Technical Report Documentation Page

1. Report No. FHWA/TX-94/1310-1F	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle COMPARISON OF CONTRACTING STRATEGIES FOR REDUCING PROJECT CONSTRUCTION TIME		5. Report Date March 1994 6. Performing Organization Code
7. Author(s) William F. McFarland, Richard J. Kabat, and Raymond A. Krammes		8. Performing Organization Report No. Research Report 1310-1F
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135		10. Work Unit No. (TRAIS) 11. Contract or Grant No. Study No. 0-1310
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Transfer Office P. O. Box 5080 Austin, Texas 78763-5080		13. Type of Report and Period Covered Final: September 1991 - August 1993 14. Sponsoring Agency Code

15. Supplementary Notes

Research performed in cooperation with the Texas Department of Transportation and the U.S. Department of Transportation, Federal Highway Administration.
Research Study Title: New Evaluations of Liquidated Damages, Motorist Liquidated Damages, and Percent Retainage

16. Abstract

The objectives of this study were: to develop criteria for evaluating alternative contracting strategies and make comparisons of the advantages and disadvantages of these strategies for different types of projects and situations; to evaluate ongoing and completed projects that use alternative bidding strategies and high liquidated damages based partially on user costs, and other alternatives for reducing project completion times; to evaluate techniques for estimating user costs during construction for different types of projects and situations. The HEEM-III and QUEWZ computer programs were used to estimate motorist costs for use in liquidated damages and for costs of lane closure. These programs were used to estimate user costs for a variety of added-capacity construction projects. Since funds are limited for construction projects, it is recommended that only 25 percent of calculated user costs be used in liquidated damages. Case studies emphasized Texas incentive/disincentive projects and other large, urban projects with emphasis on A+B bidding and use of a special CPM provision where contractors are not paid progress payments unless they meet contract provisions. In A+B bidding, contractors bid not only construction cost but also contract completion time, and both are considered in awarding the contract. At this time, it is recommended that incentive/disincentive provisions, with or without A+B bidding, should *not* be used routinely in Texas. They should be reserved for special cases of great urgency, of relatively short duration, with a clean set of plans, and with little chance of field changes. For all projects, but especially for large projects with heavy traffic in urban areas, liquidated damages *should include user costs*; so should incentives/disincentives. It is recommended that CPM scheduling and monitoring be used on large, critical projects. It is also recommended that A+B bidding be tried on a limited basis as experimental projects, when stated conditions are met and when there is a need to reduce project completion time.

17. Key Words Project Construction Time, Contracting Strategies, Liquidated Damages, A+B Contracts, Incentive Contracts, Bonus Payments, User Costs, Contract Time, Time-cost Bidding		18. Distribution Statement No restrictions. This document is available to the public through NTIS: National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161	
19. Security Classif.(of this report) Unclassified	20. Security Classif.(of this page) Unclassified	21. No. of Pages 83	22. Price

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

COMPARISON OF CONTRACTING STRATEGIES FOR REDUCING PROJECT CONSTRUCTION TIME

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Research Report 1310-1F
Research Study Number 0-1310
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Sponsored by the
Texas Department of Transportation
In Cooperation with
U.S. Department of Transportation
Federal Highway Administration

March 1994

TEXAS TRANSPORTATION INSTITUTE
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IMPLEMENTATION STATEMENT

The ultimate objective of this research is to assist in the evaluation of strategies that lead to optimal completion of highway projects. One of the Department's primary goals is to construct highways at the least total cost, including highway construction costs, costs to motorists during construction, costs to abutting businesses, and construction engineering costs. Completion of highway projects in an optimal time is increasingly important as more and more highways are reconstructed with high traffic volumes. The results of this study should assist Department decision makers in developing the optimal policies that will be most optimal in reaching Department goals for reducing highway and user costs. Better-documented liquidated damage rates should also be more defensible in court and this could lead to a reduction in costs of litigation.

Recommended Computer Programs and User Costs for Liquidated Damages

Procedures and computer programs for estimating motorist and Department costs were evaluated to determine the preferred method of developing recommended schedules of liquidated damages for different types and sizes of highway projects. These results can be used by the design division staff to develop more accurate estimates of motorist liquidated damages and will give more precise estimates of expected cost savings for different types of projects. Research results also provide guidelines that assist in clarifying the situations in which user costs can be used in incentive/disincentive contracts and other types of contracts, and this can be used to develop or defend Department policy on these types of contracts.

On the basis of the user cost evaluation, the following computer programs are recommended for estimating motorist costs for motorist liquidated damages and lane rental fees:

> HEEM-III is recommended as the computer program for estimating motorist costs for motorist liquidated damages. It is recommended that HEEM-III replace HEEM-II for this purpose, because HEEM-III performs more detailed analyses of motorist costs, permits explicit specification of traffic-handling capacities during and after a highway project, and can evaluate a greater variety of highway projects.
>
> QUEWZ-92 is recommended as the computer program for estimating hourly lane rental fees. QUEWZ-92 was designed explicitly for evaluating freeway work zone lane closures. QUEWZ-92 permits more detailed specification of lane closure configurations (direction and number of lanes closed), and schedules and provides more detailed simulation of traffic flows and estimation of motorist costs than either HEEM-III or HEEM-II. Only QUEWZ-92 provides hourly estimates of additional motorist costs.

Several tables were developed for different types of traffic handling situations in construction zones. It is recommended that about *25 percent* of these table values be used in liquidated damages and for lane closure costs.

Contracting Strategies

The contracting techniques studied fall into the two traditional "carrot and stick" categories; that is, paying a financial reward for the contractor able to complete a project ahead of a stated schedule, and penalizing a contractor who fails to meet a schedule. The case studies and previous discussions identify several contract provisions in both categories. When choosing a specific contracting strategy, each project must be viewed on its own; however, the data and experiences gathered in this study provide several suggestions, as discussed below.

No single contracting provision assures that a given contractor will complete an urgent project as fast as the contracting agency desires. For that matter, no combination of techniques can guarantee that end. But, by selecting a blend of contract provisions tailored to a specific project, rather than having a blanket policy for all projects, the odds of getting on-time project completions are greatly improved.

There is one major proviso. To meet a tight project schedule, the contractor will have to work more than one shift and use a six or seven day week. Then, the contracting agency must have a sufficient number of qualified, trained engineering/inspection personnel on hand to assure specification compliance without overworking such personnel. And headquarters personnel must be available to support the field personnel.

Contracts with A+B bidding are those where contractors bid not only the construction but also bid a project completion time. Based on the findings of this study, it is recommended that incentive/disincentive provisions, with or without A+B bidding, should *not* be used routinely in Texas at this time. They should be reserved for special cases of great urgency; of short duration; with a clean set of plans; and with little chance of field changes.

For the type of project discussed in this study liquidated damages *should include user costs*; so should incentives/disincentives. A+B bidding is a technique that does *not* have to be tied to I/D provisions. For example, there appears to be no impediment to using A+B bidding along with a CPM specification. Another alternative would be to simply use A+B bidding with increased liquidated damages with no use of an incentive bonus for early completion; this approach would use the number of days bid and the daily liquidated damages rate to calculate the "B" part of the bid.

The CPM specification that has been employed by some TxDOT Districts should be used more often, especially on large projects. As used in Texas, this CPM provision requires a contractor to submit a detailed critical path schedule for approval, and then to adhere to it. Regular meetings between the contractor and TxDOT scheduling personnel are required, along with continual monitoring of actual progress as compared with the approved CPM schedule. If the contractor falls behind the approved schedule, he must submit a new schedule showing how he will catch up. Failure to do so results in withholding of progress payments. The success of the four concurrent, abutting projects on the Southwest Freeway in Houston, constructed around 1989-93, amply demonstrates its effectiveness, even on complex, interrelated projects.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Texas Department of Transportation (TxDOT) or the Federal Highway Administration (FHWA). This report does not constitute a standard, specification, or regulation.

ACKNOWLEDGMENT

The authors are indebted to several employees of the Texas Department of Transportation (TxDOT): Howard Johnson, formerly of the Highway Design Division; Doug Dillon, formerly of the Dallas district, and Glenn Bohannon of the Abilene district for their assistance throughout this project as the technical committee for TxDOT. They are especially indebted to Mr. Johnson, Advisory Panel Chairman, for his assistance in providing background information on contracting procedures used in Texas and to Mr. Dillon not only for sharing his knowledge about contracting but also for assisting with collection of information for the case studies. They also are indebted to many other individuals in the district offices of TxDOT, especially in the Houston, Dallas, Fort Worth, and Austin districts, who provided information for case study projects. In addition, numerous individuals in other states and in the Federal Highway Administration, U.S. Department of Transportation, provided information on innovative contracting procedures in other states. The Texas Transportation Institute staff that assisted with this project included Jeff Memmott, Margaret Chui, and Linda Buzzingham.

TABLE OF CONTENTS

Page

LIST OF TABLES . . . xiii

LIST OF FIGURES . . . xiv

SUMMARY . . . xv

Use of A+B Bidding and CPM Techniques . . . xv
Bidding Contract Days with Liquidated Damages Only . . . xvi
Computer Programs for Calculating User Costs . . . xvii
Amount of User Cost to Include in Liquidated Damages . . . xviii

I. INTRODUCTION . . . 1

Reason for the Study . . . 1
Current Practices in Texas . . . 1
Study Objectives . . . 2

II. ALTERNATIVE CONTRACTING STRATEGIES . . . 3

Contract Duration and Contract Types . . . 3
Conventional Low-Bid Contracts . . . 4
Use of Incentive/Disincentive Contracts . . . 5
Time-Cost (A+B) Bidding . . . 5

III. CRITERIA FOR COMPARING CONTRACTING STRATEGIES . . . 9

General Discussion of Criteria . . . 9
- Economic Efficiency . . . 9
- Effects on Department Personnel and Costs . . . 9
- Administrative Ease . . . 9
- Legal/Policy Issues . . . 9
- Acceptability . . . 11
- Applicability . . . 11

Total Cost Model . . . 11
- Current Procedures . . . 13
- Procedures Using a Bonus . . . 14
- Bidding Contract Days . . . 17
- Bidding Contract Days with Liquidated Damages Only . . . 19
- Qualifications to Above Findings . . . 20
- Amount of User Cost to Include in Liquidated Damages . . . 20

CHAPTER IV. ESTIMATION OF MOTORIST COSTS FOR LIQUIDATED DAMAGES 23

Use of the HEEM Programs for Estimating Motorist Costs 23
Other Programs for Estimating Motorist Costs 26
Recommended Programs for Calculating Motorist Costs 28
Estimated Additional Motorist Costs 31
Motorist Costs for Liquidated Damages 32
Motorist Costs for Lane Rental Fees 41
Qualification on Use of Motorist Costs 42

CHAPTER V. CASE STUDIES 49

Definitions 49
Project Selection 49
Findings 52
Conclusions 56
Recommendations 58

REFERENCES 61

LIST OF TABLES

Table | Page

1. Example of Time-Cost (or A+B) Bidding 6

2. Summary of Features of HEEM-II, HEEM-III, and QUEWZ-92 30

3. Assumed Conditions for Estimating Additional Motorist Costs for Motorist Liquidated Damages Using HEEM-III 33

4. Additional Daily Motorist Costs Due to the Delayed Completion of a Rural Project from a 2-Lane Undivided Highway to a 4-Lane Divided Highway 34

5. Additional Daily Motorist Costs Due to the Delayed Completion of a Rural Project from a 4-Lane Undivided Highway to a 4-Lane Divided Highway 34

6. Additional Daily Motorist Costs Due to the Delayed Completion of a Rural Project from a 4-Lane Freeway to a 6-Lane Freeway 35

7. Additional Daily Motorist Costs Due to the Delayed Completion of an Urban Project from a 4-Lane Undivided Highway to a 4-Lane Divided Highway 37

8. Additional Daily Motorist Costs Due to the Delayed Completion of an Urban Project from a 4-Lane Divided Highway to a 6-Lane Divided Highway 38

9. Additional Daily Motorist Costs Due to the Delayed Completion of an Urban Project from a 4-Lane Freeway to a 6-Lane Freeway 39

10. Additional Daily Motorist Costs Due to the Delayed Completion of an Urban Project from a 6-Lane Freeway to an 8-Lane Freeway 40

11. Example of Hourly Lane Rental Fees Presented by Gaj 41

12. Additional Hourly Motorist Costs Due to the Closure of 1 Lane in 1 Direction of a 4-Lane Freeway 43

13. Additional Hourly Motorist Costs Due to the Closure of 1 Lane in 1 Direction of a 6-Lane Freeway 44

14. Additional Hourly Motorist Costs Due to the Closure of 2 Lanes in 1 Direction of a 6-Lane Freeway 45

15. Additional Hourly Motorist Costs Due to the Closure of 1 Lane in 1 Direction of an 8-Lane Freeway 46

16. Additional Hourly Motorist Costs Due to the Closure of 2 Lanes in 1 Direction of an 8-Lane Freeway 47

17. Additional Hourly Motorist Costs Due to the Closure of 3 Lanes in 1 Direction of an 8-Lane Freeway 48

18. List of Texas Case Studies 51

19. Summary, Contract Time 53

20. Case Study, Cost Comparisons 54

21. Case Study, Duration-Cost Comparisons 55

22. Summary of A+B Incentive/Disincentive Projects 57

LIST OF FIGURES

Figure | Page

1. Criteria for Comparing Alternative Contracting Strategies 10

2. Costs by Type Related to Contract Days 12

3. Marginal Costs Related to Contract Days Completed Early 15

4. Costs and Bonus Related to Contract Days 18

SUMMARY

The objectives of this study were: to develop criteria for evaluating alternative contracting strategies and make comparisons of the advantages and disadvantages of these strategies for different types of projects and situations; to evaluate ongoing and completed projects that use alternative bidding strategies, percent retainage provisions, high liquidated damages based partially on user costs, and other alternatives for reducing project completion times; and to evaluate techniques for estimating user costs during construction for different types of projects and situations. The HEEM-III and QUEWZ computer programs were used to estimate motorist costs for use in liquidated damages and for costs of lane closure. Texas incentive/disincentive projects and comparison projects were compared to assist in evaluating time-cost bidding, commonly called A+B bidding, and use of increased liquidated damages.

