an appropriate contracting strategy and allocating more accurate, realistic budgets for I/D contracting projects. One benefit for agencies includes reduction in the time spent calculating I/D dollar amounts. Critically, use of the model will result in significant monetary savings to the agencies and better use of public funds.

3. Limitations of the proposed model

Because I/D projects are relatively large-scale and financed with public funds, the misapplication of I/D provisions results in a loss of public resources. Therefore, it is especially important that candidate projects be carefully selected and effectively implemented. There are three basic types of incentives: cost-based incentives, quality-based incentives, and time-based incentives. This research is limited to the time-based incentives applicable to accelerated highway pavement construction projects.

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" [18]. This research will only take linear I/D into account.

The primary applications of the model proposed in this study are limited to urban highway pavement maintenance and renewal projects, which according to the data analysis represent 51% of all projects completed over the past eight years in California [19].

4. Use of incentives/discentives in practice

Generally, time-based I/D provisions increase costs for both agencies and contractors, but agencies benefit from the time saved by road users and the contractors benefit from incentive bonuses. Following is a summary of pros and cons of the I/D contracting method compared with the conventional contracting method:

1. Pros:
   - I/D contracting reduces construction time by 50% [6,7]. For example, 93.3% of I/D projects were completed on time or sooner whereas 41.2% of non-I/D projects were completed on time or ahead of schedule [20].
   - I/D contracting minimizes inconvenience to the traveling public and affected enterprises [5].
   - I/D contracting improves construction labor productivity by 25 to 30% and shortens schedules by 15 to 25% [21].
   - I/D contracting lowers agency risks by transferring them to the contractor (disincentive clause) [22,23].
   - I/D contracting provides a better definition of project objectives and a better definition of project design [24].
   - I/D contracting improves safety performance [22].
   - I/D contracting results in higher project bids because contractors expect to receive incentive bonuses [20], an advantage for agencies trying to reduce costs to the public.
2. Cons:
   - Increased cost to the contracting agency, if not effectively implemented [7].
   - Higher frequency and magnitude of change orders [20].
   - Higher probability of budget overflows [20].

Table 2
Contractor's additional cost growth on extra resource commitments.

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
PCCP	8 in.	Nighttime	4.23	0.38	16.90	1.14	20.42	1.90
		Weekend	0.01	0.59	13.13	1.01	20.11	1.43
		Extended (24/7)	4.90	0.64	13.14	1.29	20.00	1.52
	12 in. with 6 in. ACB	Nighttime	4.76	0.41	13.04	1.17	20.00	1.89
		Weekend	4.79	0.53	13.05	1.30	19.99	1.41
		Extended (24/7)	4.74	0.70	13.05	1.47	20.02	1.72
ACP	6 in. (3 × 2 lift)	Nighttime	4.76	0.40	13.04	1.20	19.99	2.00
		Weekend	4.64	0.40	9.89	1.20	10.12	1.99
		Extended (24/7)	4.72	0.32	10.38	1.12	0.00	1.78
MACO	6 in.	Nighttime	4.74	1.97	13.00	5.92	19.95	9.87
		Weekend	4.75	2.31	12.57	6.92	17.59	11.54
		Extended (24/7)	4.79	2.29	12.99	6.57	17.93	11.29

- More vulnerable to legal disputes between agency and contractor [8,20,22,25].
- Difficulty in administration [22].
- Greater effort required in project coordination and administration [6].

4.1. California

The California Department of Transportation (Caltrans) is one of the leading SHAs when it comes to I/D provisions. Prior to 1994, Caltrans used I/D provisions in the Ventura Improvement Project where the goal was to reconstruct and rehabilitate three heavily trafficked portions of the existing freeway of US-101. The project also included three bridge reconstructions. The general contractor for each portion was eligible to receive an incentive bonus of $6000 per day if the work was completed in 120 days or fewer, and was subject to a disincentive for the same amount if the work took longer than 120 days [25].

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 Interstate-10 in Los Angeles, the contractor completed the project 66 days ahead of schedule and received an incentive bonus of $200,000 per day [25].

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 2800 lane-km of deteriorated high-volume urban freeways with pavements designed to last more than thirty years with minimal maintenance [26]. In general, the LLPRS projects are constructed as accelerated 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 construction work zones. The rapid-rehab concepts of time-based I/D provisions have been validated and successfully implemented in the following three experimental time-critical LLPRS projects that used an I/D contract.

