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Analyzing Decision Making in Alternative Contracting for Highway Pavement Rehabilitation Projects

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ANALYZING DECISION MAKING IN ALTERNATIVE CONTRACTING FOR HIGHWAY PAVEMENT REHABILITATION PROJECTS

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by

Mohamed Ibrahim

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To: Interim Dean Ranu Jung
College of Engineering and Computing

This dissertation, written by Mohamed Ibrahim, and entitled Analyzing Decision Making in Alternative Contracting for Highway Pavement Rehabilitation Projects, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this dissertation and recommend that it be approved.

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The dissertation of Mohamed Ibrahim is approved.

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Florida International University, 2016

DEDICATION

To my father, whom without his guidance and support this work wouldn’t have been possible.

To my mother, whose encouragement and care gave me the strength to complete this work.

ABSTRACT OF THE DISSERTATION

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by

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The negative impacts associated with highway pavement rehabilitation projects drove state highway agencies (SHAs) towards increased adoption of alternative contracting methods (ACMs) to accelerate the construction of such projects; hence, reducing these impacts on the travelling public. However, the application of such methods showed mixed results due to the lack of specific guidelines addressing the adoption of such methods and the selection of the best ACM for each project. This lack of guidelines stems from the lack of research studies examining the impact of each of these methods on the time/cost trade-off relationship in highway rehabilitation projects. Existing literature includes several studies aimed at developing generic and subjective guidelines based on past experiences that do not take into consideration the unique nature of each of these methods.

Hence, this research study aimed at analyzing the SHAs' decision making process regarding two of the most-widely used ACMs: Incentive/Disincentive (I/D) and Cost + Time (A+B) contracting methods, in order to support decision makers in choosing the

most-suitable method for their projects. To this end, two models were developed in this dissertation to examine the time/cost trade-off for each method using simulation and regression analysis. Each model was validated against real-life projects and used to assign appropriate ID and “B” values based on the SHA’s desired duration reduction and available budget. Furthermore, a risk analysis module was developed to determine the most-likely duration reduction that the contractor can achieve for each project under each method.

The developed models should help improve the decision making process regarding the selection and implementation of these methods in highway rehabilitation projects. For example, the models can help SHAs identify the minimum ID level that can be offered for each project and the expected duration that the contractors can bid on under the A+B contracting method. Finally, the models were contrasted and applied to real-life projects with different characteristics to verify existing guidelines and establish the candidate ACM for each project category. The findings of this study will benefit the society, SHAs, and the economy in general by optimizing the use of available time and money resources.

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INTRODUCTION

1.1. Research Background

According to the U.S. Department of Transportation 2013 status report, only 44% of the nation's urban roadway system is classified as "pavement with a good ride quality" (DOT 2013); furthermore, the American Society for Civil Engineers (ASCE) evaluates the conditions of the nation's roadways with a grade "D" (ASCE 2013). These poor conditions are estimated to cost the travelling public approximately $67 billion per year in additional vehicle repairs and operating costs (ASCE 2013). As a result, these roadways often require maintenance and rehabilitation work (El-Rayes and Kandil 2005) which are estimated to amount to $86 billion annually in order to, at least, be able to maintain these conditions, let alone improve them (DOT 2013). This led to a shift in the focus of highway construction projects, in most states, from building new roads to maintaining and rehabilitating the existing ones (Herbsman 1995, Lee et al. 2004) which is evident in the increase in the total expenditure on highway rehabilitation projects from approximately 62% to 75% of the total allocated highway construction budget over the period from 2000 to 2010 (DOT 2013). Moreover, it is estimated that more than 40% of the nation's highways and 70% of its arterials will need repair in the near future (Olguin et al. 1995).

Nevertheless, these maintenance and rehabilitation projects are often located in urban and highly trafficked areas (Bayraktar and Hastak 2009, Choi 2008) which lead to many severe and undesirable negative impacts on the travelling public as they often include closing one or more portions of the highway; these impacts include; but are not limited to: severe congestion, limited property access, safety risks to motorists and construction workers, and increased vehicle operating costs (Choi et al. 2012; El-Rayes 2001). These negative impacts are often measured in terms of the additional daily road user costs (DRUC) that the travelling public will incur due to the presence of a work zone area (Herbsman et al. 1995). To illustrate how costly these impacts can be, consider the case of the I-66 rehabilitation project in Fairfax County, Virginia which is the main connector between Fairfax County and Washington D.C. (Mallela & Sadasivam 2011). In this project, VDOT adopted the traditional low bid contracting strategy with construction only allowed during nighttime and involved closing three lanes of the mainline for 44 nights and the full closure of the ramp for 30 nights (Mallela and Sadasivam 2011). Through utilizing the traffic data on this section of I-66 and the project characteristics, it was computed that the total road user cost for the project was $3.7 million which is approximately 75% of the total construction cost of $5 million (Mallela and Sadasivam 2011). This example demonstrates the severity and the large scale of the negative impacts of the highway rehabilitation projects and illustrates the pressing need to find ways to reduce these impacts.

Consequently, these projects subjected the SHAs to new challenges as they became under increasing pressure, from the public, to reduce these negative impacts (Fick et al. 2010). In a survey conducted in the state of Texas, the public believed that minimizing the negative impacts of the maintenance and rehabilitation projects to be the main solution for the congestion problems experienced on Texas highways (Ibarra 2002). As illustrated in figure (1-1) which is based on Olguin et al. (1995), the longer the project’s duration, the more severe these negative impacts are; hence, to reduce these impacts, SHAs need to find ways to reduce these projects' durations.

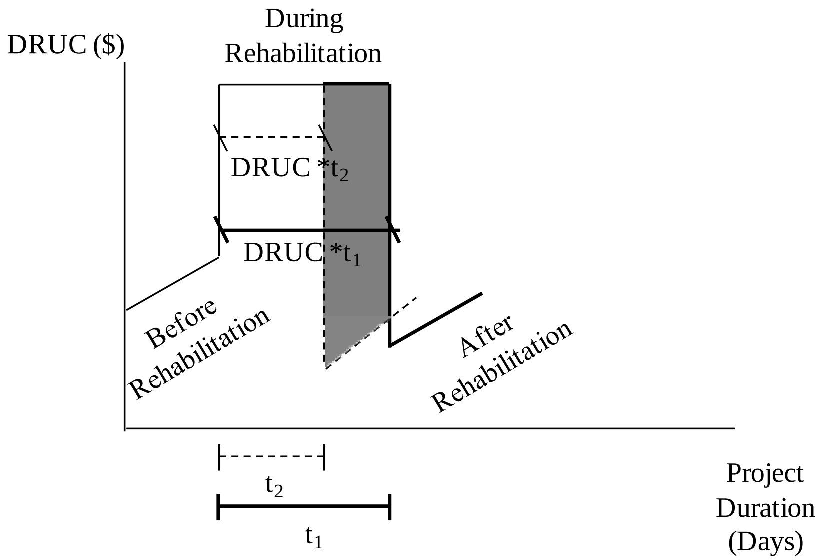

Figure 1-1: Relationship between project's duration and the DRUC

In order to combat these new challenges, the Federal Highway Administration (FHWA) established a number of programs aimed at reducing the durations of the highway maintenance and rehabilitation projects including the "Everyday Counts" program (Mallela and Sadasivam 2011). This program encouraged SHAs to start adopting alternative contracting methods (ACMs) which are aimed at motivating the contractors to reduce the projects' durations (Hancher 1999); and two of the most widely used ACMs are the Incentive/Disincentive (I/D) method and the Cost + Time (A+B) method (Fick et al. 2010). Nonetheless, in order for the contractors to reduce the project's duration using these methods, they need to utilize more resources which ultimately leads to an increase in their construction costs (El-Rayes 2001) which conflicts with the already limited budgets available to the SHAs. For instance, the Oregon Department of Transportation (ODOT) estimates that in order to maintain its current highway conditions, it needs an additional $405 million annually over its current allocated budget (ODOT 2014). In addition, some of these ACMs showed mixed results when being implemented by the SHAs either due to poor planning or the unsuitability of the method for a particular project. For example, Florida Department of Transportation projects that were contracted using the A+B method experienced, on average, 13% time growth (Ellis et al. 2007), while some of its I/D projects experienced on average 8.4% cost overrun (Dutta and Patel. 2012); moreover, Michigan Department of Transportation (MDOT) did not witness a significant duration reduction in some of its I/D projects; albeit with an increase in cost (El-Gafy 2014). These mixed results further complicate the SHAs' already complex and essential task of selecting the appropriate type of ACM for their pavement rehabilitation projects and ensure the success of their implementation (Antoniou et al. 2012); hence, the need for models to help in this task.

In order to enhance the SHAs decision making regarding the choice and applicability of the different ACMs for their pavement rehabilitation projects, decision makers need to be able to determine: 1) the time/cost trade-off relationship associated with each ACM; 2) the appropriate level of time reduction (ΔT) that can be achieved using each method; 3) the necessary monetary value of each day reduced that they are willing to give the contractor to achieve the required ΔT; 4) the total additional cost that they will incur and the savings in the DRUC that will offset this additional cost; and finally 5) the most-suitable ACM to be used based on both the project's characteristics, and their time and budgetary constraints. Nevertheless, the determination of these decision variables is not an easy feat as they often involve the determination of some decision parameters that are not readily available for the SHAs' personal (Ellis and Herbsman 1990) which explains why most SHAs do not have a formal methodology of selecting the most appropriate contracting method (Molenaar et al. 2014). To illustrate the complexity of the problem facing the SHAs' decision makers, the following example is used. In this example it is assumed that the SHA has three different rehabilitation projects that need to be constructed using either the I/D or the A+B contracting methods and each project has its own construction cost and DRUC; however, the SHA has certain budgetary constraints that it needs to fulfill. In this example, the SHA can have a total of 24 different combinations of decisions on the choice of the ACM and each choice has its own total cost and savings in the DRUC. Therefore, to optimize their decision, the chosen combination should satisfy both of the following conditions: 1) total DRUC savings should be more than the total construction cost in order not to waste the public money, and 2) total construction cost should be less than the available budget limit. However, there is no way for the SHA to guarantee the satisfaction of these conditions without being able to compute the decision variables highlighted in the previous paragraph i.e. they need to determine the time/cost trade-off relationship associated with each method. This simple example shows the task at hand and its huge consequences on the public, the contractor, and the agency; nonetheless, this task gets more complicated in real life considering the large number of projects that need to be constructed, and the availability of more types of ACMs that can be used. Consequently, there is an urgent need for new research in the area of the decision making for alternative contracting methods, especially in highway pavement rehabilitation projects, to help SHAs in selecting the most-suitable method for their projects based on the desired level of duration reduction and their budgetary constraints that is capable of: 1) determining the time/cost trade-off relationship associated with the I/D contracting method; 2) determining the time/cost trade-off relationship associated with the A+B contracting method; and 3) enhancing the decision-making regarding these two methods and selecting the best method of the above-mentioned ones for their pavement rehabilitation projects as illustrated in figure (1-2).

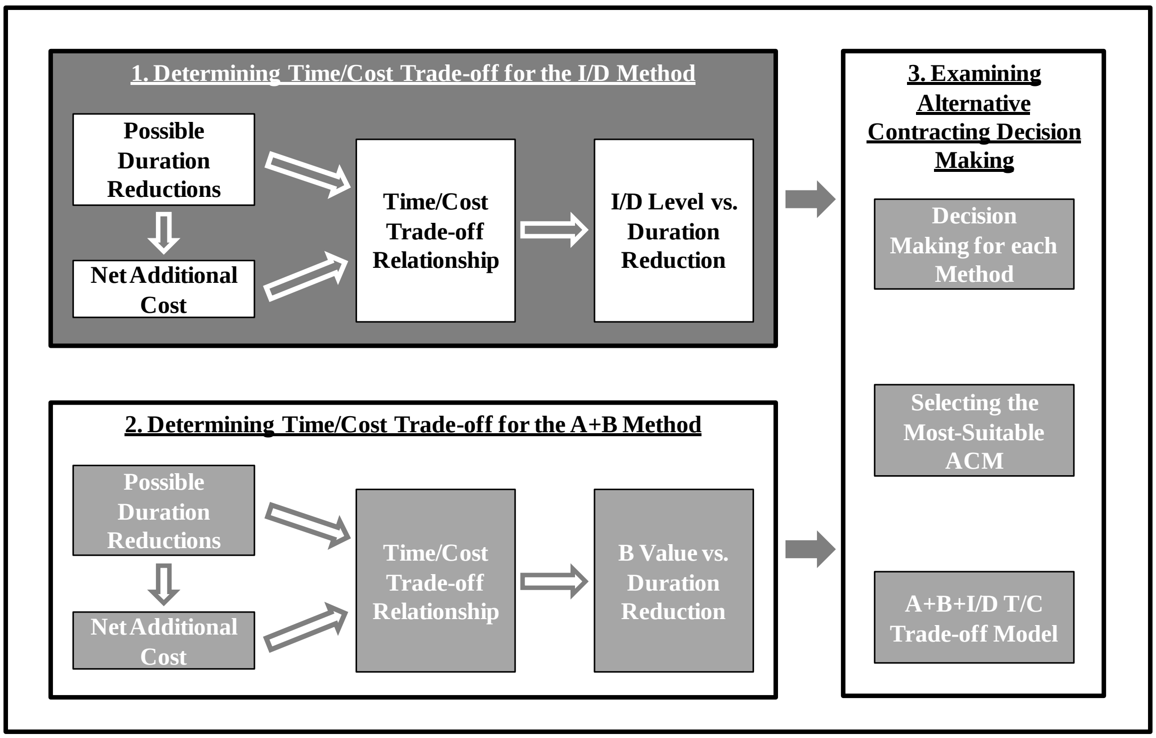

Figure 1-2: Outline of the ACMs analysis model

1.2. Problem Statement

To develop the above-mentioned ACMs' decision making model, several problems need to be addressed first; these problems are: 1) understanding the impact of the I/D contracts and the value of the ID on the time/cost trade-off for pavement rehabilitation projects; 2) understanding the impact of the A+B contracting method and the value of the "B" component on the time/cost trade-off for pavement rehabilitation projects; and 3) assisting the SHAs in selecting the most-suitable type of alternative contracting for their pavement rehabilitation projects. Consequently, to perform these tasks, this study will comprehensively examine the impacts of both the I/D and A+B contracting methods on the time/cost trade-off for pavement rehabilitation projects and develop models that are aimed at examining the SHAs' decision making with regards to these two types of ACMs.

Nonetheless, in order to first understand how the different types of ACMs can impact the time/cost trade-off relationship for a construction project, the nature of this relationship has to be investigated. Several studies in the literature proved that for any construction project, there is an interrelationship between the project's duration and cost (Kaka and Price 1991). Furthermore, it was proved that for each construction project, contracted under traditional contracting, there is a point at which the construction cost is at its minimum and any decrease or increase in the project's duration from that point will result in an increase in the project's cost as shown in figure (1-3), which is based on Cusack (1985). This is due to the fact that any additional day beyond this point will increase the project's cost due to the increase in its indirect cost and any day less will also increase the cost due to the increase in the direct cost.

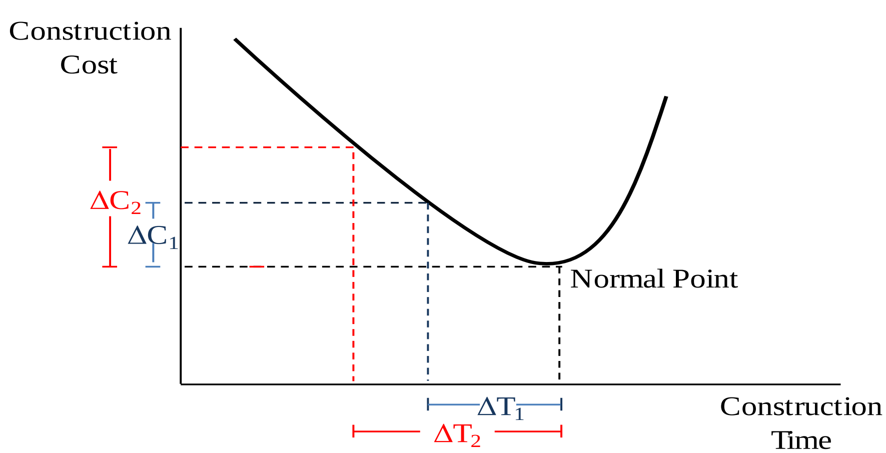

Figure 1-3: Relationship between construction cost and time for traditional contracting

Nonetheless, this relationship gets more complicated when contracting the project using alternative contracting methods. As seen from figure (1-4), the value of the time assigned, whether for the incentive/disincentive or the “B” component, has to be incorporated in the trade-off between the time and cost which will ultimately lead to the shifting of this curve and a new normal point. Moreover, the trade-off between time and cost is impacted by the type of the ACM used as each method allocates the risk differently between the involved parties (Anderson and Damnjanovic 2008). This is evident in figure (1-4), which is based on Shr et al. (2004), as the degree of the shifting in the time/cost trade-off curve differ between both the I/D and the A+B contracting methods, the reasons behind this difference will be explained in the following paragraphs.

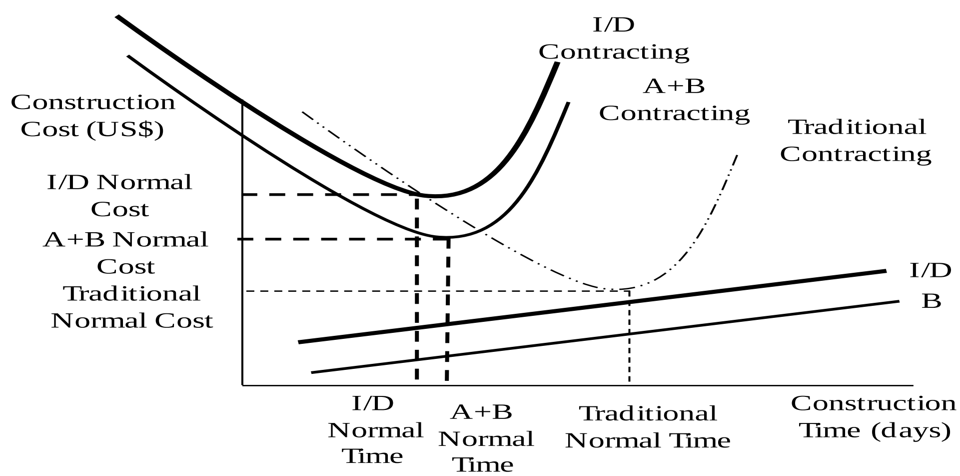

Figure 1-4: Relationship between construction cost and time for alternative contracting

First, with the regards to the I/D contracting method and its impact on the time/cost trade-off relationship for a pavement rehabilitation project, the basic rationale behind the use of this method has to be explained. This contracting method is based on including a special provision in the construction contract that awards the contractors for each day the work is completed ahead of schedule while it imposes penalties on them for each day the work is completed beyond the schedule (Jaraiedi et al. 1995, CDOT 2006, ODOT 2006). Furthermore, in most cases, the value of both the incentive and disincentive are the same (CDOT 2006) and is set by the SHAs and included as part of the bid documents (Herbsman et al. 1995, NYSDOT 1999). Hence, in order for the contractors to reduce the project's duration and earn the incentive amount, they need to increase their productivity levels by utilizing more resources which will lead to an increase in their construction costs (Anderson and Russell 2001). However, since the incentive amount act as a bonus for the contractor and the task of determining the original project duration is still with the SHA, the risk bared by the contractor remain the same as with the traditional contracting (NYSDOT 1999) which makes the calculation of the additional costs that the contractor will incur focus on how to estimate the contractors' additional productivity and resources utilized. Nonetheless, existing research concerned with determining the impact of the I/D contracting method only focus on: 1) helping the contractor with their bid preparation process for the I/D contracting method by adding the ID value, predetermined by the SHAs, to the construction cost (Shr et al. 2004); 2) setting the maximum incentive to be assigned for a given project based on the value of the DRUC (Shr and Chen 2004, Jiang et al. 2010); 3) developing models for calculating the contractors' cost of time reduction based on the SHAs engineers judgment (Sillars and Riedl 2007); 4) developing models for calculating the cost of time reduction, from the contractors' perspective, without incorporating any trade-off with the desired reduction in duration (Choi 2008); and 5) providing generic guidelines for selecting the appropriate value for the ID without providing a method for the calculation of the actual value (MnDOT 2005, Jaraiedi et al. 1995). Despite the important contributions of all of these research studies, there is a research gap in this area as no studies are aimed at quantifying these parameters from the SHAs' perspective (Choi et al. 2013), and none of them addressed the impact of the I/D contracting method on the trade-off between the desired duration reduction, the value assigned to each day of the project, and the project's cost. Therefore, there is an urgent need for a model that is capable of quantifying the impact of the I/D contracting method and the value of the incentive/disincentive on the trade-off between time and cost of pavement rehabilitation projects and determine the value of the ID to be used based on the desired level of duration reduction and the available budget.

Second, the A+B contracting method is a type of the multi-parameter bidding techniques used to select the winning contractor for highway projects. With this method, the contractor is selected on the basis of the lowest combined bid of cost and time (Felker 2002). Contractors are required to submit a bid that consists of two different components: one (A component) representing the bid price for the construction operations, and the other (B component) representing the cost of the time required to complete the project (El-Rayes 2001). The "A" component is calculated based on the unit prices multiplied by the contract quantities, while the "B" component is calculated by multiplying the number of calendar days required to complete the project by the value assigned for each day, which is determined by the SHA (PaDOT 2013). Hence, since the contractors are the entity that sets the project's duration, they assume higher risk than with the I/D contracts, as illustrated in figure (1-5), with this type of contracts that they account for in terms of additional cost (Anderson and Russell 2001). In addition, since with this type of alternative contracting, time becomes a decisive factor in determining the winning bid, the contractor is inclined to use more aggressive resource utilization scenarios in order to reduce the project's duration and win the bid which will be reflected in the additional cost incurred (Herbsman et al. 1995).

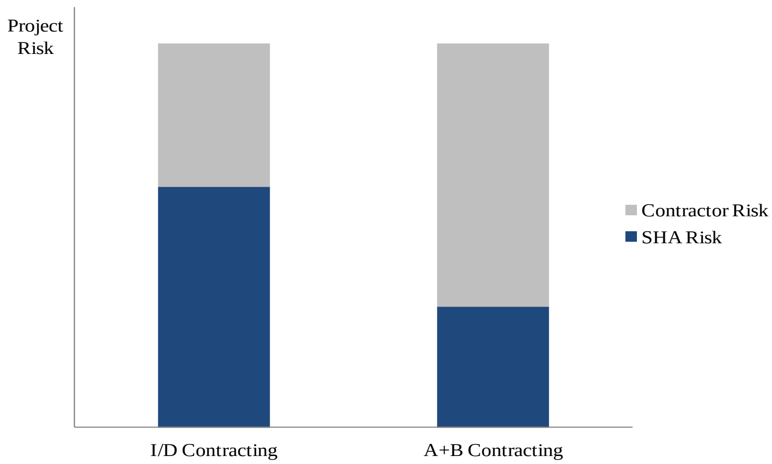

Figure1- 5: Risk allocation for the I/D vs. the A+B contracting methods

Moreover, this greater importance that is placed on the project's duration makes the contractor more eager to reduce the time to the maximum possible limit to win the bid. Thus, all of the above unique characteristics of the A+B contracting method make the calculation of the additional costs that the contractor will incur more complicated. As a result, there is a scarcity of research concerned with determining the impact of the A+B contracting method and the only available ones focus on: 1) Identifying the complexity associated with the A+B contracting method (Herbsman 1995); 2) helping the contractors in their bid preparation process for A+B contracts by optimizing the contractor's resource utilization (El-Reyes 2001, Shen et al. 1999); and 3) providing generic guidelines for the implementation of the A+B contracting method and selecting the time value associated with the "B" component (CDOT 2006, CALTRANS 2002, Felker 2002). Despite the important contributions of all of these research studies, a research gap in this area is present as none of them investigated the impact of the A+B contracting method & the value of the “B” component on the time/cost trade-off associated with pavement rehabilitation projects. Therefore, there is a pressing need for a model that is capable of quantifying the impact of the A+B contracting method and the value of the “B” component on the trade-off between time and cost of pavement rehabilitation projects and determine the value of the “B” component to be used based on the desired level of duration reduction and the available budget.

Third, due to the lack of models aimed at quantifying the impact of the I/D and A+B contracting methods on the time/cost trade-off relationship for pavement rehabilitation projects, there are no studies aimed at examining the SHAs decision making with regards to ACMs and help them in selecting the most suitable method for their projects. The only available research studies in this area are the ones that provide guidelines for selecting each method based on the project’s qualitative characteristics without comparing the results that can be obtained using each method against the other (Anderson and Damnjanovic 2008, NYSDOT 1999, CDOT 2006). Hence, the need for such models is of paramount importance as they can help the SHAs in realizing the best possible outcomes from their alternative contracting projects which in return will both save the public’s money and help enhance the poor conditions of the nation’s highways.

1.3. Research Objectives

The main goal of this research study is to investigate and quantify the impact of the I/D and A+B contracting methods on the time/cost trade-off relationship for highway pavement rehabilitation projects and improve the SHAs’ alternative contracting decision making process. In order to achieve this goal, the research objectives along with the research questions and hypothesis to achieve this goal are identified:

Objective 1:

To understand the impact of the I/D contracting method and the value of the incentive/disincentive on the trade-off between time and cost of pavement rehabilitation projects and determine the most-likely value of the I/D to be used.

Research Questions:

a. What are the resource utilization scenarios that are likely to be used by the contractor under the I/D contracting method?

b. How to calculate the net additional cost incurred by the contractor when using the I/D contracting method?

c. How to determine the relationship between the reduction in the project's duration and the additional cost incurred by the contractor under the I/D contracting method?

d. How to determine the ID value associated with each level of reduction in the project's duration and the associated cost to the owner?

e. What is the most-likely level of reduction in the project's duration for each ID level and the most-likely ID level for the entire project?

Hypothesis:

The nature of the time/cost trade-off relationship changes with the use of the I/D contracting method and the time performance of pavement rehabilitation projects procured using the I/D contracting method differ according to the value of the ID assigned.

Objective 2:

To comprehend the impact of the A+B contracting method and the value of the "B" component on the pavement rehabilitation projects' time/cost trade-off relationship and determine the most-likely value of the "B" component to be used.

Research Questions:

a. What are the resource utilization scenarios that are likely to be used by the contractor under the A+B contracting method?

b. How does the additional cost incurred by the contractor to reduce the project's duration under A+B contracts differ from the one under the I/D contracts?

c. How to calculate the net additional cost incurred by the contractor when using the A+B contracting method?

d. What is the relationship between the reduction in the project's duration and the additional cost incurred by the contractor under A+B contracts?

e. How to determine the value of the "B" component associated with each level of reduction in the project's duration and the associated cost to the owner?

f. What is the most likely level of duration reduction in the project's duration for each value of the "B" component and the most-likely value of the "B" component for the entire project?

Hypothesis:

The nature of the time/cost trade-off relationship changes with the use of the A+B contracting method and the time performance of pavement rehabilitation projects procured using A+B contracts differ according to the value of the "B" component.

Objective 3:

To examine the SHAs' decision-making process with regards to the I/D and A+B contracting methods and assist them in selecting the most-suitable method for their pavement rehabilitation projects according to their duration and budgetary constraints.

Research Questions:

a. How to examine the decision making for the I/D contracting method and assure the success of its implementation?

b. How to examine the decision making for the A+B contracting method to ensure that it fulfills its goals?

c. How to select the most-suitable alternative contracting method based on the SHAs' decision parameters and the projects' characteristics?

d. How to develop the time/cost trade-off relationship for the A+B+I/D contracting method?

Hypothesis:

Each type of the alternative contracting methods might be suitable for a particular project and specific constraints but not necessarily the other.

1.4. Research Methodology

In order to achieve the above-mentioned research objectives, the research methodology is divided into four main research tasks as follows: (a) conduct a comprehensive literature review of the latest research studies in the field of alternative contracting methods (2) determine the impact of the I/D contracting method and the value of the incentive/disincentive on the trade-off between time and cost of pavement rehabilitation projects and determine the value of the ID to be used; (3) determine the impact of the

A+B contracting method and the value of the "B" component on the pavement rehabilitation projects' time/cost trade-off relationship and determine the optimal value for the "B" component to be used; and (4) examine the alternative contracting decision making process. Each of these tasks is further divided into a number of sub-tasks as shown in figure (1-6).

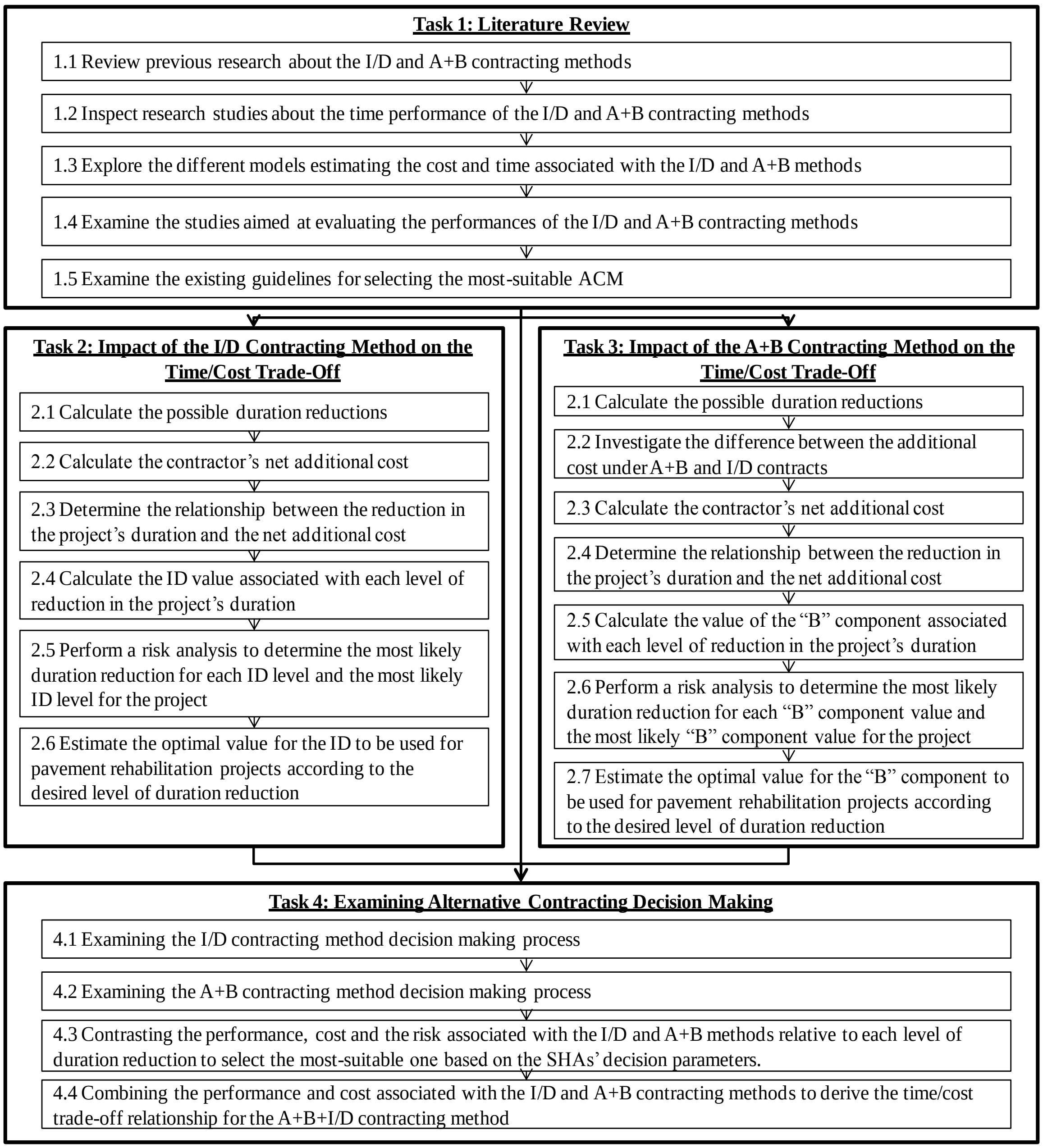

Figure 1-6: Research tasks and sub-tasks

1.4.1. Task 1: Conduct a comprehensive literature review

The objective of this task is to comprehensively explore the latest developments in the related research concerning alternative contracting methods to establish the knowledge base and identify the research gaps. This task will be accomplished by conducting the following sub-tasks:

1- Review of the previous research about the I/D contracting method.

2- Review of the previous studies about the A+B contracting method

3- Inspect research studies about the time performance of the I/D and A+B contracting methods.

4- Explore the different models that are developed to estimate the cost and time associated with the I/D and A+B contracting methods.

5- Examine the studies aimed at evaluating the performances of the I/D and A+B contracting methods.

6- Examine the existing guidelines for selecting the most-suitable ACM.

1.4.2. Task 2: Determine the impact of the I/D contracting method on the time/cost trade-off for pavement rehabilitation projects.

The objective of this task is to investigate and model the impact of the I/D contracting method and the value of the ID on the trade-off between time and cost of pavement rehabilitation projects and determine the value of the ID to be used. This research task will be accomplished by performing the following sub-tasks:

1- Calculate the possible duration reductions that the contractor will be willing to achieve under the I/D contracting method.

2- Calculate the net additional cost incurred by the contractor when using the I/D contracting method.

3- Determine the relationship between the reduction in the project's duration and the net additional cost incurred by the contractor under the I/D contracting method.

4- Calculate the ID value associated with each level of reduction in the project's duration.

5- Perform a risk analysis to determine the most likely duration reduction that can be achieved for each level of ID and the most likely ID level for the entire project.

6- Estimate the value for the ID to be used for pavement rehabilitation projects according to the desired level of duration reduction.

1.4.3. Task 3: Determine the impact of the A+B contracting method on the time/cost trade-off for pavement rehabilitation projects.

The objective of this task is to explore and model the impact of the A+B contracting method and the value of the "B" component on the trade-off between time and cost of pavement rehabilitation projects and determine the value of the "B" component to be used. This research task will be completed by performing the following sub-tasks:

1- Calculate the possible duration reductions that the contractor will be motivated to achieve under the A+B contracting method.

2- Investigate the difference between the additional cost incurred by the contractor to reduce the project's duration under A+B contracts versus I/D contracts.