Several case study projects were used to develop information for comparing contracting strategies. These emphasize major projects on heavily traveled highways in urban areas of Texas and employ contract provisions designed to shorten contract duration. In both the Houston and Dallas areas, there were a series of contiguous projects along a given highway that met the criteria for case study projects. Along US 75 and IH 45, differing contract provisions were used on these projects. Along US 59, the Southwest Freeway in Houston, four individual projects used the same techniques - but with inter-project coordination required. These three series of projects were selected because each took place within the same general time frame, each carried the same general range of traffic, and each required the same type of construction.

Use of A+B Bidding and CPM Techniques

Since World War II, techniques such as PERT and CPM have been widely used to schedule project elements and estimate project duration. But their use was hampered by the effort needed for rigorous application. In the 1980s, two advances took place: (1) development of moderately-priced, readily-learned, computer software capable of handling CPM scheduling and monitoring on major highway projects; and (2) development of moderately-priced personal computers with multi-megabyte random-access memories (RAM) and hard-discs capable of storing hundreds of megabytes, as well as peripheral equipment appropriate to the task. These developments have made use of CPM analyses for both project planning and construction viable. With adequate training, more widespread use by TxDOT can benefit the taxpayer.

The contracting techniques studied fall into the two traditional *carrot and stick* categories: a financial reward for the contractor able to complete a project ahead of a stated schedule, and penalizing a contractor who fails to meet a schedule. Contracts with A+B bidding are those where contractors bid not only the construction but also bid a project completion time. The CPM specification that has been employed by some TxDOT Districts

should be used more often, especially on large projects. As used in Texas, this CPM provision requires a contractor to submit a detailed critical path schedule for approval, and then to adhere to it. Regular meetings between the contractor and TxDOT scheduling personnel are required, along with continual monitoring of actual progress as compared with the approved CPM schedule. If the contractor falls behind the approved schedule, he must submit a new schedule showing how he will catch up. Failure to do so results in withholding of progress payments.

The case studies and previous discussions identify several contract provisions in both categories. Based on a study of these projects it is concluded that one specific strategy cannot be recommended for all projects; each project must be viewed on its own. With the exception of two of the three standard projects, the other case studies finished on time or earlier. On all of the incentive contracts where the contractor bid the contract time, i.e., A+B bidding, the contractors carried the maximum bonus allowed. The CPM provision used on the four Southwest Freeway projects ended with a substantially "on-time, under-budget" result. TxDOT/METRO staff estimate that use of CPM reduced overall combined project duration from five years to three years. Where A+B bidding was employed, in only one of seven cases was the low bidder determined by the time-bid.

The data and experiences gathered in the case studies suggested several recommendations. Regardless of the type of contract provision used, computation of working time is critical. More training in estimating time, including use of CPM techniques, should be employed--with feedback from field personnel. Whatever technique is used to minimize project duration, *TxDOT must provide enough trained field personnel* to match the effort the contractor is required to exert to meet the project schedule. If the project is urgent enough to warrant an accelerating technique, then it also warrants TxDOT's provision of commensurate resources. This applies not only to project staff but also to district and headquarters personnel.

The major recommendations on incentive/disincentive provisions are that these contracts, with or without A+B bidding, should *not* be used routinely in Texas at this time and that the CPM specification that has been employed by some TxDOT Districts should be used more often on major projects. There are many other contract provisions/techniques applicable to construction contracts, e.g. pre-qualification restrictions, partnering, and end-result specifications. However, while they may help expedite progress, avoid problems and improve quality, their basic intent is not to shorten project duration.

Bidding Contract Days with Liquidated Damages Only

An interesting strategy that to the best of our knowldge has not been tried to date is to have the contractor bid contract completion days as in the preceding strategy and to not pay a bonus for early completion, but to charge liquidated damages for any overrun past the number of days that he bids. However, the low bid would be determined by multiplying the number of days that he bids by the liquidated damages rate and adding this to his construction cost bid.

One advantage of the strategy of having the contractor bid working days but not paying bonuses is that it approximates the bonus-strategy solution without the possible negative publicity of paying bonuses. Also, if liquidated damages are set correctly, a considerable saving in combined motorist costs and Department costs should result. Another advantage is that the Department does not have to estimate working days, since these are bid by the contractor. Of course, the Department could continue to stipulate a maximum number of working days *and* also have contractors bid working days. This should have no effect on the procedure giving improved results.

The comparison of contracting strategies presented in Chapter III is based on several assumptions, including: (1) a deterministic model is used, as opposed to a stochastic model; (2) it is assumed that there is no collusion among bidders; (3) it is assumed that the curves are drawn for a given policy with respect to work times and rules; and (4) it is assumed that the project is well-defined and that all relevant costs are included in the cost curves that are discussed. The assumptions that are probably most critical are numbers (2) and (4). If there is collusion among bidders, the entire theory may be inapplicable and must be totally replaced with a theory of how firms make decisions and bids if there is collusion. Assuming that there is no collusion, the next critical assumption is that all costs are included and that the project is well defined. This assumption clearly is not always met and there often are major change orders that change both the project definition, its cost, and its construction time. Somewhat related is the possibility of claims and litigation that can change the cost considerably.

Computer Programs for Calculating User Costs

The HEEM-II, HEEM-III, and QUEWZ-92 computer programs were compared in detail. Whereas QUEWZ-92 is restricted to the evaluation of freeway work zone lane closures, HEEM-II and HEEM-III can be used to evaluate a wide range of highway improvements. HEEM-III provides greater flexibility in defining before and after improvement highway conditions and more explicit treatment of intersections and interchanges than HEEM-II. HEEM-III offers the greatest capability for specifying an alternative route and analyzing diverted and induced traffic; the diversion analysis in QUEWZ-92 is based on empirical data on traffic diversion from urban freeways during short-term lane closures. QUEWZ-92 permits the most detailed specification of the direction and duration of lane closures. HEEM-III and QUEWZ-92 provide more detailed hour-by-hour analysis of traffic conditions and motorist costs than HEEM-II which performs its analysis on a daily basis. QUEWZ-92 provides hourly estimates of average speeds and additional motorist costs, whereas HEEM-II and HEEM-III provide daily estimates of average speeds and motorist costs for the during and after highway improvement conditions. The additional motorist costs associated with highway projects have three components:

vehicle operating costs, delay costs, and accident costs. HEEM-II and HEEM-III incorporate all three components into their estimation of motorist costs; QUEWZ-92 considers only vehicle operating and delay costs.

Using these programs, user costs are calculated for a variety of types of construction projects. These user costs are shown in tables in Chapter IV. Tables 4 through 10 show the extra user costs that can be included in liquidated damages, subject to the Departmental limitation in effect at any time. Tables 12 through 17 summarize the user costs that can be considered in setting lane rental charges. Use of these values is subject to the qualification that a maximum of 25 percent of the table values in Tables 5 through 10 and 12 through 17 are recommended for use in liquidated damages or lane rental charges, as discussed below.

Amount of User Cost to Include in Liquidated Damages

If highway funds are not sufficient to fund all projects with benefit-cost ratios greater than one, it is concluded that the marginal return to construction dollars should be considered in determining the proportion of user costs to include in liquidated damages. In Texas, benefit-cost calculations indicate that the marginal return to highway expenditures is over 4 to 1. Because unfunded construction projects are available to give these high returns, scarce construction money should not be used for reducing project completion times except where such reduction also gives high returns. However, it can be argued that the discomfort and inconvenience from traveling through construction zones is probably above average and that the severe congestion that occurs in work zones has a time cost that is twice as high as normal. Given these considerations, it is recommended that 25 percent of the excess motorist costs, calculated using HEEM-III and QUEWZ-92 or taken from the tables in Chapter IV, be included in liquidated damages, incentive/disincentive payments, and lane rental charges.

CHAPTER I. INTRODUCTION

Reason for the Study

Several questions have arisen in the last several years about which process to use to optimize the timely completion of highway projects. Questions have been asked about Incentive/Disincentive (I/D) contracts, special provisions for percent retainage, and other procedures for getting contractors to complete highway projects in less time. Questions also have arisen about the level of liquidated damages that should be used on different projects in different situations. There is a need to make a comprehensive evaluation of various contracting alternatives to determine whether the Department's current process is optimal.

Previous research by the Texas Department of Transportation (TxDOT) indicates that project completion times and total project costs can often be reduced by charging the contractors higher liquidated damages. Accurately estimating liquidated damages for project overruns is becoming increasingly important as motorist costs begin to be included in the liquidated damages schedules. There are several contracting strategies that need to be more fully evaluated.

There is a need for a comprehensive verification of the current process being used by the Department. There is a need to determine what type of contract should be used on different types of projects. There also is a need to look at the rationale for considering user costs in different situations and to determine what needs to be done to optimize the completion of a project. There is a need for research that develops a clear rationale that supports the overall strategy that the Department is currently using.

An evaluation also needs to be made of the procedures used by the Department for estimating user costs associated with highway construction. Emphasis should be placed on whether the procedure is logical and is being applied consistently to all projects. The primary need is for an overall evaluation of alternative, existing approaches and models more than for development of a new or updated model. Updating the model is secondary compared to determining whether it is logical for the different situations encountered. An important question is how the HEEM model can be used for different situations; is it logical to include user costs in liquidated damages only on large projects?

Current Practices in Texas

Policy in Texas has called for using a standard liquidated damages schedule on most highway projects, with the level of liquidated damages depending on the estimated cost of the project. Current policy calls for a higher level of liquidated damages and the liquidated damages schedule is updated annually and receives FHWA concurrence. For some types of projects, a district can recommend use of a higher level of liquidated damages, which can include consideration of user costs. For these projects, a district can estimate user costs and add to this the expected construction engineering cost to obtain a recommended liquidated damages rate. Use of these higher liquidated damage rates requires administrative approval on a project-by-project basis.

The estimates of user costs used in establishing liquidated damages for selected, complex projects are typically developed by the Design Division (D-8) staff using the HEEM-II computer program. However, some districts have developed traffic handling plans and have estimated user costs as related to construction using the HEEM-II and QUEWZ computer programs. Excess user costs during construction also have been estimated by TTI for some SDHPT projects using the FREQ program.

The construction engineering cost estimate used for liquidated damages typically is a function of project type and contract amount and has a maximum of about $3,000 per day on large projects. The highest level of liquidated damages that is allowed is $10,000 per day. For critical projects, it also is possible to use calendar days instead of working days.

The Department has used incentive/disincentive contracts on several projects in the past, but these are not being used at this time. The Fort Worth District used a special provision based on excess percent retainage on some contracts and found that it worked quite well in getting a contractor to stay on schedule.

Study Objectives

This research study has three principal objectives, which are listed below.

1. Develop criteria for evaluating alternative contracting strategies and make comparisons of the advantages and disadvantages of these strategies for different types of projects and situations.

2. Evaluate ongoing and completed projects that use alternative bidding strategies, percent retainage provisions, high liquidated damages based partially on user costs, and other alternatives for reducing project completion times.

3. Evaluate techniques for estimating user costs during construction for different types of projects and situations.

CHAPTER II. ALTERNATIVE CONTRACTING STRATEGIES

Contract Duration and Contract Types

Since the early 1980s, state and federal agencies have researched and experimented with a variety of techniques intended to minimize the duration of transportation construction projects, particularly on heavily traveled highways in urban areas.

The duration of such projects is generally expressed in calendar days rather than the traditional "working day." The working day usually does not count Saturdays, Sundays, holidays, and adverse weather conditions against the contractor's allotted time. In a calendar year, a contractor may be charged only 200 working days.

In most cases, the calculation of calendar days *excludes* Sundays and a few specified holidays. For projects with a greater sense of urgency, the calendar day may be defined as a seven-day week, with or without holidays. In a calendar year, depending on the definition, a contractor would be charged from 307 to 365 calendar days. Currently, based on the literature and interviews, it appears that there is a consensus that requiring, or allowing, a contractor to work 24 hours a day and a seven-day week should not be done except for the most compelling reasons. Such projects should also be of short duration--a few weeks, or perhaps a few months, but usually not more than a year.

Two basic approaches are used. In the first, traditional approach, the contracting agency calculates how much time it will allow the contractor to complete the project. The contractor knows this allowed contract time prior to bidding and knows that he will be charged liquidated damages for running over this time, assuming it is not changed by change orders.

In establishing contract time for use in the traditional approach, state highway agencies have used numerous techniques to calculate the allowed number of days. These techniques have ranged from empiric/intuitive to the most modern computer-generated, critical path method networks. Projection rates have progressed from generalized estimates to careful analysis of specific rates for individual work items, considering weather conditions throughout the year. But, no matter how sophisticated the estimating technique and how well it is employed, the contracting agency is still attempting to out guess the contractor, who may be contemplating a totally different approach to building the project. Moreover, the estimator does not know for certain which firms are serious bidders or what their workload is at the time of bidding and does not know which firm will win the contract. The second approach avoids this problem since it requires contractors to determine the contract time through the bidding process.