4.1.1. I/D pilot project: I-10 concrete rehabilitation in Pomona

Various I/D provisions were used in the rehabilitation of the Interstate 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 2000 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 2000 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 [27].

4.1.2. I/D demonstration project: I-710 asphalt rehabilitation in Long Beach

Caltrans included time-based I/D provisions in the I-710 Long Beach 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 ten 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 [28].

4.1.3. I/D implementation project: I-15 accelerated concrete rehabilitation in Devore

Detailed I/D provisions were applied on the Interstate15 Devore urban highway reconstruction project, the first large-scale I/D implementation project, in October 2004. 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 [29]. Due to high traffic volume during closures and the public desire for earliest possible project completion, three levels of time-based incentive provisions were specified in the contract: (1) I/D clauses on a per 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 of closures and secondary incentives for the total closure days.

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 h 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 nineteen days (a total of 456 h), and was subject to a daily disincentive penalty without a limit. A late lane-opening penalty of $5900 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 [29].

4.2. Florida

The Florida Department of Transportation (FDOT) realized that overestimation of contract completion times had prevailed in highway construction 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% without experiencing any major delays in project completion dates [4].

In 1996, the Florida Legislature authorized the department to use alternative contracting techniques with the goals of controlling time and cost increases on highway construction projects. Accordingly, since 1996, FDOT has maintained the Alternative and Innovative Contracting Program to promote the use of innovative contracting methods of highway construction in order to minimize the inconvenience to the traveling public, adjacent businesses, and communities [30]. Based on a report issued by the Office of Inspector General of the 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 [30].

4.3. Michigan

The Michigan Department of Transportation (MDOT) often utilizes time-based I/D provisions in association with an A + B (cost-plus-time) bidding procedure [25] because they believe that the contract completion time estimated by the winning bidder would be more realistic than the contract time estimated by the contracting agency [23]. To be considered for an I/D clause, the following conditions should be met: (1) substantial road user cost savings are expected; (2) total additional user costs are expected to be at least 5% of the project cost, with a daily incentive of $5000 for major projects; and (3) by implementing an I/D provision the duration of lane closure can be shortened by at least 15 days [25].

4.4. Other states

In Illinois, from 1989 to 1993, all 28 highway construction projects that used time-based I/D provisions were completed ahead of schedule. About 79% of the contractors for these 28 projects received the maximum incentive payment. The average incentive amount paid per project was 4.71% of the contract amount [20].

In Kentucky, from 1999 to 2002, 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 [31].

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 responded that they had paid the maximum incentive amount [11].

5. Contractor's schedule compression versus resource changes

Table 1 shows the result of the CA4PRS schedule simulation. 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 [15], they were taken into account in the schedule simulations using CA4PRS (see Fig. 1). Each strategy such as PCCP, ACP and MACO shown in Table 1 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 h during at nighttime defined as the *nighttime* in Table 1 have been implemented widely because daytime closures may cause intolerable severe traffic delays during construction. The disadvantages of nighttime closures include 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 [28]. 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.

The simulation shows that the duration of a project is shortened as the contractor uses more resources. The three projects below represent each strategy and the following shows a brief project overview of each strategy and summarizes all the assumptions made in conducting the schedule estimates through simulations.

- Portland Cement Concrete Pavement (PCCP) strategy is based on the Interstate 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).
- Asphalt Concrete Pavement (ACP) strategy is based on the Interstate 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).
- Milling and Asphalt Concrete Overlay (MACO) strategy is based on the Interstate 15 Baker Project where the project scope was to rehabilitate an aging 43.5 lane-mile stretch of two lanes (project size: $20 million).
- 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.

6. Contractor's cost growth versus schedule compression

To estimate the CAC growth rates for shortening construction duration 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* [32]. 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 of major resources were determined based on this publication:

- Truck: $75.57 with overtime rate of 0.83
- Paver: $132.79 with overtime rate of 0.83
- Milling machine: $362.59 with overtime rate of 0.87
- Batch plant: $615 with overtime rate of 0.56 ($6.25/ton).

These four are 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 [32]. The published surcharge rates for year 2008 were 12% for regular time and 11% 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.

- $\text{Contractor}'\text{s expected cost growth} = \text{unit price } (\$/h) \times \text{number of additional resources} \times \text{labor surcharge rate} \times \text{working hours per day} \times \text{days needed to complete the project} \times \text{overtime rate} \times \text{number of shifts} \times \text{overhead cost } (15\%) \qquad (2)$

CAC rates were quantified based on Eq. (2). Table 2 contains the dependent (cost) and independent (schedule) variables used for the regression analysis, with three different resource usage levels.