3- Calculate the net additional cost incurred by the contractor when using the A+B contracting method

4- Determine the relationship between the reduction in the project's duration and the net additional cost incurred by the contractor under the A+B contracting method.

5- Calculate the value of the "B" component associated with each level of reduction in the project's duration.

6- Perform a risk analysis to determine the most likely duration reduction that can be achieved for each value of the "B" component and the most likely value of the "B" component for the entire project.

7- Estimate the value for the "B" component to be used for pavement rehabilitation projects according to the desired level of duration reduction.

1.4.4. Task 4: Examine the alternative contracting decision making process.

The objective of this task is to examine the SHAs' decision-making process with regards to the I/D and A+B contracting methods, help them improve the decision making process for these methods, and assist them in selecting the most-suitable method for their pavement rehabilitation projects based on their decision parameters. This research task will be achieved by performing the following sub-tasks:

1- Examining the I/D contracting method decision making process.

2- Examining the A+B contracting method decision making process

3- Contrasting the performance, cost and the risk associated with the I/D and A+B contracting methods relative to each level of duration reduction to select the most-suitable one based on the SHAs' desired level of duration reduction and available budget, and decision parameters.

4- Combine the performance and cost associated with the I/D and A+B contracting methods to derive the time/cost trade-off relationship for the A+B+I/D contracting method.

1.5. Scope and Limitations

This research study proposes two different models to examine the SHAs' alternative contracting decision making process. In order to develop such models, a number of preceding steps of developing models that are capable of: 1) depicting the impact of such ACMs on the time/cost trade-off relationship for pavement rehabilitation projects; and 2) determining the relationship between the value of time assigned, the desired duration reduction, and the final total project cost to the owner, were conducted.

The development of the former models involved: 1) examining the contractor's resource utilization scenarios accompanied with each method; 2) simulate the reduction in the project's duration as a result of these scenarios using construction schedule simulation software; 3) calculating the net total cost growth as a result of the increase in direct cost and the savings in the indirect costs; 4) performing regression analysis to derive the relationship between the reduction in the project's duration and the increase in its net total cost. Furthermore, several key steps were taken to increase the applicability of the developed models. First, these models accounted for the impact of different pavement strategies, pavement cross-sections, and construction windows on the productivity of the pavement rehabilitation projects which makes them applicable to the three most-widely used pavement strategies, which are: Portland Cement Concrete Pavement, Asphalt Concrete Pavement, and Milling and Asphalt Concrete Overlay. Second, when calculating the increase in the contractor's direct cost, average equipment rental rates from different sources across the nation were used; hence, the model is applicable in different regions of the nation. Finally, when calculating the indirect cost savings, several scenarios depicting the different possible percentages of the indirect costs were used which allows the user to utilize the developed models with different indirect cost scenarios.

At the same time, the development of the latter models involved: 1) calculating the value of time accompanied with each level of duration reduction; 2) calculating the corresponding total costs for the owner; and 3) performing a risk analysis to determine the most likely value of time to be used and the most likely duration reduction to be achieved. This makes the developed models applicable for all the possible ranges of duration reductions that can be achieved for any particular project.

On the other hand, several aspects of the highway rehabilitation projects using ACMs were not considered in this study. The proposed model is only aimed at examining the SHAs' decision making with regards to the I/D and A+B contracting methods; hence, the developed model cannot be used when the decision involves other types of ACMs. Moreover and as mentioned above, the model is applicable to the three most widely used pavement strategies only; thus, it cannot be used for any other pavement strategy such as: Crack and Seat Asphalt Overlay, for instance. Finally, the model is only applicable to pavement rehabilitation projects and not any other type of highway maintenance projects.

1.6. Research Significance

This research study is aimed at supporting the SHAs in their decision making process with regards to the use of alternative contracting methods. The research conducted in this study is expected to have a considerable impact on: 1) reducing the negative impacts associated with the pavement rehabilitation projects; 2) enhancing the use of the I/D and A+B contracting methods to ensure their success and the protection of the public's money; and 3) enhance the SHAs' decision making with regards to the selection of the most appropriate ACM, out of the I/D and A+B methods, to be used for their projects based on their desired level of duration reduction, their available budgets, and the risk associated with each method. Consequently, the above impacts are anticipated to provide major benefits to the society, the SHAs, and the overall economy.

1.6.1. Benefits to the Society:

By ensuring the success of the use of the alternative contracting methods, their main goal of reducing the durations of the pavement rehabilitation projects will be achieved. This will minimize the negative impacts associated with such projects which will benefit the society in a multitude of ways including, but not limited to: 1) reduce the road user costs associated with such projects resulting from additional vehicle operating costs; 2) reduce the disruptions to local communities and business; 3) minimize the safety hazards for both the traveling public and the construction workers; and 4) enhance the quality of life for the local communities by providing them with better roads and infrastructure.

1.6.2. Benefits to the SHAs:

By helping the SHAs enhancing their ACMs decision making processes, a number of significant benefits will be realized. These benefits include: 1) protecting the public money by not overspending on ACMs; 2) achieve their rehabilitation projects' targets and deliver their promises to the public; 3) make the best use of their limited budgets allocated to pavement rehabilitation projects; and 4) improving the quality of the nation's highways.

1.6.3. Benefits to the Economy:

This research study provides a number of potential benefits to the overall economy of the nation including: 1) faster and more reliable transportation of goods due to the better state of the highways; 2) protecting the federal funds allocated to pavement rehabilitation projects; and 3) reducing the transportation costs and, ultimately, the price of local goods which will make them more competitive, locally and internationally.

1.7. Dissertation Organization

This dissertation is organized into six main chapters. Chapter 1 introduced the research issues under study, the research gap and the statement of the research problem. Furthermore, it introduced the research objectives together with their accompanied questions and hypothesis, and the methodology adopted to achieve these objectives. Finally, the significance of this research study and its limitations were highlighted. Chapter 2 provides a comprehensive literature review for all the research concerned with: the I/D and A+B alternative contracting methods; the time performance of these contracting methods; the different models that are developed to estimate the cost and time associated with the I/D and A+B contracting methods; examine the studies aimed at evaluating the performance of the I/D and A+B contracting methods; and, examine the existing guidelines for selecting the most-suitable alternative contracting method. Chapter 3 presents in details the steps of developing the model used to determine the time/cost trade-off relationship under the I/D contracting method. First, the chapter presents the possible resource utilization scenarios that a contractor can use under the I/D contracting method and how to calculate both the additional construction cost and the savings in indirect cost associated with each scenario. Second, the chapter discusses the methodology of developing the time/cost trade-off model for the I/D contracting method and how the model was validated. Third, the chapter moves to the development of the model for assigning the ID value based on the desired level of duration reduction and calculate its associated cost. Next, a risk analysis module to determine the most likely ID value for the project and the most likely duration reduction for each ID value was explored. Finally, an application example of the developed model was presented.

Chapter 4 presents the details of developing the model used to determine the time/cost trade-off relationship under the A+B contracting method. First, the chapter presents the possible resource utilization scenarios that a contractor can use under the A+B contracting method and how the risk of determining the contract time affects these scenarios; then, the additional cost to offset this risk, the additional construction cost and the savings in indirect cost associated with each scenario were calculated. Second, the chapter discusses the methodology of developing the time/cost trade-off model for the A+B contracting method and how the model was validated. Third, the chapter moves to the development of the model for assigning a monetary value for the "B" component based on the required level of duration reduction and calculate its associated cost. Next, a risk analysis model to determine the most likely "B" value for the project and the most likely duration reduction for each "B" value was explored. Finally, an application example of the developed model was presented.

Chapter 5 discusses examining the SHAs' alternative contracting decision making process using the two models developed in this research study. First, how the use of each model separately can improve the SHAs' decision making with regards to their respective contracting method to ensure the success of their implementation. Second, the chapter contrasts the performance, cost and risk associated with each contracting method through the developed model to assist the SHAs in selecting the most-suitable method for their projects based on their time reduction needs and available budget. Finally, the chapter combines the two developed models in this study to derive the time/cost trade-off relationship for another widely-used ACM which is the A+B+I/D method.

Chapter 6 summarizes the conducted research and presents its conclusions, contribution to the body of knowledge, and limitations; it also lists the recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

The main objective of this chapter is to review the latest research studies concerned with examining the SHAs' alternative contracting decision making process. This comprehensive review will summarize and provide a detailed overview for the critical parameters affecting the SHAs' alternative contracting decision making process and explore the areas in which a research gap exists and which will be addressed through the development of this study. These existing research studies can be grouped into four main groups: 1) studies aimed at determining the impact of the I/D contracting method on the time/cost trade-off relationship for a pavement rehabilitation project and assigning the most appropriate ID value for the implementation of the I/D contracting method and the current practices adopted by the SHAs; 2) studies aimed at evaluating the impact of the A+B contracting method on the time/cost trade-off relationship for a pavement rehabilitation project and assigning the most suitable "B" value for the implementation of the A+B contracting method and the current practices adopted by the SHAs; 3) studies aimed at evaluating the performance of the application of the I/D and A+B contracting methods; and 4) the existing guidelines and research studies on how to select the most appropriate alternative contracting method for a particular project.

2.2. I/D Contracting Method Studies

The existing research studies concerned with the implementation of the I/D contracting method will be sub-divided into the following groups:

2.2.1. *Determination of the Time/Cost Trade-Off:*

According to the Federal Highway Administration, the I/D contracting method involves "a contract provision which compensates the contractor a certain amount of money for each day identified critical work is completed ahead of schedule" (FHWA 1989). As a result of the inclusion of this provision, the I/D contracting method impacts the time/cost trade-off for a construction project as contractors try to crash the duration beyond the project's normal point (Gillespie 1998, Daniels et al. 1999, Shr et al. 2004). Hence, In order to be able to depict the impact of the I/D contracting method on the time/cost trade-off relationship, a number of studies examined this impact first on the project's time and cost. Since with the I/D contracting method the responsibility of setting the contract time still lies in the hands of the SHAs (Herbsman et al. 1995, Sillars 2007, PaDOT 2013). Arditi and Yasamis (1998), defined the accelerated schedule under the I/D contracting method as a 6 or 7-day schedule. Later on, and as this method started gaining popularity and being adopted by more than 35 states (Pyeon and Park 2010), contractors started using additional resources to earn the incentives (Choi 2008, Jiang and Chen 2009). On the other hand, the cost of the project associated with the I/D contracting method tends to be higher than with the traditional contracting due to the trade-off relationship between these two decision variables (Arditi and Yasamis 1998, Shr 1999, Choi and Kwak 2012). In order to determine the impact of the I/D contracting method on the time/cost trade-off for the construction projects, several research studies attempted to tackle this problem through the use of different methodologies. One of these studies was the study conducted by Shr and Chen (2004). In this study the researchers used historical data from FDOT alternative contracting projects including: A+B, I/D, and No Excuse Bonus projects to develop a time/cost trade-off model for alternative contracting methods in general. The model is developed through the use of regression analysis between the (days used – final contract time)/(final contract time), as the independent variable, and the (final construction cost – award bid)/ (award bid), as the dependent variable and a second degree polynomial equation was derived. The effort conducted in the above-mentioned research was able to derive a time/cost trade-off relationship for the alternative contracting methods; however, the study assumed that all contracting methods had the same impact on this relationship; hence, providing a unified model for all. Second, the study used historical data without attempting to determine neither the contractor's productivity associated with each method, nor the increase in cost. Another study that aimed at quantifying this relationship but specifically for the I/D contracting method is the one conducted by Sillars and Riedl (2007). In this study, the researchers used a two-stage process to derive the effect of the I/D contracting method on the project's cost. Stage I started by the SHA's engineer's estimate for the project cost under traditional contracting and based on expert opinions from Oregon DOT the degree of acceleration and the associated cost were determined by identifying the impact of certain factors on the cost of acceleration. This was followed by stage II in which the cost of acceleration for the critical items were broken down into the different cost components and the impact of certain project characteristics on them was quantified. As illustrated above, this study aimed mainly at quantifying the cost of acceleration through the use of expert opinions without developing a model depicting the relationship between time and cost as a result of using the I/D contracting method. Furthermore, Jiang et al. (2010) attempted to quantify the time/cost relationship for Indiana I/D projects through the use of historical

I/D projects data. In that study, polynomial regression of the historical cost and time data of projects completed from 2006 to 2008 was performed to come up with the time/cost trade-off relationship. However, and similar to the first discussed study, historical data was utilized to derive the relationship without attempting to determine neither the contractor's productivity associated with each method, nor his increase in cost. Finally, one of the comprehensive studies attempting to quantify the time/cost trade-off relationship for I/D contracting projects was the one conducted by Choi (2008). In that study, CA4PRS software was used to simulate the project's duration under different resource utilization scenarios through the increase in the amount of resources used by fixed percentages; while, at the same time, the contractor's additional cost was calculated using a cost growth formula. After that, a regression analysis was conducted between the duration reduction and the corresponding increase in the contractor's cost and a trade-off relationship was derived. Although this study derived the relationship based on estimating the contractor's additional productivity and cost, some limitations existed. First and with regards to the productivity calculation, the percentage increase in resources was chosen arbitrarily between 5% and 25% without exploring neither the applicability of employing these additional resources into the work zone, nor the possibility of using more resources that might lead to additional duration reduction; moreover, when increasing the resources, the above study assumed that all resources' levels increase at once without considering which ones are the critical ones that practically impact the project's duration. Second, regarding the calculation of the cost increase, the savings in the contractor's indirect costs were not accounted for which might lead to an inflation in the final cost increase value.

2.2.2. *Assigning the ID Value:*

Another important decision with regards to the implementation of the I/D contracting method is the most suitable ID value to be assigned. Pyeon and Lee (2012) used a multi-step process to determine the ID amount to be assigned. These steps started by determining the project's baseline schedule, DRUC, contractor's cost increase and agency savings; then, provided a range for the ID amount from the contractor's cost increase to the summation of the DRUC and the savings. As seen, the study only provided a wide range of possible ID values to be assigned without setting a specific value that is tied to the desired duration reduction. Similar ranges were also provided by Choi and Kwak (2012). Furthermore a number of studies tackled this problem by estimating the project's DRUC and setting the ID value as a percentage of that value (Ibarra 2002, Fick et. al 2010, Jiang et al. 2010). Dutta and Patel (2012) developed a tool to calculate the incentive amount by knowing the bid cost, bid duration and planned duration. Through these parameters and with the use of a regression tool, the contractor additional cost was computed and the incentive amount was calculated by dividing this cost by the number of days to be reduced. However, by equating the ID value to the contractor's additional cost, the success of the implementation of the ID method might be in jeopardy as it provides the contractor with a minimum motivation to seek any duration reduction. At the same time, the majority of the current SHAs' I/D contracting guidelines only states that the ID value to be assigned should be related to the DRUC (NYSDOT 1999, CDOT 2006, ODOT 2006, PaDOT 2013, FDOT 2015, MDOT 2015), among others.

2.3. A+B Contracting Method Studies

The existing research studies concerned with the implementation of the A+B contracting method will be sub-divided into the following groups:

2.3.1. *Determination of the Time/Cost Trade-Off:*

A+B contracting method is a contracting method in which the low bidder is selected on the basis of combined low construction cost and time (WSDOT 2015); hence, the contractor seeks to reduce the project's duration to win the bid which impacts the time/cost trade-off relationship for the project. Nevertheless, the determination of this impact is a difficult task for the SHAs as the productivity rate differs from one contractor to another and only each contractor knows the resources available to him (Ellis and Herbsman 1990). As a result, most of the studies concerned with examining the impact of the A+B method did that from the contractor's point of view. For example, Shen et al. (1999) developed a model to help the contractor in selecting the optimal bid to submit for A+B projects. The model uses the value of time assigned by the SHA to reach the optimal cost-time bid. The model is based on the fact that for a given value of time, there can be infinite combinations of time and cost and hence develops a total combined bid ISO map. From the ISO map, the ISO line with the lowest combined value is selected and then added to the contractor's time-cost curve under the traditional contracting method and the point of intersection gives the optimal bid. As seen, the model is aimed only at helping the contractors in determining the optimal bid by using their traditional contracting time/cost trade-off and the value of time assigned by the SHA; thus, the trade-off relationship under the A+B was not developed and the above model cannot be used by the SHAs as they don't have access to the information regarding the contractors' traditional trade-off curve. Another effort with regards to the A+B contracting method was the one conducted by El-Rayes (2001). This effort developed a model for optimizing the contractors' resource utilization under the A+B method in order to enable them to minimize the total combined bid amount using different crew formations and continuity scenarios and applying dynamic programming to reach the optimal resource utilization scenario that will lead to the lowest combined bid. In spite of the importance of the above study, it also only aimed at helping the contractors with their A+B decision not the SHA as the model depends on the amount of resources that are available for the contractor which are not known for the SHAs. On the other hand, the only study aimed at helping the SHAs with their A+B decision making process is the one conducted by Shr et al. (2004). This study was based on the model developed by Shr and Chen (2004) and it uses the model developed in that study to calculate the minimum bid that the contractor should submit and then use this amount as the basis for the SHAs to set a range for the acceptable time bids. Nevertheless, since this model is based on Shr and Chen (2004) model, it inherits its same problems which are: assuming a unified time/cost trade-off relationship for all alternative contracting methods, and using historical data rather than calculating the actual productivities.

2.3.2. *Assigning the "B" Value:*

There is a lack of studies in the area of assigning the most suitable "B" value based on the SHAs' decision variables and the project's characteristics. As a result, most of the guidelines developed by the different SHAs for the A+B contracting method states that the "B" value should be equal to the DRUC (TXDOT 1998, NYSDOT 1999, MnDOT 2005, CDOT 2006, ODOT 2006, PaDOT 2013, MDOT 2015, WSDOT 2015).

2.4. Evaluating the Performance of the I/D and A+B Contracting Methods:

Several studies attempted to assess the results of implementing the different types of ACMs using data from projects that have already been executed. One of these studies is the one conducted by the University of Florida that assesses the effectiveness of ACMs implemented by Florida Department of Transportation (FDOT) in terms of time and cost (Ellis et al. 2007). In this study the researchers studied 1132 ACM projects and divided them by the type of work required. They then used three different ratios to assess the cost effectiveness of these methods which are:

i. Initial Award Performance, which compares FDOT's initial cost estimate with the award bid.

ii. Cost Growth Performance, which compares the actual costs with the award bid.

iii. Actual Cost Performance, which compares the actual costs with FDOT's initial cost estimate.

Based on these ratios, they found that the performance of each method varied among these ratios; for instance, the A+B contracting method had the best performance in terms of initial award performance. At the same time, in terms of project type, a general assessment of all ACMs was performed and it showed that for all project types identified, ACMs performed positively with regard to initial award performance and actual cost performance, with exception of bridges; while they all experienced significant cost growths. With regard to the time performance, again three similar ratios were used and similar variation in performance was recorded as the A+B contracting method proved best in the initial time performance and lane rental was the worst in all three ratios.

In addition, a similar study was conducted by Michigan State University to evaluate the impacts of using ACMs for projects let by Michigan DOT (El-Gafy 2014). In this study, the performances of different ACMs; namely: A+B, Accepted for Traffic, Interim Completion, Lane Rental, and No Excuse, in terms of time, cost, and quality were assessed. To assess the time effectiveness of these methods, two performance indices for each project were calculated:

i. Original Time Performance Index (OTPI), which is calculated as follows: ((Actual Duration Used – Original Contract Duration)/(Original Contract Duration))

ii. Present Time Performance Index (PTPI), which is calculated as follows: ((Actual Duration Used – Present Contract Duration)/(Present Contract Duration)).

Next, a statistical analysis was performed to examine whether the actual contract duration was affected by the presence of the different ACMs and whether certain acceleration techniques shortened the project duration relative to the conventional projects. Similarly, a project Cost Performance Index (CPI) for each project was calculated as follows: *((Authorized Contractor Cost – Original Contract Cost)/Original Contract Cost))* which was then followed by a statistical analysis to investigate the degree by which the project cost is affected by the presence of ACMs, how much the ACMs increased project cost, and whether ACMs increase the projects' costs significantly compared to conventional projects. Finally to examine the impact of ACMs on the project quality, the distress index and the remaining service life of the pavements were used. Based on the above, several conclusions were reached by this study:

1- There is no statistical difference in terms of time performance between the projects procured using ACMs and the conventional projects.

2- Projects procured by ACMs had better cost control than those procured conventionally.

3- In terms of quality, ACM projects showed better long term quality than conventional projects.

Another study that aimed to evaluate the effectiveness of ACMs is the one conducted by Anderson & Damnjanovic (2008). This study was based on a questionnaire sent to all SHAs asking them to assess the different methods in terms of reduction in time and whether the cost is under or over budget. For the former parameter a scoring scale of 1 to 5 was developed where “1” means increase in projects’ duration while “5” means more than 10% reduction in the project’s duration. Similarly, for cost “1” means more than 5% over budget and “5” means more than 5% under budget. According to this study, the A+B and I/D methods showed the greatest time reduction as more than 30% of the respondents said that these methods reduced time by 5-10%. On the other hand, in terms of cost, most of the respondents stated that all methods increased the cost over the initial budget with A+B being the method that most frequently leads to cost overruns.

Moreover, Strong (2006) conducted a national survey of different SHAs’ construction engineers to rank the performance of different ACMs & traditional contracting in different project types using eight performance factors. The ACMs studied were: A+B, lane rental, and design build and the factors considered were: administrative cost, construction cost, time, management complexities, road user costs, disruption to third parties, quality, and innovation. Based on this survey, A+B was the highest ranked method for all the nine types of projects examined.

Finally, Choi et al. (2012) attempted to determine the schedule effectiveness of both the A+B and I/D contracting methods using data from transportation projects in California. In this study, the researchers compared three different types of rehabilitation projects executed by these two methods with projects executed by traditional contracting methods through computing a schedule effectiveness ratio which is calculated by subtracting the original contract time from the final contract time and then dividing it by the original contract time. Through this study it was found that the I/D method was very effective in terms of schedule reduction while the A+B method showed schedule overruns in over 30% of the studied projects.

As demonstrated by all of the above studies, the performance of each type of the alternative contracting methods differs according to the type of work, project characteristics and the parameters examined; hence, there is a pressing need for guidelines and models that can help the SHAs in selecting the most suitable alternative contracting method for their projects.

2.5. Selecting the Most Suitable Alternative Contracting Method:

The literature concerning this research area can be divided into two distinct groups: SHAs' guidelines, and research developed guidelines.

2.5.1. SHAs' Guidelines

As previously illustrated, each of the above ACMs has its own advantages and disadvantages which makes them suitable to apply for certain types of projects rather than the others. In an attempt to identify the applicability of each method, several SHAs developed general guidelines, based on past experiences, of which types of ACMs are suitable for which types of projects. Some of these guidelines were developed for the use of ACMs in general while others for the use of a specific type of ACM. An example of the former type is the one developed by Ohio Department of Transportation. The Ohio DOT (2006) sets several criteria that if any of them is met, then the project may use an ACM, these criteria are:

i. Interstate or freeway projects that involve reconstruction, widening, interchange, or bridge work.
ii. Projects in heavily populated or travelled areas that require total road closures.
iii. Projects that have considerable effects on emergency services, school, or businesses.
iv. Projects that complete a gap in the highway system.

On the other hand, several SHAs developed specific guidelines for each type of ACM; for example, California Department of Transportation (CALTRANS) guidelines suggest that the use of A+B contracts is best for projects with total estimated cost of at least $5 million and DRUC of at least $5,000 (Felker 2002). At the same time, Minnesota Department of Transportation guidelines (MNDOT) (2005) identified types of projects were A+B should not be used which are: when there are pending right of way issues, potential utility conflicts, and incomplete design plans. They also specified specific project works that are suitable for A+B contracting among which are mill & overlay, bridge painting, and un-bonded concrete overlay. Finally, NYSDOT (1999) added that A+B contracts are best suitable for:

i. Projects that have preconstruction level of D or worse.

ii. Projects with high accident locations.

iii. Projects with DRUC of at least $3,000.

iv. When the total B portion is large enough to influence the bidding amount.

With regard to I/D contracts, the Federal Highway Administration (FHWA) identified five characteristics that if any of them is present in projects will warrant the use of I/D provisions, these characteristics are:

i. Projects that severely disrupt the traffic.

ii. Projects that significantly increase road user cost.

iii. Projects that significantly impact neighboring businesses.

iv. Major bridges out of service.

v. Projects with lengthy detours.

Furthermore, NYSDOT (1999) stated that certain conditions if present in a project will favor the use of I/D contracts over other ACMs, these conditions are:

i. When the project has critical milestones or phases that affect traffic.

ii. When the project is let using a number of contracts; hence, the shorter ones are best let by I/D contracts.

iii. When projects can only be constructed over a fixed period of time but its estimated duration exceeds this period.

iv. If the project is of short duration, hence, the B portion is insignificant.

2.5.2. Research Studies' Guidelines

In addition to the above guidelines, several research studies attempted to help SHAs in selecting the best ACM by defining other guidelines as well, an example of these is the one conducted by Fick et al. (2010). In this study, the researchers conducted a survey of several SHAs asking about their experiences with each ACM and from these results they developed guidelines for the use of A+B and I/D contracting methods. Moreover, Jaraiedi et al. (1995) conducted a survey of both highway contracting agencies and highway contractors about the projects that are best suitable for I/D contracts and came up with five guidelines, which are:

i. Projects that impair emergency services.
ii. Projects where the safety of the road users is in jeopardy.
iii. Projects which severely impact traffic.
iv. Projects that affects businesses.
v. Projects with lengthy detours.

As evident from the above two categories of guidelines, most of them provide general and broad types of projects for the use of alternative contracting methods and do not attempt to provide guidelines for the use of one alternative contracting method over the other according to the project's characteristics or the SHAs' decision parameters.

2.6. Conclusion:

This chapter provided an extensive literature review on the latest research studies conducted in the following areas: 1) studies aimed at determining the impact of the I/D contracting method on the time/cost trade-off relationship for a pavement rehabilitation project and assigning the most appropriate ID value for the implementation of the I/D contracting method and the current practices adopted by the SHAs; 2) studies aimed at evaluating the impact of the A+B contracting method on the time/cost trade-off relationship for a pavement rehabilitation project and assigning the most suitable "B" value for the implementation of the A+B contracting method and the current practices adopted by the SHAs; 3) studies aimed at evaluating the performance of the application of the I/D and A+B contracting methods; and 4) the existing guidelines and research studies on how to select the most appropriate alternative contracting method for a particular project. However, the review showed that there is an urgent need for further research in these areas to cover important gaps and optimize the SHAs' alternative contracting decision making process. These research needs include:

1- Determining the impact of the I/D contracting method on the time/cost trade-off relationship for highway pavement rehabilitation projects.

2- Assigning the most appropriate ID value for each individual project based on required duration reduction and budgetary constraints.

3- Determining the impact of the A+B contracting method on the time/cost trade-off relationship for highway pavement rehabilitation projects.

4- Assigning the most appropriate "B" value for each individual project based on required duration reduction and budgetary constraints.

5- Examine the SHAs' alternative contracting decision making process.

CHAPTER 3

DEVELOPING THE TIME/COST TRADE-OFF MODEL FOR THE I/D CONTRACTING METHOD

3.1. Introduction

The main objective of this chapter is to develop a time/cost trade-off model for pavement rehabilitation projects contracted under the I/D contracting method that has the capabilities of: 1) determining the relationship between the duration reduction and the increase in cost under the I/D contracting method; 2) assigning the appropriate ID value to be offered to the contractor based on the desired level of duration reduction and the owner's budgetary constraints; and 3) determining the most likely duration reduction that can be achieved for each level of ID and the most likely ID level for the entire project. Consequently, the proceeding sections will focus on: 1) quantifying the achievable duration reductions and their associated costs under the I/D contracting method; 2) deriving a relationship between the duration reduction and the increase in cost under the I/D contracting method; 3) relating the value of the ID to be assigned to the desired degree of duration reduction; 4) performing a risk analysis to determine the probability of achieving each ID level and each corresponding duration reduction; and 5) demonstrating the abilities of the developed model by applying it to a real-life pavement rehabilitation project. The above tasks will be achieved through the use and combination of four modules as shown in figure (3-1); namely: 1) Time/cost trade-off module, 2) ID level calculation module, 3) owner's cost calculation module, and 4) risk analysis module.

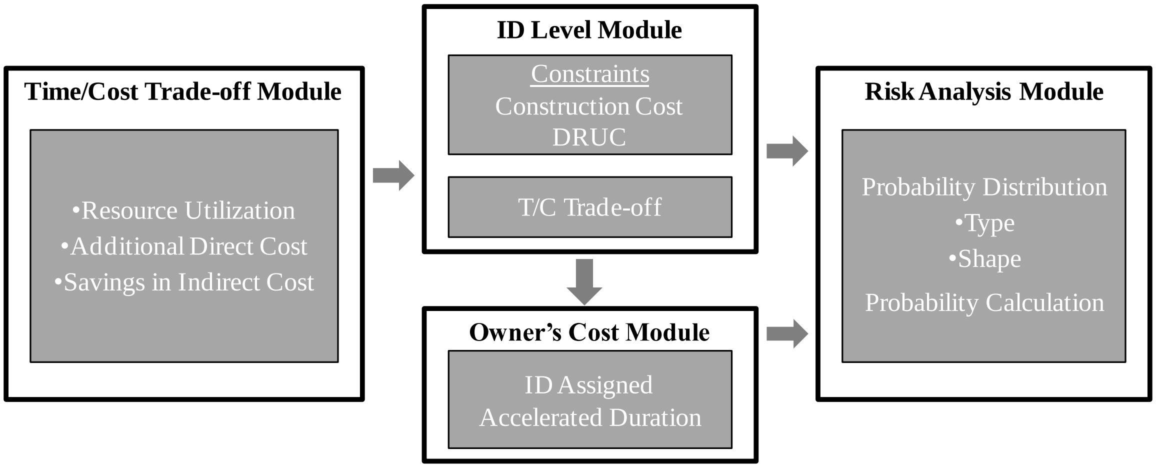

Figure 3-1: I/D trade-off calculation model

3.2. Time/Cost Trade-off Module

The main objective of this module is to help SHAs in determining the relationship between the reduction in a pavement rehabilitation project's duration and the contractor's additional cost associated with that reduction under the I/D contracting method; hence, the first step to achieve this objective is to quantify each component of this relationship. In an attempt to quantify these components under the I/D contracting method, Choi (2008) used simulation and a cost growth equation to calculate the above-mentioned parameters from the contractor's perspective; nevertheless, in that attempt, all the resources were increased incrementally to establish the utilization scenarios and the savings in the time-related indirect cost resulting from the reduction in the project's duration were not accounted for which might lead to an inflation in the value of the contractor's additional cost. Hence, in this research a similar methodology to the one used in the above-mentioned study was adopted but with: focusing on increasing the levels of the critical resources only as these are the ones that impact the project's duration, and incorporating the indirect cost savings to calculate the net additional cost incurred by the contractor as outlined in the following sub-sections.

3.2.1. Contractor's Schedule Compression due to Resource Utilization:

In order to simulate the project's duration as a result of the change in the contractor's resource utilization levels, the Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) schedule simulation software was utilized. CA4PRS was developed by the University of California at Berkeley Pavement Research Center and is specialized in pavement rehabilitation projects and was validated and implemented in a number of different states (Lee et al. 2008). CA4PRS has three main modules: work zone analysis module, schedule simulation module, and cost estimation module; in addition to real-life project examples already stored in its database. Furthermore, to account for all the major factors impacting the production of pavement rehabilitation projects, the different construction strategies, construction windows, and cross-section designs were taken into consideration when conducting the schedule simulations (Choi 2008). Accordingly, the first step to conduct the schedule simulation is to extract the base-line schedule used for the project accompanied by its corresponding critical resources' levels from CA4PRS; second, the levels of the critical resources, as analyzed by CA4PRS, were increased incrementally and the corresponding projects' duration were simulated till reaching the maximum limits of these resources (Lee 2011). These two steps were done for each different pavement strategy, cross-section, and construction window which resulted in a number of resource utilization scenarios and their corresponding durations as shown in table (3-1):

Table 3-1: Resource Utilization Scenarios and their Corresponding Durations

Strategy	**Cross-Section Profile**	**Constru-ction Window**	**Duration (days)**				
			Ordinary Usage	**Inc. Level 1**	**Inc. Level 2**	**Inc. Level 3**	**Inc. Level 4**
PCCP	12 inch	Nighttime	361	268	247	229	211

Strategy	Cross-Section Profile	Constru-ction Window	Duration (days)				
			Ordinary Usage	Inc. Level 1	Inc. Level 2	Inc. Level 3	Inc. Level 4
		Weekend	196	178	164	152	140
		Extended	193	175	161	149	138
	8 inch	Nighttime	201	140	127	116	105
		Weekend	87	78	70	64	58
		Extended	85	76	69	63	57
ACP	6 inch	Nighttime	229	208	177	154	139
		Weekend	24	22	19	17	15
		Extended	24	22	19	16	15
MACO	6 inch	Nighttime	131	117	106	99	98
		Weekend	25	23	21	20	19
		Extended	24	22	20	19	18

3.2.2. Contractor's Direct Cost Growth

As discussed earlier, as a result of reducing the project's duration, the contractor had to use additional resources which in return will lead to an increase in the project's direct cost. This cost (CAC) can be expressed using the contractor's cost growth formula below (Choi 2008):

$$\text{CAC} = \text{unit price} \times \text{number of additional resources} \times \text{labor surcharge rate} \times \text{working hours per day} \times \text{overtime rate} \times \text{project duration} \times \text{overhead cost} \qquad (3\text{-}1)$$

To calculate this formula, the unit prices for the different critical resources were collected from 17 different sources ranging from states' published rental rates to other federal and nationwide resources and the average of these rates was used. The use of more than one source helps in accurately reflecting the contractor's cost increase without the influence of specific locations' conditions and increasing the applicability of the developed model across the different regions of the country. As a result, the additional CAC for each resource utilization scenario in table (3-1) was calculated as shown in table (3-2):

Table 3-2: Contractor's Additional Cost Increase

Strategy	Cross-Section Profile	Construction Window	Inc. Level 1	Inc. Level2	Inc. Level 3	Inc. Level 4
PCCP	12 inch	Nighttime	2.64%	4.84%	6.73%	9.63%
		Weekend	4.67%	8.58%	11.92%	17.06%
		Extended	4.58%	8.42%	11.70%	16.74%
	8 inch	Nighttime	1.37%	2.49%	3.41%	4.77%
		Weekend	2.03%	3.68%	5.04%	7.05%
		Extended	1.98%	3.59%	4.93%	6.89%
ACP	6 inch	Nighttime	1.04%	2.64%	3.82%	4.82%
		Weekend	0.29%	0.74%	1.08%	1.37%
		Extended	0.29%	0.73%	1.05%	1.33%
MACO	6 inch	Nighttime	0.83%	1.51%	2.11%	2.48%
		Weekend	0.14%	0.26%	0.36%	0.42%
		Extended	0.14%	0.25%	0.35%	0.41%

3.2.3. Contractor's Time-Related Indirect Cost Savings

Time-related indirect costs are those costs that the contractor incurs everyday in the project regardless of the nature or quantity of work that is done on that day. Therefore, whenever the contractors can reduce the project's duration, the total amount of these costs decreases providing realized savings for the contractor. In order to quantify the savings in the indirect costs, the magnitude of these costs for a construction project has to be first quantified. This task was attempted by a number of previous research studies and one of the most comprehensive attempts to quantify the amount of indirect costs was conducted by Assaf et. al (1999). In that study, the researchers found that the project overhead ranges from 11% to 20% of the total project's direct cost with the norm at 14.9%; moreover, of these project overheads, the time-related ones accounted for 60% (Assaf et. al 1999). Therefore, to account for the savings in the time-related indirect cost, this study assumed that their average value account for 8.9%, which is 60% of the norm value, of the project's total direct cost and the calculation of the savings were done using the following steps:

1- Assume the total cost = direct cost + 0.089*Direct Cost and calculate the direct cost.