Beginning in the late 1970s and early 1980s, this second approach, commonly called time-cost or A+B bidding, was used on some contracts. This approach apparently was first used in Mississippi in the late 1970s, where it was used on only one contract. It next was used, in the early 1980s, by about five states, including Texas, on a few contracts, and in England, on numerous contracts. Although Texas has stopped using A+B contracts, several other states are now using it on numerous contracts and England continues to use the approach extensively.

An A+B contracting procedure requires the contractor bidding on a job to bid how many days he will take to do the work as well as the construction cost. The contract is then awarded to the bidder whose *combined construction cost bid plus estimated time cost bid, or A+B bid,* is the lowest. The "B" part of the bid, the contractor's time cost bid, is calculated as his time bid in days multiplied by the time cost per day listed in the request for bids, which usually is the incentive/disincentive rate per day. In England, the time cost for a contract is calculated by multiplying the time cost per day by *the contractor's bid time minus the minimum time bid by any contractor bidding on the job.* This approach used in England gives exactly the same results as does the approach used in the United States.

Conventional Low-Bid Contracts

Most highway agencies currently award construction contracts to the qualified construction firm submitting the lowest-cost bid. An integral part of the contract is that the construction firm agrees to complete the project within a stipulated number of days (contract days) which are set by the highway agency prior to bidding, or pay liquidated damages at a given rate for each day that the contractor overruns the contract days. The liquidated damages rate per day, which is higher for more costly projects, in the past has generally followed quidelines developed by the American Association of State Highways and Transportation Officials (AASHTO). These guidelines were established mainly to cover extra construction engineering costs associated with project overruns.

Highway engineers usually estimate the number of contract working days using bar charts, statistical relationships, and historical data for similar projects. A major difficulty in setting contract working days is that the estimating engineer does not know which firm will be the low bidder and what the firm's current workload is. Since there is no way for the highway engineer to determine how much it will cost the winning contractor to reduce the project completion time, it is difficult to implement an optimal strategy with the current approach.

Use of Incentive/Disincentive Contracts

There has been considerable interest in incentive/disincentive (I/D) contracts in the United States in the last decade. Prior to 1979, only a few states had experience with I/D contracts, partially due to FHWA policy that prohibited incentive payments for early project completion from 1968 to 1977. In 1977, the FHWA initiated the National Experimental and Evaluation Program Project Number 24 (NEEP 24) to evaluate the use of I/D provisions in expediting project completion. After several states used I/D contracts to expedite construction, FHWA rescinded their earlier prohibition by publication of a new regulation in the *Federal Register*, Vol. 49, No. 115, on June 13, 1984. The FHWA concluded that:

> The I/D provisions have been proven to be effective in reducing the contract completion time. The increase in costs due to use of I/D provisions (double shifts, overtime pay, etc.) has been more than offset by: (1) reducing inflationary costs, (2) minimizing inconvenience to the traveling public caused by delays, (3) increased safety through the construction zone, (4) reducing expenses associated with maintaining traffic control during construction, and (5) reducing the costs of project administration and inspection.

An informal survey conducted by TTI in 1986 [*3*] found that at least 30 states had used I/D contracts on at least 58 projects for the specific purpose of attaining earlier completion of a project. (Some states also use I/D contracts to obtain other results, such as pavement smoothness.)

Texas has used I/D provisions to reduce contract time on several projects and has used A+B contracts as discussed previously, but current policy prohibits use of these types of contracts and recommends simply using regular contracting methods, together with higher liquidated damages and contract days stated in calendar days instead of working days.

Time-Cost (A+B) Bidding

Conventional highway construction contracts are awarded to the contractor who bids the lowest price. As discussed previously, in time-cost, or A+B bidding, bidders are required to bid both the price *and* the number of days they will take to complete the project (or some critical part thereof). Each day is assigned a dollar value, usually based on road user cost. The contract is then awarded to the bidder whose price *plus* time A+B bid is the lowest. Information shown from an A+B contract in Table 1 illustrates this technique.

In the example shown in Table 1, Bidder No. 2 has the lowest A+B bid of $21,117,830 and would be awarded the contract for the construction bid price of

Table 1. Example of Time-Cost (or A+B) Bidding

BIDDER	COST OF BID ITEMS (A)	CONTRACT TIME BID, DAYS	ROAD USER COST AT $10,000/DAY (B)	TOTAL FOR BID COMPARISON (A+B)
1	$15,719,690	665	$6,650,000	$22,369,690
2	15,867,830	525	5,250,000	21,117,830*
3	16,478,040	605	6,050,000	22,528,090
4	16,331,470	665	6,650,000	22,981,470
5	17,691,950	600	6,000,000	23,691,950

* Low Bidder (A+B)

$15,867,830 and would be required to complete the project in 525 days. Once underway, the contract would be handled the same as conventionally-bid contracts, except that the winning contractor would be paid an incentive payment if he runs under 525 days and would be charged $10,000 per day if he runs over 525 days.

In most cases, A+B bidding is used in conjunction with some other contractual technique to assure that the successful bidder will, in fact, complete the project within the specified time, or sooner. Such techniques include many variations of the "carrot or the stick" approach, e.g., incentive-disincentive clauses (I/D), high liquidated damages (including road user costs), and withholding progress payments for failure to adhere to an approved construction schedule.

It is clear that the use of A+B bidding is growing. In the mid-1980s, the FHWA had just allowed experimental use of A+B bidding; only five states had used A+B bidding at that time [*3*]. Although the FHWA still considers A+B bidding experimental in most states, they encourage its use under Special Experimental Project No. 14 (SEP 14), "Innovative Contracting Practices." By early 1992, the FHWA, under SEP 14, furnished the states with a sample contract provision for A+B bidding. By mid-1993, at least 17 states and the District of Columbia had used A+B bidding, some on several projects.

In Texas, A+B bidding was first used in 1983 on a joint project, in Houston, between the then State Department of Highways and Public Transportation (now the Texas Department of Transportation) and the Metropolitan Transit Authority of Harris County (METRO). Between 1983 and 1987, TxDOT used A+B bidding on at least ten projects. In each case, A+B bidding was used in conjunction with an incentive/ disincentive, (I/D) provision. However, in 1987 TxDOT ceased the use of I/D provisions. Because A+B bidding and I/D provisions were always used together as a package, TxDOT has not used A+B bidding since.

In most instances where A+B bidding and I/D provisions are used together, the contracting agency specifies a maximum time-bid that it will allow; it also often sets a minimum time-bid that it will accept (to forestall unrealistically low time-bids intended to achieve award of the contract without the intent to finish on time). And a maximum incentive payment is usually specified. In most of the observed cases, the successful bidder has bid the minimum time allowed and therefore has been eligible for the maximum incentive payment allowed. This always raises the question of how good the agency's estimate of time was and whether a tighter schedule should have been specified.

The need to specify a minimum time can be illustrated by an example where a contractor bids one day on a contract that is estimated to take 300 days. By bidding one day, the contractor is willing to pay the disincentive charge per day. However, he presumably included the expected cost of running over the contract time (the charge per day multiplied by his expected time to complete the job minus one day). The contractor presumably was willing to give up the possibility of an incentive payment because he would get paid extra per unit of construction work (presumably the inflated unit cost including the imputed disincentive payment and possibly the expected bonus that he estimated that he could have gotten) as the work progressed and would in effect get the interest off of this early payment.

The difficulty in accurately estimating contract time is illustrated by a project in Michigan in 1993. The 3.8 mile project entailed replacement of a metal-beam median barrier with a concrete barrier and a glare screen. To minimize interference with traffic, MDOT used A+B bidding and specified a $12,000 per day incentive/disincentive. The maximum number of days allowed was 80 calendar days without a minimum; the maximum incentive was $60,000 (for five days early completion).

The low bidder's bid was $1,377,313.80 and *18 calendar days, or 62 days under the engineer's estimate*! No other bidder came close; the average of the other five bidders was about 68 days. There was skepticism that the contractor could do the work in 18 days. In fact, he completed the work in *13 days* - and earned the $60,000 maximum incentive. Both MDOT and FHWA engineers rated the quality of work as excellent.

CHAPTER III. CRITERIA FOR COMPARING CONTRACTING STRATEGIES

Criteria for evaluating different contracting alternatives were identified and described based mainly on the case study projects and previous research. A list of these criteria for evaluating alternative contracting strategies is given in Figure 1. Each of these categories is discussed in turn.

General Discussion of Criteria

Economic Efficiency

Economic efficiency implies the most efficient use of all resources. For the purposes of these criteria, economically efficient use of resources is assumed to be measured by the costs associated with highway project construction. The economic efficiency objective is best met by the contracting strategy that gives the minimum total cost.

A highway construction project has four principal types of costs associated with it during the construction phase of the project: (1) the construction cost paid by the Department to the contractors, (2) the cost to the Department for monitoring the project, as estimated by the construction engineering costs, (3) the extra costs to motorists associated with construction activity, for different types of projects, and (4) the non-user costs associated with the project construction, including the cost to businesses adjacent to the project, in terms of lost profits due to construction activity. To choose an economically efficient solution, all of these costs should be considered.

Effects on Department Personnel and Costs

Different types of contracts have differing effects on Deapartment personnel and costs. These effects include effects on work hours and effects on morale and safety.

Administrative Ease

Administrative factors that are important in comparing contracting strategies include the effects on contract complexity and administrative costs and the effects on change orders and claims.

Legal/Policy Issues

Legal and policy issues include whether the contracting strategy is consistent with

1. **Economic Efficiency**

    a. **Effects on Department costs**
    b. **Effects on construction costs**
    c. **Effects on motorists' costs**
    d. **Effects on abutting businesses**
    e. **Other Non-user Costs**
    f. **Long run effects on competition and costs**

2. **Effects on Department Personnel and Costs**

    a. **Effects on work hours and overtime**
    b. **Effects on morale and safety**

3. **Administrative Ease**

    a. **Effect on change orders, claims, etc.**
    b. **Administration costs/complexity**

4. **Legal/Policy Issues**

    a. **Change required in Department policy**
    b. **Change required in State law**
    c. **Federal laws and requirements**

5. **Acceptability**

    a. **Department**
    b. **Contractors**
    c. **Public/motorists/businesses**

6. **Applicability**

    a. **By type of project**
    b. **Traffic handling situation**
    c. **Sequencing of related projects**
    d. **Other**

Figure 1. Criteria for Comparing Alternative Contracting Strategies

TxDOT policy, Texas law, and federal laws and requirements.

Acceptability

The contracting strategy should be acceptable to TxDOT, contractors, motorists, the general public, and businesses.

Applicability

Applicability refers to the applicability of the contracting strategy for specific types of projects, traffic handling situations, or where sequencing of related projects is important.

Total Cost Model

For purposes of the following analysis, it is assumed that the goal of the Department is to attempt to select working days to minimize the total cost to the Department and to motorists for constructing a highway. This goal can be presented diagrammatically, as shown in Figure 2. The three lower curves in Figure 2 are the first three types of costs discussed above.

The top curve, labeled total cost, is derived by summing the three lower cost curves. The general shape of each of these curves is of interest and bears further discussion. For ease of exposition, each of the bottom two curves is shown as a straight line increasing with working days. The rationale for the curves is that the longer it takes to complete the construction project, the greater will be both the excess cost to motorists and the construction engineering cost.

The construction cost curve represents the contractor's cost for completing a project, and is assumed to include a normal profit. The construction cost curve is shown decreasing rapidly from a small number of working days, such as A days, then becoming relatively flat in the middle part of the curve, reaching a minimum at Point H, and then increasing gradually as working days increase to the right of Point H. This curve implies that, in the absence of liquidated damages and bonuses, the contractor would want to complete the job in C working days. To complete the job in fewer days would cost more which might include paying overtime, using additional subcontractors, hiring more workers who might be less efficient, etc.