7. Modeling the time–cost relationship

A well-known trade-off effect exists between construction cost and schedule. As Fig. 2 shows, there is a normal point beyond the tradeoff

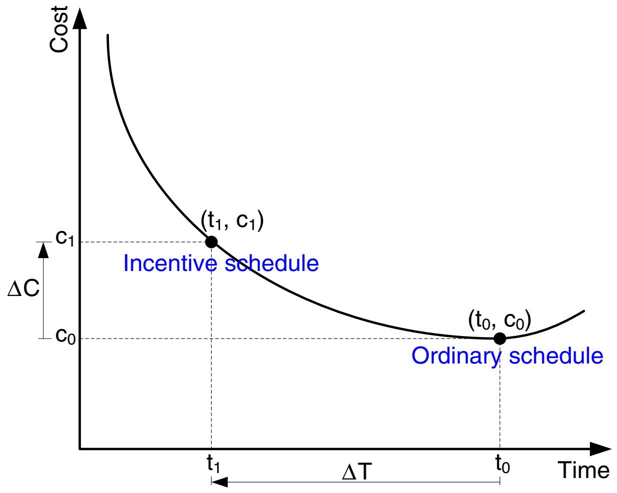


Fig. 2. Theoretical time–cost tradeoff curve (adapted from [18]).

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.

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. [11].

Fig. 3, which draws on the 27 time–cost tradeoff data for regression in Table 2, confirms that contractors' cost growth as a function of reduced construction times can be projected using the following quadratic regression equation, which shows a strong tradeoff relationship between schedule and cost.

$$Cost = \beta_0 + \beta_1(Time) + \beta(Time)^2. \tag{3}$$

An R-squared value of 0.627 showing a very strong fit indicates that schedule compression results in an increase in project cost.

Table 3 shows that the quadratic equation of contractors' cost growth rate is adequate (F-ratio = 26.005, significant at 0.001 level). Since all three coefficients are significant, the following regression equation for determining the lower bound of incentives is generated.

$$\text{Cost} = 1.828 + 0.114(\text{time}) + 0.039(\text{time})^2. \tag{4}$$

8. Equation derivation

By performing a regression analysis, the coefficients β_0, β_1, and β_2 were determined. From Fig. 2, it is seen 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 Eq. (3), a time function can be defined as follows:

$$f = \beta_0 + \beta_1 t + \beta_2 t^2. \tag{5}$$

Since the CAC increase is expressed as a function of shortening time by ΔT, the following relationship can be derived from Fig. 2:

$$\text{CAC}(\Delta C) = f(t_1) - f(t_0) = f(t_1) - f(t_1 + \Delta t). \tag{6}$$

where, $t_0 = t_1 + \Delta T$

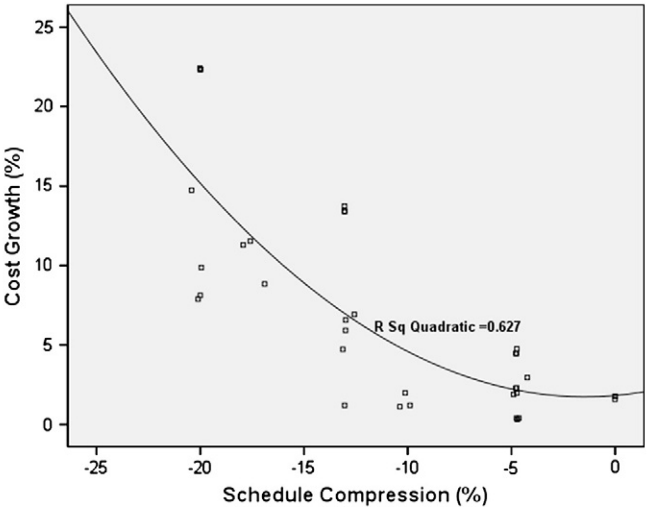


Fig. 3. Contractor's time–cost tradeoff curve.

Table 3
Summary of regression analysis results.

Model	Coefficient	Std. Error	Beta	t-value
Intercept	1.828	2.207		0.828**
Time	0.114	0.469	0.115	0.244*
Time·Time	0.039	0.020	0.903	1.917**
R^2: 0.627 F ratio: 26.005***				

The F-ratio of 26.005 is significant at level 0.001, which suggests that the regression equation is adequate.
The R-squared value of 0.627 indicates a strong reasonable fit between time and cost.
* $p<0.05$.
** $p<0.01$.
*** $p<0.001$.