2- Calculate indirect cost = 0.089*Direct Cost.

3- Calculate indirect cost/day = indirect cost/project's duration

4- Calculate the time-related cost savings = (indirect cost/day)*(number of days reduced).

After calculating the two components of the change in the project's cost as a result of the duration reduction, the contractor's net cost growth can be expressed using equation (3-2) with the results shown in table (3-3):

$$\text{Contractor's Net Cost Growth (\$)} = \text{Engineer's Cost Estimate} + \text{CAC} - \text{Indirect Cost Savings} \quad (3\text{-}2)$$

Table 3-3: Duration Reductions vs. Net Cost Growth

Strategy	Profile (inch)	Constru-ction Window	Trade-Off							
			Inc. Level 1 (%)		Inc. Level 2 (%)		Inc. Level 3 (%)		Inc. Level 4 (%)	
			ΔT	ΔC	ΔT	ΔC	ΔT	ΔC	ΔT	ΔC
PCCP	12	Nighttime	-25.7	0.54	-31.7	2.25	-36.7	3.73	-41.7	6.22
		Weekend	-9.20	4.26	-16.6	7.84	-22.7	10.9	-28.8	15.8
		Extended	-9.18	4.18	-16.6	7.69	-22.7	10.7	-28.8	15.5
	8	Nighttime	-30.3	0.01	-36.9	0.81	-42.4	1.49	-48.2	2.58
		Weekend	-10.4	1.83	-18.9	3.31	-25.8	4.54	-33.3	6.40
		Extended	-10.4	1.78	-18.9	3.23	-25.8	4.43	-33.3	6.25
ACP	6	Nighttime	-9.04	0.53	-22.9	1.36	-33.0	1.98	-39.6	2.61
		Weekend	-8.88	0.24	-22.8	0.61	-32.8	0.89	-39.2	1.14
		Extended	-8.84	0.24	-22.6	0.60	-32.9	0.86	-39.6	1.10
MACO	6	Nighttime	-10.8	0.54	-19.5	0.98	-24.8	1.45	-25.9	1.79
		Weekend	-10.2	0.09	-18.4	0.17	-23.9	0.24	-26.4	0.29
		Extended	-9.54	0.09	-18.1	0.16	-23.7	0.24	-26.3	0.28

3.2.4. Modeling the Time/Cost Trade-Off Relationship

Using the data shown in table (3-3), and knowing that the relationship between the construction cost and time can be expressed by a second degree polynomial, a polynomial regression was performed to derive the relationship between the project's duration and its cost under the I/D contracting method as shown in figure (3-2):

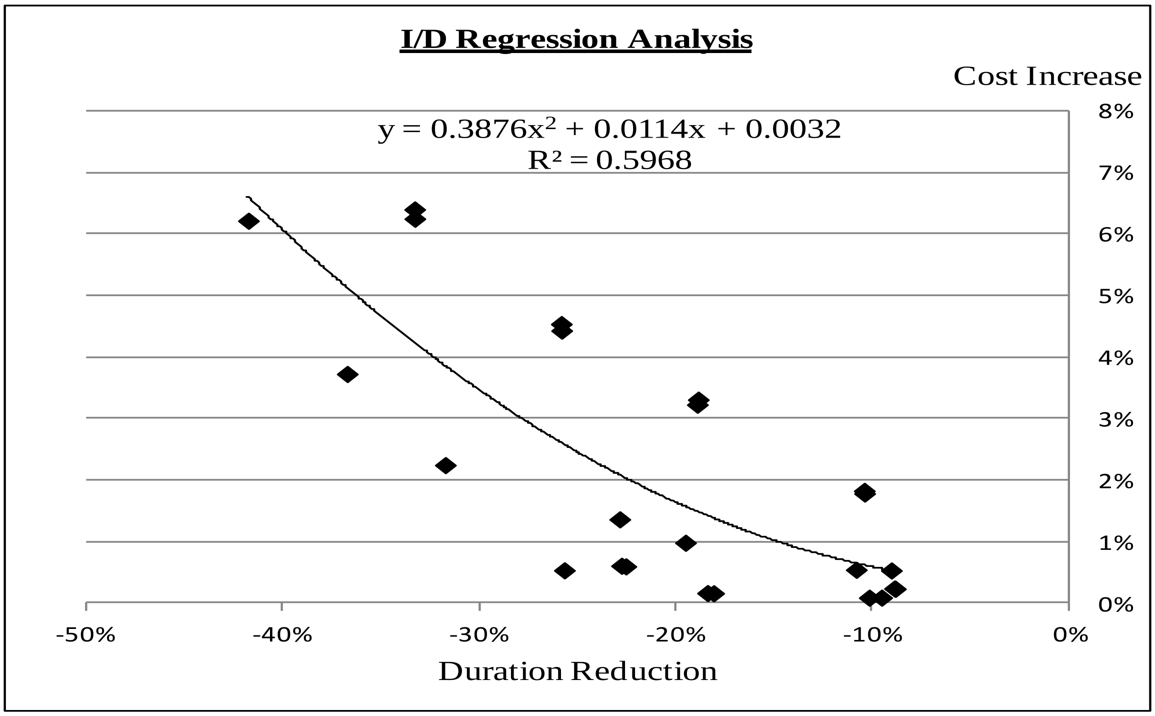

Figure 3-2: I/D contracting method time/cost trade-off

The performed regression analysis yielded the relationship shown by equation (3-3) between the construction cost and time under the I/D contracting method with R-squared value of approximately 0.60 emphasizing a very good fit:

$$C = 0.3876\ T^2 + \ 0.0114\ T + 0.0032 \qquad (3\text{-}3)$$

Following Choi (2008) steps to convert the above equation in terms of the relationship between the increase in the construction cost and the reduction in the project's duration, equation (3-3) can be rewritten as follows:

$$\Delta C = 0.0114 + 0.7752 t_0 - 0.3876 \Delta t \qquad (3\text{-}4)$$

where: ΔC = contractor cost increase expressed as a percentage of the engineer's cost estimate; t_0 = engineer's project duration estimate expressed as 100%; and Δt = reduction in project's duration expressed as a percentage of the engineer's duration estimate.

By deriving equations (3-3) and (3-4), the trade-off relationship between the time and cost of a pavement rehabilitation project under the I/D contracting method can now be accurately defined.

3.2.5. Model Validation

To test the accuracy of this model, a validation test against real life pavement rehabilitation projects contracted through the I/D contracting method was conducted. To validate the above developed model, the expected cost derived from the model was validated against the final cost of real-life I/D projects. To perform this task, data from 76 different I/D projects was gathered from different sources. The model validation was performed through the following steps:

1- Calculating the expected final cost of the project as a result of reducing its duration using the developed model. This was done using the projects' engineer's time estimate as t_0, the project's actual time to calculate Δt, and the engineer's cost estimate and applying equation (3-4) to these values.

2- Comparing the calculated costs with the actual costs from the projects which was done using a paired-sample t-test. This test was chosen as it has the capability of detecting the difference in the mean of the two datasets and its suitability for the available data as they represent the same project with two different scenarios and their large number fulfills the normality assumption for the t-test.

3- Examine the resulting p-value and confidence intervals from the performed t-test. Accordingly, table (3-4) shows a summary of the results of the paired-sample t-test conducted for the calculated cost vs. the actual cost.

Table 3-4: Paired-Sample t-test Results

	Paired Differences		**t**	**df**	**Sig. (2-tailed)**
	95% Confidence Interval of the Difference				
	Lower	**Upper**			
FinalCost - CalcCost	-1094497.5	94005.7	-1.67	75	.098

From the above table, the p-value for the t-test, at a 95% confidence level, was equal to 0.098 which is larger than 0.05; hence, we do not reject the null hypothesis (H_0) and the means of the costs can be assumed equal; furthermore, the lower limit of the confidence interval has a negative value while the upper limit has a positive one which shows that sometimes the mean of the calculated cost is larger than the mean of the final cost and sometimes the opposite is true. This supports the conclusion that the two means can be assumed equal since the confidence interval does not lie away from the "0" point.

3.2.6. Sensitivity Analysis

After validating the relationship between the increase in cost and the reduction in the project's duration under the I/D contracting method, sensitivity analysis for the developed model was conducted. Two analyses were performed to examine the impact of certain independent variables on the time/cost trade-off relationship for the I/D pavement rehabilitation projects; these variables are: the percentage that the indirect cost constitutes of the project's direct cost and the equipment rental rates used to calculate the increase in the contractor's direct cost. Regarding the former, three percentages of the indirect cost representing the upper and lower bounds of the range concluded by Assaf et al. (1999), as well as its norm, were used to calculate the net cost growth incurred by the contractor under the I/D contracting method. When applying these different percentages to the calculation of the time/cost trade-off, while keeping all other variables constant, the results showed that as the percentage of the indirect cost decreases, the net cost growth increases for the same duration reduction, and vice-versa (figure 3-3) which was further reinforced when a scenario of no indirect costs savings i.e. only the increase in the direct costs, was examined.

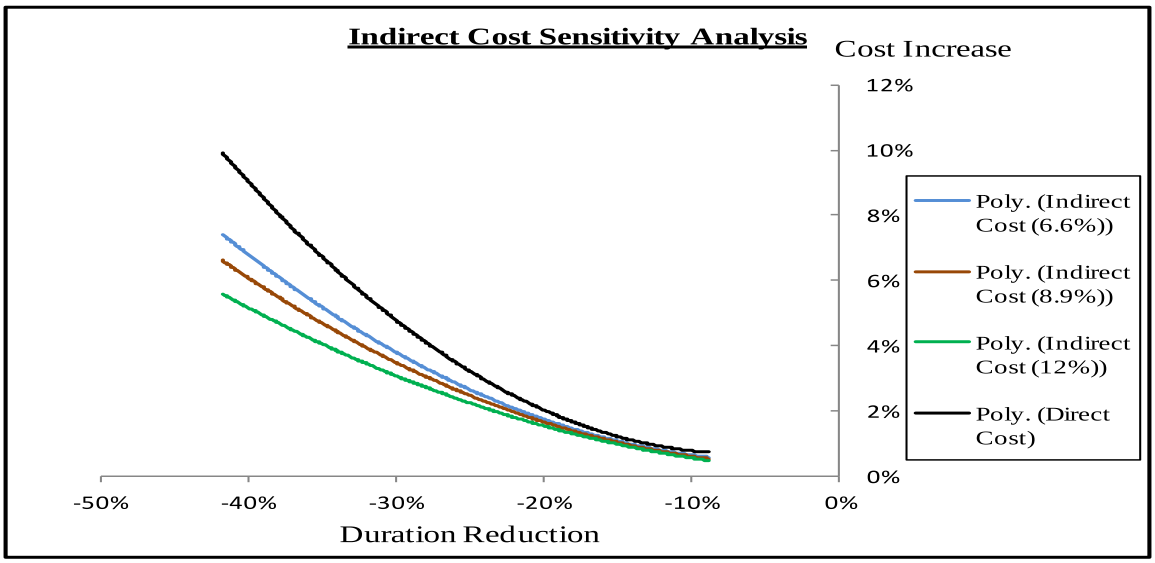

Figure 3-3: Indirect cost sensitivity analysis

With regards to the latter variable, and besides the average rates that were originally used to develop the model, the maximum, minimum, and a sample of one of the SHAs rates (CALTRANS) were used to test the impact of these rates on the time/cost trade-off relationship for pavement rehabilitation projects under the I/D contracting method. When applying these different rates to the calculation of the time/cost trade-off, while keeping all other variables constant, it was observed that these rental rates are positively correlated with the net cost growth for the same duration reduction, and vice-versa (figure 3-4); furthermore, it was proved that the CALTRANS rental rates almost yielded the same trade-off relationship as the maximum rates which means that these particular rates are among the highest in the country. It is also worth noting that at very low time reductions, the impact of the different rental rates is minimal as only few more resources are needed.

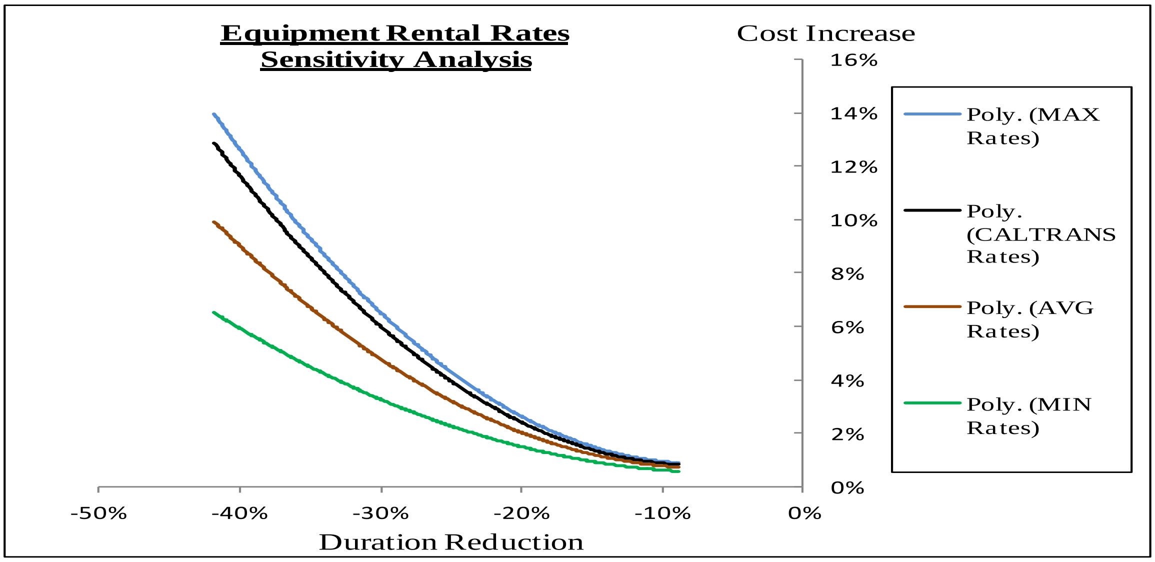

Figure 3-4: Equipment rental rates sensitivity analysis

3.3. ID Level Calculation Module

After deriving the relationship between the increase in cost and the reduction in the project's duration for a pavement rehabilitation project contracted under the I/D contracting method, the ID level calculation module will be used to assign the appropriate ID level for pavement rehabilitation projects based on the desired level of duration reduction. To achieve this objective, a relationship between the duration reduction and the ID level to be assigned has to be developed and the first step in developing such a relationship is to understand the rationale behind using such type of contracts; and consequently, the constraints imposed on them. As discussed in the previous chapters, the main objective for SHAs behind adopting the I/D contracting method is to reduce the negative impacts of the pavement rehabilitation projects on the road users. However, with the adoption of such method, SHAs will incur more costs, than what they would have incurred using traditional contracts, reflected in the incentive offered; albeit, this additional cost must not exceed the DRUC in order to protect the public money. On the other hand, in order for the contractor to be able to reduce the project's duration, additional resources have to be committed which is reflected in an increased cost. Hence, to motivate the contractors to accelerate the project's duration, the incentive offered must be more than the additional cost that they will incur (CC) (Jaraiedi et al. 1995). These constraints can be expressed in the form of the following inequality:

$$CC \ \leq ID \leq DRUC \tag{3-5}$$

Hence, by substituting equation (3- 4) into the equation (3-5), the inequality can be expressed as:

$$(0.0114 + 0.7752t_0 - \ 0.3876\Delta t) \ \leq ID \leq DRUC \tag{3-6}$$

As shown from equation (3-6), the constraints for selecting the appropriate ID level can now be expressed in terms of the duration reduction which will be used in developing the ID module. Furthermore, by calculating the ID level as a percentage of the DRUC, where this percentage ranges from 0-100%, SHAs will be sure that the second constraint of equation (3-6) is satisfied i.e. the savings realized by accelerating the project are more than the additional cost incurred. Moreover, setting a variable ID level for a given project based on the desired level of duration reduction, means that each pavement rehabilitation project can have more than one ID level which ultimately means that the relationship between the ID level and the project duration can be depicted as shown in figure (3-5):

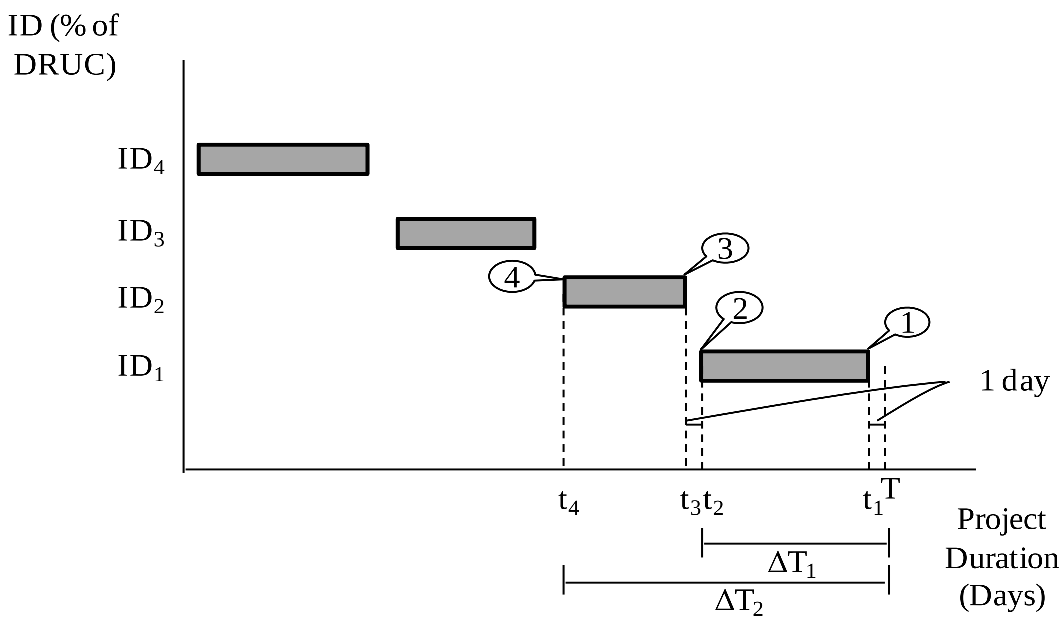

Figure 3-5: Relationship between the ID level and the project's duration

From figure (3-5), in order to be able to assign the appropriate ID level for each duration reduction, the coordinates of points 1 through 4, i.e. time and ID, have to be calculated. These points represent the lower and upper bounds of the possible duration reductions for the first two ID levels that can be assigned for a given pavement rehabilitation project. As seen in the figure, point (1) represents the minimum duration reduction that can be achieved for a project (t_1) and the corresponding minimum ID level that can be assigned to achieve it (ID_1); while point (2) represents the maximum duration reduction that can be achieved using ID_1 (t_2). Similarly, if the SHA needs to reduce the time beyond t_2, then point (3) represents the next possible time reduction after t_2 (t_3) and the corresponding ID level that needs to be assigned to achieve such a reduction (ID_2); and finally, point (4) represents the maximum duration reduction (t_4) that can be achieved using ID_2. The steps to calculate the coordinates of these four points are summarized in figure (3-6) and explained in details in the following sections:

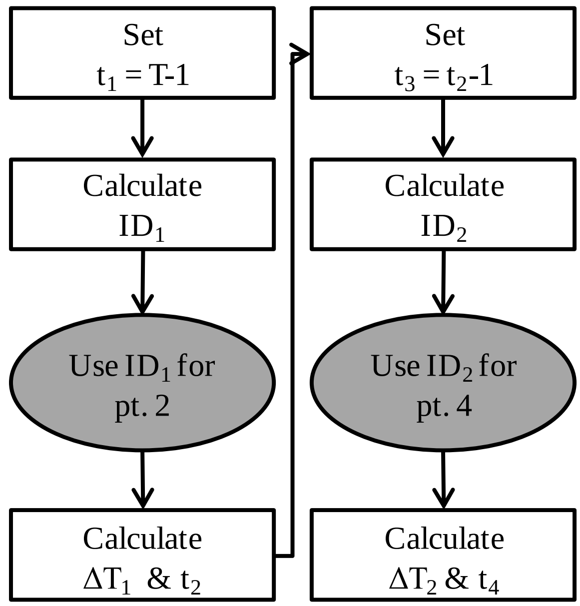

Figure 3-6: Steps for calculating the coordinates of points 1 through 4

3.3.1. Point 1: (Minimum Duration Reduction & Minimum ID Level):

- *Step 1.1: Calculate the minimum duration reduction for any project (t_1).* By developing the engineers estimate of the baseline schedule for the project under traditional contracting (T), SHAs can assume the minimum duration reduction which is 1 day to be the time at point 1; hence, (t_1) can be calculated using the following equation:

$$t_1 = T - 1 \quad (3\text{-}7)$$

- *Step 1.2: Calculate the minimum ID level that has to be offered (ID_1).* Through utilizing the first constraint of equation (3-6), the minimum ID that can be offered is the one that is, at least, equal to the additional cost incurred by the contractor. Hence, by using equation (3-6) while assuming t_0 = 100%, expressing ΔT as a percentage of t_0 and the ID as a percentage of DRUC, the minimum ID to be offered (ID_1) can be calculated by knowing the engineer's cost estimate associated with the baseline schedule (C) as shown in equation (3-8):

$$ID_1 = \frac{\left[0.7866 - 0.3876 \times \left(-\frac{1}{T}\right)\right] \times C}{DRUC} \qquad (3\text{-}8)$$

3.3.2. Point 2: (Maximum Duration Reduction using ID_1):

- *Step 2.1: Calculate the ID Value*. Point 2 represents the maximum duration reduction that can be achieved by using ID_1; in other words, the ID for this point is still equal to ID_1.

- *Step 2.2: Calculate the maximum duration reduction that can be achieved using ID_1 (ΔT_1)*. Through utilizing the first constraint of equation (3-6) and substituting with ID_1, ΔT_1 can be calculated as a percentage of the baseline duration using the following equation:

$$\Delta T_1(\%) = -\frac{\left[\left(\frac{ID_1 \times DRUC}{C}\right) - 0.7866\right]}{0.3876} \qquad (3\text{-}9)$$

Where the negative sign reflects a reduction in the project's duration.

And consequently, the maximum days of duration reduction that can be achieved by offering ID_1 can be calculated using equation (3-10):

$$t_2 = T + \Delta T_1(\%) \times T \qquad (3\text{-}10)$$

3.3.3. Point 3: (Duration Reduction Beyond t_2 and the Corresponding ID Level):

- *Step 3.1: Calculate the reduced duration (t_3)*. Similar to point 1, SHAs can assume the minimum duration reduction beyond t_2 to be 1 day; hence, (t_3) can be calculated using the following equation:

$$t_3 = t_2 - 1 \qquad (3\text{-}11)$$

- *Step 3.2: Calculate the ID level associated with t_3 (ID_2).* By using the first constraint of equation (3-6), ID_2 can be calculated as follows:

$$ID_2 = \frac{\left[0.7866 - 0.3876 \times \left(\Delta T_1' - \frac{1}{T}\right)\right] \times C}{DRUC} \tag{3-12}$$

Where ΔT_1' is ΔT_1 adjusted to the nearest whole number of days reduced.

3.3.4. Point 4: (Maximum Duration Reduction Using ID_2):

- The calculations for the coordinates of point 4 are similar to point 2; thus, the ID = ID_2 and ΔT_2 and t_4 can be calculated using equations (3-9) and (3-10).

Finally, for any given project there might be additional feasible ID levels, beyond ID_2, that can be assigned to achieve more duration reduction; hence, the calculation of the coordinates of their boundary points will be similar to points (3) and (4) and by using the following generalized equations:

$$t_i = t_{i-1} - 1 \tag{3-13}$$

$$ID_i = \frac{\left[0.7866 - 0.3876 \times \left(\Delta T_{i-1}' - \frac{1}{T}\right)\right] \times C}{DRUC} \tag{3-14}$$

$$\Delta T_i(\%) = -\frac{\left[\left(\frac{ID_i \times DRUC}{C}\right) - 0.7866\right]}{0.3876} \tag{3-15}$$

where: t_i = project's duration at point i expressed in days; ID_i = the level of ID associated with the duration at point i expressed as a percentage of the DRUC; T = engineer's project duration estimate expressed in days; C = engineer's project cost estimate expressed in dollars; DRUC = daily road user cost expressed in dollars; ΔT_i = maximum reduction in the project's duration at point i expressed as a percentage of the engineer's duration estimate; and ΔT_i' is ΔT_i adjusted to the nearest whole number of days reduced.

Nevertheless, SHAs need to determine the feasibility of any further ID levels by examining the availability of additional resources in their markets, and whether any additional resources can be logistically deployed into the construction site or not; furthermore, some SHAs have a maximum ID amount that they can pay (Pyeon and Lee 2012); once any of these conditions is met, then the maximum possible duration reduction, and its corresponding ID level, are reached for that particular project and the calculations using the ID module are completed.

3.4. Owner Cost Calculation Module

Another important factor in the SHAs decision regarding the suitable ID level for their projects is the total cost of the project that they will incur as a result of selecting each ID level. Previous studies concerned with the I/D contracting method attempted only at quantifying this cost from the contractors' perspective (Choi et al. 2013). Nevertheless, through utilizing the owner's cost module component of the developed model and after determining the accelerated duration associated with each ID level from the ID module, the total project cost from the SHA's perspective can be calculated. Recalling figure (3-6) and points 1 through 4 shown in that figure, the owner's cost at each of these points can be calculated using equations (3-16) through (3-19), respectively.

$$C_1 = C + ID_1 \times DRUC \tag{3-16}$$

$$C_2 = C + (ID_1 \times DRUC \times (-\Delta T_1') \times T) \tag{3-17}$$

$$C_3 = C + \left(ID_2 \times DRUC \times (T - t_3)\right) \tag{3-18}$$

$$C_4 = C + (ID_2 \times DRUC \times (-\Delta T_2') \times T) \tag{3-19}$$

Generally, for any point beyond point (4), the owner cost can be calculated using the following equations:

For odd-numbered points:

$$C_i = C + \left(ID_{i-1} \times DRUC \times (T - t_i)\right) \qquad (3\text{-}20)$$

For even-numbered points:

$$C_i = C + \left(ID_{i-2} \times DRUC \times (-\Delta T'_{i-2}) \times T\right) \qquad (3\text{-}21)$$

where: C_i = project's cost at point i expressed in dollars; C = engineer's cost estimate expressed in dollars; ID_{i-1} = the level of ID associated with the duration at point i-1 expressed as a percentage of the DRUC; DRUC = daily road user cost expressed in dollars; T = engineer's duration estimate expressed in days; t_{i-1} = project duration at point i-1 expressed in days; and $\Delta T'_{i-2}$ = maximum reduction in the project's duration at point i-2 after being adjusted for a whole number of days and expressed as a percentage of the engineer's duration estimate.

Consequently, through utilizing the above two modules summarized in figure (3-7), SHAs can accurately set the appropriate ID level according to their desired acceleration level and their own budgetary constraints which will guarantee the success of adopting the I/D contracting method and prevent any waste of the public money.

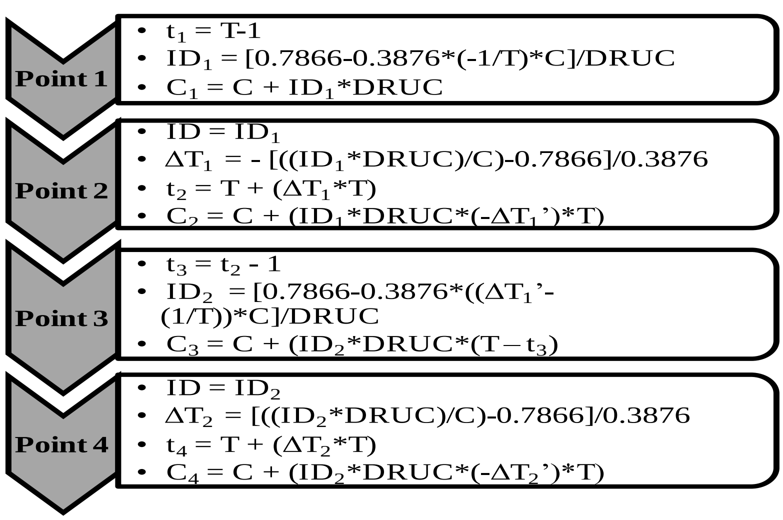

Figure 3-7: Summary of ID, time, and owner's cost calculation steps

3.5. Model Application

As explained above, in order for the SHAs to be able to utilize the ID level calculation module, they need to calculate the project's DRUC, engineer's time estimate, and engineer's cost estimate. Therefore, one of CA4PRS stored projects; namely: I-15 Devore project in San Bernardino, California, was used to test the application of the ID and owner's cost modules. This project involved the rehabilitation of a 2.67 mile stretch, equivalent to 10.7 lane-mile, of damaged concrete truck lanes on I-15 which is a highly trafficked corridor in Southern California with an AADT of approximately 100,000 with 10% truck rate (Choi and Kwak 2012).

The first step in the application of the model was to calculate its three inputs, DRUC, engineer's time estimate, and engineer's cost estimate, using CA4PRS. To calculate the DRUC, the traffic volume and the lane closure pattern for the project were defined and the DRUC value came out to be $243,551, it is worth noting that this value includes both the user and agency daily costs (Choi and Kwak 2012). With regards to the engineer's time estimate (baseline schedule), the project scope, resources types and quantities, and their production rates were the inputs used and the baseline schedule was simulated to be 201 days based on nighttime closure. Finally, regarding the engineer's cost estimate, the estimated cost for this project as per the project data stored in CA4PRS was $18 million (Choi and Kwak 2012). Next, the ID module steps were applied to determine the different ID levels that can be offered for this project together with their corresponding duration reductions. Figure (3-8) shows the results for I-15 Devore project. As seen from the figure, there are 18 different daily ID levels that can be used for this project ranging from 59% of DRUC to 76% of DRUC, which are equivalent to $143,695 to $185,099, with corresponding duration reductions ranging from 1 to 125 days out of the original project duration of 201 days, respectively. Consequently, this wide range of possible duration reductions led to an increase in the project's final total cost, from the SHA's perspective, ranging from $18.1 million to $41 million, an increase of $0.1 million to $23 million, respectively, and corresponding DRUC savings ranging from $0.2 million to $30 million.

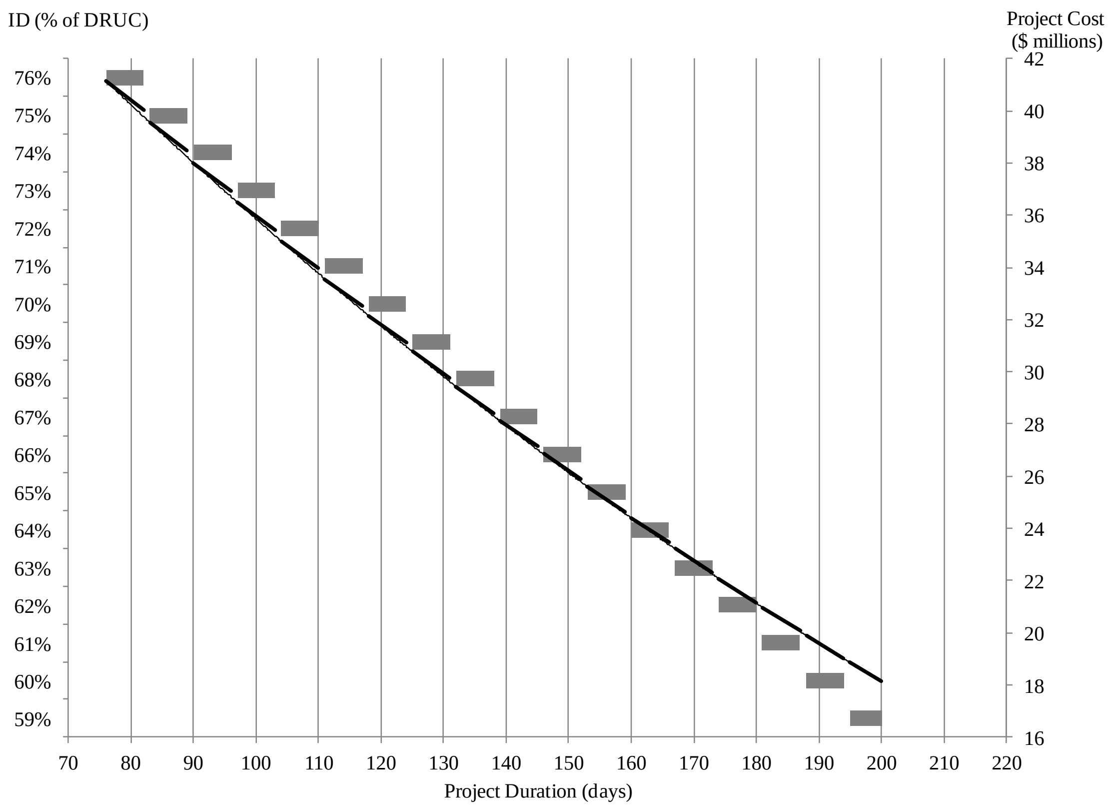

Figure 3-8: I-15 Devore ID levels

To test these results, the schedule simulation module of CA4PRS was utilized as discussed earlier and shown in figure (3-9).