To the right of Point H the contractor's costs increase because the job has not been completed in an optimal way, i.e., he has not used the best mix of labor, equipment, and management, so that it takes too long to complete the job. This can result from an inefficient scale of operations or from problems that arise because of excessive time on the

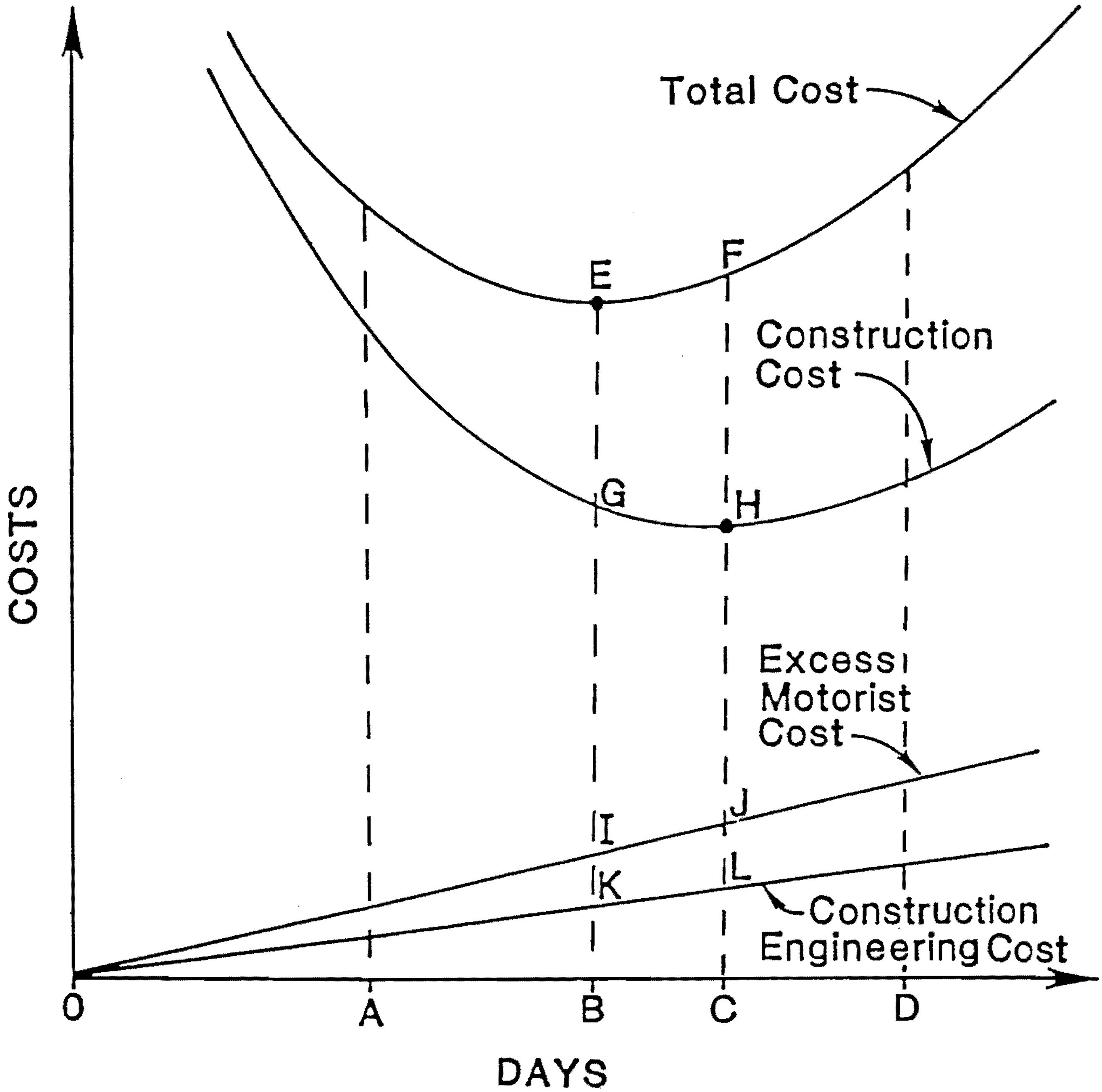

Figure 2. Costs by Type Related to Contract Days

job. For example, taking too long on one part of a job might mean that another part of the job has to be postponed because of inclement weather. Another reason the curve slopes upward to the right of the minimum point is that the contractor cannot collect his entire contracted amount until he completes the job so he loses the return on these funds when he delays completion of the job.

As mentioned previously, it is presumed that the goal of the Department is to minimize total costs, represented by the total cost curve in Figure 2. With motorist costs and construction engineering costs increasing with more working days, the minimum point on the total cost curve will be on the left of the minimum point on the construction cost curve.

The general problem of what policy of liquidated damages and bonuses the Department should have can be characterized by the problem of determining what incentive/disincentive schemes will lead a contractor to complete a job in B working days instead of C working days. Three possible incentive/disincentive strategies are outlined below and the extent to which they accomplish the objective of minimizing total cost is analyzed.

Current Procedures

Current procedures in Texas on most contracts consist of charging liquidated damages for each working day that the contractor overruns the working days allowed in the contract (plus any additional working days granted in contract changes). This procedure should achieve the desired goal of minimizing total cost if two conditions are met. First, the number of working days allowed in the contract, in terms of Figure 2, must be set at B working days or less. Second, the daily rate of liquidated damages must be equal to the rate of change per day in excess motorist costs plus construction engineering costs. When these two conditions are not met, total costs are not minimized. For example, again in terms of Figure 2, if contract days are set at C days or greater, the contractor will have no incentive to complete the job in less than C days. (Note: The above discussion is written in terms of a contractor, but actually from the viewpoint of the present discussion, it is more accurate to view the construction cost curve in Figure 2, as being the envelope of minimum bid points for all contractors bidding on a job.)

If contract days are set at C working days or greater, and the contractor completes the job in C days instead of B days, the Department would obtain a savings in construction costs, equal to the difference between construction costs at Points G and H, but would have additional construction engineering costs, the difference between construction engineering costs at Points K and L. Motorists would have additional costs equal to the difference between Points I and J on the Excess Motorist Cost Curve. The total combined loss would be the difference between total cost at Points E and F. If contract days are set between B and C, then the contractor would attempt to complete the job in exactly the contract working days. This assumes that the liquidated damages are set equal to the rate of change per day in excess motorist costs plus construction engineering costs, which is the sum of the slopes of these two curves in Figure 2. Only if contract working days are set at B or less will the contractor complete the job in B days.

The principal problem the Department has in pursuing the optimal policy with the current approach is that the Department does not know the shape of the construction cost curves for contractors bidding on a job. Nevertheless, the implications of the analysis are clear. To minimize total costs, the Department should charge liquidated damages per working day that fully cover motorist and Department costs for overruns and should set very tight working days so that, hopefully, the contract working days will be B or less.

In the extreme case, it would be possible for the Department to minimize total costs by simply charging liquidated damages for all working days from the beginning of the contract. In this case, in terms of Figure 2, assuming the rate of liquidated damages is equal to the rate of increase of the excess motorist cost plus construction engineering cost, the successful bidder presumably would bid an amount equal to total cost at Point E, would complete the job in B days, and would pay liquidated damages equal to the motorist excess cost at Point I and construction engineering cost at Point K.

The contractor's net return after liquidated damages would be the construction costs, which is assumed to include normal profit at Point G. One possible disadvantage to setting very low contract working days is that some contractors might have an aversion to bidding on contracts where they expect to have to pay significant liquidated damages, so they might not bid even though they might potentially be the low-cost bidder.

Procedures Using a Bonus

As explained previously, if contract working days are set to be greater than B days in Figure 2, total cost will not be minimized even if the liquidated damages charged per working day are the optimal amount. For example, if contract working days are set at D days, the winning bidder will simply bid the construction cost at Point H and complete the job in C days. However, if the contractor is paid a bonus per day for early completion equal to the liquidated damages rate, then the contractor will complete the job in B days. This is illustrated in Figure 3 which is based on the curves in Figure 2. Points A, B, C, and D in Figure 3 correspond to the same points in Figure 2. However, in Figure 3, it is assumed that D days in Figure 2 are taken as a reference point and the horizontal axis in Figure 3 measures the number of working days that the job is completed early with respect to D days. Three curves are shown in Figure 3.

Each of these three curves shows the marginal cost *per day* due to completion in less than D working days. The marginal construction cost curve is negative at D days, increases to zero at C days, and is positive beyond C days. The marginal construction cost curve is

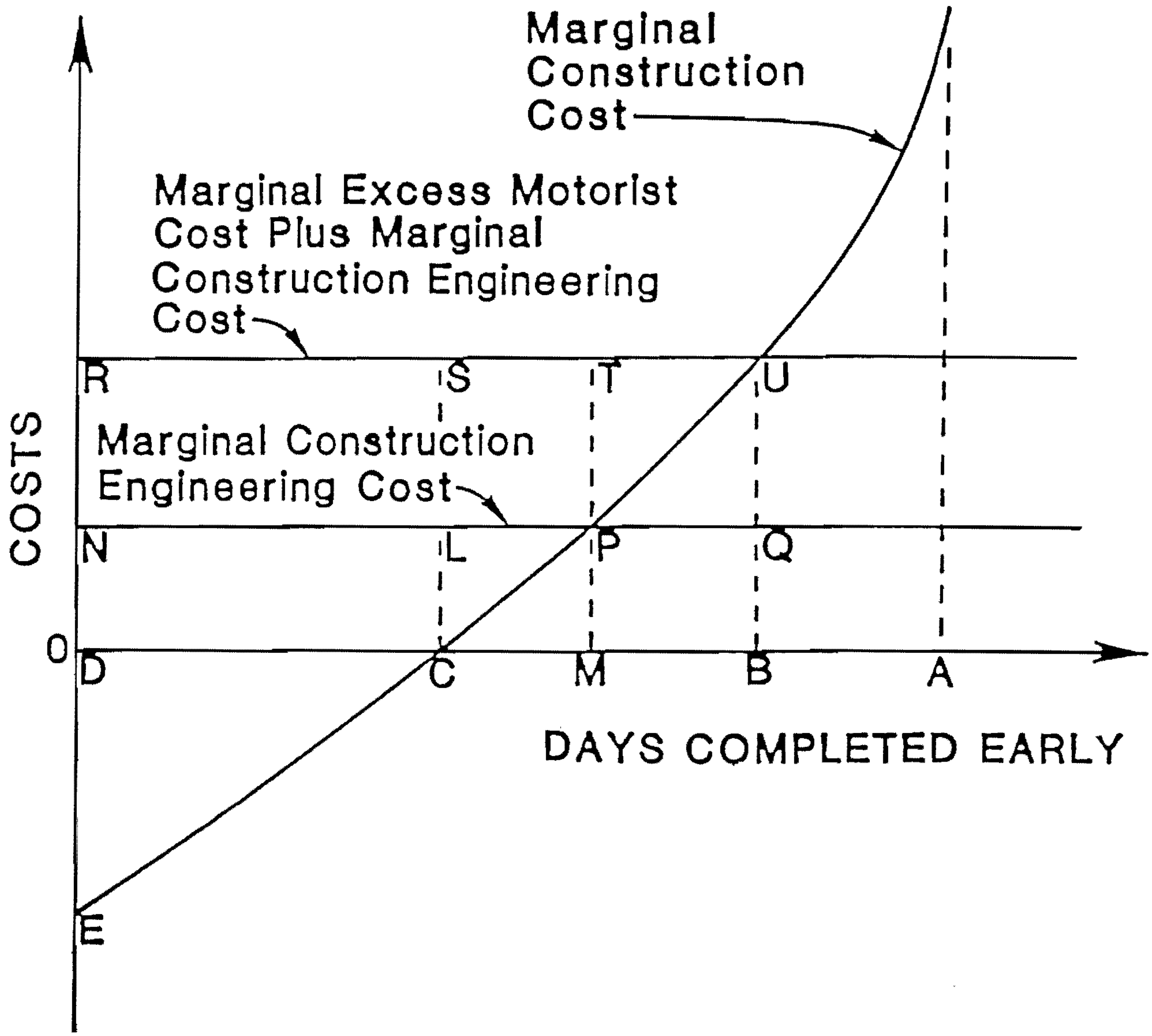

Figure 3. Marginal Costs Related to Contract Days Completed Early

defined as the change in construction costs as working days are decreased below D days in Figure 2. Therefore, in Figure 3, marginal construction costs are negative from D to C days, are zero at C days, and increase to the right of C days. Since these curves are marginal curves, the areas between the curves and the horizontal axis represent total cost, between any two values for working days. In the following discussion, the marginal excess motorist cost plus marginal construction engineering cost is also referred to as the marginal non-construction costs, for convenience of exposition.

If a bonus equal to marginal non-construction cost is paid for each day of early completion, relative to contract days, then the contractor would expect to maximize his total profits (normal profits, assumed to be contained in the construction cost curve, plus bonus) by completing the job early up to the point where marginal construction cost equals marginal non-construction cost, or B working days in Figure 3. This is because his bonus per day for reducing the number of working days exceeds his increase in construction cost for reducing working days. This is the situation as long as the marginal construction cost curve is below the bonus rate (or below the marginal excess motorist cost plus marginal construction cost in Figure 3).

If contract working days are set at D days, then the contractor would receive a bonus equal to Area DRUB if he completes the job B days early. His increase in construction costs for completing the job early, relative to the minimum construction cost at C days would be equal to the triangular Area CUB. Note that even without a bonus he would want to complete the job C working days early. However, by completing the job B days early, he gains an additional bonus equal to Area CSUB for a cost of only CUB, for a net increase in total profit equal to the triangular Area CSU. However, if there is effective competition in the construction industry, this increase in profit should be competed away so that the reduction in working days from C to B would only cost Area CUB. For reducing working days from C to B, the contractor would be paid a bonus of CSUB but he would reduce his construction cost bid by CSU for a net cost to the Department of CUB. The benefit to the Department and motorists would be increased by Area CSUB at a cost of CUB in reducing working days from C to B for a net gain of CSU.

It is also interesting to note what the result would be if the bonus were set equal to marginal construction engineering costs only. For ease of exposition, assume contract working days are set at C in Figures 2 and 3. The contractor would complete the job early by the number of working days from C to M, and would be paid a bonus of CLPM. However, part of this bonus equal to area CLP would be competed away so that the cost to the Department for construction and bonus would be the construction cost at C days plus Area CPM. Thus, the net cost to the Department for the bonus and construction cost for completing the job early would only be Area CPM. In return, the Department saves Area CLPM in construction engineering cost and motorist save Area LSTP.

The loss from setting the bonus on the basis of Department costs alone while ignoring motorist costs also can be seen in Figure 3, where the contractor chooses M days instead of B days. The cost to the Department of moving to point B is Area MPUB which is partially offset by a reduction in construction engineering cost equal to Area MPQB, giving an increase in Department cost equal to Area PUQ to reduce motorist cost by Area PTUQ, with a net gain of Area PTU. If contractor costs increase at an increasing rate for the contractor completing the job faster, then the loss to motorists will be more than twice what the Department's additional cost paid to the contractor for earlier completion.

The general conclusion from the above analysis is that paying a bonus for early completion always results in a reduction in the total cost of a project if the following conditions are met:

1. The cost curves are of the general shape indicated.
2. Costs to the Department and to motorists are accurately estimated.
3. There is effective competition between contractors, and contractors are fairly accurate in predicting their construction costs at different numbers of working days.
4. The costs and times in the figure are not changed by a meaningful amount due to change orders on the contract.