The following equation is derived by combining Eqs. (5) and (6):

$$\Delta C \text{ in total} = -\Delta T\ (2\beta_2 t_1 + \beta_1 + \beta_2\ \Delta T). \tag{7}$$

The negative sign means that cost decreases as time increases. In Eq. (**7**), 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, Eq. (7) needs to be divided by the number of days saved (i.e., ΔT), which cancels out ΔT. Thus, the contractor's daily additional cost growth rate equals $2\ \beta_2 t_1 + \beta_1 + \beta_2\ \Delta T$.

Based on coefficients generated through the regression analysis, the following equations are derived to predict the level of the CAC to the original contract amount:

$$\Delta C = 0.114 + 0.078 t_1 + 0.039 \Delta T \text{ for roadway renewal projects} \tag{8}$$

where, $t_1 = t_0 - \Delta T$

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

$$\Delta C = 0.114 + 0.078\ t_0 - 0.039 \Delta T. \tag{9}$$

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. In symbols,

$$0.114 + 0.078\ t_0 - 0.039 \Delta T \le \text{DailyI/D} \le \text{Discounted total savings}. \tag{10}$$

9. Case studies: model practicality

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 2800 lane-km of high-volume urban freeway with premium pavements [26]. Most LLPRS projects are large-scale and located in heavily trafficked urban areas; 80% are within the Los Angeles Basin and 15% of them are in the San Francisco Bay Area [16].

The robustness of the proposed model of Eq. (9) in predicting realistic I/D amounts were validated in the following two LLPRS projects already completed and deemed to be experimental with the use of detailed I/D provisions.

9.1. Example I: I-710 Long Beach asphalt concrete I/D project (EA 1384U4)

The Interstate 710 (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 4.4-km (2.7-mi) stretch of badly damaged concrete pavement with long-life asphalt concrete pavements during eight, 55-hour weekend closures in spring 2003. The project consisted of three full-depth asphalt concrete replacement sections (1.0 mile total) under freeway overpasses, and two sections (1.7 mile total) with crack, seat, and overlay of existing PCC slabs with asphalt concrete (AC) [28]. The following list summarizes key information about the I-710 project:

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

Given the project's scope, pavement design, and construction working methods, the agency estimated 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. 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 (15% more). Labor productivity for the incentive schedule was assumed to be equivalent to that of the conventional schedule. Therefore, four working days (1.8 closures) was the estimated maximum probable number of days that I/D use could eliminate.

According to the agency's traffic sensitivity analysis to quantify the road user cost on this project, for this project's given AADT and percentage of trucks, the expected daily monetary saving to road users was estimated to be $526,347. The expected closure-based monetary saving to road users was $1,206,212.

By shortening construction times, the contracting agency can also save agency costs proportionate to the number of days the I/D project eliminates. For the accelerated LLPRS I/D projects presented in this study, the savings include reductions in the costs of:

1. Construction zone enhanced enforcement program: $700/day/officer and 4.5 officers/day are required to be present at construction sites at an overtime rate of 1.2.
2. Agency engineering cost: $320/day/staff and four resident engineers are required at an overtime rate of 1.5 with three shifts.
3. Moveable concrete barrier rental cost: $60/m for the first month and $11/meter for the second month with an additional transformer cost at $30,0000 for the first month and $15,000 for the second month.

The expected savings in agency cost by completing the project four days early was then estimated to be $68,400 ($156,750 per closure).

Based on the maximum probable number of days, schedule compression rate (ΔT) is determined as -0.166 (16.6% reduction of t_0). The contractor's daily additional cost growth rate (ΔC) is determined as follows by applying Eq. (9):

$$\begin{aligned} 0.114 + 0.078\, t_0 - 0.039\Delta T &= 0.114 + 0.078(1.000) + 0.039(0.166) \\ &= 0.198\% = \$33,066\,/\,\text{day}\ (\$75,776/\text{closure}). \end{aligned}$$

Table 4 summarizes the lower and upper bounds for determining the most realistic I/D amount for the given project. 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 quantitative model presented in this study provides a reasonable range-based estimate by establishing the I/D lower bound.

Table 4
Predicted values of ΔC for the selected I/D projects.