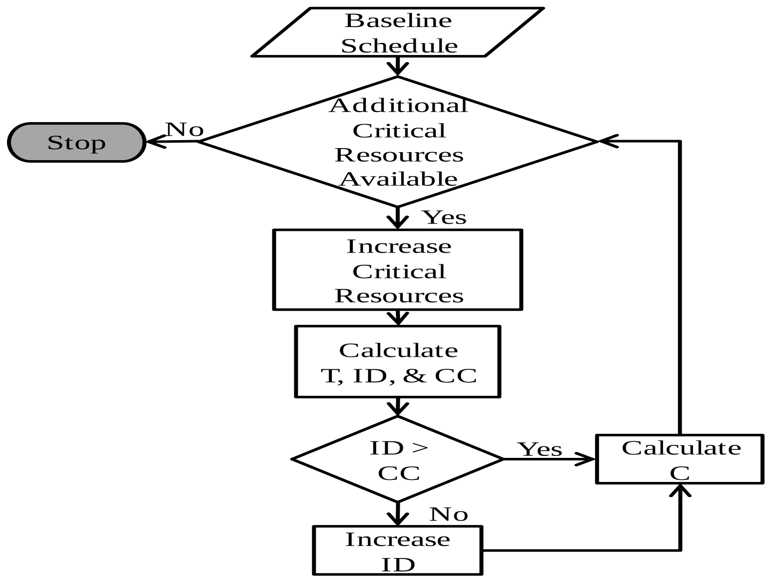

Figure 3-9: Steps for testing the ID and owner's cost modules

In order for the contractors to be able to reduce the duration of the project, they will need to increase the resources they utilize; hence, using the critical resource output provided from the baseline schedule simulation, the levels of these resources were increased incrementally and the new corresponding schedules were simulated and the contractor's costs were calculated using equation (3-4). This process was repeated until no more critical resources can be increased (Lee 2008). These durations and costs were consistent with the durations and costs calculated through the model as shown in table (3-5):

Table 3-5: Duration Reduction and Corresponding ID Levels for I-15 Devore Project

Point	Calculated Duration Reduction	Simulated Duration Reduction	ID (% of DRUC)[a]	ID ($/day)	Additional Contractor Cost ($/day)
1	200	199	59	143,695	141,935
2	195	197	59	143,695	143,671
3	194	192	60	146,131	144,018
4	188	189	60	146,131	146,100

where the calculated duration reduction refers to the one derived from the I/D model, the simulated duration reduction refers to the one calculated using CA4PRS, the ID calculated using the developed model and the additional contractor cost is calculated using equation (3-4).

As seen from table (3-5), all the simulated duration reductions fall within the calculated intervals for each ID level; and for all the points, the additional cost incurred by the contractor is less than the ID value offered which was calculated using the ID module.

3.6. Risk Analysis Module

Although the ID level and the owner's cost calculation modules can help SHAs in deciding the level of ID to be used based on the desired levels of time reduction, as evident from the I-15 Devore example, there can be many different ID levels to be used for a given project and each has a wide range of possible time reductions. This can create a conflict of interest between the owner and the contractor as the owner will want to achieve the maximum time reduction that can be possibly achieved by the selected ID level to get the maximum possible benefits from the additional money invested, while the contractors will want to achieve the minimum time reduction for such an ID value to maximize their profits. Furthermore, the higher the duration reduction, the less chance it can be achieved and the less motivated the contractor will be which applies both to the different ID levels and within each ID level. Hence a risk analysis module is developed to help SHAs in selecting the most likely level of ID to be achieved by the contractors and the most likely time reduction that can be achieved by this selected ID level. An expected risk model is used to evaluate this risk which involves determining the type of probability distribution that best represents this problem. According to Fente et al. (2000), and Ozolin and Muench (2007), the most suitable probability distribution type that can represent the risk related to a construction project's duration is the beta distribution; thus, in this module, the beta distribution will be assumed to represent the probability of the most likely duration reduction; and the shape corresponding to $\alpha < \beta$ is assumed to be the most appropriate shape. This latter assumption is based on two factors: first, the probability of the contractors being able to achieve the duration reduction closer to the minimum boundary is higher than the ones closer to the maximum boundary as the latter requires a sophisticated level of management skills and a high number of resources to be allocated that might not be available to the average contractor; and second, the motivation of the contractor to achieve the former is much higher than the latter. After setting the most suitable probability distribution, the probability of each duration reduction is calculated using the cumulative density function for this particular shape of the beta distribution.

By applying the risk analysis module to the results obtained from the I-15 Devore example and as shown in table (3-6), it was deduced that the ID level with the highest probability of being achieved is the 62% of DRUC which corresponds to a time reduction ranging from 10.4% to 13.4% of the original project's duration.

Table 3-6: ID Probability Levels

ΔT (% of Original Duration)	**ID (% of DRUC)**	**Probability**
0% - 3.0%	59%	3.04%
3.5% - 6.5%	60%	9.19%
7.0% - 10.0%	61%	12.50%
10.4% - 13.4%	62%	13.67%
13.9% - 16.9%	63%	13.35%
17.4% - 20.4%	64%	12.08%
20.9% - 23.9%	65%	10.28%
24.4% - 27.4%	66%	8.28%
27.9% - 30.8%	67%	6.31%
31.3% - 34.3%	68%	4.53%
34.8% - 37.8%	69%	3.05%
38.3% - 41.3%	70%	1.89%

ΔT (% of Original Duration)	ID (% of DRUC)	Probability
41.8% - 44.8%	71%	1.06%
45.3% - 48.3%	72%	0.52%
48.8% - 51.7%	73%	0.21%
52.2% - 55.2%	74%	0.06%
55.7% - 58.7%	75%	0.01%
59.2% - 62.2%	76%	0.00%

Furthermore, within this ID level and by applying the same calculation procedures, it was concluded that a duration reduction of 1.1% of the maximum duration for this ID level, which is equivalent to a 11.5% duration reduction from the original project's duration, or in other words 178 days, is the most likely duration reduction that can be achieved by the contractor using the 62% ID level as shown in figure (3-10).

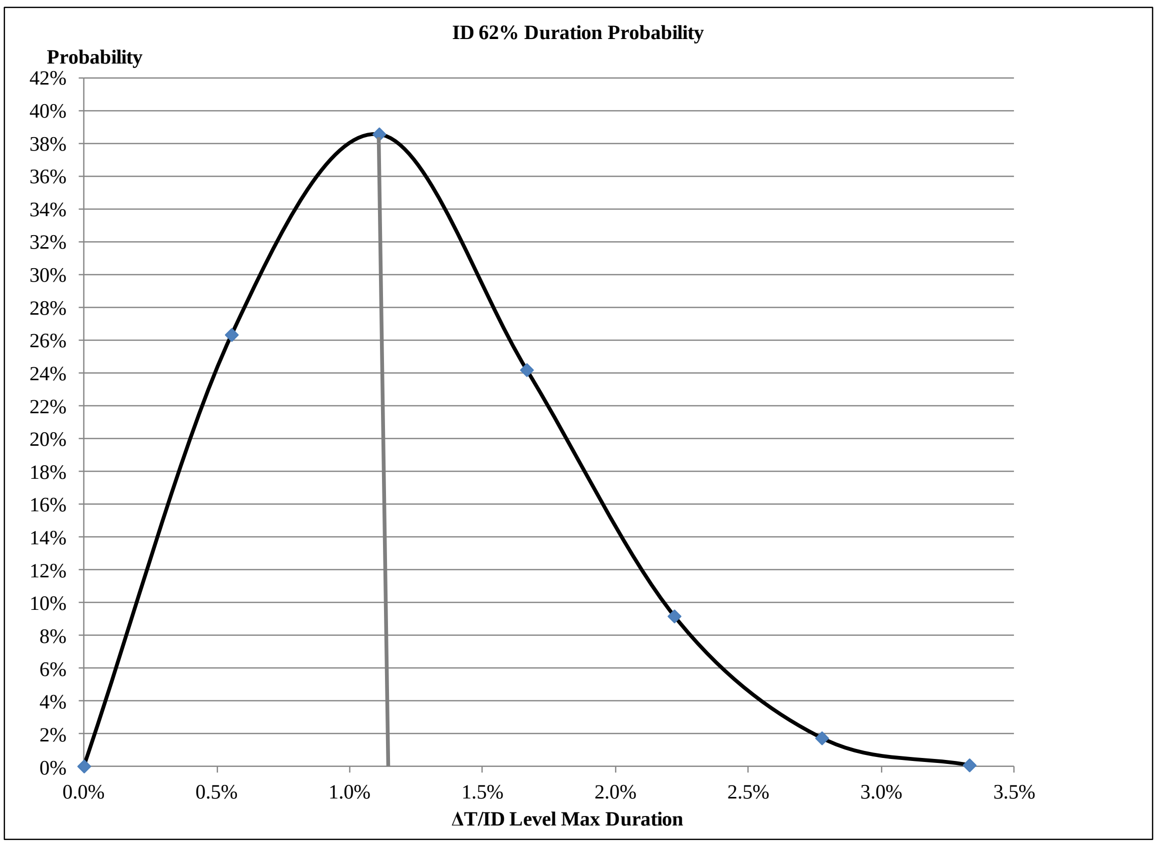

Figure 3-10: Risk analysis results

Hence through utilizing the four modules that constitute the developed ID time/cost trade-off model, SHAs' I/D contracting decision making process will greatly improve.

3.7. Conclusion

In this chapter a new model aimed at quantifying the impact of the I/D contracting method on the time/cost trade-off relationship and the impact of the different ID levels on the trade-off between time and cost of pavement rehabilitation projects was developed. The model assigns the appropriate ID values based on the desired level of reduction in the project's duration and estimates the additional cost, incurred by the owner, associated with each ID level due to the acceleration of the project's construction and finally determines the likelihood of achieving these desired levels of duration reduction. The model consists of four modules; namely: time/cost trade-off module, ID level calculation module, owner's cost calculation module, and risk analysis module. The development process of this model and its application on a real-life project, were presented in this chapter. The results of this application showed that this model has some distinctive capabilities including: 1) the ability to accurately depict the time/cost trade-off relationship for the pavement rehabilitation projects contracted using the I/D contracting method, 2) the ability to assign the proper ID level based on the desired duration reduction, 3) the ability to calculate the additional cost incurred by the owner as a result of selecting a certain ID level, 4) the ability to determine the most likely level of ID to be achieved for the project, and 5) the ability to precisely determine the duration reduction to be expected from adopting that particular ID level.

The developed model can help improve the SHAs planning process for their pavement rehabilitation projects using the I/D contracting method as it will enable the decision makers to make better informed decisions when contracting such projects. These decisions are both related to the duration and cost of the project which will help in reducing the negative impacts of the pavement rehabilitation projects and save the public's money; while, at the same time, allow the SHAs to best utilize their available budget.

Chapter 4

DEVELOPING THE TIME/COST TRADE-OFF MODEL FOR THE A+B CONTRACTING METHOD

4.1. Introduction

The main objective of this chapter is to develop a time/cost trade-off model for pavement rehabilitation projects contracted under the A+B contracting method. The model is designed to have the ability of: 1) depicting the relationship between the duration reduction and the increase in the contractor's cost under the A+B contracting method; 2) allocating the appropriate value for the "B" component of the contract based on the desired level of duration reduction and the SHA's budgetary constraints; and 3) setting the most likely duration reduction that can be achieved for each value of the "B" component and the most likely "B" value for the entire project. Accordingly, the following sections will focus on: 1) determining the resource utilization scenarios that are likely to be adopted by the contractor under the A+B contracting method, the contractors' additional degree of motivation to reduce the project's duration, and the resulting levels of duration reductions; 2) calculating the additional cost incurred by the contractors as a result of the new resource utilization scenarios and the additional risk they assumed as a result of setting the project's duration, 3) deriving a relationship between the duration reduction and the increase in cost under the A+B contracting method; 4) tying the value of the "B" component to be assigned to the desired duration reduction; 5) conducting a risk analysis to determine the probability of achieving each "B" value and each corresponding duration reduction; and 6) exhibiting the capabilities of the developed model by applying it to a real-life project example. This is achieved through the use and combination of four different modules as shown in figure (4-1); namely: 1) Time/cost trade-off module, 2) the “B” component’s value calculation module, 3) owner’s cost calculation module, and 4) risk analysis module.

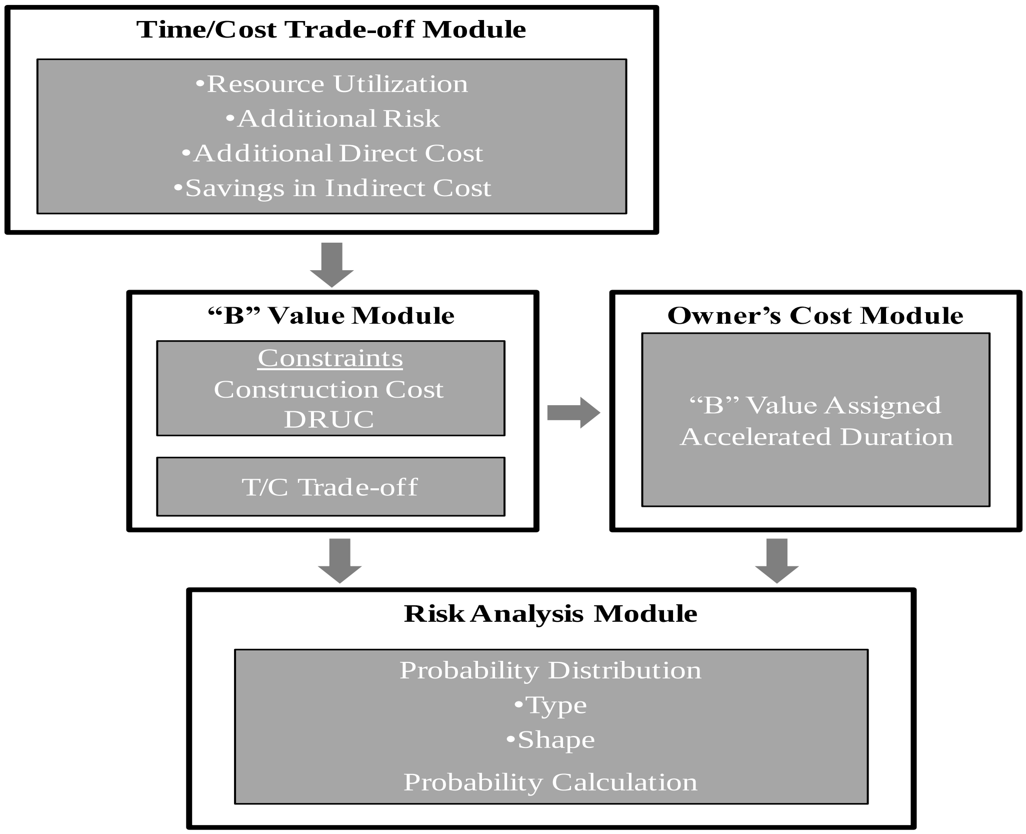

Figure 4-1: A+B trade-off calculation model

4.2. Model Development

The development of the model passes through different steps as shown in figure (4-2) starting by determining the extent of the duration reductions that the contractor will aim for (ΔT) under the A+B contracting method; followed by computing the increase in the total net cost associated with every level of duration reduction (ΔC). Subsequently, and through utilizing these two parameters, a regression analysis will be performed to derive the time/cost trade-off relationship which will then be validated using real-life projects.

Finally, a sensitivity analysis will be conducted to investigate the impact of a number of different independent variables on the derived relationship. The next sections will describe these steps in details.

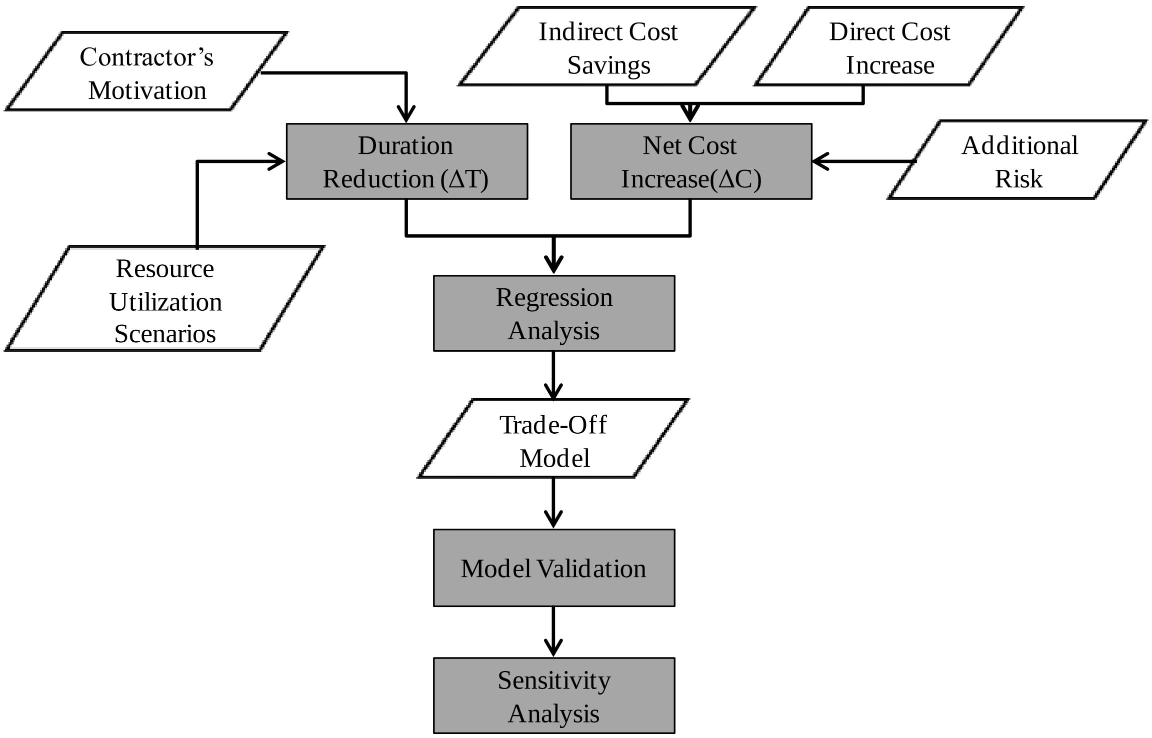

Figure 4-2: Steps of developing the A+B time/cost trade-off relationship

4.2.1. Determining the Impact on the Project's Duration

There are two main aspects related to the duration of a pavement rehabilitation project that are impacted by the use of the A+B contracting method; which are: resource utilization and contractor's motivation. First: since with the A+B contracting method time becomes a decisive factor in determining the winning bid, the contractor is inclined to use more aggressive resource utilization scenarios in order to reduce the project's duration and win the bid. Moreover, this greater importance placed on the project's duration makes the contractor more eager to reduce the time to the maximum possible limit to win the bid. The following sections will aim at quantifying these impacts and calculate the final duration reductions as a result of the use of the A+B contracting method.

4.2.1.1. Resource Utilization Scenarios:

One of the main advantages of the A+B contracting method is that it encourages the contractors to aggressively utilize their available resources to reduce the total value of the "B" component of the bid by working overtime and double shifts (NYSDOT 1999, Anderson and Russell 2001, CALTRANS 2002). Hence, when simulating the duration reduction as a result of the use of the A+B contracting method, not only does the increase in the number of resources utilized has to be taken into account, but also the increase in the working hours per day; namely: 12 and 16-hours days (NYSDOT 1999). Hence, in order to simulate the project's duration as a result of the change in the contractor's resource utilization levels and working hours, and similar to the method used for developing the trade-off model for the I/D contracting method, the Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) schedule simulation software was used. In addition to its capability of analyzing the project's resources and determine the critical ones, CA4PRS also provides the user with the option of changing the number of working hours per day. Furthermore, all the major factors that impact the production of pavement rehabilitation projects were taken into consideration when conducting the schedule simulations, such as: the different construction strategies, construction windows, and cross-section designs (Choi & Kwak 2012). Accordingly, to conduct the schedule simulation, first the base-line schedule used for the project accompanied by its corresponding resources' levels needed to be extracted from CA4PRS; then, the levels of the critical resources, were increased incrementally for each working hours scenario and the associated project's duration were simulated till no extra resources can be added (Lee 2011) which resulted in a number of resource utilization scenarios shown in table (4-1).

Table 4-1. A+B Resource Utilization Scenarios and their Corresponding Durations

Strategy	**Cross-Section Profile (inch)**	**Construction Window**	**Duration (days)**				
			Ordinary Usage	**Inc. Level 1**	**Inc. Level 2**	**Inc. Level 3**	**Inc. Level 4**
PCCP	12	Nighttime 10hrs	362	269	247	229	211
		Nighttime 12hrs	362	197	181	168	155
		Nighttime 16hrs	362	129	118	110	101
		Weekend	197	179	164	152	140
		Extended	193	175	161	149	138
	8	Nighttime 10hrs	201	140	127	116	105
		Nighttime 12hrs	201	97	88	81	73
		Nighttime 16hrs	201	60	55	50	45
		Weekend	87	78	71	65	58
		Extended	85	76	69	63	57
ACP	6	Nighttime 10hrs	229	209	177	154	139
		Nighttime 12hrs	229	41	35	30	27
		Nighttime 16hrs	229	35	30	26	23
		Weekend	25	22	19	17	15
		Extended	24	22	19	16	13
MACO	6	Nighttime 12hrs	132	117	106	99	98
		Nighttime 16hrs	132	41	38	35	35
		Weekend	26	23	21	20	19
		Extended	25	22	20	19	18

It is worth noting from table (4-1) that the "nighttime 10hrs" resource utilization scenario was not applicable to the milling and asphalt overlay project (MACO) due to the extended hours needed to demobilize the equipment which makes working for 10hrs/day, only, a non-economical strategy.

4.2.1.2. Contractor's Motivation:

Another advantage of the A+B contracting method when it comes to fulfilling the goal of reducing the duration of a pavement rehabilitation project is that the contractors become more eager to reduce the duration in order to increase their chances of winning the bid and hence encourages them to maximize the efficiency of their resources and bid on lower durations (NYSDOT 1999). This is evident when data for the bid duration versus the engineer's estimate from the A+B projects were analyzed against those from traditional and other alternative contracting projects. For instance, when analyzing the ratio of "the bid time versus the engineer's estimate" for FDOT's A+B pavement rehabilitation projects (Ellis et al. 2007), it was found that it is equal to, on average, -26.31%, while the same ratio for traditional contracting was only equal to -0.03%. Furthermore, when analyzing "the actual time versus the engineer's estimate" for other types of alternative contracting methods; namely: incentive/disincentive, lane rental, and liquidated savings, it was equal to: -0.52%, 0%, and -0.02%, respectively. This demonstrates that the unique nature of the A+B contracting method encourages the contractors to bid on lower durations than what they would have bid using any other contracting method as they are more eager to win the bid. Another example that reinforces this conclusion is from the Minnesota DOT alternative contracting data (Strong 2006). When analyzing the ratio of "bid time per mile" for the A+B projects versus traditional projects, it was found that this ratio was 20.3% less for the A+B projects. By analyzing these two sets of data, it is clear that in addition to the aggressive resource utilization scenarios, the contractors factor-in their desire and eagerness to win the bid by bidding on further reduced durations that are not reflected by the resource utilization scenarios alone. Therefore, to quantify this eagerness, this study assumed and applied an eagerness factor (EF) to the simulated durations resulting from the different resource utilization scenarios, in the previous section, equal to 23% which is the average of the above two datasets. Consequently, the duration reductions simulated in table (4-1) will be further reduced by applying this eagerness factor to reach the final duration reductions that can be achieved using the A+B contracting method as shown in table (4-2).

Table 4-2. A+B Contracting Final Durations' Reductions

Strategy	**Cross-Section Profile (inch)**	**Construction Window**	**Duration (days)**				
			Ordinary Usage	**Inc. Level 1**	**Inc. Level 2**	**Inc. Level 3**	**Inc. Level 4**
PCCP	12	Nighttime 10hrs	362	207	190	176	162
		Nighttime 12hrs	362	152	140	130	119
		Nighttime 16hrs	362	99	91	85	78
		Weekend	197	138	127	117	108
		Extended	193	135	124	115	106
	8	Nighttime 10hrs	201	108	98	90	81
		Nighttime 12hrs	201	75	68	62	56
		Nighttime 16hrs	201	47	42	39	35
		Weekend	87	60	55	50	45
		Extended	85	59	53	49	44
ACP	6	Nighttime 10hrs	229	161	136	118	107
		Nighttime 12hrs	229	31	27	23	21
		Nighttime 16hrs	229	27	23	20	18
		Weekend	25	17	15	13	12
		Extended	24	17	15	13	11
MACO	6	Nighttime 12hrs	132	90	82	76	75
		Nighttime 16hrs	132	32	29	27	27
		Weekend	26	18	16	15	15
		Extended	25	17	16	15	14

4.2.2. Determining the Impact on the Project's Cost:

By attempting to reduce the project's duration, the final cost of the project will be impacted as a result. With the A+B contracting method, this impact is a result of a change in three components of the final construction cost; these components are: the direct construction cost, the risk associated with the project, and the project's indirect cost. The following sections will demonstrate how these cost components are impacted as a result of using the A+B contracting method and how these impacts can be quantified.

4.2.2.1. Direct Construction Cost (CAC):

As discussed in the previous chapter and proven by several studies in the literature, for each construction project, there is a point at which the construction cost is at its minimum and any decrease in the project's duration from that point will result in an increase in the project's cost (Cusack 1991). Hence, assuming the normal point to be the duration of a pavement rehabilitation project under the traditional contracting method (engineer's estimate), using the A+B contracting method will result in an increase in the project's cost as a consequence of reducing the project's duration. Therefore, when considering the resource utilization scenarios adopted by the contractor under the A+B contracting method, discussed in the previous section, not only will the contractor's cost (CAC) increase as a result of using more critical resources, but also the costs of the original number of critical and non-critical resources will increase when the contractor adopts the extended working hours scenarios which can be expressed by equation (4-1).

$$\begin{aligned} \text{CAC} = &\\ &\text{Cost of Additional Critical Resources (CCR)} + \\ &\text{Additional Cost of Original Critical Resources (COR)} + \\ &\text{Additional Cost of NonCritical Resources (CNR)} \end{aligned} \quad (4\text{-}1)$$

By adopting the cost growth formula used by Choi (2008) to express the increase in the direct cost of the resources, this cost, for each individual component of equation (4-1) can be calculated using equations (4-2) through (4-4), respectively.

$$\begin{aligned} \text{CCR} = &\ \text{unit price} \times \text{number of additional resources} \times \text{labor surcharge rate} \times \\ &\text{working hours per day} \times \text{overtime rate} \times \text{project's duration} \times \text{overhead cost} \end{aligned} \quad (4\text{-}2)$$

$$\mathrm{COR} = \text{unit price } \times \text{number of original critical resources } \times \text{labor surcharge rate } \times \text{additional working hours per day } \times \text{overtime rate } \times \text{project's duration } \times \text{overhead cost} \quad (4\text{-}3)$$

$$\mathrm{CNR} = \text{unit price } \times \text{number of original noncritical resources } \times \text{labor surcharge rate } \times \text{additional working hours per day } \times \text{overtime rate } \times \text{project's duration } \times \text{overhead cost} \quad (4\text{-}4)$$

Where additional working hours = scenario's working hours - 8

In order to calculate the above three equations, the unit prices for the resources were collected from 17 different states' and federal rental rates and the average of these rates was used. The use of more than one source helps in accurately reflecting the contractor's cost increase without the influence of specific locations' conditions and increasing the applicability of the developed model across the different regions of the country. As a result, the additional CAC for each resource utilization scenario in table (4-1) was calculated as shown in table (4-3):

Table 4-3: Contractor's Additional Cost Increase

Strategy	**Cross-Section Profile (inch)**	**Construction Window**	**Inc. Level 1**	**Inc. Level 2**	**Inc. Level 3**	**Inc. Level 4**
PCCP	12	Nighttime 10hrs	6.86%	8.37%	9.68%	11.85%
		Nighttime 12hrs	10.95%	12.34%	13.12%	14.67%
		Nighttime 16hrs	15.18%	15.53%	15.86%	16.85%
		Weekend	4.01%	6.99%	10.02%	13.91%
		Extended	3.95%	6.87%	9.84%	13.66%
	8	Nighttime 10hrs	3.91%	4.61%	5.18%	6.12%
		Nighttime 12hrs	6.06%	6.37%	6.63%	7.18%
		Nighttime 16hrs	7.36%	7.39%	7.73%	7.95%
		Weekend	1.98%	3.21%	4.68%	6.15%

Strategy	Cross-Section Profile (inch)	Construction Window	Inc. Level 1	Inc. Level 2	Inc. Level 3	Inc. Level 4
		Extended	1.94%	3.14%	4.59%	6.02%
ACP	6	Nighttime 10hrs	1.31%	3.09%	3.99%	4.78%
		Nighttime 12hrs	1.23%	1.39%	1.51%	1.63%
		Nighttime 16hrs	1.88%	2.00%	2.08%	2.19%
		Weekend	0.65%	1.41%	1.56%	1.71%
		Extended	0.64%	1.40%	1.53%	1.67%
MACO	6	Nighttime 12hrs	1.27%	1.92%	2.98%	3.35%
		Nighttime 16hrs	2.90%	2.98%	3.12%	3.27%
		Weekend	0.75%	0.98%	1.66%	1.77%
		Extended	0.74%	0.96%	1.64%	1.73%

4.2.2.2. Additional Risk Assumed by the Contractor:

The main characteristic of the A+B contracting method that distinguishes it from other contracting methods is that the contractor bids on both cost and time, i.e. the contractor is the entity that sets the project's duration. Therefore, by assuming the task of setting the project's duration, the contractors take a higher risk, relative to other contracting methods as shown in figure (1-5), which they tend to account for in terms of additional cost (Anderson and Russell 2001).

Hence, when attempting to calculate the net additional cost that the contractor will incur under the A+B contracting method, the additional cost as a result of the time risk has to be quantified which will be achieved through the following steps:

1. Risk Definition:

The first step in quantifying the additional risk assumed by the contractor is to define this risk. Consequently, since the contractors are the entity that determines the project's duration, they assume more risk in case they don't meet that duration. Hence, the extent of this risk can be expressed in terms of the percentage difference between the bid time and the actual time of the project. To quantify this percentage, data from real-life projects contracted using the A+B contracting method were collected from different sources. The ratio of the “Actual Time/Bid Time” for each of these projects was calculated to reflect the extent of the delay that these projects faced or, in other words, the risk that the contractors do not meet the bid time they set.

2. Risk Categorization:

Since the additional risk assumed by the contractors stems from their inability to meet the bid duration they set, it is logical that this risk will be directly proportionate to the degree of the duration reduction they decide upon when submitting their bids. In other words, the severity of the risk associated with the A+B contracting method increases with the number of days reduced which can be expressed as the ratio between the bid time and the engineer’s time estimate. Accordingly, for the collected projects, the ratio of “Bid Time/Engineer’s Time Estimate” was calculated; and the results showed that this ratio ranged from 0% to -60%. As a result, to categorize the above data, the equal interval categorization method was used. In this method, the range of the data is divided into equal intervals with close number of data points. Consequently, the collected data was divided into three intervals, each with a 20% range i.e. from 0% to -20%, from -21% to -40%, and from -41% to -60%. Through this categorization, the risk of not meeting the bid time under the A+B method is now tied to the degree of the duration reduction that the contractor initially bid on.

3. Risk Calculation:

For each of the above intervals of duration reduction there was a wide range of possible risk values associated with them. Therefore, to calculate the most likely value of the risk associated with each interval, the probability of each of these values has to be calculated and the one with the highest probability will be the risk value associated with that respective interval. To calculate these probabilities a Monte-Carlo simulation for the risk values associated with each interval was conducted. This was performed by using the mean and the standard deviation of the collected data to generate random variables and conduct 10,000 iterations. The respective histograms that resulted from these iterations were generated as shown in figure (4-3), and accordingly the most likely risk values were determined as shown in table (4-4).

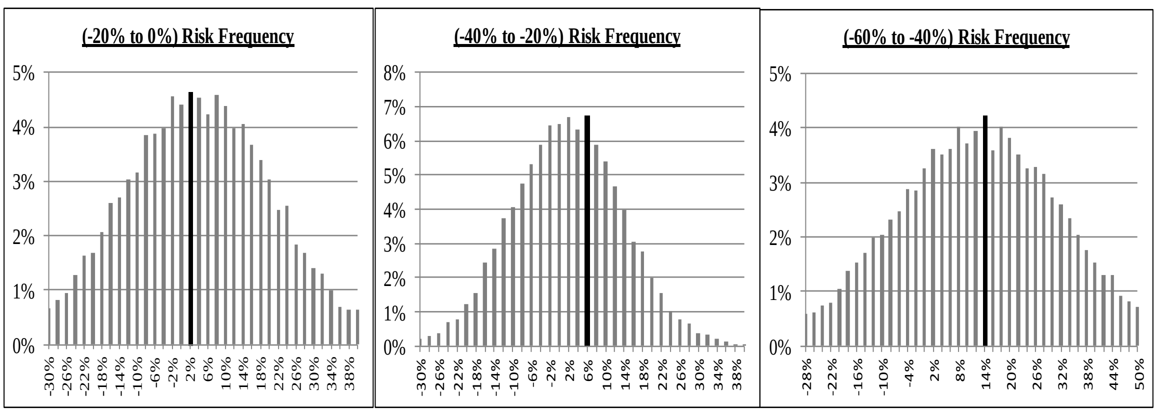

Figure 4-3: Monte-Carlo simulation results

Table 4-4. The Most-Likely Risk Values

Duration Reduction Range	**Risk (%)**
0% – (-20%)	2%
(-21%) – (-40%)	6%
(-41%) – (-60%)	14%

From the results of the Monte-Carlo simulation, it was concluded that the risk values associated with each duration interval are not equal and supports the hypothesis that these values increase with the degree of duration reduction that the contractor opt for. Nonetheless, since the collected data has a range of duration reduction till -60% only, to complete the calculation of the risk values for the remaining intervals, the above three points were used to interpolate a relationship between the risk and the duration reduction intervals. Consequently, the risk values for the remaining two duration reduction intervals were calculated as shown in table (4-5).