A possible disadvantage of paying bonuses is that when the contract working days exceed the optimal working days by a large margin, a contractor will be paid a very large bonus. Even though effective competition would reduce construction costs to largely offset this bonus, it might be difficult for the Department to explain this to the general public and elected officials.

Bidding Contract Days

On some critical construction jobs where there would be high motorist costs associated with construction activity, TxDOT has let some contracts using a procedure by which the contractor's bid consists not only of his construction cost bid but also of his number of contracted working days. The Department agrees to pay a bonus if the job is completed in less than the number of days bid by the contractor. The contractor pays liquidated damages for each day he runs over the number of days that he bids. The rate of bonus/liquidated damages is set in advance by the Department based mainly on estimated excess motorist costs, not to exceed $10,000 per day. The low bidder is determined by adding the contractor's bid for construction cost to the amount derived by multiplying his number of bid working days by the bonus/liquidated damages rate per working day. It also is sometimes stipulated in the contract that the bid cannot exceed a specified number of days.

This type of contract can be analyzed using an approach similar to that used for the preceding strategies. The contractor can determine his best bid by constructing a diagram as shown in Figure 4. First, he estimates his construction cost curve, which is the same as

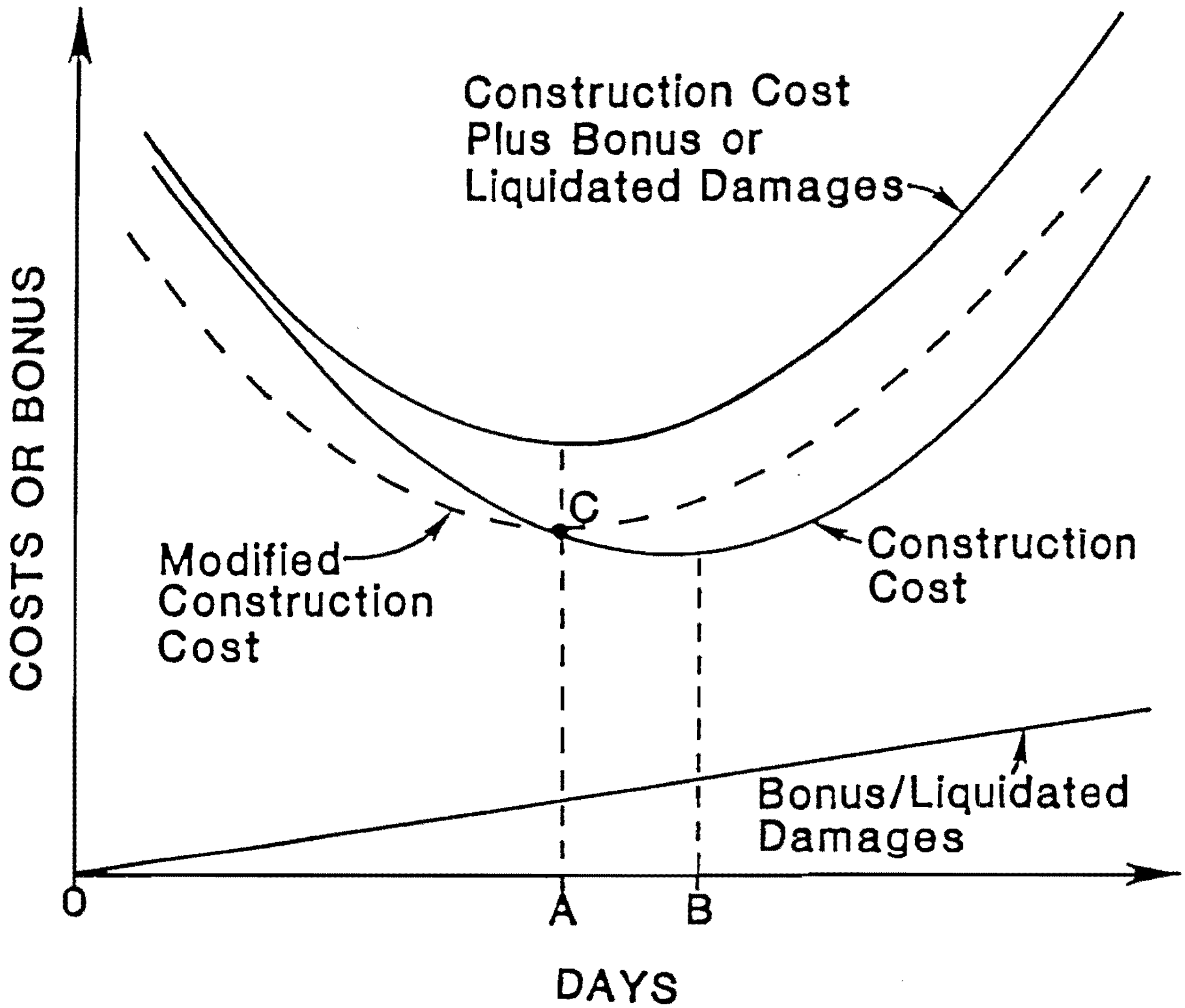

Figure 4. Costs and Bonus Related to Contract Days

that described previously for Figure 2. Next, he constructs a curve showing the amount of bonus he would be paid, which equals the bonus/liquidated damages rate multiplied by the working days, shown as the lower, straight line in Figure 3. Summing these two curves gives the top curve in Figure 3. The number of working days corresponding to the minimum point on this top curve is the number of working days that he should bid (A days in Figure 4). The construction costs that he should bid is Point C on the construction cost curve. His new expected total cost, reflecting a bonus to the left of A working days and payment of liquidated damages to the right of A working days, is shown as the dashed curve in Figure 4 and is labeled "modified construction cost." This modified construction cost curve is parallel to the top curve and reaches its minimum at the same number of working days A. This strategy, therefore, gives the same general result as the bonus strategy discussed in the preceding section as long as the bonus per day is the same.

Bidding Contract Days with Liquidated Damages Only

Another interesting strategy that has not been tried to date, to the best of our knowledge, is to have the contractor bid contract completion days as in the preceding strategy and to not pay a bonus for early completion, but to charge liquidated damages for any overrun past the number of days that he bids. However, the low bid would be determined by multiplying the number of days that he bids by the liquidated damages rate and adding this to his construction cost bid.

In this strategy, the contractor's true total cost curve would be the solid portion of his construction cost curve to the left of Point C and the dashed curve to the right of Point C in Figure 4. His best strategy would be to bid A working days as before and to bid construction costs at Point C. This conclusion, however, has the limitation that it assumes he knows his cost curve and that he expects with certainty to complete the job in A working days. In actuality, he might view the curve as a probabilistic concept, in which case he might have some probability of completing the job in less than A days and some probability of completing it in more than A days. Additional information about contractors' cost curves as related to working days is needed before this aspect of the problem can be fully developed. Nevertheless, it probably can be concluded that some jobs would not be completed as rapidly without the bonus. One reason for this is that a contractor might unexpectedly get ahead of schedule on a job such that he would go ahead and complete it ahead of time if he can get a bonus. Without the bonus, his best procedure might be to reorganize his schedule so that he does not complete the job early.

One advantage of the strategy of having the contractor bid working days but not paying bonuses is that it approximates the bonus-strategy solution without the possible negative publicity of paying bonuses. Also, if liquidated damages are set correctly, a considerable saving in combined motorist costs and Department costs should result. Another advantage is that the Department does not have to estimate working days, since these are bid by the contractor. Of course, the Department could continue to stipulate a maximum number of working days *and* also have contractors bid working days. This should have no effect on the procedure giving improved results.

Qualifications to Above Findings

The discussion in this chapter is based on several assumptions, including: (1) a deterministic model is used, as opposed to a stochastic model; (2) it is assumed that there is no collusion among bidders; (3) it is assumed that the curves are drawn for a given policy with respect to work times and rules; and (4) it is assumed that the project is well-defined and that all relevant costs are included in the cost curves that are discussed. The assumptions that are probably most critical are numbers (2) and (4). If there is collusion among bidders, the entire theory may be inapplicable and must be totally replaced with a theory of how firms make decisions and bids if there is collusion. Assuming that there is no collusion, the next critical assumption is that all costs are included and that the project is well defined. This assumption clearly is not always met and there often are major change orders that change both the project definition, its cost, and its construction time. Somewhat related is the possibility of claims and litigation that can change the cost considerably.

Amount of User Cost to Include in Liquidated Damages

If highway funds are not sufficient to fund all projects with benefit-cost ratios greater than one, then the marginal return to construction dollars should be considered in determining the proportion of user costs to include in liquidated damages. The marginal benefit-cost ratio for spending highway funds to complete jobs early to save motorists' costs can be discussed in terms of Figure 3. As explained previously in discussing Figure 3, the average benefit-cost ratio of completing a job B days early instead of M days early is at least 2 to 1. The Area PTUQ divided by Area PUQ is exactly 2 to 1 if the segment PU is a straight line. Since costs typically would increase at an increasing rate, the average ratio typically would exceed 2 to 1.

The marginal benefit-cost ratio for reducing working days is the ratio of the marginal excess motorist cost to the marginal construction cost minus the marginal construction engineering cost. Between M and B working days, this equals the ratio of the distance PT to the height of the marginal construction cost curve above the horizontal line PQ. This ratio is very large immediately to the right of M working days, is 2 to 1 midway between M and B working days, and is 1 to 1 at B working days.

Therefore, if sufficient highway funds are available for funding all projects that give a benefit-cost ratio greater than 1.0, then a policy should be followed of including full excess motorist costs in liquidated damages, which would lead, in terms of Figure 3, to completion of projects B days early. If funds are available only for projects that give a benefit-cost ratio of 2.0 or greater, then only half of excess motorist costs should be included in liquidated damages, corresponding to the point halfway between M and B in Figure 3, where the marginal benefit-cost ratio for spending to reduce excess motorist cost is 2 to 1.

In Texas, recent calculations indicate that the marginal return to highway expenditures is about 4 to 1. Applying this ratio would lead to the recommendation that about 12.5 percent of the motorist costs in Chapter IV be included in liquidated damages. However, considering that accident costs were not included in the values in Chapter IV, this percent probably should be increased. Also, considering that the discomfort and inconvenience from traveling through construction zones is probably above average and considering that severe congestion like in work zones is estimated to have a time cost that is twice as high as normal, it is recommended that 20 to 30 percent of the motorist costs in Chapter IV be included in liquidated damages.

CHAPTER IV. ESTIMATION OF MOTORIST COSTS FOR LIQUIDATED DAMAGES

A comprehensive evaluation was made of different models for estimating user costs for use in developing liquidated damages for different types of highway projects. Emphasis was placed on evaluating and verifying the current procedure for calculating user costs and on evaluating the use of user costs for different types of projects with different levels of traffic. This evaluation included HEEM-II, HEEM-III, QUEWZ, and other related models. User costs were developed using the HEEM-III and QUEWZ models for possible use by TxDOT.

Use of the HEEM Programs for Estimating Motorist Costs

The calculation of road user costs to be included in liquidated damages is simple conceptually, but is sometimes difficult in practice to estimate. Benefit-cost methodologies and computer programs calculate the motorist costs of the *existing condition* and an *improved condition*. The difference between these two costs is defined as the motorist benefits of the improvement. In the case of liquidated damages, the purpose is to calculate the additional costs incurred by delaying the opening of the improved facility. Therefore, to accurately calculate the road user portion of that additional cost, using benefit-cost analysis, the *existing condition* is the during-construction situation, and the *improved condition* is the situation after the improved facility is open for traffic. It is very important that these situations be accurately represented in order to make road user cost estimates for use in liquidated damages.

Two of the critical variables affecting the estimation of road user costs are the reductions in capacity during construction and the duration of that restricted capacity. Obviously these factors can vary considerably between individual projects, especially different types of projects. The various benefit-cost methodologies and computer programs handle each of these variables differently and can have a significant effect on the estimated road user costs.

The HEEM-II model uses *technical factors* to adjust the capacity. This is a very powerful adjustment factor because it is not only used to adjust the capacity, but the inverse is used to adjust the speed for a given capacity. It would be very easy to overestimate the delay of a construction activity if that technical factor is set too low, since it is not possible to see directly what effect the technical factor is having on the capacity and speed. The HEEM-III and the QUEWZ model have a much better method of handling the capacity adjustment, because the hourly per-lane capacity is given as part of the input data and can be changed directly by the user. This allows the user to directly see the impacts on the estimated road user costs.

The HEEM-II has a much better methodology to handle the effects of the duration of restricted capacity, with the ability to explicitly specify an alternate diversion route for traffic and a safety-valve diversion when all specified routes reach capacity. The QUEWZ on the other hand has very limited capability for handling diversion. It was designed for short-term workzone activities on freeways, and does not explicitly model the diversion that would take place as motorists adapt to a longer-term restricted capacity environment, by choosing alternate routes or varying the timing of trips. The HEEM-III model has the best methodology, with an explicit alternate route capability and the ability to specify increases in the total traffic after the facility is opened. This allows for explicit calculation of the effects of both diverted and induced traffic. This is particularly important in cases where significant new capacity is being added to an existing facility or a new facility is being constructed. An additional feature of the HEEM-III is that it allows for estimates of intersection/interchange projects, not possible with the other models.

The HEEM-II computer program [*10*] has been used in various applications by the Texas Department Transportation (TxDOT) since it was released in 1982. These include motorist impacts for environmental impact statements, estimation of motorist liquidated damages, evaluation of route studies, and estimation of the benefit-cost ratio of proposed major freeway projects. It has proven to be a valuable tool in a variety of situations.