Estimates (1)	I-710 Long Beach project		I-15 Devore project	
	Daily I/D	Closure I/D	Daily I/D	Closure I/D
	(2)	(3)	(4)	(5)
Lower bound (ΔC)	$33,066	$75,776	$35,640	$106,920
Upper bound (total savings)[a]	$594,747	$1,362,962	$243,551	$730,653
Savings to road users	$526,347	$120,6212	$175,151	$525,453
Savings to the agency	$68,400	$156,750	$68,400	$205,200

[a] Upper bound = savings to road users + savings to the agency.

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 ($75,776) of I/D lower bound in Table 4. 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% 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 enough 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 (see Table 4), it was not sufficient for the contractor to add additional resources in order to achieve the earliest possible completion, as the actual incentive amount paid to the contractor turned out to be close to the lower bound.

9.2. Example II: I-15 Devore concrete I/D project (EA 0A4234)

The scope of the I-15 Devore project (Caltrans project ID: EA 0A4234) was the rehabilitation of a heavily trafficked 4.3 km (2.67 mi) stretch of badly damaged concrete truck lanes on I-15 in Devore in Southern California. The following list includes key information about the rehabilitation project:

- 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;
- AADT: approximately 100,000 vehicles; and
- Percentage of trucks at the construction work zone: 10%.

Given the project's scope, pavement design, and construction working methods, the agency estimated 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) in an I/D contracting strategy. Therefore, four working days (1.3 closures) is the estimated maximum probable number of days that I/D use can eliminate for this project.

According to the agency's calculation, the estimated total saving to road users was estimated to be $175,151 given this project's AADT (100,000) and percentage of trucks (10%). The expected savings in agency cost by completing the project four days early was estimated to be $68,400.

Based on the maximum probable number of days that I/D use could eliminate, the schedule compression rate ΔT is set to -0.166

(16.6% reduction of t_0). The contractor's daily additional cost growth rate (ΔC) is estimated as follows using Eq. (9):

$$\begin{aligned}0.114 + 0.078\,t_0 - 0.039\Delta T &= 0.114 + 0.078(1.000) + 0.039(0.166)\\ &= 0.198\% = \$35,640/day.\end{aligned}$$

This analysis reveals that the project is appropriate for 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 4 shows the lower and upper bounds for determining the most economical I/D amount for the given project. The maximum incentive amount in this range is within 5% of the agency's budget for this 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.

10. Summary and conclusions

This study introduces a quantitative model that can be used to establish the *lower bound* for an incentive/disincentive (I/D) contract, an estimate of the additional costs required by a contractor expediting construction so that an accelerated incentive schedule can be met. Using the schedule simulation function of CA4PRS, a data set of the contractors' time–cost tradeoff was created on four different resource usage levels. A linear regression analysis was then performed to develop a predictive model that determines contractors' most likely additional cost growth. The robustness of the model for predicting realistic I/D amounts was tested using case studies of two I/D completed rehabilitation projects that were deemed experimental at their time of construction.

The results of the case studies reveal that both projects were appropriate for application of an I/D provision since the estimated lower bound was smaller than the total time value savings. The case studies also proved the analytical capability of the model for highway rehabilitation projects in estimating realistic I/D amounts. Specifically, Caltrans 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 lower bound ($75,776 per closure) predicted by the model. However, in the post-construction meeting with the contractor, Caltrans acknowledged that the incentive amount paid to the contractor was not enough for the contractor to recoup the cost added for accelerating construction. 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.

Use of the proposed model can 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 reliable, realistic incentives when they consider the implementation of an I/D provision. If the agency allocates an incentive smaller than the contractor's added cost, this may keep competitive contractors from submitting a bid. Use of this model can also benefit contractors bidding on projects that include an I/D provision because it can provide advance knowledge of the balanced time–cost tradeoff amount required to account for the added costs of schedule acceleration and incentives.

The model developed in this study can serve as the basis for future research to develop a comprehensive decision-support computer model for determining realistic I/D amounts by integrating the following four crucial components: schedule that serves as the baseline, total time value saving to motorists and agencies that serves as the upper bound, contractors' expected additional cost growth that serves as the lower bound, and optimal discounting factor that balances between the upper and lower bounds. It is recommended that following areas be addressed in the future study to fine-tune the proposed model's capabilities: (1) expand the model to establish the I/D upper bound, (2) expand the model to cover other project types in order to enhance the model's analysis capability and give contracting agencies a wider choice of construction strategies, and (3) provide point-based estimates of I/D amounts by considering level of service (LOS), which indicate the levels of traffic disruption to motorists.

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