Table 4-5. The Final Risk Values Used

Duration Reduction Range	**Risk (%)**
0% – (-20%)	2%
(-21%) – (-40%)	6%
(-41%) – (-60%)	14%
(-61%) – (-80%)	26%
(-81%) – (-100%)	42%

4. Risk Conversion:

Although the most-likely risk values were calculated using the Monte-Carlo simulation, these values are expressed in terms of days; hence, to calculate the additional cost the contractors add to the bid as a result of this risk, the values in table (4-5) need to be converted to dollar values. This conversion will be achieved using the liquated damages that the contractor will pay for each day of delay in the project. Therefore, and using CALTRANS liquidated damage formula (CALTRANS 2004), the additional cost that the contractors will assign to their bid can be expressed using equation (4-5):

$$Risk\ (\$) = Risk\ (\%) \times Bid\ Time \times Liquidated\ Damage \qquad (4\text{-}5)$$

Where the liquidated damage can be calculated using CALTRANS liquidated damage formula (CALTRANS 2004) as follows:

$$\frac{10\% \times Engineer's\ Cost\ Estimate}{Engineer's\ Time\ Estimate} \qquad (4\text{-}6)$$

Hence, using the above two equations, the additional cost that the contractors will add to their bid to account for the risk associated with setting the contract duration can be quantified and used to calculate the net additional cost that the contractor will incur as a result of the A+B contracting method.

4.2.2.3. Contractor's Time-Related Indirect Cost Savings:

To quantify the savings in the indirect costs, and similar to the methodology adopted for the I/D contracting method, this study assumed that the time-related indirect cost accounts for 8.9% of the project's total direct cost.

Consequently, and following the same steps as with the I/D contracting method, the contractor's net cost growth as a result of reducing the project's duration through the A+B contracting method can be expressed using equation (4-7) with the results shown in table (4-6):

$$\text{Contractor's Net Cost Growth (\$)} = \text{Engineer's Cost Estimate} + \text{CAC} + \text{Risk} - \text{Indirect Cost Savings} \quad (4\text{-}7)$$

Table 4-6. Schedule Reduction Rate vs. Net Cost Growth Rate

Strategy	**Cross-Section Profile (inch)**	**Construction Window**	**Trade-Off**							
			Inc. Level 1		**Inc. Level 2**		**Inc. Level 3**		**Inc. Level 4**	
			ΔT (%)	**ΔC (%)**	**ΔT (%)**	**ΔC (%)**	**ΔT (%)**	**ΔC (%)**	**ΔT (%)**	**ΔC (%)**
PCCP	12	Nighttime 10hrs	-42.8	3.4	-47.5	4.5	-51.3	5.5	-55.2	7.3
		Nighttime 12hrs	-58.4	6.2	-61.5	7.3	-64.3	7.9	-67.1	9.2
		Nighttime 16hrs	-72.6	9.2	-74.9	9.4	-76.7	9.6	-78.6	10.4
		Weekend	-30.1	2.7	-35.8	5.4	-40.5	8.2	-45.2	11.9
		Extended	-30.1	2.6	-35.8	5.3	-40.5	8.1	-45.2	11.7
	8	Nighttime 10hrs	-46.4	0.1	-51.4	0.4	-55.6	0.6	-60.1	1.2
		Nighttime 12hrs	-62.9	0.9	-66.8	0.9	-69.3	0.9	-72.4	1.3
		Nighttime 16hrs	-77.0	1.1	-79.2	0.9	-81.0	1.1	-82.9	1.2
		Weekend	-31.0	0.9	-37.5	1.8	-42.9	3.1	-48.6	4.4
		Extended	-31.0	0.9	-37.6	1.8	-42.9	3.1	-48.6	4.3

Strategy	Cross-Section Profile (inch)	Construction Window	Trade-Off							
			Inc. Level 1		Inc. Level 2		Inc. Level 3		Inc. Level 4	
			ΔT (%)	ΔC (%)	ΔT (%)	ΔC (%)	ΔT (%)	ΔC (%)	ΔT (%)	ΔC (%)
ACP	6	Nighttime 10hrs	-29.9	-1.1	-40.6	-0.2	-48.4	0.1	-53.5	0.4
		Nighttime 12hrs	-86.4	-5.8	-88.5	-5.8	-90.0	-6.0	-91.0	-5.8
		Nighttime 16hrs	-88.4	-5.4	-90.1	-5.4	-91.4	-5.5	-92.3	-5.3
		Weekend	-29.8	0.4	-40.5	1.1	-48.3	1.1	-53.2	1.2
		Extended	-29.8	0.4	-40.4	1.1	-48.3	1.1	-53.5	1.2
MACO	6	Nighttime 12hrs	-31.3	-1.3	-38.0	-1.2	-42.1	-0.5	-42.9	-0.1
		Nighttime 16hrs	-75.9	-3.3	-78.2	-3.4	-79.7	-3.4	-79.9	-3.2
		Weekend	-30.8	0.3	-37.2	0.4	-41.5	1.0	-43.3	1.1
		Extended	-30.3	0.3	-36.9	0.4	-41.3	1.0	-43.3	1.1

4.2.3. Modeling the Time/Cost Trade-Off for the A+B Contracting Method:

Utilizing the data in table (4-6), and since the relationship between the construction cost and time can be expressed using a second degree polynomial, a regression analysis was performed to derive the relationship between the project's duration and its cost under the A+B contracting method as shown in figure (4-4):

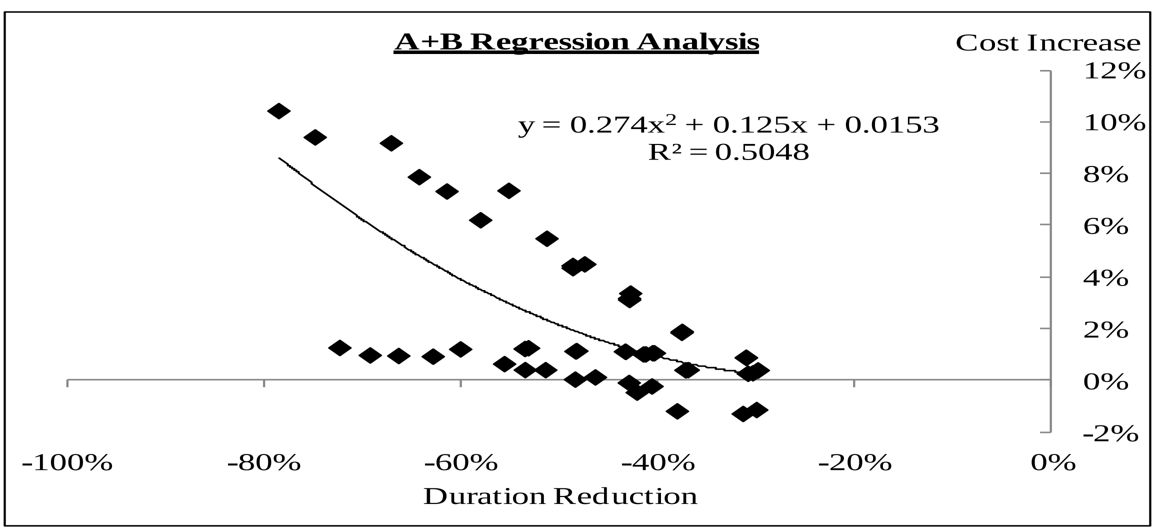

Figure 4-4: A+B contracting method time/cost trade-off

The results of the regression analysis show that the relationship between the construction cost and time, under the A+B contracting method, can be represented using equation (4-8) which has R-squared value of approximately 0.51 emphasizing a very good fit:

$$C = 0.274\,T^2 + 0.125\,T + 0.0153 \qquad (4\text{-}8)$$

Similar to the I/D model and following Choi (2008) steps to convert the above equation in terms of the relationship between the increase in the construction cost and the reduction in the project's duration, equation (4-8) can be rewritten as follows:

$$\Delta C = 0.125 + 0.548 t_0 - 0.274 \Delta t \qquad (4\text{-}9)$$

where: ΔC = contractor cost increase expressed as a percentage of the engineer's cost estimate; t_0 = engineer's project duration estimate expressed as 100%; and Δt = reduction in project duration expressed as a percentage of the engineer's duration estimate.

From equations (4-8) and (4-9), the trade-off relationship between the time and cost of a construction project under the A+B contracting method can now be accurately defined.

4.2.4. Model Validation

After developing the time/cost trade-off model, its validity has to be tested against real-life pavement rehabilitation projects. Therefore, to validate the A+B time/cost trade-off model, the expected bid cost derived from the model has to be validated against the bid price of real-life A+B projects. This task was performed using data from 19 different pavement rehabilitation projects contracted through the A+B contracting method and gathered from different sources. The model validation process was conducted through the following steps:

1- Computing the model's expected bid cost of the project as a result of bidding on a reduced duration using the projects' engineer's time estimate as t_0, the project's actual time to calculate Δt, and engineer's cost estimate and applying equation (4-9) to these values.

2- Comparing the calculated costs with the actual bid prices from the projects using a paired-sample t-test. This test was chosen as it has the capability of detecting the difference in the mean of the two datasets and its suitability for the available data as they represent the same project with two different scenarios and their large number fulfills the normality assumption for the t-test.

3- Examining the resulting p-value and the confidence intervals from the performed t-test.

Accordingly, table (4-7) shows a summary of the results of the paired-sample t-test conducted for the calculated bid cost vs. the actual bid price.

Table 4-7: Paired-Sample t-test Results

	Paired Differences		t	df	Sig. (2-tailed
	95% Confidence Interval of the Difference				
	Lower	Upper			
BidCost – CalcCost	-9910993.4	372266.3	-1.95	18	.067

From the above table, the p-value for the paired-sample t-test, at a 95% confidence level, is equal to 0.067 which is larger than 0.05; hence, we do not reject the null hypothesis (H_0) and the means of the bid prices can be assumed to be equal; furthermore, the lower limit of the confidence interval has a negative value while the upper limit has a positive one which shows that sometimes the mean of the calculated costs is larger than the mean of the bid costs and vice-versa. This supports the conclusion that the two means can be assumed to be equal since the confidence interval does not lie away from the “0” point.

4.2.5. Sensitivity Analysis

Having validated the relationship between the increase in cost and the reduction in the project’s duration under the A+B contracting method, sensitivity analyses for the model’s independent variables was conducted. Three analyses were performed to examine the impact of certain independent variables on the time/cost trade-off for the A+B projects; these variables are: the percentage that the indirect cost constitutes of the project’s direct cost, the equipment rental rates used to calculate the increase in the contractor’s direct cost, the eagerness factor applied by the contractors to reflect their willingness to win the bid, and the impact of the different pavement strategies. For the first variable, three percentages of the indirect cost representing the upper and lower bounds range concluded by Assaf et al. (1999), as well as its norm, were used to calculate the net cost growth incurred by the contractor under the A+B contracting method. Accordingly figure (4-5) shows the results when applying these three percentages to the calculation of the time/cost trade-off, while keeping all other variables constant.

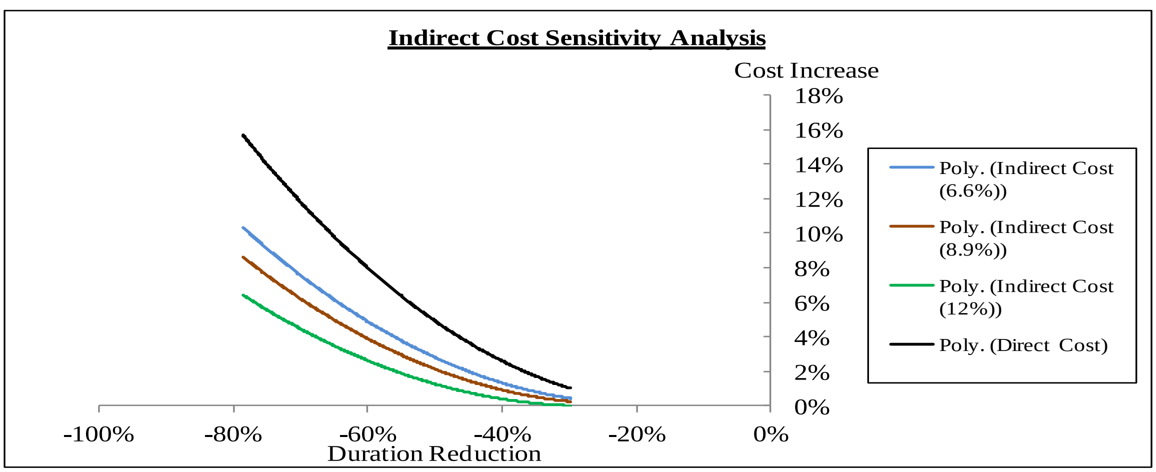

Figure 4-5: Indirect cost sensitivity analysis

The results showed that the indirect cost is inversely proportionate to the net cost growth or, in other words, as the percentage of the indirect cost decreases, the net cost growth increases for the same duration reduction, and vice-versa. This observation was further proved when examining a scenario of no indirect costs savings i.e. only the increase in the direct costs were taken into consideration.

Regarding the second variable, in addition to the average rates that were originally used to develop the model, the maximum, minimum, and a sample of one of the SHAs rates (CALTRANS) were used to test the impact of these rates on the time/cost trade-off relationship under the A+B contracting method. When applying these different rates to the calculation of the time/cost trade-off, while keeping all other variables constant, it was concluded that these rental rates are directly proportionate to the net cost growth for the same duration reduction (figure 4-6); furthermore, it was proved that the CALTRANS rental rates almost yield the same trade-off relationship as the maximum rental rates have yielded.

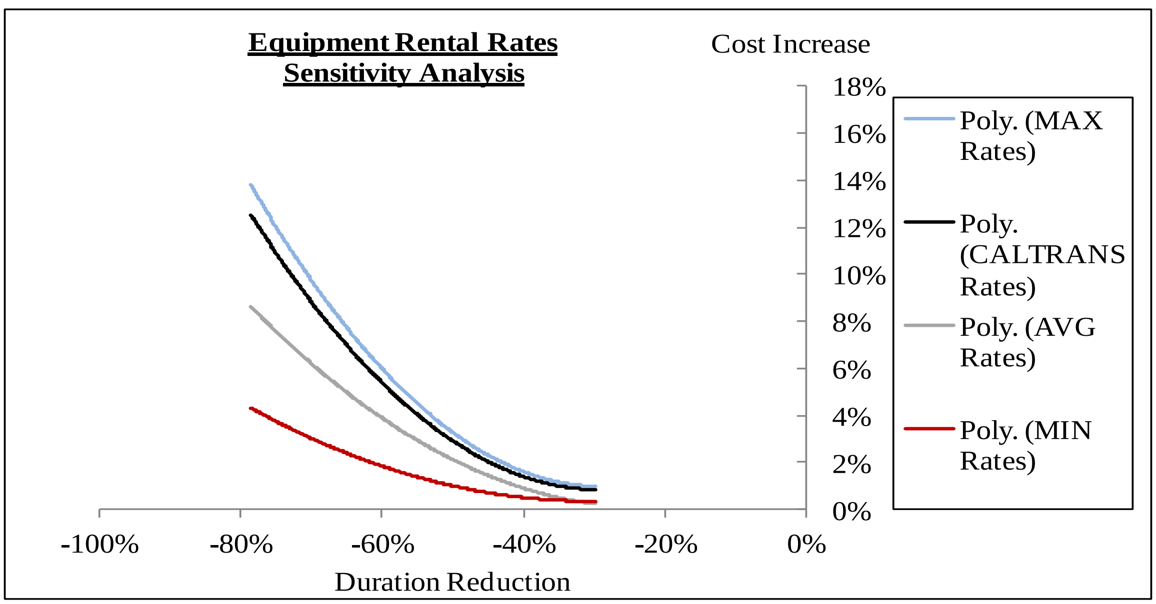

Figure 4-6: Equipment rental rates sensitivity analysis

Regarding the third variable, since the eagerness factor used to develop the model was the average of two datasets, higher and lower values were used to examine the impact of this independent variable on the additional cost increase. When applying these different rates to the calculation of the time/cost trade-off, while keeping all other variables constant, it was deducted that if the eagerness factor decrease, the bid time will increase and the indirect cost savings will decrease; hence, the total additional cost will increase as demonstrated in figure 4-7.

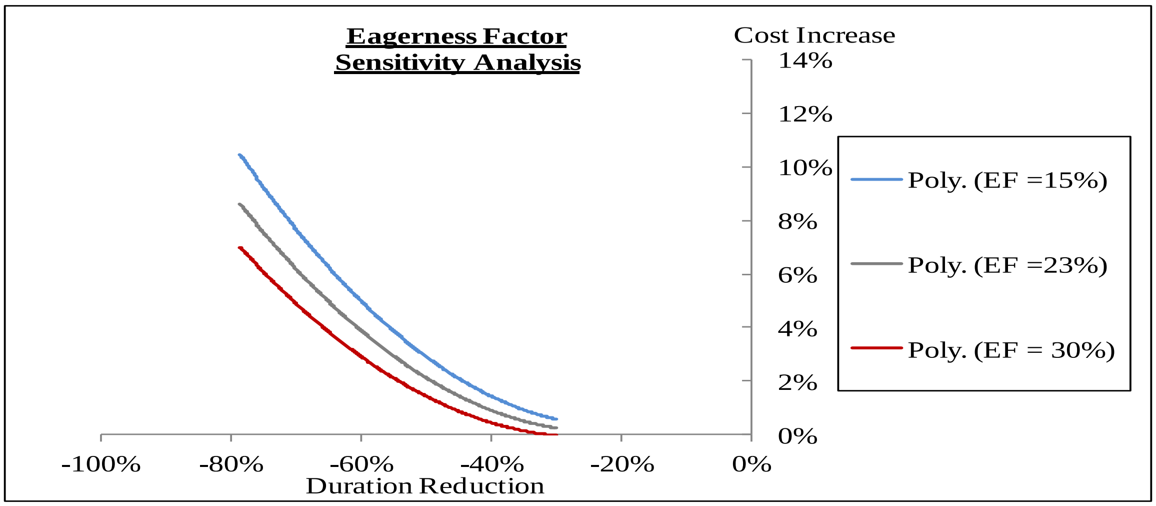

Figure 4-7: Eagerness factor sensitivity analysis

The final sensitivity analysis that was conducted for the A+B model is the one regarding the impact of different pavement strategies. Although the model developed and validated in this study is considered a good fit, it can be further broken down into two different models based on the pavement strategy, i.e. a model for PCCP 12 and another for PCCP 8, ACP and MACO strategies, which are presented in figure (4-8). As shown from the figure, the increase in cost associated with the PCCP 12 strategy is higher than the one associated with the other strategies which might influence the decision on the choice of the most-suitable ACM to be used which will be explored in details in the following chapter.

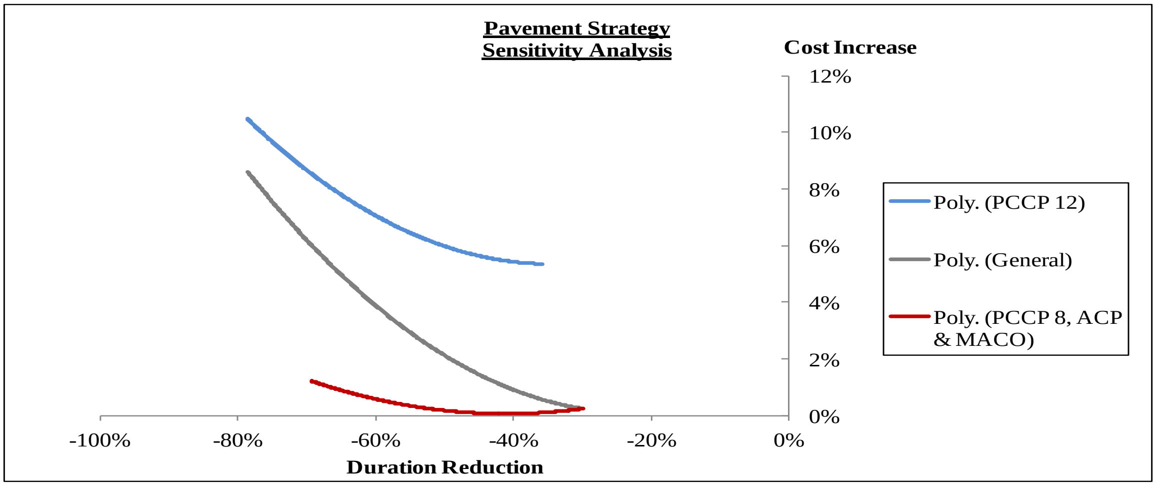

Figure 4-8: Pavement strategies sensitivity analysis

4.3. "B" Component Value Calculation Module

After developing and validating the relationship between the increase in cost and the reduction in the project's duration under the A+B contracting method, the "B" component value calculation module will be developed to assign the appropriate "B" component values for pavement rehabilitation projects based on the SHA's desired level of duration reduction. Consequently, a relationship between the duration reduction and the "B" component value to be assigned has to be developed and since the aim of both the A+B and the I/D contracting methods is to reduce the negative impacts of pavement rehabilitation projects on the road users; hence, the constraints imposed on adopting the A+B contracting method are similar to those imposed on the I/D contracting method which can be expressed in the form of the following inequality:

$$CC \leq B \leq DRUC \tag{4-10}$$

To further explain the rationale behind these constraints and focusing on the first part of the inequality, since the assigned "B" value impacts the degree of importance of the project's duration relative to the overall bid; thus, the higher the "B" value, the more eager the contractor will be to reduce the project's duration, and the overall bid value, which will lead to an increase in the construction cost as proved by the trade-off relationship. This increase in the construction cost will be reflected in the "A" portion of the bid; therefore, the "B" value should be higher than the contractor's additional cost to balance the weight assigned to the two portions, motivate the contractor to reduce the duration to the desired level, and provide a fair opportunity for the competent contractor to be able to win the bid. At the same time, the assigned "B" value should not exceed the DRUC otherwise there will be no advantage in reducing the project's duration.

Hence, by substituting equation (4- 9) into equation (4-10), the inequality can be expressed as:

$$(0.125 + 0.548t_0 - 0.274\Delta t) \leq B \leq DRUC \qquad (4\text{-}11)$$

From equation (4-11), the constraints for selecting the appropriate "B" component value can now be expressed in terms of the duration reduction which will be used in developing the "B" component module. Moreover, setting a variable "B" value for a given project based on the desired level of duration reduction means that for each pavement rehabilitation project there can be more than one "B" value and that the relationship between the "B" value and the project duration can be depicted as shown in figure (4-7):

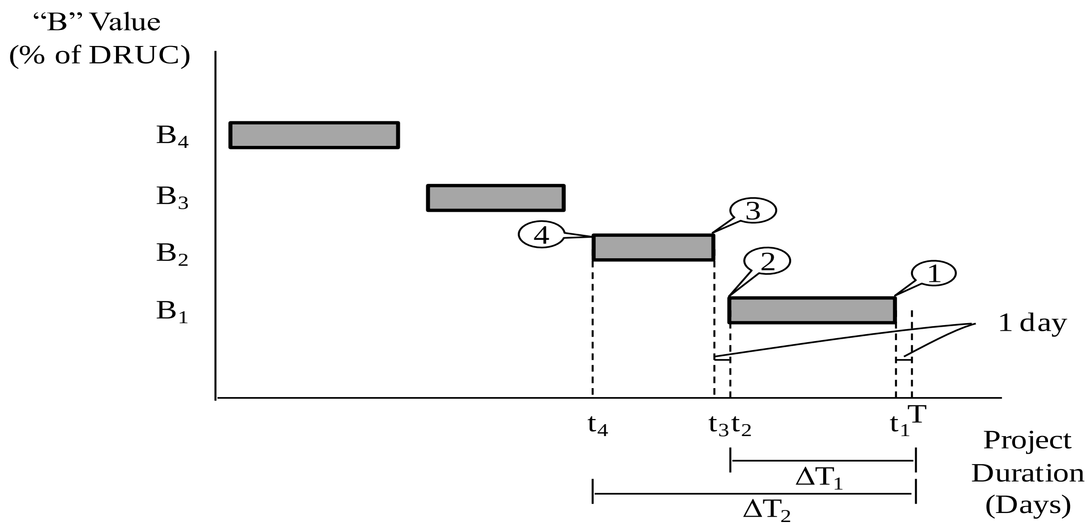

Figure 4-9: Relationship between the "B" value and the project's duration

As shown from figure (4-9), calculating the coordinates of points 1 through 4, i.e. time and "B" value, is essential when attempting to assign the appropriate "B" value for each duration reduction. These points represent the lower and upper bounds of the possible duration reductions for the first two "B" values that can be assigned for a given pavement rehabilitation project. As shown in the figure, point (1) represents the minimum duration reduction that can be achieved for a project (t_1) and the corresponding minimum "B" value that can be assigned to it (B_1); while point (2) represents the maximum duration reduction that can be achieved under B_1 (t_2). Similarly, if the SHA needs to reduce the time further than t_2, then point (3) represents the next possible time reduction after t_2 (t_3) and the corresponding "B" value that needs to be assigned to achieve this duration reduction (B_2); and finally, point (4) represents the maximum duration reduction (t_4) that can be achieved under B_2. As a result, the steps of calculating the coordinates of these four points are summarized in figure (4-10):

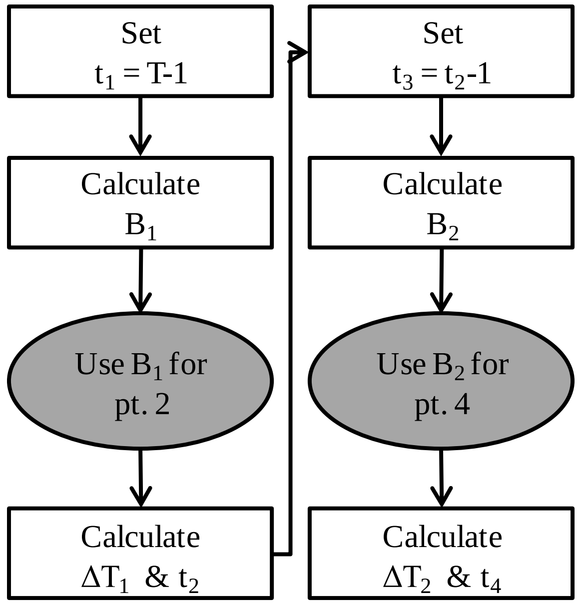

Figure 4-10: Steps for calculating the coordinates of points 1 through 4

4.3.1. Point 1: (Minimum Duration Reduction & Minimum "B" Value):

- *Step 1.1: Calculate the minimum duration reduction for any project (t_1).* Through developing the engineer's estimate for the baseline schedule for the project under traditional contracting (T), SHAs can assume the minimum duration reduction to be 1 day less than the engineer's estimate which will be the time at point 1; hence, (t_1) can be calculated using the following equation:

$$t_1 = T - 1 \quad (4\text{-}12)$$

- *Step 1.2: Calculate the minimum "B" value to be offered (B_1).* Through employing the first constraint of equation (4-11), the minimum "B" value that can be offered is the one that is, at least, equal to the additional cost incurred by the contractors to motivate them to reduce the duration. Hence, by using equation (4-9) and assuming t_0 = 100%, expressing ΔT as a percentage of t_0 and the "B" value as a percentage of DRUC, the minimum "B" value that the SHA has to offer (B_1) can be calculated by knowing the engineer's cost estimate associated with the baseline schedule (C) and using equation (4-13):

$$B_1 = \frac{\left[0.673 - 0.274 \times \left(-\frac{1}{T}\right)\right] \times C}{DRUC} \quad (4\text{-}13)$$

4.3.2. Point 2: (Maximum Duration Reduction using B_1):

- *Step 2.1: Calculate the "B" value*. Point 2 corresponds to the maximum duration reduction that can be achieved by using B_1 meaning that the "B" value for this point is still B_1.

- *Step 2.2: Calculate the maximum duration reduction that can be achieved using B_1 (ΔT_1)*. By using the first constraint of equation (4-11) and substituting with B_1, ΔT_1 can be calculated as a percentage of the baseline duration using the following equation:

$$\Delta T_1(\%) = -\frac{\left[\left(\frac{B_1 \times DRUC}{C}\right) - 0.673\right]}{0.274} \quad (4\text{-}14)$$

Where the negative sign reflects a reduction in the project's duration.

And consequently, the maximum days that can be reduced using B_1 as the value for "B" can be calculated using equation (4-15):

$$t_2 = T + \Delta T_1(\%) \times T \quad (4\text{-}15)$$

4.3.3. Point 3: (Duration Reduction Beyond t_2 and the Corresponding B Value):

- *Step 3.1: Calculate the reduced duration (t_3)*. Similar to point 1, SHAs can assume the minimum duration reduction beyond t_2 to be 1 day; hence, (t_3) can be calculated as follows:

$$t_3 = t_2 - 1 \quad (4\text{-}16)$$

- *Step 3.2: Calculate the "B" value associated with t_3 (B_2).* Using the first constraint of equation (4-11), B_2 can be calculated as follows:

$$B_2 = \frac{\left[0.673 - 0.274 \times \left(\Delta T_1' - \frac{1}{T}\right)\right] \times C}{DRUC} \quad (4\text{-}17)$$

Where ΔT_1' is ΔT_1 adjusted to the nearest whole number of days reduced.

4.3.4. Point 4: (Maximum Duration Reduction Using B_2):

- The calculation of the coordinates for point 4 is similar to point 2; thus, the B value = B_2 and ΔT_2 and t_4 can be calculated using equations (4-14) and (4-15).

Finally, for any given project there might be a number of additional feasible "B" values, beyond B_2, that can be assigned to achieve more duration reductions; hence, the calculation of the coordinates of the boundary points for these "B" values will be similar to the calculation of points (3) and (4) using the following generalized equations:

$$t_i = t_{i-1} - 1 \quad (4\text{-}18)$$

$$B_i = \frac{\left[0.673 - 0.274 \times \left(\Delta T_{i-1}' - \frac{1}{T}\right)\right] \times C}{DRUC} \quad (4\text{-}19)$$

$$\Delta T_i(\%) = -\frac{\left[\left(\frac{B_i \times DRUC}{C}\right) - 0.673\right]}{0.274} \quad (4\text{-}20)$$

where: t_i = project's duration at point i expressed in days; B_i = the value of B associated with the duration at point i expressed as a percentage of the DRUC; T = engineer's project duration estimate expressed in days; C = engineer's project cost estimate expressed in dollars; DRUC = daily road user cost expressed in dollars; ΔT_i = maximum reduction in the project's duration at point i expressed as a percentage of the engineer's duration estimate; and ΔT_i' is ΔT_i adjusted to the nearest whole number of days reduced.

Nevertheless, SHAs need to determine the feasibility of any further "B" values by examining the availability of additional resources in their markets, and whether any additional resources can be logistically deployed into the construction site or not.

4.4. Owner Cost Calculation Module

Another important factor that impacts the SHAs' decision on the suitable "B" value for their projects is the total cost of the project that they will incur as a result of selecting each of these values. Therefore, the owner's cost module component of the developed model will be used to calculate the total project's cost from the SHA's perspective for each duration reduction. Recalling figure (4-8) and points 1 through 4 shown in that figure, the owner's cost at each of these points can be calculated by multiplying the cost of each day reduced, expressed as a percentage of the engineer's cost estimate, by the number of days reduced by the engineer's cost estimate and adding the resulting cost to the engineer's cost estimate and as expressed by equations (4-21) through (4-24), respectively.

$$\mathrm{C}_1 = \left[\left(\frac{0.673-0.274\times\left(-\frac{1}{\mathrm{T}}\right)}{100}\right)+1\right]\times C \tag{4-21}$$

$$C_2 = [\left(\frac{0.673-0.274\times\left(\Delta T_1'\right)}{100}\right)\times\ C\ \times(T-t_2)]+C \tag{4-22}$$

$$C_3 = [\left(\frac{0.673-0.274\times\left(\Delta T_1'-\frac{1}{T}\right)}{100}\right)\times\ C\ \times(T-t_3)]+C \tag{4-23}$$

$$C_4 = [\left(\frac{0.673-0.274\times\left(\Delta T_2'\right)}{100}\right)\times\ C\ \times(T-t_4)]+C \tag{4-24}$$

Generally, for any point beyond point (4), the owner cost can be calculated using the following equations:

For odd-numbered points:

$$C_i = [\left(\frac{0.673 - 0.274 \times \left(\Delta T'_{i-2} - \frac{1}{T}\right)}{100}\right) \times \; C \; \times (T - t_i)] + C \qquad (4\text{-}25)$$

For even-numbered points:

$$C_i = [\left(\frac{0.673 - 0.274 \times \left(\Delta T'_{i-2}\right)}{100}\right) \times \; C \; \times (T - t_i)] + C \qquad (4\text{-}26)$$

where: C_i = project's cost at point i expressed in dollars; C = engineer's cost estimate expressed in dollars; B_{i-1} = the value of B associated with the duration at point i-1 expressed as a percentage of the DRUC; DRUC = daily road user cost expressed in dollars; T = engineer's duration estimate expressed in days; t_{i-1} = project duration at point i-1 expressed in days; and $\Delta T'_{i-2}$ = maximum reduction in the project's duration at point i-2 after being adjusted for a whole number of days and expressed as a percentage of the engineer's duration estimate.

Consequently, through adopting the "B" value and the owner's cost calculation modules which are summarized in figure (4-11), SHAs can accurately set the appropriate value of the "B" component according the desired acceleration level for their projects and their own budgetary constraints which will guarantee the success of adopting the A+B contracting method and prevent any waste of the public money.