There are, however, several significant drawbacks to the HEEM-II program. Perhaps the most significant is the use of Average Daily Traffic (ADT) to calculate average speeds rather than hourly volumes. While the use of ADT greatly reduces the time to run the program, it is not compatible with current practice of using hourly volumes to define traffic flow performance, such as the 1985 *Highway Capacity Manual* [26]. In addition it is very difficult to model traffic operations that affect only certain hours of the day, such as HOV lanes and workzones.

Another weakness of HEEM-II is the lack of explicit calculation of intersection or interchange delay. It is incorporated indirectly into the ADT/speed calculation, but the size of that effect is not known and it would not be possible to adjust for specific intersection/interchange characteristics. The lack of a specific analysis of intersection delay greatly reduces the usefulness of the program. Even for a freeway improvement, there is frequently a signalized parallel facility that should be included in the analysis.

The HEEM-III program [*25*] is a complete revision to the HEEM-II computer program to address the issues described above, as well as numerous other more minor weaknesses. The program is similar to past versions, in that it is designed for use on a mainframe computer, with batch input. There is also a personal computer (PC) version that allows for input data entry and edit on a PC. The general structure of the program, as well as the PC menus follow the TRIP program, which was developed for TxDOT use in evaluating interchanges and other grade separations.

HEEM-III includes an analysis of the major motorist user costs associated with highway improvement projects including delay costs, vehicle operating costs, and accident costs. The delay costs consist of delay traveling along a segment of highway, delay at a signed or signalized intersection or an at-grade highway-railroad crossing while a train is passing, and the delay of slowing down to cross over railroad tracks. The vehicle operating costs consist of running costs traveling along a highway segment, the speed-change cycling costs of congestion, the costs of slowing down and stopping at an intersection or a highway-railroad grade crossing, the idling costs while waiting in a queue, and costs of slowing down to cross railroad tracks. Accident costs consist of the accident rates and costs associated with traveling along a highway section, as well as the additional accident costs of an intersection, interchange, or highway-railroad grade crossing.

The program also allows for adjustment of the calculated vehicle operating costs for changes in pavement condition. The user can input a pavement condition, Present Serviceability Index (PSI), for each year. The program uses a base of 4.5, so if the pavement condition is less than 4.5, the vehicle operating costs are increased. The opposite occurs for a pavement condition higher than 4.5. There is also the ability to input annual routine maintenance or rehabilitation costs.

The PC version HEEM-III provides an easy-to-use and flexible method of inputting and editing the data. The minimal data required to run a problem is prompted from the user. That data, along with the other assumed data, can be changed at any time through a set of data menus. The input data set can then be saved and read directly into the program in subsequent applications. The output can be displayed on the screen, sent to a printer, or saved in a file.

One important feature of the bypass/new location analysis is the through traffic allocation. The program provides for a procedure to allocate the through traffic to an existing route, a proposed bypass, and an optional alternate route. The allocation procedure is built into the HEEM-III program. The traffic is allocated based upon an iterative process that gives traffic to each route such that the motorist user costs are the same. An important added feature is the ability to override the allocation provided by the program. The user can directly input the traffic that will remain on the existing routes and the amount to use the bypass or other new location facility. Also, the traffic can be reallocated at any time, for example, when some input data item has been changed. This gives both the flexibility and control that should make it useful in a wide variety of applications.

Another important feature of the HEEM-III computer program is the ability to analyze induced traffic. Previous versions of HEEM as well as nearly all other benefit-cost computer programs require that the corridor traffic for the "do-nothing" alternative be the same as the "if-improved" alternative. There may be some diversion between the routes, but the totals must be the same. The reason for this restriction is the difficulty in calculating the benefits of new vehicles using the corridor. These additional vehicles may be diverting from some other routes outside the corridor, or may represent new trips resulting from the increased capacity and better traffic conditions. The problem is what costs to attribute to these additional trips if the facility is not improved, the "do-nothing" alternative.

The most widely-accepted method to deal with this problem comes from economic theory and is the consumer surplus approach. This approach, simplified greatly, gives the additional induced traffic half of the reduction in user costs experienced by the other drivers. This is the approach used in the HEEM-III computer program. This feature allows the user to analyze in a much more realistic fashion a planned major new location facility. In many cases the traffic on the new facility far exceeds the combined total of the alternate parallel facilities. Rather than artificially increasing the existing traffic or reducing the traffic on the new location facility, the actual anticipated volumes can be input and the program will analyze those conditions.

The HEEM-III documentation report describes the use of the program, how to set up a problem, how to enter the data through the PC, how to use the PC edit menus, and the use of the mainframe version. Report appendices contain descriptions of the delay and other user cost calculations, a program listing of the mainframe version, and an example of program input and output.

Other Programs for Estimating Motorist Costs

At least five additional computerized procedures have been developed for calculating user costs associated with traffic delays and speed changes in highway construction zones. The first of these is called Subroutine USER and is used for calculating user costs associated with traffic disruption. It is part of pavement design programs called Flexible Pavement System (FPS) and Systems Analysis and Management for Pavement (SAMP) [*4, 5*]. The other three programs have the same basic framework as Subroutine USER. One of these programs was developed for comparison of pavement strategies in Canada [*6*] and another was developed on an FHWA project [*22*]. The fourth model, which is also similar to Subroutine USER, was developed by Midwest Research Institute for use in an accident countermeasure evaluation program [*23*]. The fifth model, which was developed for evaluating user costs associated with different traffic control strategies, is QUEWZ [*24*].

Subroutine USER is used in the Flexible Pavement Systems (FPS) programs, Rigid Pavement Systems (RPS), and SAMP series of pavement design programs. This subroutine actually is a fairly detailed computer program that can easily be used separately from the pavement design programs for other types of projects. It calculates the increased time and vehicle operating costs for five different types of roadway stoppage situations. Subroutine USER is documented in NCHRP Report 160 [*5*]. The Canadian model [*6*] is similar to Subroutine USER.

Another computerized approach very similar to the above models, called EAROMAR, was developed for estimating highway user costs associated with pavement maintenance activities [*22*]. The 'Motorist Module' of EAROMAR was developed for estimating user costs for several different types of lane closure and detour for freeways. The program calculates the effects of lane closures on time costs, vehicle operating costs, accident costs, and air pollution levels.

A fourth computerized model for calculating highway user costs associated with maintenance operations was developed by Midwest Research Institute as part of a Benefit-Cost Model for evaluating the effectiveness of alternative skid reduction measures [*23*]. Two subroutines, DTOUR and DCOSTS, are used to calculate time costs, vehicle operating costs, and accident costs. Time costs and vehicle operating costs are calculated using methods and formulas similar to those used in the SAMP and EAROMAR programs. Like SAMP's Subroutine USER, DTOUR calculated user costs using several different types of traffic delay formulas. Accident cost changes associated with maintenance activities are calculated from user input data giving the expected percent increase in accident rates due to highway maintenance.

QUEWZ, which stands for Queue and User Cost Evaluation of Work Zones, is a tool for evaluating highway work zone lane closures. QUEWZ simulates traffic flow through freeway segments both with and without a work zone lane closure in place and estimates the changes in traffic flow characteristics and additional road user costs resulting from a lane closure whose time schedule and lane configuration are described by the model user. QUEWZ can also apply the same traffic flow simulations to identify acceptable time schedules for lane closures.

The original version of QUEWZ was developed at TTI in 1982 using the same basic approach as Subroutine USER but providing for use of hourly traffic. It was developed as part of TxDOT Study 292 and was documented in TTI Research Report 292-1 [*24*]. The original model provided estimates of traffic speeds, queue lengths, and additional road user costs resulting from a work zone lane closure. QUEWZ-85, a microcomputer version of QUEWZ, was developed at the SDHPT in 1985 [*14*].

An enhanced version of the model, QUEWZ2, was developed at TTI under Interagency Contract 84-85-0413 with the Houston Urban Office of TxDOT and was documented in TTI Report 0187-1 [*15*]. Two enhancements were incorporated into QUEWZ2 to satisfy the specific needs of the Houston Office of TxDOT: (1) an input option that allowed the traffic volume data requirements of the model to be satisfied by providing an Annual Average Daily Traffic Volume (AADT) rather than directional hourly volumes, and (2) an output option that provides a schedule of the times of day during which a particular number of lanes may be closed without causing excessive queueing. Adjustment factors were computed for freeways in Houston and were included in the model to estimate directional hourly volumes for a specified day of the week and month from the AADT.

Another version of the model, QUEWZ412, was developed for use in SDHPT Study 2-6-85-412 [*2*]. QUEWZ412 was used to estimate the additional road user costs per day resulting from the delayed completion of construction projects. The principal modification was the addition of an algorithm that accounted for the diversion of traffic away from the freeway in response to the queues and delays caused by the work zone lane closure. The adjustment factors for estimating directional hourly volumes from AADT were changed to represent the average hourly distribution of traffic at automatic traffic recorder stations on urban and rural Interstates in Texas.

QUEWZ3, which was developed as part of TxDOT Study 2-8-87/8-1108 [*17*], represents the consolidation of the enhancements included in QUEWZ2 and QUEWZ412 into one program. In addition, the default values for several model constants were updated. QUEWZ3-PC [*18*] is a microcomputer version of the mainframe model QUEWZ3.

User costs associated with resurfacing or other maintenance activities as calculated by the above programs are a function of: (1) the type of roadway and the way in which traffic is handled during resurfacing, reconstruction, and construction; (2) the amount and type of traffic on the roadway; and (3) the length of time that roadway is affected by the highway maintenance activity.

Recommended Programs for Calculating Motorist Costs

Based on the review of available computer programs, three programs were determined to be most appropriate for calculating motorist costs by the Texas Department of Transportation:

* HEEM-II,
* HEEM-III, and
* QUEWZ-92.

All three programs were developed at the Texas Transportation Institute under State Planning and Research (SPR) studies sponsored by the Texas Department of Transportation.

HEEM-II was developed to evaluate proposed highway improvements. It provides both an economic measure (benefit/cost ratio) and a mobility measure (average speed) of proposed improvements. Its uses include examining the economic feasibility of different design alternatives for a specific project and ranking a slate of different projects in an improvement program. In addition, the Texas Department of Transportation has developed a procedure for using HEEM-II to estimate the additional motorists costs due to highway reconstruction or rehabilitation projects. The additional costs are the difference between the costs during the project versus the costs after the project is completed. These estimated costs are used by the Department to estimate motorist liquidated damages.

HEEM-III is an updated and revised version of HEEM-II. The major enhancements incorporated into HEEM-III are as follows:

* Replacing average daily traffic with hourly volumes as the basis for calculating speeds, delay, and motorist costs,

* Incorporating specific calculations for intersections and interchanges, and thereby bringing the effects of urban arterials into the analysis,

* Incorporating the updated speed-volume and capacity information from the 1985 *Highway Capacity Manual* [*26*],

* Improving the analysis of HOV improvements by modeling specific peak period usage, and

* Accounting for anticipated induced traffic resulting from a proposed new location facility.

HEEM-III can be used in the same way as HEEM-II to estimate the additional motorist costs during reconstruction or rehabilitation projects.

QUEWZ-92 was designed as an analysis tool for planning and scheduling freeway work-zone lane closures. It estimates the queue lengths and additional motorist costs due to freeway work-zone lane closures. QUEWZ-92 simulates traffic flows through freeway segments with and without work-zone lane closures in place and estimates the changes in traffic flow characteristics and additional motorist costs (vehicle operating and delay costs) resulting from the specified lane closure schedule and configuration.

Table 2 summarizes how the features of HEEM-II, HEEM-III, and QUEWZ-92 compare. Whereas QUEWZ-92 is restricted to the evaluation of freeway work-zone lane closures, HEEM-II and HEEM-III can be used to evaluate a wide range of highway improvements. HEEM-III provides greater flexibility in defining before and after improvement highway conditions and more explicit treatment of intersections and interchanges than HEEM-II. HEEM-III offers the greatest capability for specifying an alternative route and analyzing diverted and induced traffic; the diversion analysis in

Table 2. Summary of Features of HEEM-II, HEEM-III, and QUEWZ-92

Feature	HEEM-II	HEEM-III	QUEWZ
Roadway Types	Undivided, divided, and freeway	Undivided, divided, and freeway	Freeway
Project Types	70 specified improvements	New location, added-capacity, interchange, and highway-railroad grade crossing	Freeway lane closure
HOV Facilities Option	Available	Available	Not available
Directional Analysis Option	Analysis for both directions combined only	Analysis for both directions combined only	Each direction evaluated independently
Intersection Analysis	Implicitly only	Explicitly	Not available
Diversion Analysis	Explicit specification of alternative diversion route	Explicit specification of alternative route, and explicit treatment of both diverted and induced traffic	Estimates short-term duration to unspecified alternative route
Time Period for Specifying Restricted Capacity	Year	Year	Hourly up to 24 hours
Time Period for Estimating Speeds and Motorist Costs	Day	Hour	Hour
Input Volume Data	Average Daily Traffic	ADT or Hourly Volume as a Percent of ADT	ADT or Directional Hourly Volume
Motorist Costs	Vehicle Operating, Delay, and Accident Costs	Vehicle Operating, Delay, and Accident Costs	Vehicle Operating and Delay Costs

QUEWZ-92 is based on empirical data on traffic diversion from urban freeways during short-term lane closures. QUEWZ-92 permits the most detailed specification of the direction and duration of lane closures. HEEM-III and QUEWZ-92 provide more detailed hour-by-hour analysis of traffic conditions and motorist costs than HEEM-II which performs its analysis on a daily basis. QUEWZ-92 provides hourly estimates ofaverage speeds and additional motorist costs, whereas HEEM-II and HEEM-III provide daily estimates of average speeds and motorist costs for the during and after highway improvement conditions. The additional motorist costs associated with highway projects have three components: vehicle operating costs, delay costs, and accident costs. HEEM II and HEEM III incorporate all three components into their estimation of motorist costs; QUEWZ-92 considers only vehicle operating and delay costs.

On the basis of this evaluation, the following computer programs are recommended for estimating motorist costs for motorist liquidated damages and lane rental fees:

* HEEM-III is recommended as the computer program for estimating motorist costs for motorist liquidated damages. It is recommended that HEEM-III replace HEEM-II for this purpose, because HEEM-III performs more detailed analyses of motorist costs, permits explicit specification of traffic-handling capacities during and after a highway project, and can evaluate a greater variety of highway projects.

* QUEWZ-92 is recommended as the computer program for estimating hourly lane rental fees. QUEWZ-92 was designed explicitly for evaluating freeway work zone lane closures. QUEWZ-92 permits more detailed specification of lane closure configurations (direction and number of lanes closed), and schedules and provides more detailed simulation of traffic flows and estimation of motorist costs than either HEEM-III or HEEM-II. Only QUEWZ-92 provides hourly estimates of additional motorist costs.

Estimated Additional Motorist Costs

HEEM-III and QUEWZ-92 were used to estimate the additional motorist costs associated with typical highway projects. The HEEM-III estimates provide a basis for motorist liquidated damages associated with the delayed completion of a highway project, whereas the QUEWZ-92 estimates are an appropriate basis for setting hourly lane rental fees for freeway work-zone lane closures.

These estimates illustrate the general relationship between additional motorist costs and traffic volumes for several typical highway projects. The estimates were based on nominal capacities for these projects. Although the estimates indicate the magnitude of additional motorist costs that can be expected, they are intended only for informational purposes. The appropriate computer program should be used in conjunction with project-specific data to estimate the additional motorist costs for a particular project.

Motorist Costs for Motorist Liquidated Damages

HEEM-III was used to estimate the additional motorist costs per day due to the delayed completion of seven types of added capacity projects. Table 3 summarizes the assumed conditions for the during and after construction conditions. Capacity adjustment factors from the 1985 *Highway Capacity Manual* [*4*] were used to estimate the capacities associated with these assumed conditions. Additional motorist costs were estimated for a range of average daily traffic volumes and percentages of trucks for each type of project.

Tables 4 through 6 summarize the estimated additional motorist costs for three rural projects, as follows:

* Table 4: 2-lane undivided highway to a 4-lane divided highway
* Table 5: 4-lane undivided highway to a 4-lane divided highway
* Table 6: 4-lane freeway to a 6-lane freeway

Table 3. Assumed Conditions for Estimating Additional Motorist Costs for Motorist Liquidated Damages Using HEEM-III

Location	During Construction Condition*	After Construction Condition*
Rural	2 lane undivided 12 ft lanes 6 ft shoulders 40% no passing zones	4 lane divided 12 ft lanes 6 ft shoulders
Rural	4 lane undivided 12 ft lanes 0 ft shoulders	4 lane divided 12 ft lanes 6 ft shoulders
Rural	4 lane freeway 11 ft lanes 2 ft shoulders	6 lane freeway 12 ft lanes 6 ft shoulders
Urban	4 lane undivided 12 ft lanes 0 ft shoulders	4 lane divided 12 ft lanes 6 ft shoulders
Urban	4 lane divided 11 ft lanes 2 ft shoulders	6 lane divided 12 ft lanes 6 ft shoulders
Urban	4 lane freeway 11 ft lanes 2 ft shoulders	6 lane freeway 12 ft lanes 6 ft shoulders
Urban	6 lane freeway 11 ft lanes 2 ft shoulders	8 lane freeway 12 ft lanes 6 ft shoulders

* Metric conversions, using 1 ft = 0.3048 meters: lane widths: 11 ft = 3.353 meters and 12 ft = 3.658 meters; shoulder widths: 2 ft = 0.610 meters and 6 ft = 1.829 meters.

Table 4. Additional Daily Motorist Costs Due to the Delayed Completion of a Rural Project from a 2-Lane Undivided Highway to a 4-Lane Divided Highway

AADT	Additional Daily Motorist Costs ($/day)		
	5% Trucks	10% Trucks	20% Trucks
5000	0	100	100
10000	200	200	300
15000	300	400	500
20000	600	700	1000
25000	1000	1200	1500
30000	1600	1900	2400

Table 5. Additional Daily Motorist Costs Due to the Delayed Completion of a Rural Project from a 4-Lane Undivided Highway to a 4-Lane Divided Highway

AADT	Additional Daily Motorist Costs ($/day)		
	5% Trucks	10% Trucks	20% Trucks
10000	100	100	100
20000	200	200	300
30000	300	400	500
40000	500	600	800
50000	800	1000	1300
60000	1300	1500	1900
70000	2900	3200	3700
80000	7300	7800	8600

Table 6. Additional Daily Motorist Costs Due to the Delayed Completion of a Rural Project from a 4-Lane Freeway to a 6-Lane Freeway

AADT	Additional Daily Motorist Costs ($/day)		
	5% Trucks	10% Trucks	20% Trucks
10000	0	30	44
20000	100	119	175
30000	200	300	400
40000	400	500	700
50000	600	800	1100
60000	1000	1200	1700
70000	1500	1800	2500
80000	2500	2900	3700
90000	6500	7100	8200
100000	11300	12000	13500
110000	21200	22300	24400
120000	36100	37700	40700

Tables 7 through 10 summarize the estimated additional motorist costs for four urban projects, as follows:

* Table 7: 4-lane undivided highway to a 4-lane divided highway
* Table 8: 4-lane divided highway to a 6-lane divided highway
* Table 9: 4-lane freeway to a 6-lane freeway
* Table 10: 6-lane freeway to an 8-lane freeway

Table 7. Additional Daily Motorist Costs Due to the Delayed Completion of an Urban Project from a 4-Lane Undivided Highway to a 4-Lane Divided Highway

AADT	Additional Daily Motorist Cost ($/day)	
	5% Trucks	10% Trucks
10000	500	500
20000	1100	1100
30000	1800	1900
40000	2600	2800
50000	3900	4100
60000	6000	6300
70000	16300	17100
80000	31200	32600

Table 8. Additional Daily Motorist Costs Due to the Delayed Completion of an Urban Project from a 4-Lane Divided Highway to a 6-Lane Divided Highway

AADT	Additional Daily Motorist Cost ($/day)	
	5% Trucks	10% Trucks
10000	0	0
20000	100	100
30000	300	300
40000	500	600
50000	1000	1100
60000	1700	1900
70000	2900	3200
80000	5200	5700
90000	17900	18400
100000	31100	32600

Table 9. Additional Daily Motorist Costs Due to the Delayed Completion of an Urban Project from a 4-Lane Freeway to a 6-Lane Freeway

AADT	Additional Daily Motorist Costs ($/day)	
	5% Trucks	10% Trucks
10000	0	0
20000	100	100
30000	200	300
40000	400	500
50000	600	800
60000	900	1100
70000	1400	1700
80000	2100	2500
90000	3600	4100
10000	12000	12700
110000	21400	22500
120000	27700	29000

Table 10. Additional Daily Motorist Costs Due to the Delayed Completion of an Urban Project from a 6-Lane Freeway to an 8-Lane Freeway

AADT	Additional Daily Motorist Cost ($/day)	
	5% Trucks	10% Trucks
10000	0	0
20000	0	100
30000	100	100
40000	200	200
50000	300	400
60000	400	600
70000	600	800
80000	800	1000
90000	1100	1400
100000	1400	1800
110000	1900	2300
120000	2500	3000
130000	3600	4100
140000	6500	7100
150000	15700	16600
160000	26300	27600
170000	32600	34100
180000	38800	40500

Motorist Costs for Lane Rental Fees

Table 11 provides an example of a typical hourly lane rental fee structure. This example was presented by Gaj [27], who indicates that the fees are for "illustrative purposes only" and that "appropriate rental charges must be determined for each project on a case-by-case basis." The hourly lane rental fees in Table 11 vary based upon two factors:

* Time of day (i.e., peak or off peak), and
* Amount of roadway space occupied by the work activity.

Table 11. Example of Hourly Lane Rental Fees Presented by Gaj [27]

Closure	Hourly Lane Rental Fee ($/hour)	
	Peak Periods (6:30-9:00 a.m., 3:00-6:00 p.m.)	All Other Hours
1 lane	2000	500
2 lanes	4000	1250

Three other factors also significantly affect the magnitude of additional motorist costs due to work zones:

* Normal capacity of the roadway,
* Normal traffic volumes using the roadway, and
* Direction of traffic affected by the work zone (i.e., peak or off-peak).

QUEWZ-92 is the recommended computer program to estimate the additional motorist costs associated with lane closures for determining lane-by-lane rental fees when assessed on an hourly basis. In order to demonstrate the effect of these five factors on the additional motorist costs due to freeway work zone lane closures a series of QUEWZ-92 runs were performed. Three freeway cross sections were evaluated: 4, 6, and 8 lane. Two time periods were considered: peak (7-8 a.m.) and off-peak (1-2 p.m.). For each time period, both peak and off-peak directions of traffic were analyzed. For the 4-lane freeway, the closure of 1 lane was evaluated; for the 6-lane freeway, the closure of 1 and 2 lanes was evaluated; and for the 8-lane freeway, the closure of 1, 2, and 3 lanes was evaluated. Additional motorist costs were estimated at 10,000 vpd increments for each combination of these factors. Typical directional and hourly distributions of daily traffic were used to estimate the directional hourly volume. The distributions represent the average distribution of daily traffic at all automatic traffic recorder stations on urban Interstate highways in Texas.

Tables 12 through 17 summarize the results. The results indicate that all five factors significantly affect the magnitude of additional motorist costs due to freeway work zone lane closures and should be accounted for in an hourly lane rental fee schedule.

Qualification on Use of Motorist Costs

In Chapter III, it was demonstrated that, under certain assumptions, including motorist costs in liquidated damages can lead to a better solution with less total transportation cost (construction cost plus other TxDOT cost plus motorists excess costs associated with construction delays). The savings in motorist costs from such a policy was shown to be at least twice as much as the net cost to the Department, the precise multiple depending upon the shape of the contractors's cost curves. If the Department had sufficient funding to build all construction projects with a benefit-cost ratio greater than 1.0, and if there were a high degree of accuracy in the estimates of motorist costs, then it could be strongly recommended that full excess motorist costs be included in liquidated damages and bonuses.

However, in the section of Chapter III entitled "Amount of User Cost to Include in Liquidated Damages," it was argued that, since there is a shortage of highway construction funds, only part of motorist costs be included in liquidated damages. Therefore, if sufficient highway funds are available for funding all projects that give a benefit-cost ratio greater than 1.0, then a policy should be followed of including full excess motorist costs in liquidated damages. If funds are available only for projects that give a benefit-cost ratio, for example, of 2.0 or greater, then only half of excess motorist costs should be included in liquidated damages, since the marginal benefit-cost ratio for spending to reduce excess motorist cost is 2 to 1.

In Texas, recent calculations indicate that the marginal return to highway expenditures is about 4 to 1. Applying this ratio would lead to the recommendation that about one-eighth or 12.5 percent of the motorist costs shown in the preceding tables should be included in liquidated damages. However, considering that accident costs were not included in these table values, this percent probably should be increased. Also, considering that the discomfort and inconvenience from traveling through construction zones is probably above average and considering that severe congestion in work zones is estimated to have a time cost that is twice as high as normal, it is recommended that 25 percent of the motorist costs in these tables be included in liquidated damages.