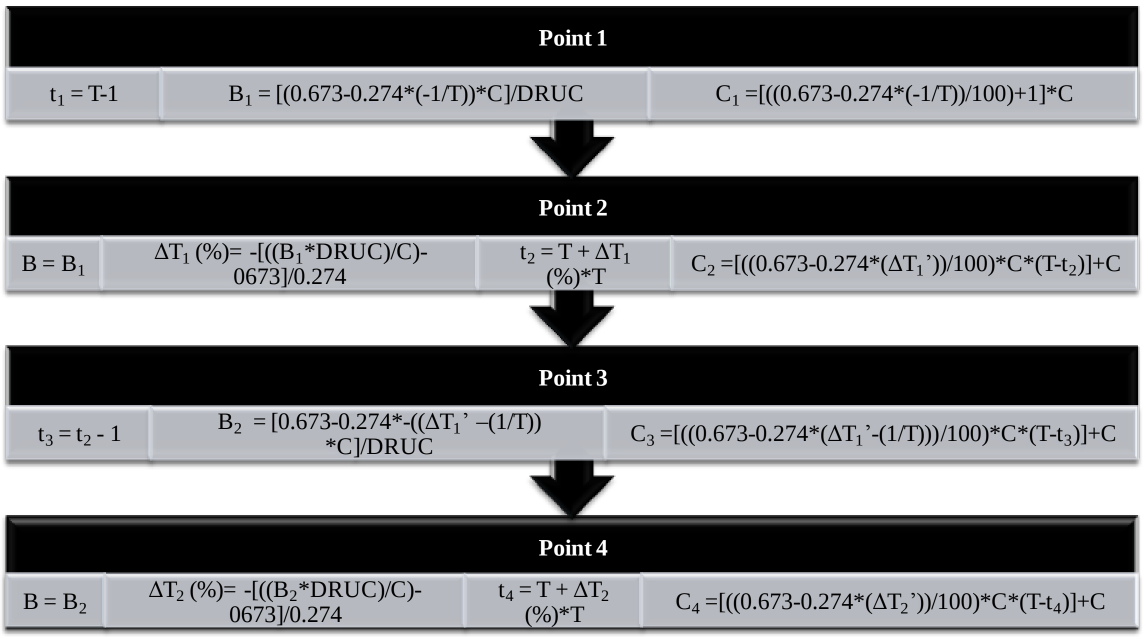

Figure 4-11: Summary of "B" value, time, and owner's cost calculation steps

4.5. Model Application

To test the application of the "B" value and owner cost modules, the I-15 Devore pavement rehabilitation project in San Bernardino, California, was used. The first step in the application of the model was to calculate its three inputs which are: DRUC, engineer's time estimate, and engineer's cost estimate, using CA4PRS. As outlined in the application of the I/D model in the previous chapter, the DRUC value for this project was equal to $243,551, while the engineer's time estimate (baseline schedule) was 201 days based on nighttime closure and the engineer's cost estimate was $18 million. Next, the "B" value module steps were applied to determine the different "B" values that can be offered for this project together with their corresponding duration reductions. Figure (4-12) shows the results for I-15 Devore project if it was contracted using the A+B contracting method and after applying the developed model. As observed from the figure, there are 16 different "B" values that can be used for this project ranging from 50% of

DRUC to 65% of DRUC with corresponding duration reduction ranging from 1 to 145 days out of the traditional project duration of 201 days, respectively. As a result, this wide range of possible duration reductions yielded an increase in the project's final total cost to be between $18.1 million to $40.7 million, an increase of $0.1 million to $22.7 million, respectively, and corresponding DRUC savings of $0.24 million to $35 million.

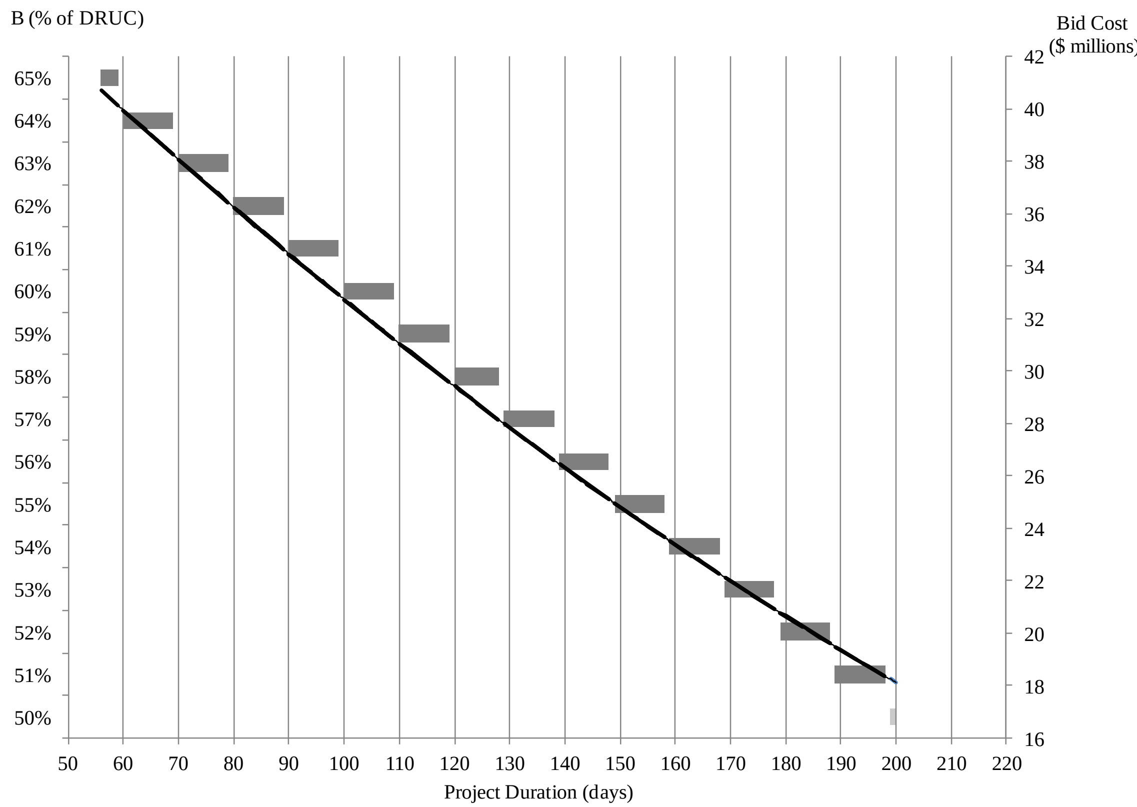

Figure 4-12: I-15 Devore "B" values

To test these results, the schedule simulation module of CA4PRS was utilized as discussed earlier and shown in figure (4-13).

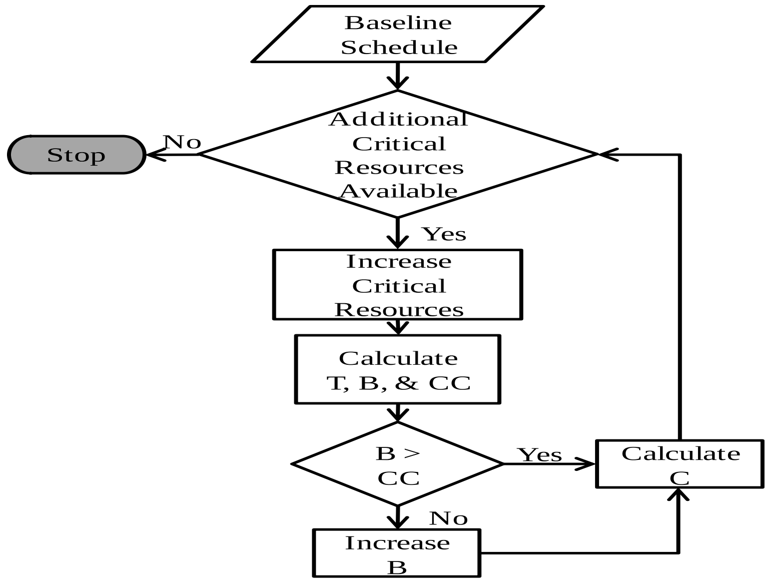

Figure 4-13: Steps for testing the "B" value and the owner's cost modules

In order for the contractors to be able to reduce the duration of the project, they will need to increase the resources they utilize; hence, using the critical resource output provided from the baseline schedule simulation, the level of these resources was increased incrementally and the new corresponding schedules were simulated and the contractor's cost was calculated using equation (4-9). This process was repeated until no more critical resources can be increased (Lee 2008). These durations and costs were consistent with the durations and costs calculated through the model as shown in table (4-8):

Table 4-8: Duration Reduction and Corresponding "B" Values for I-15 Devore Project

Point	Calculated Duration Reduction	Simulated Duration Reduction	B (% of DRUC)	B ($/day)	Additional Contractor Cost ($/day)
1	200	199	50	121,776	121,385
2	199	199	50	121,776	121,631
3	198	196	51	124,211	121,876
4	189	190	51	124,211	124,084

where the calculated duration reduction refers to the one derived from the A+B model, the simulated duration reduction refers to the one calculated using CA4PRS, the "B" value calculated using the developed model and the additional contractor cost is calculated using equation (4-9).

As seen from table (4-8), all the simulated duration reductions fall within the calculated intervals for each “B” value; and for all the points, the additional cost incurred by the contractor is less than the “B” value offered which was calculated using the “B” value module.

4.6. Risk Analysis Module

As proved by the model application, the “B” value and the owner’s cost calculation modules can help SHAs in deciding the value of the “B” component to be used based on the desired levels of duration reduction; however, as apparent from the I-15 Devore example, there can be many different “B” values to be used for a given project and each has a wide range of possible time reductions. This can create a conflict between the owner and the contractor similar to the one created with the I/D contracting method. Hence a risk analysis module is developed to help SHAs in selecting the most likely value of the “B” component to be achieved by the contractors and the most likely time reduction that can be achieved by this selected “B” value. An expected risk model is used to evaluate this risk using the same type of probability distribution (beta) with the shape corresponding to $\alpha < \beta$. Nevertheless, and unlike the assumption made for the I/D contracting method, the difference between the α and β values was increased for the calculation of the most likely time reduction that can be achieved by a selected “B” value. This increase will impact the calculation of the probabilities as it will increase the probability of the values towards the lower end of the duration reduction. The rationale behind this assumption was that due to the more aggressive resource utilization scenarios adopted by the contractor and the eagerness associated with the desire of winning the bid, there is a small room for further duration reductions that the contractor can achieve; hence, the probability of achieving the ones towards the upper end becomes increasingly difficult and unachievable in some cases. Nevertheless, for the most likely "B" value, the assumption used for the calculations of the I/D contracting method is still valid. Next, after setting the most suitable probability distribution and the values of the α and β, the probability of each duration reduction is calculated using the cumulative density function for this particular shape of the beta distribution.

By applying the risk analysis module to the results obtained from the I-15 Devore example and as shown in table (4-8), it was deduced that the "B" value with the highest probability of occurrence is the 55% of DRUC level which corresponds to a time reduction ranging from 21.4% to 25.9% of the original project's duration.

Table 4-9: "B" Values Probability Levels

ΔT (% of Original Duration)	**B (% of DRUC)**	**Probability**
0% - 1.0%	50%	0.11%
1.5% - 6.0%	51%	3.56%
6.5% - 10.9%	52%	7.51%
11.4% - 15.9%	53%	10.16%
16.4% - 20.9%	54%	11.67%
21.4% - 25.9%	55%	12.22%
26.4% - 30.8%	56%	11.96%
31.3% - 35.8%	57%	11.05%
36.3% - 40.3%	58%	8.76%
40.8% - 45.3%	59%	8.12%
45.8% - 50.2%	60%	6.26%
50.7% - 55.2%	61%	4.38%
55.7% - 60.2%	62%	2.66%
60.7% - 65.2%	63%	1.25%
65.7% - 70.1%	64%	0.33%
70.6% - 72.1%	65%	0.01%

Furthermore, within this “B” value and by applying the same calculation procedures, it was concluded that a duration reduction of 0.6% of the maximum duration for the 55% “B” value, which is equivalent to a 21.9% duration reduction from the original project’s duration i.e. 157 days, is the most likely duration reduction that can be achieved by the contractor using the 55% “B” figure (4-14).

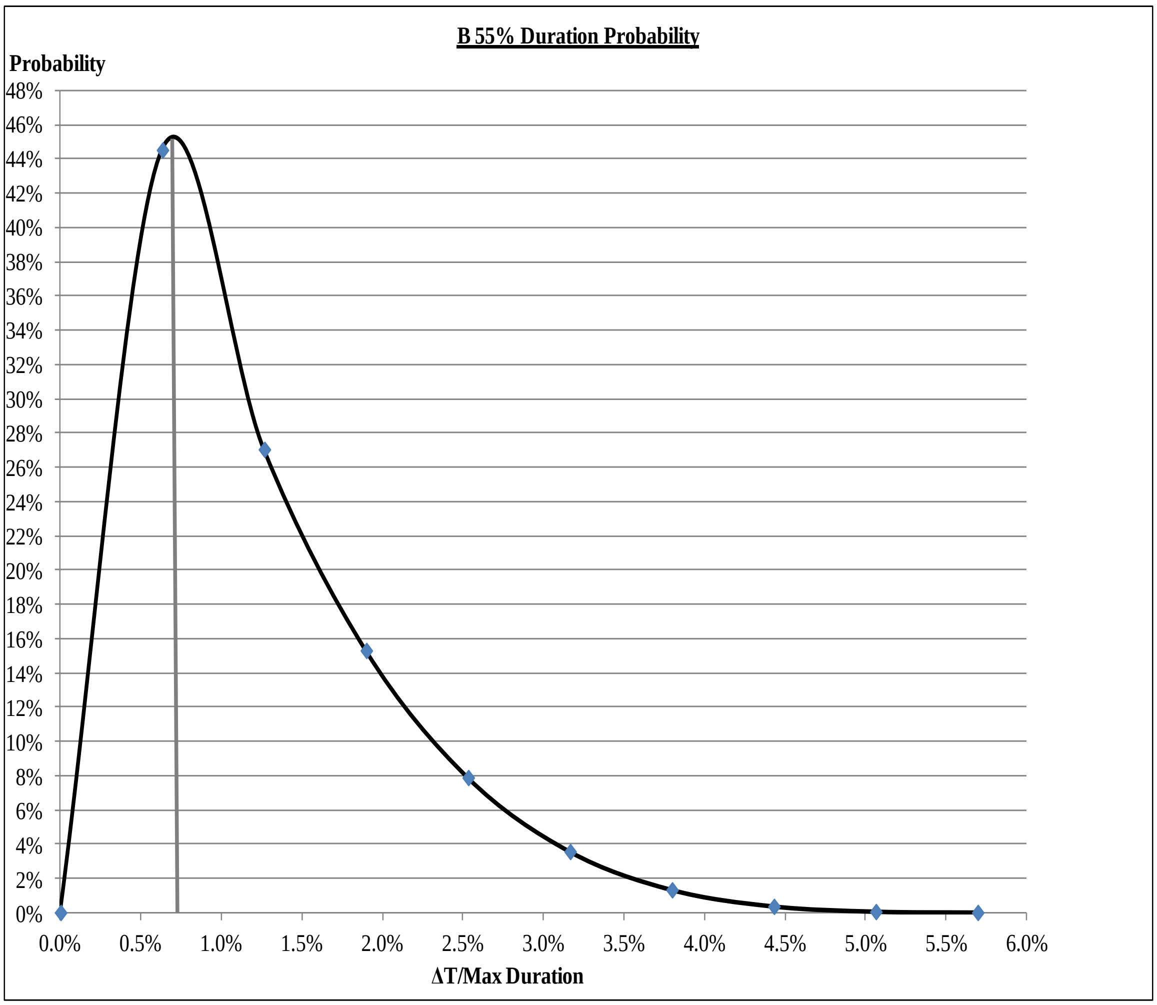

Figure 4-14: Risk analysis results

Hence through utilizing the four modules that constitute the developed “B” value time/cost trade-off model, SHAs’ alternative contracting decision making process will greatly improve.

4.7. Conclusion

In this chapter a new model aimed at quantifying the impact of the A+B contracting method on the time/cost trade-off relationship and the impact of the different "B" values on the trade-off between time and cost of pavement rehabilitation projects was developed. The developed model first determines the relationship between the time reduction and cost increase for an A+B pavement rehabilitation project and then assigns the appropriate "B" values based on the desired level of reduction in the project's duration and estimates the additional cost, incurred by the owner, associated with each "B" value due to the acceleration of the project's construction and finally determines the likelihood of achieving these desired levels of duration reduction. The model consists of four modules; namely: time/cost trade-off module, "B" value calculation module, owner's cost calculation module, and risk analysis module. The development process of this model and its application on a real-life project, were presented in this chapter. The results of this application showed that this model has some distinctive capabilities including: 1) the ability to accurately depict the time/cost trade-off relationship for pavement rehabilitation projects contracted under the A+B contracting method, 2) assign the appropriate "B" value based on the desired duration reduction, 3) the ability to calculate the additional cost incurred by the owner as a result of selecting a certain "B" value, 4) the ability to determine the most likely value of the "B" component to be achieved for the project, and 5) the ability to precisely determine the duration reduction to be expected from adopting that particular "B" value.

The developed model can help improve the SHAs planning process for their pavement rehabilitation projects using the A+B contracting method as it will enable the decision makers to make better informed decisions when contracting such projects. These decisions are both related to the duration and cost of the project which will help in reducing the negative impacts of the pavement rehabilitation projects and save the public's money; while, at the same time, allow the SHAs to best utilize their available budget.

Chapter 5

EXAMINING THE SHAS' ALTERNATIVE CONTRACTING DECISION MAKING PROCESS

5.1. Introduction

The main objective of this chapter is to examine the SHAs' alternative contracting decision making process for their pavement rehabilitation projects by taking into account their decision variables and project characteristics. The aforementioned process will involve a number of different tasks, each with a specific aim; namely: 1) examining the SHAs' decision making process with regards to the I/D contracting method to ensure the success of its implementation; 2) examining the SHAs' decision making process with regards to the A+B contracting method so it can fulfill its planned goals; 3) contrasting the performance, cost and risk associated with each of the two contracting methods through using the developed time/cost trade-off models to assist the SHAs in selecting the most-suitable method for their projects based on their decision variables and the project's characteristics; and 4) combining the two developed time/cost trade-off models to derive the time/cost trade-off relationship for the A+B+I/D alternative contracting method. Accordingly, the next sections will concentrate on: 1) determining the most important factors impacting the success of the I/D contracting method and how the developed model can enhance the SHAs' decisions regarding these factors; 2) determining the most critical parameters regarding the success of the A+B contracting method and how the developed model can improve the SHAs' decisions with regards to these parameters, 3) comparing both models to select the most-suitable method depending on the SHAs' decision variables and the project characteristics; and 4) developing a time/cost trade-off model for the A+B+I/D contracting method. The above objectives will be achieved through the use of the models developed in chapters 3 and 4 as shown in figure (5-1).

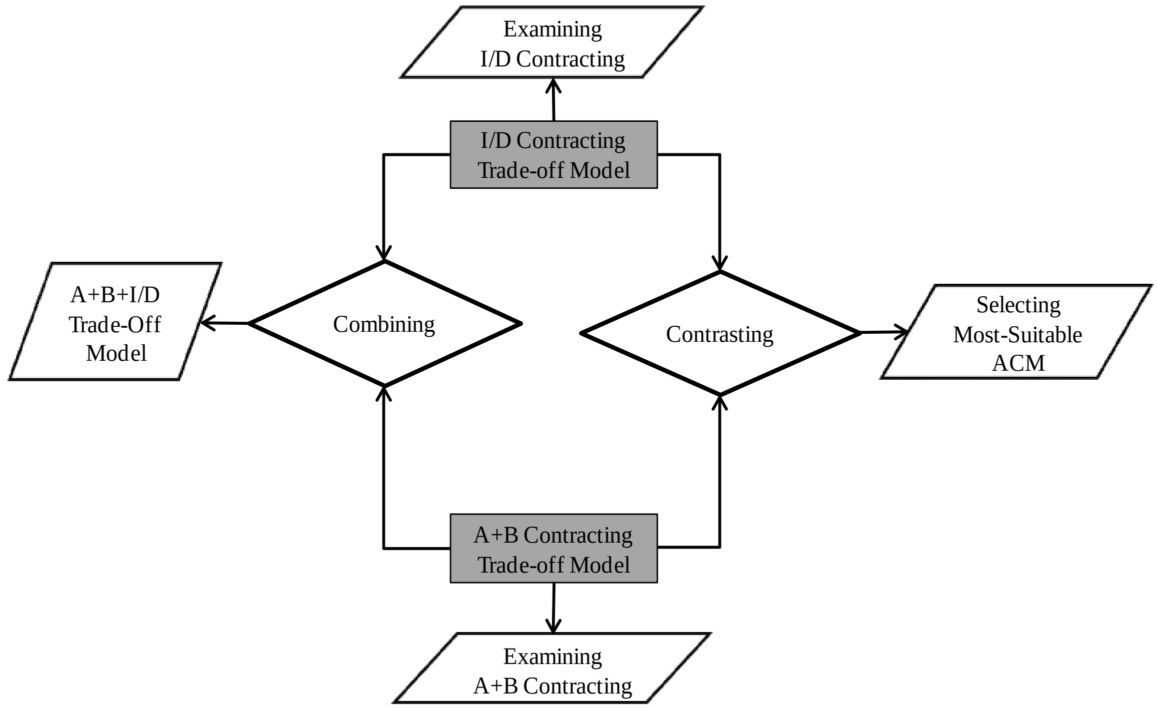

Figure 5-1: Use of the I/D and the A+B trade-off models to enhance the SHA's alternative contracting decision making process

5.2. Examining the I/D Contracting Method Decision Making Process

The developed time/cost trade-off model for the I/D contracting method can help the SHAs in enhancing their decision making process regarding certain important factors that impact the outcome of the use of this method. Through the use of any individual module or a combination of modules that constitute the developed model, several decisions regarding the implementation of the I/D contracting method can be greatly improved; these decisions involve: 1) determining the most suitable ID level to be assigned based on a certain desired level of duration reduction; 2) setting the maximum ID value for a project; 3) identifying the minimum ID level that can be offered for a given pavement rehabilitation project and decide if it meets the SHA's guidelines; 4) knowing the cost that the SHA will incur with each duration reduction before the start of the project; and 5) determining the most likely duration reduction that can be achieved for each specific project. The next sections will describe how the developed model can help with each of these decisions in details.

5.2.1. Determining the Most Suitable ID Level to be Assigned:

One of the main decision parameters that impacts the success of the implementation of the I/D contracting method is setting the ID value itself. Nonetheless, and as discussed in chapter 1, the current SHAs' practices do not relate the ID value to the desired duration reduction as they only use their experience to determine what percentage of DRUC to be used (Sillars 2007) which creates a lot of problem while implementing the I/D contracting method. For instance, MnDOT guidelines states that the ID value should be sufficient to encourage the contractor to reduce the duration and recommends a daily ID ranging from $5,000 to $10,000 for all project types and durations (MnDOT 2005), while TxDOT uses a value of $25,000 per day for reconstruction projects of high traffic volumes (Anderson and Ullman 2000). However, through the use of the ID value calculation module and as demonstrated by the I-15 Devore example, SHAs can accurately select the ID level based on their desired duration reduction which will prevent any over or under valued ID values and avoid wasting the public's money. To demonstrate the usefulness of the developed model, consider a resurfacing project of US-1 from district 6 at FDOT. For this project, the SHA paid approximately an additional $700,000 to reduce the duration by 10 days; however, if they had utilized the I/D trade-off model, they should have offered a daily I/D amount of $55,721 to achieve the desired

10 days duration reduction which would have resulted in an additional cost of approximately only $557,000 amounting for a savings of $138,000 of the public's money.

5.2.2. Setting the Maximum ID Value:

Setting the maximum ID to be paid to the contractor for a given project can have a big impact on the project's success as it predetermines the maximum days to be saved and, in return, the maximum total cost that the SHA will pay. However, the current SHAs' practices regarding the setting of this value only follow generic guidelines and do not assure neither the success of the I/D contracting method implementation nor provide adequate planning from the SHAs' perspectives. For instance, and as demonstrated in table (5-1) which is based on Herbsman et al. (1995), and Shr and Chen (2004), first there are three different methods currently in use by the SHAs for setting the maximum ID value; and second, none of these techniques is project specific or tied to the SHAs' goals for a particular project. For instance, district 6 at FDOT sets the maximum I/D to be offered as a percentage of the total project cost disregarding the DRUC value for that particular project.

Table 5-1. Types of Maximum ID Values Used by the SHAs

Type of Maximum ID Value	**Number of States Implementing**
Percentage of Project's Cost	9
Fixed Dollar Amount	8
Number of Days	1

Nevertheless, through the use of the developed model, the SHAs' can either set the maximum ID value based on their desired duration reduction and budgetary constraints or even use their current generic guidelines to set the expectations for the maximum duration reduction and improve their planning for the implementation of the I/D contracting method. Each of these strategies will be demonstrated using the application example from chapter 3.

Regarding the former strategy, through the use of the ID value module, SHAs' can relate the desired duration reduction to the appropriate ID value to be offered; hence, through utilizing the owner cost module, they can calculate the maximum ID that they will have to pay to achieve this desired reduction. Therefore, and through this new practice, SHAs can better plan their financial resources and avoid any unexpected cost overruns resulting from additional paid incentives. To demonstrate this approach, consider the I-15 Devore project and its application from chapter 3, if, for example, CALTRANS wanted a maximum duration reduction of 14 days for this project, then they will have to offer the contractor a daily ID value equivalent to 61% of the DRUC ($148,566/day); consequently, the maximum ID they should set can be calculated as follows:

$$148{,}566 * 14 = \$2{,}079{,}924$$

And the maximum project's cost that they will incur will be $20,079,926 and at the same time they will realize a total DRUC savings of $3,409,714.

On the other hand and regarding the latter strategy, assuming that CALTRANS has a 10% of the total project's cost cap on the total ID to be paid, which is equivalent to $1,800,000; therefore, according to their reduction needs they can have a couple of options to choose from as shown in table (5-2):

Table 5-2. I-15 Devore Maximum ID Options

Duration Reduction Aimed For (days)	**Daily ID Value to be offered ($)**	**Total Additional Cost ($)**	**DRUC Savings ($)**
1-6	143,695	143,695 – 862,170	243,551 – 1,461,306
7-12	146,131	1,022,917 – 1,753,572	1,704,857 – 3,166,163

Hence, the developed I/D trade-off model can be used by the SHAs to set the maximum ID to be offered or the expected days to be reduced based on their current maximum ID guidelines which will greatly improve their planning practices for the I/D contracting method and avoid any cost overruns or misuse of the ID provision by the contractor.

5.2.3. Identifying the Minimum ID Value to be Offered:

Through the use of the ID value calculation module, the minimum ID value, which is equal to the contractor's additional cost for a one-day duration reduction, can be precisely calculated. The calculation of the minimum ID value will help enhance the SHAs' I/D contracting decision making in a number of ways. First, it will assure that the ID offered presents enough motivation for the contractor to reduce the project's duration because if the minimum ID value does not cover the contractor's additional cost, then no time reduction will be achieved and the use of the I/D contracting method will be deemed to fail. This problem was faced by a number of SHAs; for instance, from data about the I/D projects actual time versus contract time collected from FDOT district 6, approximately 13% of these projects experienced no duration reduction resulting from the use of the I/D contracting method. For instance, for a resurfacing project of SR 986, the contractor was not able to achieve any duration reduction over the bid time as the daily I/D offered was $5,000 while the additional cost to reduce one day was $7,880; hence, the I/D amount offered should be at least $7,920 as calculated by the developed model. Second, it will help in deciding whether the use of the I/D contracting method is suitable for their project or not at the early planning stage based on the following criteria:

1- If the project meets their budgetary constraints.

2- If the minimum ID value is consistent with their guidelines and rules.

5.2.4. Knowing the Final Project Cost that the SHA will Incur:

Due to the limited financial resources available to the SHAs and the large number of pavement rehabilitation projects that they have to construct, being able to accurately estimate the final cost for the I/D projects is a vital planning task from their part. However, with the current I/D contracting practices and without tying the ID value with the desired duration reduction, SHAs only have a rough estimate of the possible range of the project's cost which might lead to cost overruns and consequently creates problems in terms of appropriately allocating their financial resources and avoid public outrage. For example, in a study of FDOT I/D projects, Ellis et al. (2007) found that the I/D projects' actual cost experienced a cost overrun over the award cost of an average 12.5% which was mainly due to additional incentives paid to the contractor. Thus, through the use of the owner's cost calculation module, this problem can be solved and SHAs can accurately estimate, barring any unforeseen circumstances, the final cost that they will incur and plan their financial resources more efficiently. An example to demonstrate this capability of the developed model is the project SR907 in Florida. For this project, the engineer's cost estimate was US$ 1.6 million which was 25% less than the actual final cost of US$ 2.1 million; however, the final cost calculated using the I/D model was less than 10% off the actual final cost which is considered a very acceptable degree of accuracy.

5.2.5. Determining the Most Likely Duration Reduction:

When setting their desired duration reduction for a given pavement rehabilitation project, SHAs need to examine the likelihood of achieving this reduction so as not to: 1) discourage contractors from bidding by setting unrealistic targets, 2) avoid public discontent when the target is not met, and 3) preserve their resources. Nevertheless, neither the current practices nor the available research provide any guidelines towards quantifying this likelihood; however, they tend to provide broad guidelines and lean towards avoiding any types of risks at all. Therefore, through the use of the risk analysis module, and as demonstrated by the I-15 Devore example, SHAs can know the probabilities of both achieving each ID level and each duration reduction within that ID level. The benefits of the developed model can be demonstrated through figure (5-2) which compares the three practices: traditional contracting, current I/D practice, and the developed I/D model, against each other in terms of duration reduction, additional owner cost, and user cost savings.

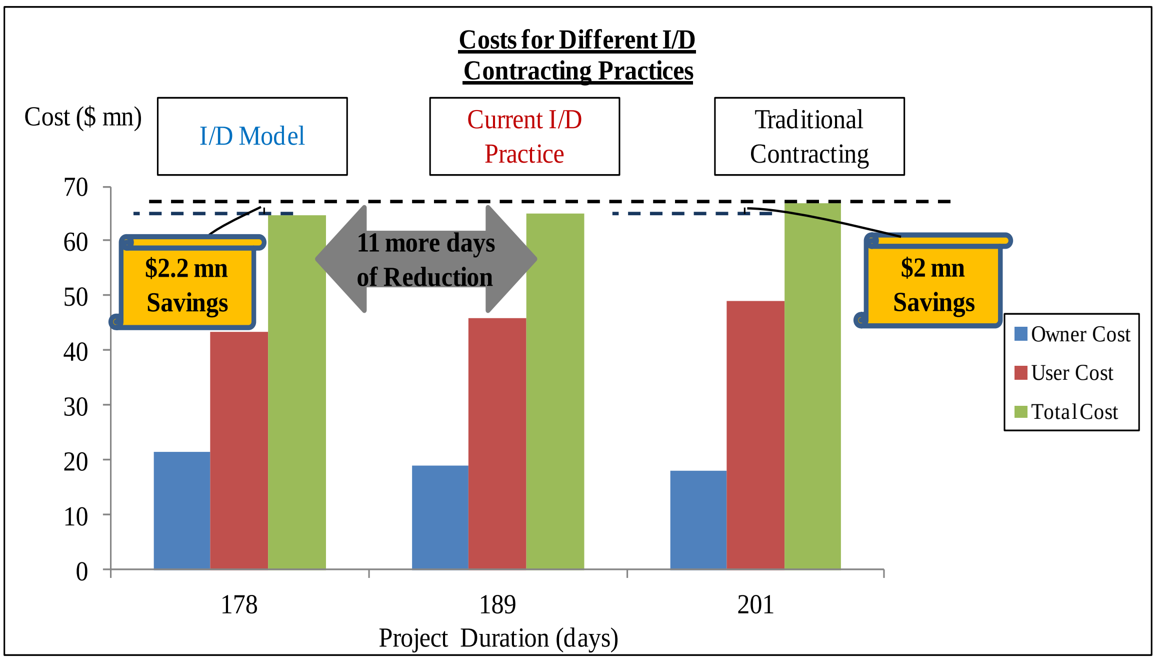

Figure 5-2: Comparison between the developed I/D model and the current practice

As seen from the figure, for that particular project, the current I/D practice led to a duration reduction of 12 days with an increase in owner cost of $900,000 and user cost savings of $2,900,000; i.e. total dollar savings of $2,000,000. Nevertheless, both the time and cost performance of this project would have improved with the use of the developed

I/D model as it will lead to a duration reduction of 23 days with an increase in owner cost of $3,400,000 and user cost savings of $5,600,000; i.e. total dollar savings of $2,200,000; hence, providing more duration reduction with a higher dollar savings.

5.3. Examining the A+B Contracting Method Decision Making Process

Certain aspects regarding the SHAs' current decision making practices for the A+B contracting method can be greatly improved by the use of the A+B time/cost trade-off model developed in this study. These decisions include: 1) assigning the "B" value based on the desired duration reduction; 2) identifying the expected and maximum duration reductions that the contractor can bid on i.e. have a firm idea about the project's final duration before the bid submission phase; 3) helping in identifying the unbalanced bids submitted by the contractors; 4) knowing the cost that the SHA will incur with each duration reduction; and 5) finding out the probabilities of achieving each desired duration reduction. The next sections will provide details of how the application of the developed model can help with each of these decisions in details.

5.3.1. Assigning the "B" Value:

Assigning a dollar value to the "B" component of the bid is one of the pivotal tasks that influence the success of the implementation of the A+B contracting method. Nonetheless, currently, most SHAs only use their engineering judgment to determine this value which hinders the opportunities of the success of the implementation of the A+B method (Anderson and Russell 2001). Furthermore, in some instances, the SHA does not tie the value assigned to the "B" portion to the DRUC at all; for example, Utah DOT uses the liquidated damages used for traditional contracting, which are fixed amounts based on the project's cost (table 5-3), as the "B" value for projects with AADT less than 10,000

(UDOT 2011). This practice might actually prove damaging to the purpose of the A+B contracting method as it might not entice the contractor to bid on a reduced duration. For example, for the project SR-35 by UDOT, the SHA assigned $1,570 for the "B" value as per table (5-3) while according to the general A+B model, the minimum value to be assigned for the "B" component for this project should have been $4,200; which did result in the project being constructed over a longer duration by 7 days than if it was constructed using traditional contracting. Also, when applying the strategy-specific models to this example, it was found that in case of PCCP 12, the minimum "B" value should have been $4,430; while in case of the other strategies, the minimum "B" value should have been $2,550.Therefore, through the use of the "B" value module, the task of assigning the "B" value can be performed in a much more methodical way, as a percentage of the DRUC and according to the SHAs' desired duration reduction on which they want the contractor to bid on, which increases the opportunities of the success of its implementation.

Table 5-3. UDOT Liquidated Damages

Original Contract Amount ($)		**Daily Liquidated Damage**
From	**To**	
$0	$100,000	$560
100,000	500,000	930
500,000	1,000,000	1,200
1,000,000	5,000,000	1,570
5,000,000	10,000,000	2,130
10,000,000	30,000,000	2,430
30,000,000		4,870

5.3.2. Identifying the Expected and Maximum Duration Reductions:

Since the task of setting the project's duration is in the hands of the contractors without any control from the SHA, the SHA might end up with a project that has a longer duration than if it was contracted using traditional contracting. For instance, for a minor rehabilitation project for SR-35 in Utah, the engineer estimate for the project's duration was 45 days; however, the winning bid was for 50 days and even the second lowest bid received was for 48 days which voids the A+B contracting method from its main goal (UDOT 2016). Hence, a tool by which the SHA can estimate a possible range for the project's durations that the contractor will bid on becomes essential. This is achieved through the use of the developed model as the duration range associated with each "B" value can be accurately computed before the invitation to bid phase and through this computation the SHA can avoid any high duration bids and eliminate the above-mentioned problem completely.

At the same time, sometimes the contractors bid on an unrealistic low duration to win the bid but later they cannot fulfill this duration (UDOT 2011); nevertheless, due to the lack of means of tying the duration reduction with the expected cost, SHAs use fixed percentages to get to the minimum duration reduction; for instance, Utah DOT uses 30-35% below the estimated duration (UDOT 2011). Thus, the use of the developed A+B trade-off model will help the SHA in knowing the minimum duration that the contractor can bid on, i.e the maximum duration reduction that can be achieved for that particular project.

5.3.3. Recognizing the Unbalanced Bids:

One of the major problems with the A+B contracting method is the problem of the unbalanced bids which occurs when the contractor intentionally reduce the duration while excessively increasing its cost ("A" component) to win the bid (UDOT 2011, Sillars 2007). This practice, although not illegal, often jeopardizes the success of the project and wastes the SHA's financial resources. However, with the use of the developed model, SHAs can know beforehand the expected cost associated with each duration so they will be able to determine, during the bid opening phase, if the contractor used this practice or not. This can be illustrated by the use of the I-15 Devore example and considering the different bidding scenarios that could have been submitted to CALTRANS as shown in table (5-4):

Table 5-4. Balanced Versus Unbalanced Bid Scenarios

Bid Scenario	**A ($)**	**B (days)**	**Balanced/Unbalance**
1	18,860,003	194	Balanced
2	21,487,900	189	Unbalanced

As seen from the above table, through the use of the developed model, SHAs can determine if the bids submitted to them are balanced or not and prevent this practice by the contractor from a very early stage.

5.3.4. Knowing the Final Cost that the SHA will Incur:

Due to the limited budgets available to the SHAs and the large number of pavement rehabilitation projects in their states, being able to accurately estimate the final cost for their A+B projects is a vital planning task. However, with the current practices and without tying the "B" value with the desired duration reduction, SHAs only have a vague estimate of the possible range of the project's cost at the pre-bidding phase which create problems in terms of appropriately allocating their financial resources and avoid public outrage. Thus, through the use of the owner's cost calculation module, this problem can be solved and the SHAs can accurately estimate, barring any unforeseen circumstances, the final cost that they will incur and plan their financial resources more efficiently. An example to demonstrate how the developed model can be used to enhance this project's parameter is the project SR5. For this project, the engineer's cost estimate was US$ 7.2 million which was almost 30% less than the actual final cost of US$ 10.3 million; however, the final cost calculated using the developed A+B model was approximately 4.5% less than the actual final cost. At the same time, if this project was constructed using the PCCP 12 strategy, the final cost would have been 3.9% off the actual final cost; while, if constructed using the other strategies, the final cost would have been 15% less than the actual final cost.

5.3.5. Finding the Probabilities of Achieving Each Duration Reduction:

When setting their desired duration reduction for a given pavement rehabilitation project, SHAs need to examine the likelihood of achieving this reduction so as not to: 1) discourage the contractors from bidding, 2) avoid public discontent when the target is not met, and 3) not waste their resources. Nevertheless, neither the current practices nor the available research provide any guidelines towards quantifying this likelihood. Therefore, through the use of the risk analysis module, and as demonstrated by the I-15 Devore example, SHAs can know the probabilities of both achieving each "B" value and each duration reduction within that "B" value. The benefits of the developed model can be demonstrated through figure (5-3) which compares the three practices: traditional contracting, current A+B practice, and the developed A+B model, against each other in terms of duration reduction, additional owner cost, and user cost savings for Utah SR-31 project.

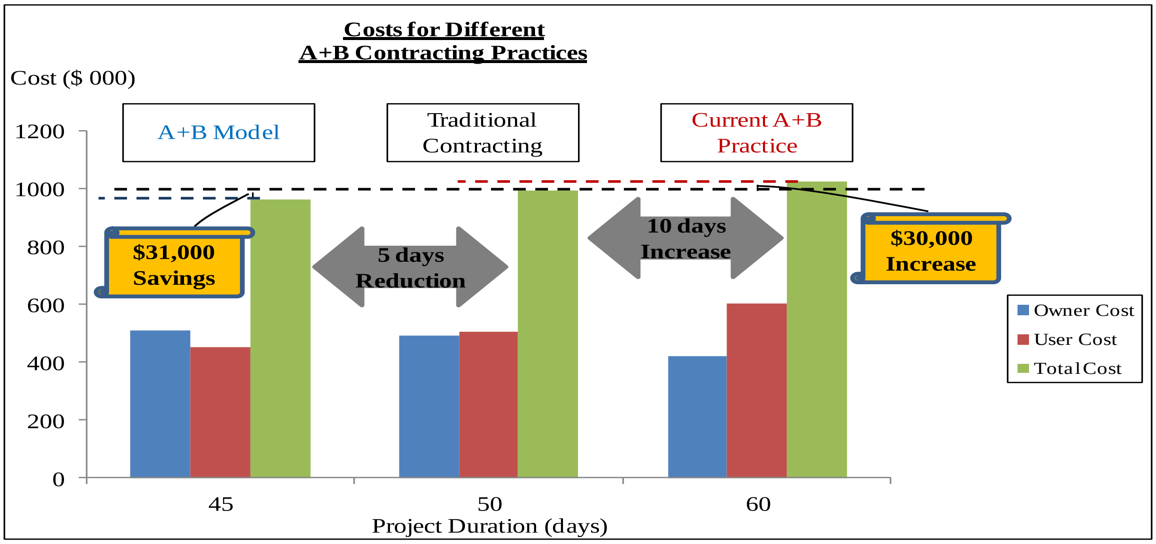

Figure 5-3: Comparison between the developed A+B model and the current practice

As seen from the figure, for that particular project, the current A+B practice led to a duration increase of 10 days albeit with a decrease in the owner cost of $70,000 but with an increase in user cost of $100,000; i.e. total additional dollar cost of $30,000. Nevertheless, both the time and cost performance of this project would have improved with the use of the developed A+B model as it will lead to a duration reduction of 5 days with an increase in owner cost of $20,000 and user cost savings of $51,000; i.e. total dollar savings of $31,000; hence, providing a duration reduction with a higher dollar savings. In addition, when applying the specific pavement strategies models developed in chapter 4, it is evident that the use of the developed models will lead to both cost and time savings over the current practice for all pavement strategies as shown in figure (5-4).

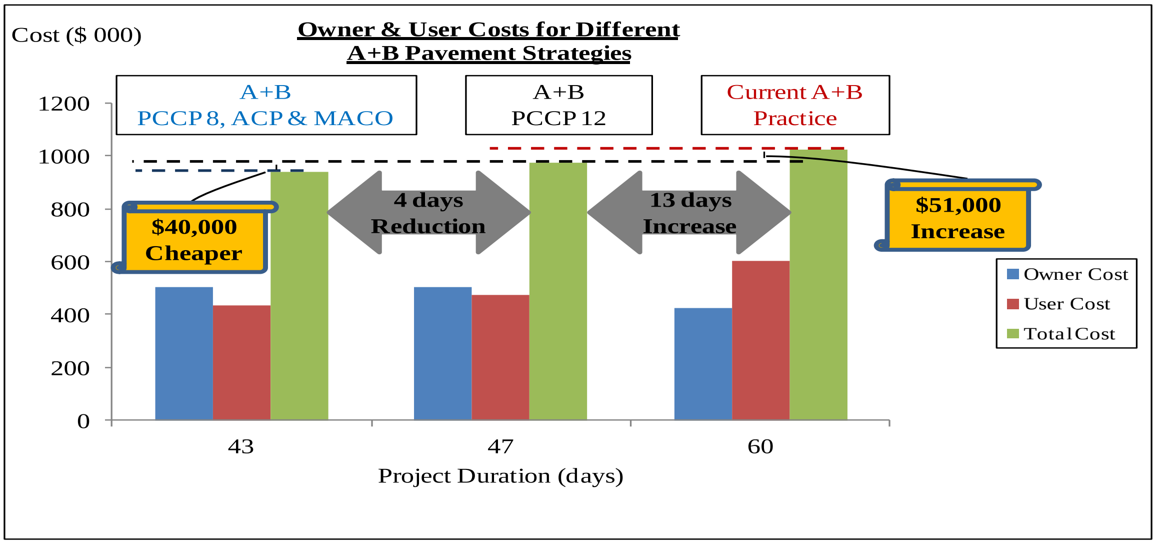

Figure 5-4: Comparison between the different A+B strategies and the current practice

5.4. Selecting of the Most-Suitable ACM:

One of the main challenges facing any SHA when dealing with alternative contracting methods is how to select the one method that best suits its project and fulfills its planned objectives. Nevertheless, the current practice in choosing the most suitable alternative contracting method depends on generic guidelines that decide on the ACM based on the project’s qualitative characteristics without any comparison between the methods in question (Anderson and Damnjanovic 2008); an example of these guidelines for both the I/D and A+B contracting methods is presented in table (5-5) from PaDOT (2013) and NYSDOT (1999), respectively:

Table 5-5. I/D and A+B Guidelines

I/D Guidelines	**A+B Guidelines**
High traffic volume	High traffic volume
Lengthy detours	Safety Concerns
Constructability	Major reconstruction
Safety concerns	Complete a gap in the highway system
Public interest in early completion	Lengthy Detours
Major emergency route	

As seen from the above table, the guidelines for the selection of the appropriate ACM are very general and almost the same for the two methods to the extent that Georgia SHA states that "candidate projects [for I/D contracting method] are same as for A+B Bidding" (Carpenter 2013) ; nonetheless, with the use of the two developed models, SHAs can now base their selection of the most suitable ACM for their project on quantitative decision parameters. The selection process will depend on each SHA's decision parameters as demonstrated in the following sections.

5.4.1. The Construction Cost is the Sole Decision Parameter:

By comparing the time/cost trade-off curves for the I/D and A+B contracting methods the decision of selecting the most-suitable contracting method can be quantitatively reached. Figure (5-5) shows the comparison of the two trade-off curves for the I-15 Devore project.

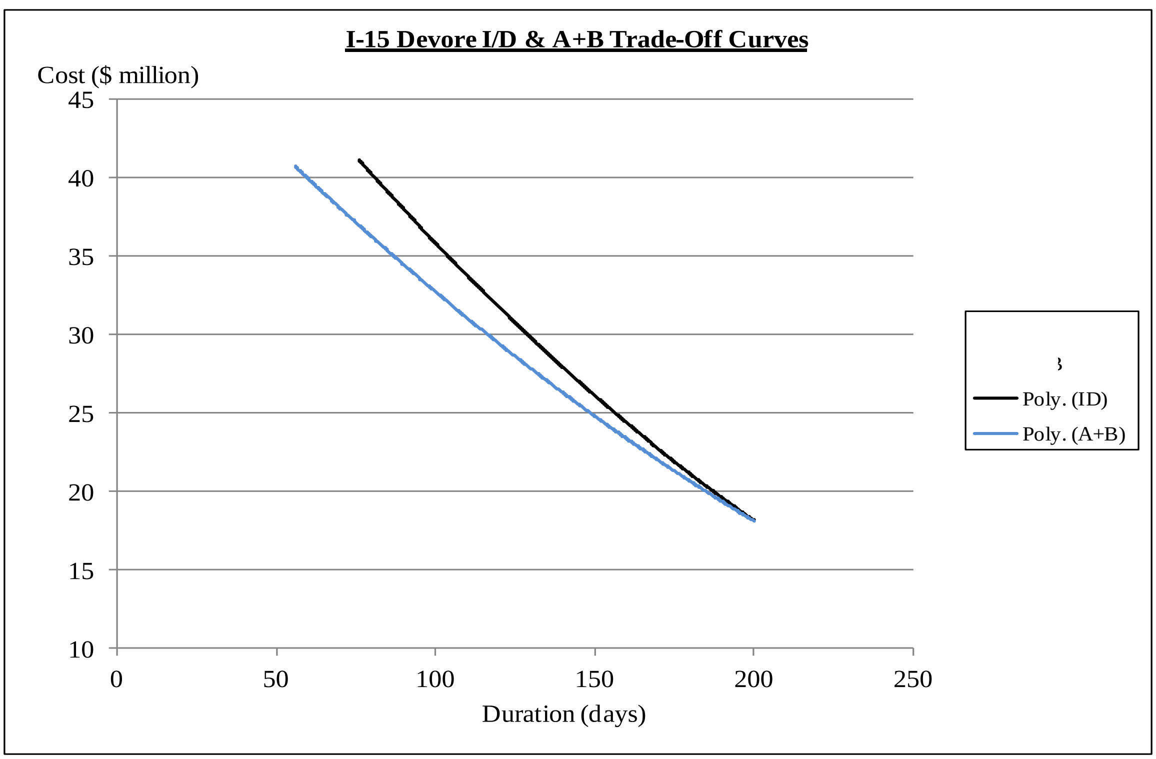

Figure 5-5: Time/cost trade-off curves for I/D and A+B contracting methods

From the above figure, and when the cost is the only decision parameter considered by the SHA, it is clear that the A+B contracting method provides a cheaper alternative for the same duration reduction with the exception of the very low duration reductions (<=1%). In addition to the above conclusion, a number of additional observations can be deduced from the above figure that will help the SHAs in their choice of the appropriate ACM for their project; these observations are:

1- The two curves are not parallel; meaning that the savings in cost between the two methods increase with the increase in the extent of the required duration reduction to the favor of the A+B contracting method.

2- The A+B contracting method can reach higher duration reductions that are not achievable via the use of the I/D contracting method which means that if these high duration reductions are aimed for by the SHA, then the A+B contracting method should be the method of choice.

Nevertheless, when comparing the additional construction costs associated with each method, SHAs need to take into consideration the unique nature of each of these methods. One of the main differences between these two methods is that with the I/D method, the SHA does not pay for the cost of acceleration until it is already achieved; unlike with the A+B method where the cost of acceleration becomes the contract cost and will be paid regardless of whether the desired duration is achieved or not which associates more risk with the A+B method. Therefore, when comparing the two methods based on the construction cost, the net expected costs should be the values compared rather than the absolute cost values. Therefore, the expected cost for the I/D contracting method should reflect the cost and probability of occurrence, calculated from the risk analysis module, of every duration, higher than the desired one as illustrated by equation (5-2):

$$ID\ Expected\ Cost = \sum_{1}^{T-desired\ T} C_i \times P_i \qquad (5\text{-}2)$$

where; C_i is the cost of duration i, and P_i is the probability of duration i.

On the other hand, the expected cost for the A+B method will always be the cost of the desired duration reduction as shown in equation (5-3):

$$A + B\ Expected\ Cost = C_i \times 100\% \qquad (5\text{-}3)$$

Hence, the net expected risk (NER) will be computed as the difference between the two expected costs where a negative value will indicate that the I/D contracting method is less risky, in terms of cost, than the A+B method and vice-versa. By applying the above analysis to a sample of the projects from different categories, the following results were obtained (table 5-6):

Table 5-6. Projects Net Expected Risk Sample

Project	**% Duration Reduction**	**I/D Expected Cost ($)**	**A+B (General) Expected Cost ($)**	**NER ($)**
1	-0.9%	7,999,111	8,070,290	-71,179
	-3.6%	8,197,083	8,235,131	-38,049
	-6.4%	8,214,054	8,403,567	-189,513
2	-2.7%	2,592,320	2,572,181	20,139
	-4.3%	2,670,774	2,656,607	4,167
	-6.3%	2,751,483	2,759,388	-7,905

As seen from the above table, the net expected risk for the first project is always a negative value for the desired duration reductions which means that the I/D method is less risky, in terms of cost, for that particular project; however, for the other two projects, and depending on the desired duration reduction the I/D contracting method can be less or more risky, in terms of cost, than the A+B method. Consequently, although, the cost of the specific duration reduction for the I/D contracting method is higher, when considering the net expected risk, this cost might end up lower and it is up to the SHA to set and assess the degree of risk they are willing to accept for their project.

Furthermore, when comparing the NER values for the different A+B models respective to the different pavement strategies, table (5-7) shows that the most-suitable method for the PCCP 12 strategy conforms with the one selected by the general model, while for the other strategies, this type of analysis tend to favor the A+B method more; albeit, only in few scenarios.

Table 5-7. Pavement Strategies Net Expected Risk Values

Project	% Duration Reduction	NER (General) ($)	NER (PCCP 12) ($)	NER (PCCP 8, ACP & MACO) ($)
1	-0.9%	-71,179	- 75,322	-48,583
	-3.6%	-38,049	- 54,692	53,472
	-6.4%	-189,513	- 218,767	-27,362
2	-2.7%	20,139	10,025	75,595
	-4.3%	4,167	1,816	104,970
	-6.3%	-7,905	-32,068	129,012

5.4.2. DRUC Savings Versus the Additional Construction Cost:

Nevertheless, in most cases, the cost of the project is not the only decision parameter considered by the SHA, but also the DRUC savings realized from the application of these methods. Therefore, SHAs need to calculate the benefit/cost ratio associated with each method to select the most suitable one based on the different projects' characteristics. Before conducting this type of analysis, the fact that the risk of not achieving the required duration reduction is higher with the A+B contracting method because the contractor is the entity that determines the project duration (Herbsman et al. 1995) needs to be taken into account. Therefore, considering that the risk associated with the A+B contracting method ranges from 1% to 8% more than the one associated with the I/D contracting method (Ellis et al. 2007, Choi et al. 2012), with an average of 4.5%; and by comparing the time/cost trade-off curve for the I/D and A+B contracting methods, SHAs' can select the most suitable ACM for their projects. Hence, in order to reach a decision, the SHAs need to compare the cost difference between the two methods versus the difference in the DRUC savings that can be achieved by each since the higher risk associated with the use of the A+B contracting method will have an impact on the DRUC savings realized by the SHA; and consequently, the benefit/cost ratio associated with the use of both methods. As illustrated from figure (5-6), and assuming that the additional risk associated with the A+B contracting method will be reflected in achieving a duration higher than the targeted one by 4.5%, and although the cost associated with the I/D contracting method is higher than the A+B method, the additional risk associated with the A+B method will result in lower DRUC savings than with the I/D method as it will lead to achieve a lower duration reduction. Thus, in order to be able to select the best method for a given project, the different benefit/cost ratios (B/C) associated with each method and for each project category have to be computed and compared to reach a conclusion on the most suitable method for each project category. To perform the above-mentioned analysis, several steps were conducted as described in the following sections.

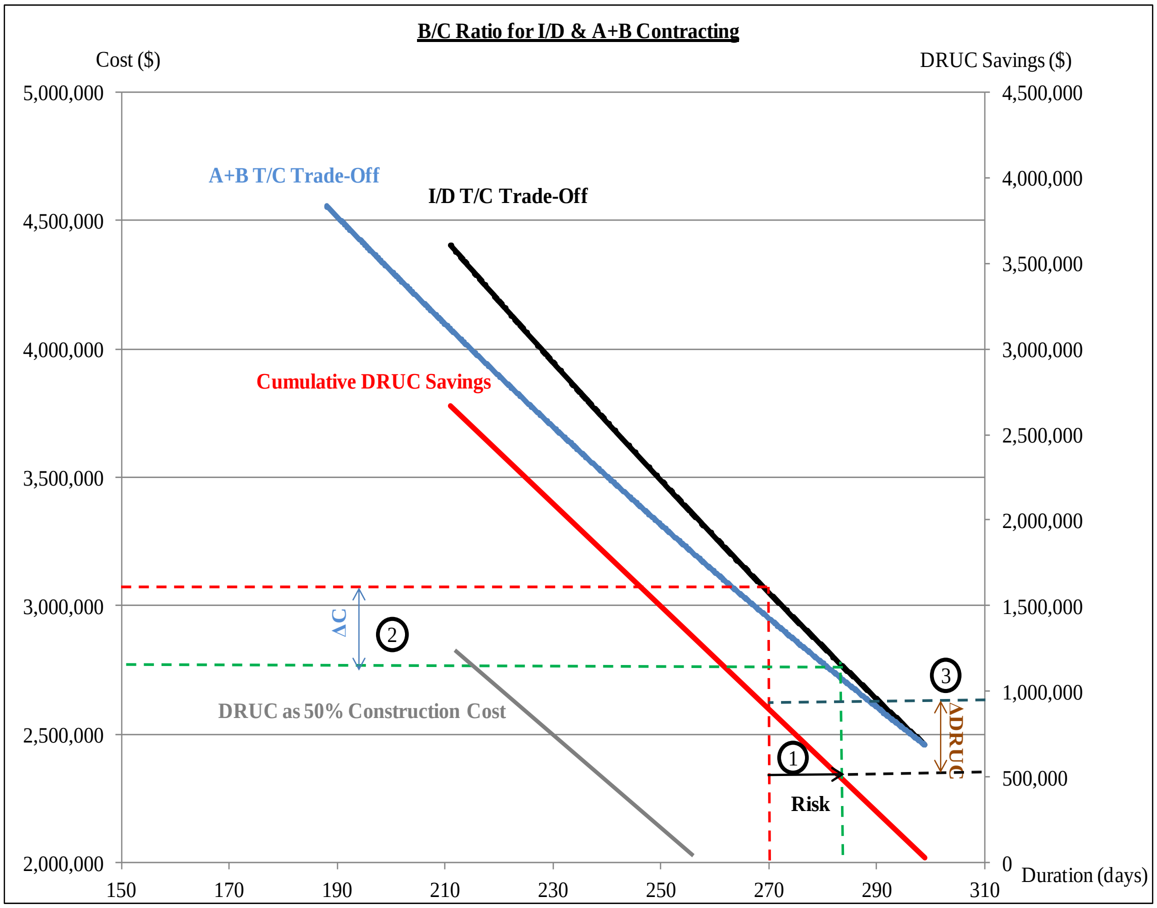

Figure 5-6: Cost and benefit associated with each contracting method

5.4.2.1. Data Collection and Preparation:

In order to perform the above-mentioned analysis and be able to draw conclusions with regards to the different projects categories, data from real-life pavement rehabilitation projects, contracted through both traditional and alternative contracting methods, from six different states were collected through utilizing the SHA's websites. The collected data included the project's engineer's time and cost estimates and the AADT. From the AADT, the DRUC associated with each project was calculated using the DRUC tables developed by Daniels et al. (1999). Nonetheless, since these tables were developed in 1999, an inflation adjustment was applied to the resulting DRUC values based on the ratio of the transportation components of the CPI indices for 2015 versus 1999 obtained from the Bureau of Labor Statistics website (www.bls.gov 2016). Furthermore, since the developed tables are based on Texas costs, the DRUC for each of the 83 projects was adjusted according to each project's location using the RS Means location indices (RS means 2010).

5.4.2.2. Data Categorization:

After preparing the data for analysis, the data was grouped and categorized according to three main project's characteristics: engineer's duration estimate, DRUC, and engineer's cost estimate. For the first category, the duration of the collected data ranged from 24 to 600 days; hence, the equal interval method was used to categorize these projects into four categories of 150-days range each as this method proved suitable for the collected data since all categories had close number of data points. For the DRUC and engineer's cost estimate, the equal quantile method was used to categorize the data into three and two unequal-interval categories, respectively, since the data were clustered close to certain values.

5.4.2.3. Data Analysis and Results:

All projects collected in the previous step were analyzed using the two models developed in chapters 3 and 4; and since the data were not defined according to the different pavement strategies; hence, the A+B general model was used. Using the engineer's time and cost estimates and the DRUC for each project and assuming the project was contracted once by the I/D contracting method and once by the A+B contracting method, the costs and the DRUC savings for each method were calculated for each level of duration reduction. However, as illustrated in figure (5-6), each contracting method will have a different cost and DRUC savings for the same targeted duration reduction; hence, a benefit/cost (B/C) ratio for the difference in DRUC savings versus the difference in additional cost was computed for each project using equation (5-1):

$$B/C = \frac{DRUC\ Savings_{I/D} - DRUC\ Savings_{A+B}}{Project\ Cost_{I/D} - Project\ Cost_{A+B}} \quad (5\text{-}1)$$

After computing the B/C ratio for each project, the averages of all projects belonging to the same group for each contracting method were computed and compared for different levels of duration reductions; consequently, a B/C ratio of more than 1 means that the I/D contracting method is better than the A+B method for that particular group of projects, while a B/C ratio of less than 1 means that the A+B contracting method is better. Figure (5-7) shows the results for the different categories of project durations.

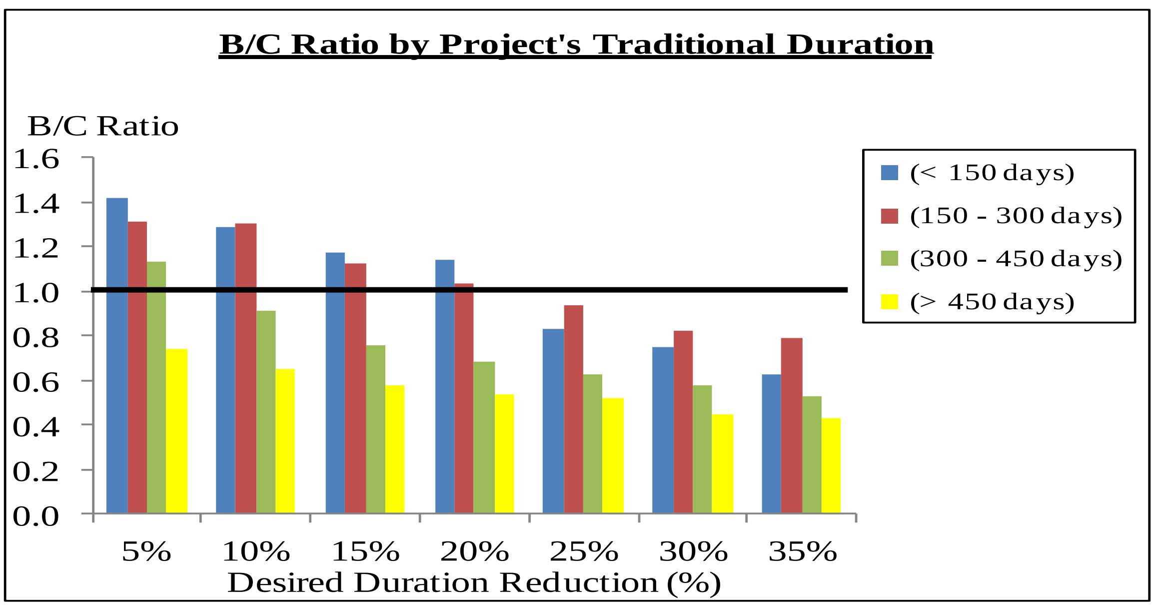

Figure 5-7: B/C ratio by project's traditional duration

From the figure, the following conclusions can be drawn:

1- For projects with a traditional duration of less than 300 days, the I/D contracting method should be chosen by the SHA if the desired duration reduction is less than 20%; otherwise, the A+B method should be chosen.

2- For projects with a traditional duration between 300 and 450 days, the I/D method should only be chosen by the SHA if the desired duration reduction is 5% or less; otherwise, the A+B method should be chosen.

3- For projects with a traditional duration of more than 450 days, the A+B method should always be chosen.

These results are consistent with some SHA's already in use guidelines; such as: Utah and Ohio (Anderson and Damnjanovic 2008), which demonstrates the accuracy and applicability of the developed time/cost trade-off models for the I/D and A+B contracting methods.

Furthermore, figure (5-8) shows the results for the different categories of project DRUCs.

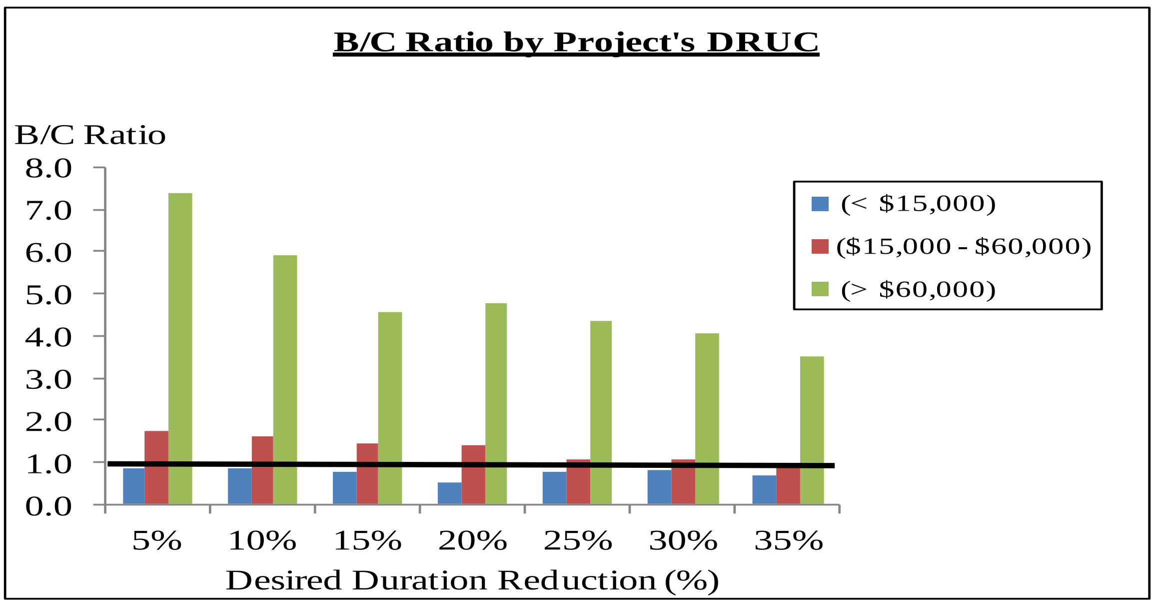

Figure 5-8: B/C ratio by project's DRUC

As seen from the above figure, the following conclusions can be drawn:

1- The A+B contracting method is the most suitable method for projects with low DRUC, less than $15,000.

2- The I/D contracting method is the most suitable method for projects with high DRUC, more than $15,000

These results conform with some research studies and SHA's already in use guidelines; such as: Michigan and Pennsylvania (Anderson and Damnjanovic 2008, Jaraiedi et al. 1995, Dutta and Patel 2012, PaDOT 2013), which demonstrates the accuracy and applicability of the developed time/cost trade-off models for the I/D and A+B contracting methods.

Finally, figure (5-9) shows the results for the different categories of project traditional costs.

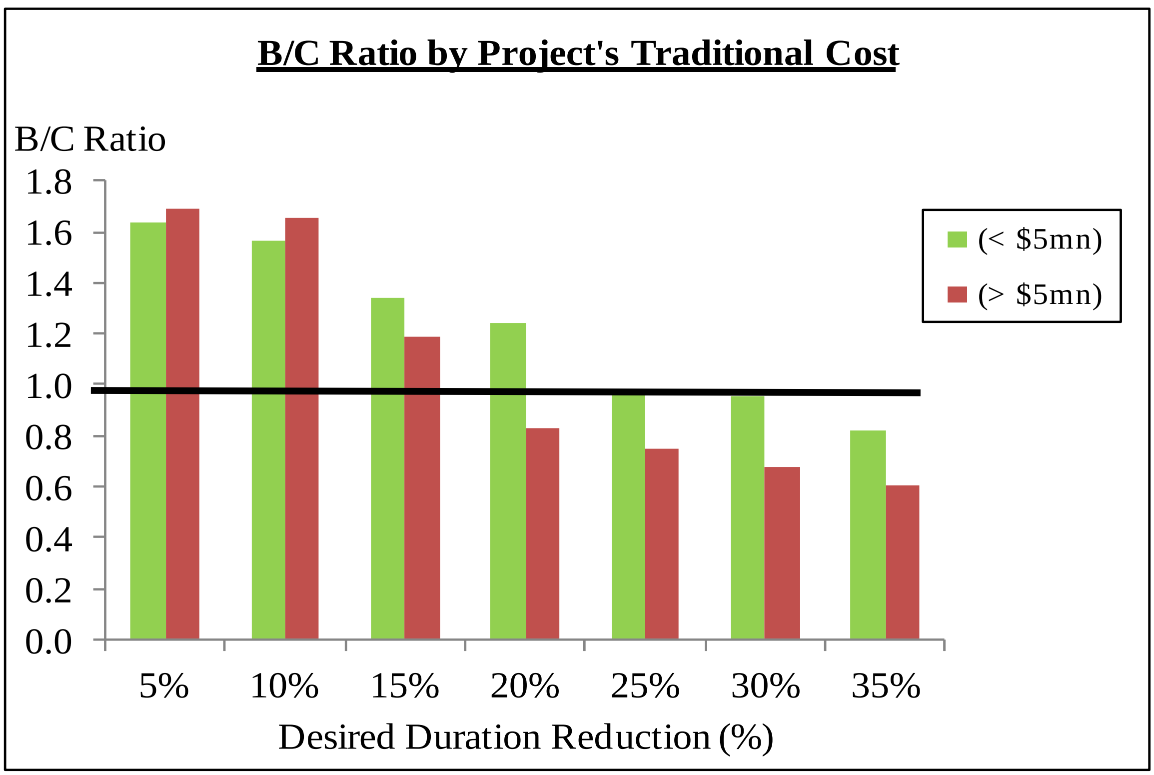

Figure 5-9: B/C ratio by project's traditional cost

As seen from the above figure, the following conclusions can be drawn:

1- For projects with a low traditional cost, less than $5 million, the I/D method should be chosen by the SHA if the desired duration reduction is less than 20%; otherwise, the A+B method should be chosen.

2- For projects with a high traditional cost, more than $5 million, the I/D method should be chosen by the SHA if the desired duration reduction is less than 15%; otherwise, the A+B method should be chosen.

These results are in-line with some SHA's already in use guidelines; such as: Utah and Pennsylvania (UDOT 2011, PaDOT 2013), which demonstrates the accuracy and applicability of the developed time/cost trade-off models for the I/D and A+B contracting methods.

5.4.2.4. Sensitivity Analysis:

Since the risk associated with the A+B contracting method might change from location to another, a sensitivity analysis was conducted to examine the impact of the change in this risk on the decision of selecting the most suitable alternative contracting method. This hypothesis was tested on projects from category 2 of the engineer's duration estimate and the results are shown in figure 5-10.

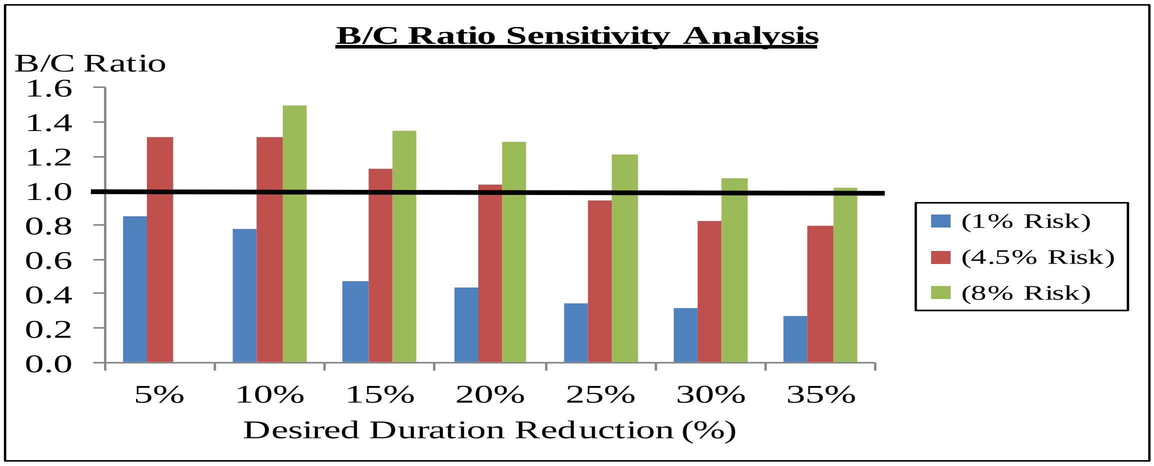

Figure 5-10: B/C ratio sensitivity analysis

From the figure above, it is noted that the risk value associated with the A+B contracting method has a direct impact on the B/C ratio of the projects and; hence, an impact on the decision regarding the best alternative contracting method to be used. For example, if the risk value is towards the lower end of the range (1%), the A+B contracting method will be the better method across the board of all duration reductions; however, if the risk value is towards the higher end of the range (8%), the I/D contracting method will be the better method across all of the desired duration reductions. Therefore, when choosing the best alternative contracting method for their projects, SHAs need to apply the value of the risk that best reflects the conditions in their markets in order to reach an accurate decision. Another type of sensitivity analysis that can be performed is the one concerned with how the SHAs view the worth of each DRUC dollar versus the construction cost dollar. In the above analysis, it was assumed that the SHAs view these dollar values as equal; i.e. a ratio of 1:1; however, in some instances the value of the DRUC dollar might be lower since it is not actual money spent. In that case, and as depicted by the grey line in figure (5-6), the B/C ratio for each contracting method will be lower and in some cases the benefit might be less than the additional cost which, in that particular case, will favor the use of the traditional contracting method over both the I/D and A+B methods.

5.4.3. Probability of Achieving the Duration Reductions:

If the probability of achieving the desired durations' reductions is the most-important decision parameter for the SHA, then they can utilize the risk analysis modules of the two models to compare the two methods and select the most-suitable one. To demonstrate the above analysis, the following two examples are applied (table 5-8):

Table 5-8. Difference in Probability of Occurrence for Certain Duration Reduction Intervals

Project	**Duration reduction Interval**	**Probability of Occurrence (I/D vs. A+B)**
Time Category 3	0% - 2.7%	less by 18.48%
	3.3% - 13.3%	more by 52.46%
	14% - 24%	less by 23.36%
	24.7% - 34.7%	less by 6.88%
Time Category 4	0% - 1.7%	less by 0.85%
	2% - 6.3%	more by 10.51%
	6.7% - 11%	more by 8.74%
	11.3% - 15.7%	less by 0.76%
	16% - 20.3%	less by 6.82%
	20.7% - 25%	less by 1.06%
	25.3% - 30%	less by 0.66%

As seen from the above table, the probability of occurrence for each interval of duration reduction is unique for each project and depends on its initial duration, DRUC, and the number of possible I/D and "B" values that can be assigned to that particular project. Furthermore, the probability fluctuates between the two contracting methods; thus, the SHA needs to examine each desired duration reduction separately against its corresponding NER and B/C ratio in order to be able to select the most suitable alternative contracting method for its particular project depending on the importance and weights it assigns to the different decision parameters that can be extracted from the above three types of analyses.

5.5. Time/Cost Trade-off Model for A+B+I/D Contracting Method

Another popular and relatively new type of alternative contracting methods, which has been adopted by the SHAs, is the A+B+I/D method (Sillars 2007). This method is basically a combination of both the A+B and the I/D contracting methods; hence, with the A+B+I/D method, the contractors bid on both the construction cost and time and after the lowest combined bid is selected by the SHA and its bid time becomes the contract time, an I/D provision is added to the contract to encourage the contractor to further reduce the duration (Anderson and Russell 2001). Due to its aggressive approach towards duration reduction, this method was used and adopted by different SHAs in highly trafficked roads, critical bridges, and emergency routes (Shr et al. 2004). Nonetheless, and similar to the A+B and I/D contracting methods, there were no studies attempting to quantify the parameters of this contracting method from the SHAs' perspectives and help them in their decision making process, as the only available studies focus on the contractors' perspective; for instance, Shr et al. (2004). As a result, and through combining the two time/cost trade-off models developed in this study for the I/D and A+B contracting methods, the time/cost trade-off relationship for the A+B+I/D can be established.

5.5.1. Model Development:

As seen from the definition of the A+B+I/D method, the SHA first applies the A+B contracting method for the bidding process on the project, then after the project is awarded, the I/D method is applied. Hence, the time/cost trade-off relationship for this contracting method can be considered as a two-step process as shown in figure (5-11). First, the SHA starts by applying the A+B trade-off model for the traditional contracting method as explained in chapter 4; then, using the selected "B" value and its corresponding bid cost, the trade-off model for the I/D contracting method will be applied to reach the final duration reduction that can be achieved and its corresponding project cost. Through these two steps, the SHAs can be able to determine the trade-off for the A+B+I/D contracting method at an early project phase. It is worth-noting, that due to the general approach in developing this trade-off model, the A+B model used in the two-step process is the general model that is applicable to all pavement strategies.

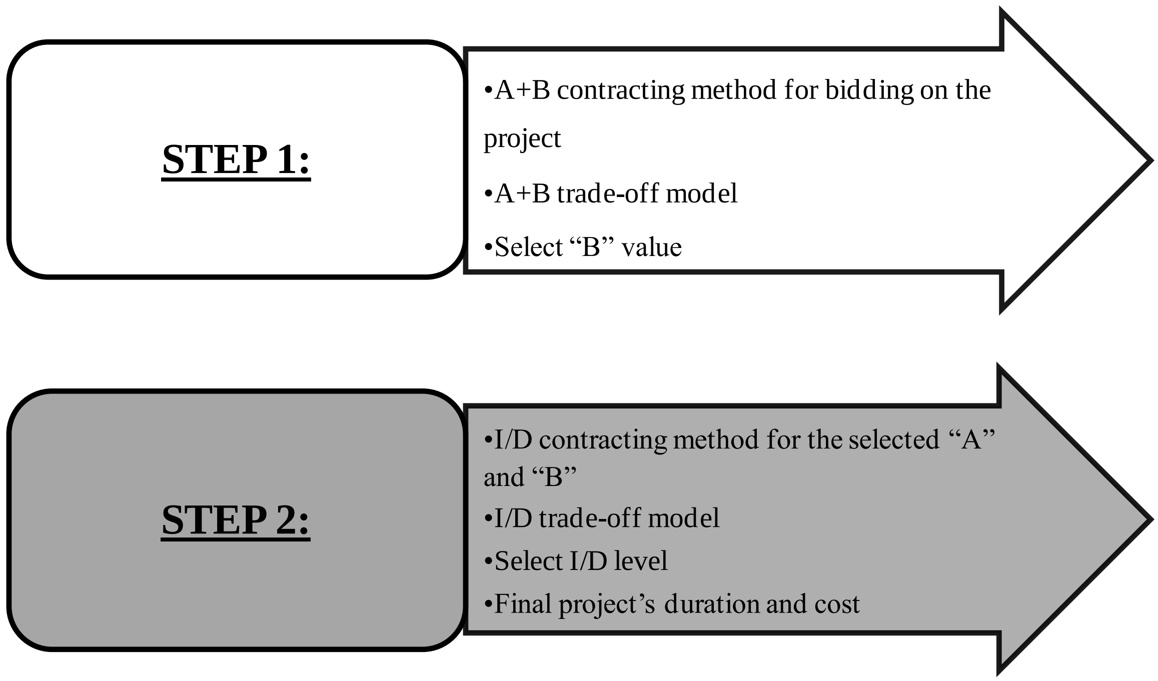

Figure 5-11: Time/cost trade-off relationship steps for A+B+I/D contracting method:

To illustrate this methodology and revisiting figure (4-8), since by using the "B" value module, there can be a number of possible "B" values to be used by the SHA; hence, to reach the final project duration and cost, the I/D trade-off model will have to be applied to every possible point on this graph. However, by using the A+B risk analysis module for each "B" value, the calculation can be simplified and the final time/cost trade-off relationship for the project can be depicted as shown in figure (5-12).

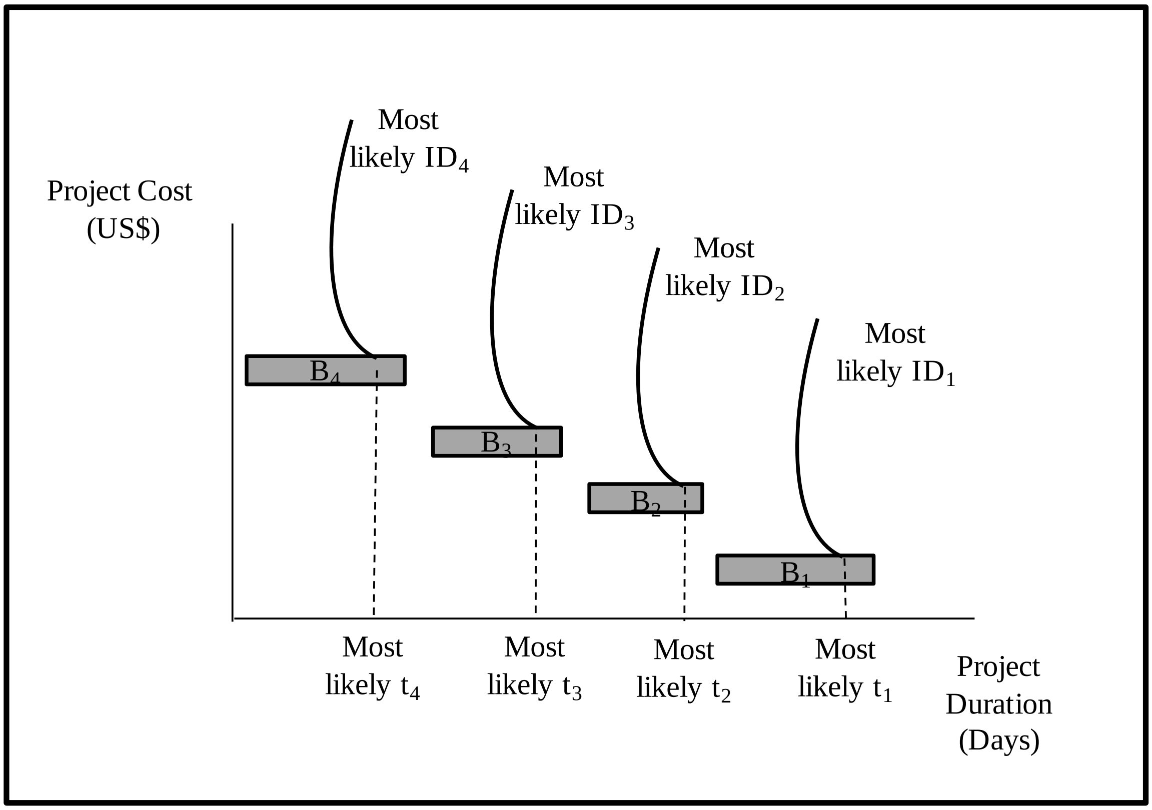

Figure 5-12: Final time/cost trade-off relationship for A+B+I/D contracting method

As seen from the figure, after determining the most-likely duration reduction to be achieved by each “B” value and their corresponding costs, the I/D model will be applied but with the most-likely bid duration as the project initial duration (T), and its corresponding bid cost as the projects initial cost (C). Thus, when using the equations developed in chapter 3 for the ID level module and the owner’s cost module, the variables “T” and “C” will no longer be the engineer’s estimates, but the contractor’s bid-upon duration and cost. After conducting the above steps, the risk analysis module for the I/D contracting method can be applied to determine the most-likely final duration for the project and its corresponding cost.

5.5.2. Model Application:

The application of the A+B+I/D time/cost trade-off model passes through a number of different steps as shown in figure (5-13) and explained below:

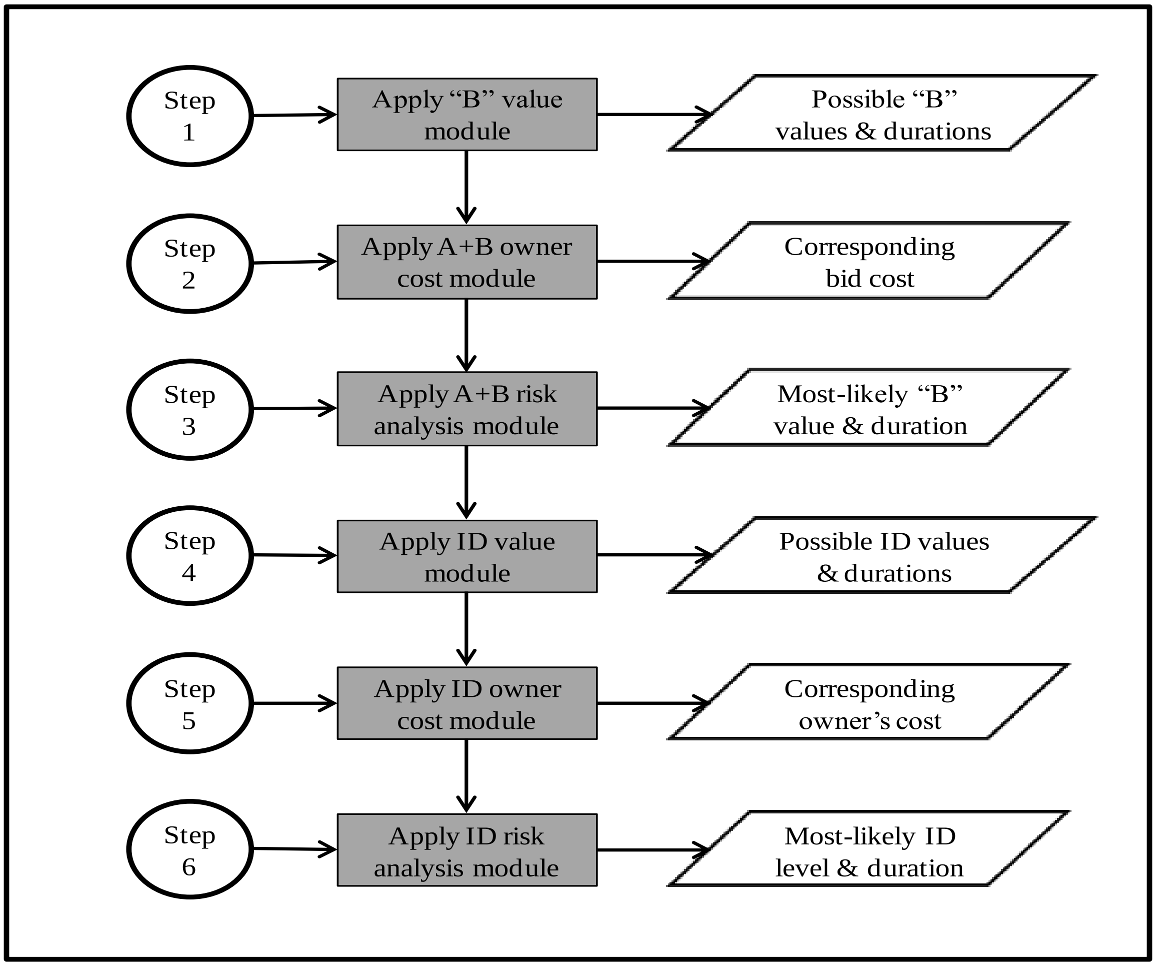

Figure 5-13: Steps of applying time/cost trade-off model for A+B+I/D contracting method

1- Apply the "B" value module and equations (4-12) to (4-20) to calculate the possible "B" values and their corresponding durations.

2- Apply the A+B owner's cost calculation module and equations (4-21) to (4-26) to calculate the corresponding bid cost.

3- Apply the A+B risk analysis module to compute the most-likely duration reduction associated with each "B" value and its corresponding bid cost.

4- For each of the most-likely durations, apply the ID value calculation module and equations (3-7) to (3-15) but with substituting the duration and cost calculated from step 3 for the "T" and "C" values to calculate the possible ID values that can be offered for each selected "B" value.

5- For each of the most-likely durations, apply the I/D model's owner's cost calculation module and equations (3-16) to (3-21) but again with substituting the duration and cost calculated from step 3 for the "T" and "C" values to calculate the associated cost with each duration reduction achieved by the selected ID level.

6- For each "B" value, the stopping criteria will be when ID ≥ DRUC.

7- For some "B" values, the I/D provision cannot be added because the minimum ID level that has to be offered will be greater than the DRUC; therefore, if the SHA wants to implement the A+B+I/D method, then they must chose lower "B" value.

8- Apply the I/D risk analysis module to compute the most-likely ID level and the most-likely duration reduction associated with each ID level and its corresponding owner's cost.

When applying the following steps to the I-15 Devore project, and using the results from chapter 4 with the most likely "B" value of 55% of DRUC and most likely duration of 157 days with a cost of $23.8 million, the minimum ID level that can be offered for that project will be 78% of the DRUC while the maximum will be 97% of DRUC as no more reduction can be achieved. Moreover, applying the I/D risk analysis module, the most likely ID level to be achieved for the "B" value of 55% is the 81% of DRUC (figure 5-

14) which leads to a time reduction ranging from 8.3% to 10.8% of the "B" value's most likely bid duration and 28.4% to 30.3% of the original project's duration under the traditional contracting method. In addition, by applying the I/D risk analysis module to the 81% ID level, it was concluded that a duration reduction of 0.7% of the maximum duration for the 81% ID level under the 55% "B" value, which is equivalent to a 8.9% duration reduction from the bid time and 28.9% duration reduction from the original project's duration under the traditional contracting method i.e. 143 days, is the most likely duration reduction that can be achieved by the contractor using the 55% "B" value in an A+B+I/D contract. Furthermore, the highest "B" value that the SHA can use for this project is the 59% of the DRUC as any higher "B" will lead to an ID level greater than the DRUC.

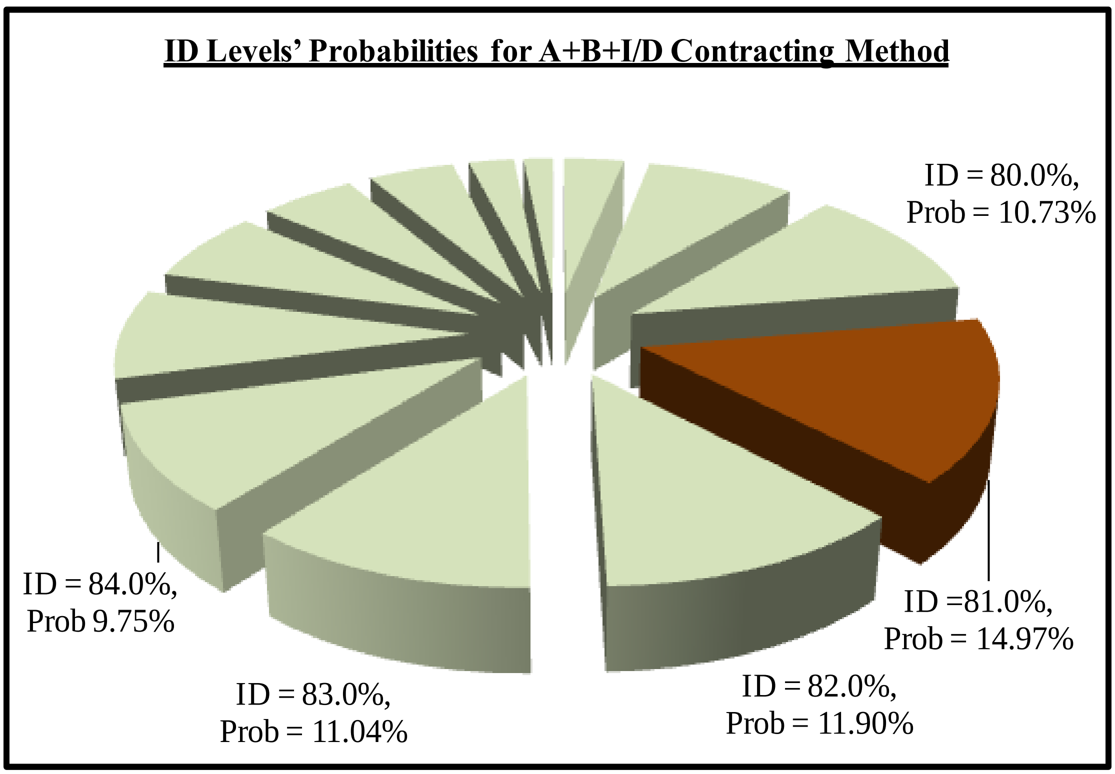

Figure 5-14: Most likely ID level for the 55% "B" value

5.6. Conclusion

This chapter presented how the use of the two developed models in chapters 3 and 4 can help SHAs in enhancing their alternative contracting decision making process in a number of different ways. First the chapter illustrated how each model can be used separately to greatly enhance the SHAs' current decision making practices with respect to each corresponding contracting method. With regards to the use of the I/D model, SHA's can now: 1) set the maximum ID value for a project; 2) determine the most suitable ID level to be assigned based on a certain desired level of duration reduction; 3) identify the minimum ID level that can be offered for a given pavement rehabilitation project and decide if it falls within the SHA's guidelines; 4) know the cost that the SHA will incur with each duration reduction; and 5) find out the probabilities of achieving each desired duration reduction. Considering the use of the A+B model, SHAs can: 1) assign the "B" value based on the desired duration reduction; 2) identify the expected and maximum duration reductions that the contractor can bid on before the bid submission phase; 3) identifying the unbalanced bids submitted by the contractors; 4) know the cost that the SHA will incur with each duration reduction; and 5) find out the probabilities of achieving each desired duration reduction.

In addition, the chapter discussed how the SHAs can select the best alternative contracting method for their project using the developed models and deduced solid quantitative conclusions regarding the choice between the I/D and A+B contracting methods given different project characteristics and SHAs' decision variables. Finally, the chapter demonstrated the usefulness of the developed models by developing a time/cost trade-off model for the A+B+I/D method through combining the two models together.

CHAPTER 6

CONCLUSIONS

6.1. Conclusions

The research study introduced in this dissertation aimed at enhancing the SHAs' alternative contracting decision making process for highway pavement rehabilitation projects. In order to be able to achieve such a goal, a number of research advances and developments were conducted; these developments include: 1) a time/cost trade-off model for pavement rehabilitation projects contracted through the I/D contracting method; 2) a time/cost trade-off model for pavement rehabilitation projects contracted under the A+B contracting method; and 3) models for enhancing the SHAs' decision making process with regards to the use of the above-two alternative contracting methods. The first of these developments involved developing a time/cost trade-off model for the I/D contracting method in order to be able to determine the relationship between the reduction in the project's duration and the increase in the project's cost resulting from the use of this contracting method. The model was developed by examining the different resource utilization scenarios that the contractor can adopt when constructing a project under the I/D contracting method, calculating the additional direct cost as a result of these resource utilization scenarios, determine the savings in the indirect costs due to the reduction in the project's duration, and deriving a relationship between the duration reduction and the total net cost increase. As a result, the model is capable of defining the time/cost trade-off relationship for the I/D contracting method. Furthermore, the model related the level of the ID that the SHAs have to offer with their desired duration reduction and calculated the cost that the owner will incur as a result of this reduction. Moreover, the probabilities of achieving each ID level together with the probabilities of achieving each duration reduction within each ID level were defined and calculated. As a result, the developed model and all its components provided some breakthroughs with regards to the research and application of the I/D contracting method including: 1) the ability to accurately depict the time/cost trade-off relationship for the pavement rehabilitation projects contracted using the I/D contracting method, 2) the ability to assign the proper ID level based on the desired duration reduction, 3) the ability to calculate the additional cost incurred by the owner as a result of selecting a certain ID level, 4) the ability to determine the most likely level of ID to be achieved for the project, and 5) the ability to precisely determine the duration reduction to be expected from adopting that particular ID level.

The second development achieved in this research study involved developing a time/cost trade-off model for the A+B contracting method in order to be able to determine the relationship between the reduction in the project's duration and the increase in the project's cost resulting from the use of this contracting method. The model was developed by examining the different resource utilization scenarios and work schedules that the contractor can adopt when constructing a project under the A+B contracting method, defining the additional motivation imposed by this type of contracts on the contractors to further reduce the project's duration in order to win the bid, calculating the additional direct cost as a result of these resource utilization scenarios and working hours schedules, defining and estimating the extent of the additional risk that the contractor's assume with this type of contracts and how they account for it in terms of additional cost, determining the savings in the indirect costs due to the reduction in the project duration, and deriving a relationship between the duration reduction and the total net cost increase. As a result, the model is capable of defining the time/cost trade-off relationship for the A+B contracting method; in addition, it was able to relate the value of the "B" component that the SHAs have to set with their desired duration reduction and calculated the cost that they will incur as a result of this reduction. Moreover, the probabilities of achieving each "B" value together with the probabilities of achieving each duration reduction within each "B" value were defined and calculated. As a result, the developed model and all its components showed some distinctive capabilities including: 1) the ability to accurately depict the time/cost trade-off relationship for pavement rehabilitation projects contracted under the A+B contracting method, 2) assign the appropriate "B" value based on the desired duration reduction, 3) the ability to calculate the additional cost incurred by the owner as a result of selecting a certain "B" value, 4) the ability to determine the most likely value of the "B" component to be achieved for the project, and 5) the ability to precisely determine the duration reduction to be expected from adopting that particular "B" value.

Finally, the above-two developed models were utilized to develop an enhancement and optimization process with regards to the SHAs' alternative contracting decision making. This process aimed at enhancing the aforementioned decision making process from a number of different aspects; which are: 1) enhancing the SHAs' decision making process with regards to the I/D contracting method to ensure the success of its implementation; 2) improving the SHAs' decision making process with regards to the A+B contracting method so it can fulfill its aimed goals; 3) contrasting the performance, cost and risk associated with each of the two contracting methods through using the developed time/cost trade-off models to assist the SHAs in selecting the most-suitable method for their projects based on their decision variables and the project's characteristics; and 4) combining the two developed time/cost trade-off models to derive the time/cost trade-off relationship for another alternative contracting method which is the A+B+I/D method. Regarding the first aspect, the developed I/D time/cost trade-off model provided the SHAs with a reliable and accurate tool to: 1) set the maximum ID value for a project; 2) determine the most suitable ID level to be assigned based on a certain desired level of duration reduction; 3) identify the minimum ID level that can be offered for a given pavement rehabilitation project and decide if it meets the SHA's guidelines; 4) know the cost that the SHA will incur with each duration reduction before the start of the project; and 5) find out the probabilities of achieving each desired duration reduction; which were not achievable with their current decision-making practices. Second, the developed A+B time/cost trade-off model provided the SHAs with a reliable and accurate tool to: 1) assign the "B" value based on the desired duration reduction; 2) identify the expected and maximum duration reductions that the contractor can bid on i.e. have a firm idea about the project's final duration before the bid submission phase; 3) help in identifying the unbalanced bids submitted by the contractors; 4) know the cost that the SHA will incur with each duration reduction; and 5) find out the probabilities of achieving each desired duration reduction; which their current decision making practices cannot help with. Third, the process of choosing the best ACM for their pavement rehabilitation project, which was primarily based on experience and non-distinctive qualitative measures, can now be performed in a much more quantitative way by contrasting the two developed trade-off models. This process helps the SHA in choosing the best ACM for their project based on their decision variables and the project's characteristics which personalizes the decision for each specific project. Finally, through combining the two-developed models, the time/cost trade-off relationship for one of the most newly popular ACMs, which is the A+B+I/D, can be defined. The SHA starts by applying the A+B trade-off model for the traditional contracting method; then, using the selected "B" value and its corresponding bid cost, the trade-off model for the I/D contracting method will be applied to reach the final duration reduction that can be achieved and its corresponding project cost. Through these two steps, the SHAs can be able to determine the trade-off for the A+B+I/D at an early project phase and enhance their decision making process.

The above-mentioned research advances improve the current practices of the highway pavement rehabilitation projects contracted under the alternative contracting methods and can help in: 1) reducing the negative impacts of the pavement rehabilitation projects on the traveling public; 2) ensuring the success of the implementation of the I/D and A+B contracting methods; 3) enhancing the SHAs' decision making with regards to the adoption of the alternative contracting methods; and 4) helping in preserving the SHAs' limited budgets and protecting the public's money. Consequently, the above impacts are anticipated to provide major benefits to the society, the SHAs, and the overall economy.

6.2. Research Contributions:

The developed research study contributes tremendously to the current alternative contracting and highway rehabilitation body of knowledge; these contributions include:

1- Capturing the different ways by which the adoption of the I/D contracting method impacts the time and cost of a pavement rehabilitation project. This was achieved through developing an inclusive time/cost trade-off model for the I/D contracting method; as well as, a novel model that can relate the level of the ID to be assigned with the desired level of duration reduction, calculate the expected final cost that the SHA will incur and the most-likely duration reduction that can be achieved within each ID level.

2- Identifying the unique ways by which the adoption of the A+B contracting method impacts the time and cost of a pavement rehabilitation project and the contractor's motivation which was accomplished by formulating a comprehensive time/cost trade-off model for the A+B contracting method. In addition, the relationship between the "B" value to be allocated to the project's duration and the desired level of duration reduction was quantified through the development of an original model that also has the capabilities of calculating the expected final cost that the contractor will bid on at an early planning stage and determining the most-likely "B" value to be achieved and the most-likely duration reduction that can be achieved within each "B" value.

3- Enhancing the decision making process for each of the two alternative contracting methods, I/D and A+B, by providing the SHAs' with the ability of determining the most critical factors that impact the success of these methods in an accurate manner.

4- Enhancing the selection of the most suitable alternative contracting method to be used for a particular pavement rehabilitation project by taking into consideration the SHAs' decision variables and the project's unique characteristics.

5- Devising a two-step time/cost trade-off relationship for the A+B+I/D contracting method that fully captures the complicated nature of this newly adopted alternative contracting method.

6.3. Recommendation for Future Research

The presented research study introduced new highway pavement rehabilitation time/cost trade-off models for the two most popular types of alternative contracting methods, the I/D and A+B methods. Although these models present a breakthrough in the alternative contracting research and are effective tools in enhancing the SHAs' alternative contracting decision making process, a number of future research opportunities are available to further enhance and improve this process. These opportunities include, but not limited to: 1) developing time/cost trade-off models for other popular types of alternative contracting methods; such as: lane rental and warranties; 2) expanding the models developed in this study to cover other types of highway maintenance and rehabilitation projects; 3) improving the accuracy of the models by linking them to the available tools used to calculate the different input values; and 4) introducing more decision variables and including more project characteristics to the process of selecting the alternative contracting methods.

6.3.1. *Develop Models for Other Types of ACMs:*

In this study, time/cost trade-off models were developed for the I/D and A+B contracting methods and later for the A+B+I/D method; however, there are other frequently used types of ACMs, each with their unique characteristics, including: lane rental, warranties, interim completion date, and no-excuse incentives (Anderson and Damnjanovic 2008). Therefore, the above-developed models do not apply to these types of ACMs and new type-specific models need to be developed that account for: 1) the impact of each method on the project's duration, and 2) the impact of each method on the project cost.

6.3.2. *Include Other Types of Highway Maintenance Projects and Other Construction Methods:*

There are a number of different highway maintenance and rehabilitation projects depending on either: the type of work done or the component of the system that requires maintenance; for instance, 25.9% of the total bridges in the United States are either considered structurally deficient or functionally obsolete; hence, requiring significant maintenance & repair works (DOT 2013). Nevertheless, these different project types differ from each other in terms of the resources used and the sequence of work which impacts the time/cost trade-off relationship even when using the same contracting method. Therefore, future research opportunities are present in this area and can build on the developed models in one of two ways:

1- Develop more individual models for the different types of works or different highway system's elements.

2- Expand the current model to be applicable for more than one project type or more highway system element.

Furthermore, the methodology used to develop the models in this study can be used to develop models for other construction methods such as: accelerated bridge construction (ABC); however, the success of developing such models depends on the availability of real-life projects' data and tools to simulate the construction schedule under these methods similar to the CA4PRS software.

6.3.3. *Linking the Developed Models to Different Tools Used to Calculate the Inputs:*

Since the developed models depend on certain types of inputs; namely, engineer's traditional time and cost estimates, and the DRUC; hence, improving the accuracy of these inputs will, in return, improve the accuracy of the developed models. However, there are already different types of tools available to the SHAs to calculate these parameters; thus, linking these tools to the developed models to calculate the whole set of the different project parameters together will help enhancing the accuracy of the final models' outcomes.

6.3.4. *Introduce More Decision Variables and/or Project Characteristics to the Selection Process:*

Some SHAs might have additional decision criteria that they take into consideration when deciding on the contracting method that they want to use for their projects; these variables can include, but not limited to: quality and safety (El-Gafy 2014). Moreover, each project has its own unique characteristics, whether physical or non-physical. Nevertheless, when improving the decision making process in this study, only time, cost, and risks were taken into consideration; in addition, to the project's non-physical characteristics. Hence, future models that are capable of including these variables and characteristics which are not covered by this study will prove beneficial for the SHAs and improve their alternative contracting decision making process.

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