Table 12. Additional Hourly Motorist Costs Due to the Closure of 1 Lane in 1 Direction of a 4-Lane Freeway

AADT (veh/day)	Additional Hourly Motorist Costs ($/hour)		
	A.M. Peak Hour Peak Direction	A.M. Peak Hour Off-Peak Direction	Off-Peak Hour Peak Direction
10000	0	0	0
20000	100	0	0
30000	300	100	0
40000	4900	200	100
50000	11400	1300	200
60000	21100	4100	2000
70000	36300	7900	5000
80000	56400	12800	8800
90000	70400	17600	12700
100000	84700	22600	17000
110000	99900	27800	21400
120000	114900	33200	26100

Table 13. Additional Hourly Motorist Costs Due to the Closure of 1 Lane in 1 Direction of a 6-Lane Freeway

AADT (veh/day)	Additional Hourly Motorist Costs ($/hour)		
	A.M. Peak Hour Peak Direction	A.M. Peak Hour Off-Peak Direction	Off-Peak Hour Peak Direction
10000	0	0	0
20000	0	0	0
30000	100	0	0
40000	100	0	0
50000	300	100	100
60000	700	100	100
70000	5200	200	100
80000	10800	300	200
90000	18400	400	300
100000	28900	2500	400
110000	43800	5500	1700
120000	60800	9100	4300

Table 14. Additional Hourly Motorist Costs Due to the Closure of 2 Lanes in 1 Direction of a 6-Lane Freeway

AADT (veh/day)	Additional Hourly Motorist Costs ($/hour)		
	A.M. Peak Hour Peak Direction	A.M. Peak Hour Off-Peak Direction	Off-Peak Hour Peak Direction
10000	0	0	0
20000	100	0	0
30000	400	100	0
40000	4600	200	100
50000	9700	1200	200
60000	16000	3900	1900
70000	2400	6900	4400
80000	34500	10500	7200
90000	48500	14600	10600
100000	65500	19600	14600
110000	86900	25500	19600
120000	112000	32400	25500

Table 15. Additional Hourly Motorist Costs Due to the Closure of 1 Lane in 1 Direction of an 8-Lane Freeway

AADT (veh/day)	Additional Hourly Motorist Costs ($/hour)		
	A.M. Peak Hour Peak Direction	A.M. Peak Hour Off-Peak Direction	Off-Peak Hour Peak Direction
10000	0	0	0
20000	0	0	0
30000	0	0	0
40000	100	0	0
50000	100	0	0
60000	200	100	0
70000	300	100	100
80000	500	100	100
90000	1000	200	100
100000	5600	200	200
110000	10800	300	200
120000	17300	400	300
130000	25700	500	400
140000	36700	900	400
150000	51500	3900	600
160000	66900	6800	1000

Table 16. Additional Hourly Motorist Costs Due to the Closure of 2 Lanes in 1 Direction of an 8-Lane Freeway

AADT (veh/day)	Additional Hourly Motorist Costs ($/hour)		
	A.M. Peak Hour Peak Direction	A.M. Peak Hour Off-Peak Direction	Off-Peak Hour Peak Direction
10000	0	0	0
20000	0	0	0
30000	100	0	0
40000	200	0	0
50000	300	100	100
60000	700	100	100
70000	5000	200	100
80000	9900	300	200
90000	15700	500	300
100000	22800	2500	400
110000	31500	5200	1700
120000	42300	8300	4000
130000	56400	11800	6700
140000	72600	15800	9800
150000	92000	20400	13300
160000	112800	25600	17500

Table 17. Additional Hourly Motorist Costs Due to the Closure of 3 Lanes in 1 Direction of a 8-Lane Freeway

AADT (veh/day)	Additional Hourly Motorist Costs ($/hour)		
	A.M. Peak Hour Peak Direction	A.M. Peak Hour Off-Peak Direction	Off-Peak Hour Peak Direction
10000	0	0	0
20000	100	0	0
30000	400	100	100
40000	4400	200	100
50000	9000	1200	200
60000	14400	3800	1900
70000	20700	6600	4200
80000	28200	9700	6700
90000	37100	13200	9600
100000	47900	17000	12700
110000	61500	21400	16300
120000	76800	26300	20400
130000	94900	31900	25100
140000	116200	38200	30500
150000	141700	45500	36700
160000	168800	53500	44000

CHAPTER V. CASE STUDIES

Several case study projects were chosen for comparing the use of incentive contracts using A+B bidding with standard contracts, most of which use increased liquidated damages. In this chapter, the selected projects are described along with findings and conclusions from the case studies.

Definitions

For the case studies, abbreviated listings have been used in report tables, using the following definitions:

1. CPM is used to denote a contracting specification or method with language similar to TxDOT Special Provisions Item 8, 008-223, (2-93). In general, this provision requires a contractor to submit a detailed critical path schedule for approval, then adhere to it. Regular monthly meetings between Contractor and TxDOT scheduling personnel are required, along with continual monitoring of actual progress compared to the approved schedule. If a Contractor falls behind schedule, he must submit a new schedule showing how he will catch up. Failure to do so results in withholding of progress payments.

2. STD means the standard, or conventional, type of bidding and/or project, usually with standard liquidated damages.

3. I/D 10K 60 indicates that an Incentive/Disincentive contract is used with $10,000 per day for Incentive/Disincentive payment, with maximum incentives of 60 days, or $600,000.

4. CAL-7, CAL-7H, CAL-6 etc. specify the method of determining contract time. CAL means a calendar day, 7 or 6 means Sundays are or are not included, and H means that holidays are not included. For example, CAL-7 means 365 contract days per year. CAL-6H means a six-day week with contractually specified holidays off.

5. LD-$1500 means liquidated damages of $1,500 per day and LD-$10K means liquidated damages of $10,000 per day.

Project Selection

Several criteria were used to select case study projects. In general, an attempt was made to identify all A+B and incentive projects constructed in Texas with any type of TxDOT involvement. In addition, an attempt was made to select similar non-A+B projects that could be used as controls for studying the effects of the A+B projects. The specific criteria used to select projects are listed below.

- Case study projects are major projects on heavily-traveled highways in urban areas of Texas.

- Case study projects employ contract provisions designed to shorten contract duration.

- Case study projects include, to the extent possible, projects that innovative contracting techniques of different types and projects that are similar and were completed at about the same time but do not use such techniques

Using these criteria and talking to district personnel in the largest cities of Texas, fourteen projects were chosen for inclusion in the case studies. In both the Houston and Dallas areas, a series of contiguous projects along a given highway were chosen for study. Along US 75 and IH 45 differing techniques were used. Along US 59, the Southwest Freeway in Houston, four individual projects used the same techniques, but inter-project coordination was required. These three series of projects were selected because each took place within the same general time frame, each carried the same general range of traffic, and each required the same type of construction. These case study projects are listed in Table 18.

Case Study Projects 1 through 4, the first four projects listed in Table 18, are in the Dallas area, and all are located contiguously on U.S. 75. The first two projects used A+B bidding with an incentive rate of $10,000 per day, and the second two used standard bidding with liquidated damages of $2,500 per day. Case Study Project 1 included work on Sundays but omitted major holidays (Cal-7H). The other three projects omitted work on both Sundays and major holidays (Cal-6H).

Case Study Projects 5 through 7 are all located on IH-45 in the Houston area. Case Study Project 5 used A+B bidding with an incentive payment of $5,000 per day and liquidated damages of the same rate, $5,000 per day. Case Study Project 6 also used A+B bidding but used a slightly larger incentive rate of $6,000 and used liquidated damages of $12,000. The third project on IH-45, listed as Case Study 7 was a standard contract with a liquidated damages rate of $3,328 per day. Case Study 5 is the only one in the entire sample that included Sundays and holidays in contract time (Cal 7). Case Study 6 omitted Sundays and holidays (Cal-6H) and Case Study 7 omitted only holidays (Cal-7H).

Case Study 8 is located in the Dallas area on SH 289 and used A+B bidding. Like Case Study Projects 1 and 2 in the Dallas area, the incentive rate was $10,000 per

Table 18. List of Texas Case Studies

Study No.	Highway	Limits	County	City	Control Section Job No.	Contractor	Contract Price $ Millions	Type of Bidding	Circa	Type of Time Charge*	Progress Method*	Liquidated Damages $ per day
1	US-75	I-635 to Beltline	Dallas	Dallas	47-7-112	Sunmount	39.83	A+B	1985-88	Cal 7-H	Incentive $10,000/Day	1,500
2	US-75	15th St. to Spring Cr. Parkway	Collin		47-6-70	Abrams	39.78	A+B	1987-89	Cal 6-H	Incentive $10,000/Day	1,500
3	US-75	Beltline to Collin C/L	Dallas		47-7-141	Austin Br.	41.50	Standard	1987-90	Cal 6-H	Standard	2,800
4	US-75	Collin C/L to 15th St	Collin		47-6-61	Zachry	23.58	Standard	1989-92	Cal 6-H	Standard	2,500
5	IH 45	CBD to Shepherd, Phase 1B	Harris	Houston		Champaign-Weber	8.19	A+B	1983-85	Cal 7	Incentive $5,000/Day	5,000
6	IH 45	CBD to Shepherd, Phase 2	Harris			Yeargin-Western	43.36	A+B	1985-87	Cal 6-H	Incentive $6,000/Day	12,000
7	IH 45	Shepherd to N.Belt., Phase 3	Harris		110-6-89	Brown & Root	67.87	Standard	1986-90	Cal 7-H	Standard	3,328
8	SH 289	Carpenter Rd to Prop. SH 190	Collin	Dallas	91-5-25	Thurman	15.87	A+B	1987-89	Cal 6-H	Incentive $10,000/Day	1,500
9	IH 35	Oltorf & Woodword Bridges	Travis	Austin		Allan	3.23	A+B	1986	Cal 7-H	Incentive $10,000/Day	10,000
10	West Beltway 8	Buffalo Bayou to IH 10	Harris	Houston	3256-1-30,39,40	Abrams	46.75	A+B	1986-87	Cal 6-H	Incentive $10,000/Day	10,000
11	US 59	Westpark to New Castle	Harris		27-13-123	Granite	59.07	Standard	1989-93	Cal 7-H	CPM	15,000 10,00 15,000 (milestones)
12	US 59	Beachnut to Westpark	Harris		27-13-126	Zachry	46.97	Standard	1989-92	Cal 7-H	CPM	15,000
13	US 59	Bissonnet to Beachnut	Harris		27-13-100	Traylor Bros.	47.50	Standard	1989-92	Cal 7-H	CPM	15,000
14	US 59	Newcastle to Shepherd	Harris		27-13-133	Abrams	40.12	Standard	1990-93	Cal 7-H	CPM	15,000

day and liquidated damages were $1,500 per day. It omitted Sundays and holidays (Cal-6H).

Case Study 9 is the only case study project located in Austin. It used A+B bidding and has incentive and disincentive rates of $10,000 per day. It allowed work on Sundays and omitted only holidays (Cal-7H).

Case Study 10 is located in the Houston area on West Beltway 8, from Buffalo Bayou to IH 10. It used A+B bidding and had incentives and disincentive rates of $10,000 per day. It omitted work on Sundays and holidays (Cal-6H).

Case Study projects 11 through 14 are all located on the Southwest Freeway (US 59) in Houston. All of these projects used large liquidated damages and controlled the work with a CPM schedule. All projects omitted work only on holidays (Cal-7H). Liquidated damages ranged from $10,000 to $15,000 on Case Study project 10, varying for different project milestones. Liquidated damages were $15,000 on all of the other projects. The use of CPM and project history for these projects is summarized very well in paper by Giaramita and White [27].

Findings

Table 19 contains a summary of the contract time data for the case study projects. All of the A+B projects were completed in less time than estimated. It is difficult to determine how much earlier they were completed than would have been the case without the A+B provision, since the estimated times apparently assume accelerated work. It can be concluded that, whatever its other shortcomings, A+B bidding certainly is effective in reducing project completion times.

Table 20 summarizes case study cost data. With one exception, A+B and I/D projects cost from 6 to 38% more than the Engineer's Estimate. Of the three standard projects, one was under and two were over the engineer's estimate: -1.3%, +6.5%, and +17.1%. The four CPM projects were at or under the Engineer's Estimate. In no case did the final cost of a project vary greatly from the contract amount.

Table 21 examines the average rate of construction cost per month. Two of the incentive contracts averaged over $2,000,000 per month, they were concentrated work areas. From the rest of the rates, one could conclude that $1,000,000 per month might be a reasonable rule of thumb regardless of the techniques employed.

Table 19. Summary, Contract Time

Case Study Number	Bidding Method*	Progress Method*	Liquidated Damages	Contract Time (Cal Days)	Additional Days Granted	Total Days Allowed	Day Used
1	A+B	I/D 10K60	1,500	1010 I/D 1040 Total	0 0	1010 1040	950 1036
2	A+B	I/D 10K60	1,500	850 I/D 1100 Total	0 0	850 1100	698 698
3	Standard	Standard	2,800	852	20	872	892
4	Standard	Standard	2,500	780	20	800	770
5	A+B	I/D 5K90	5,000	360 I/D 540 Total	0 0	360 540	269 470
6	A+B	I/D 12K120	12,000	750	120	870	700
7	Standard	Standard	3,328	900	131	1031	1087
8	A+B	I/D 10K60	1,500	525	0	525	465
9	A+B	I/D 10K	10,000	61	0	61	42
10	A+B	I/D 10K60	10,000	791	0	791	579
11	Standard	CPM	15,000	1200	32	1232	1200
12	Standard	CPM	15,000	1020	48	1068	1068
13	Standard	CPM	15,000	1005	36	1041	1041
14	Standard	CPM	15,000	1190	0	1190	1069

* Definitions:

1. A+B, I/D indicates use of A+B bidding with incentive/disincentive contract provisions.
2. Standard means the conventional type of bidding and/or project, with standard liquidated damages and no incentive/disincentive provision in the contract.
3. CPM denotes a contracting specification or method similar to TxDOT Special Provisions, Item 8, 008–223, (2-93). In general, this provision requires a contractor to submit a detailed critical path schedule for approval, then adhere to it. Regular monthly meetings between contractor and TxDOT scheduling personnel are required, along with continual monitoring of actual progress compared to the approved schedule. If a contractor falls behind schedule, he must submit a new schedule showing how he will catch up. Failure to do so results in withholding of progress payments.

Table 20. Case Study, Cost Comparisons

Study No.	Highway Location	Methods Used*	Engineers Estimate plus Misc. $ Millions	Low Bid plus Misc.	Percentage Over (Under) Estimate	Contract Amount $Millions	Final Estimate $ Millions	Percentage Over (Under) Contract
1	US 75 Dallas	A+B I/D	44.298	54.015	22.0	39.834	40.782	2.4
2	US 75 Dallas	A+B I/D	41.762	52.319	25.3	39.781	40.394	1.5
3	US 75 Dallas	Standard	42.486	41.920	(1.34)	41.502	41.221	(0.7)
4	US 75 Dallas	Standard	22.175	23.610	6.5	23.584	23.712	0.5
5	IH 45 Houston	A+B I/D	8.684	8.187	(7.8)	8.187	NA	NA
6	IH 45 Houston	A+B I/D	39.153	43.361	10.7	43.361	NA	NA
7	IH 45 Houston	Standard	63.836	74.727	17.1	67.865	72.959	7.5
8	SH 289 Dallas	A+B I/D	21.385	22.736	6.3	15.868	16.181	2.0
9	IH-35 Austin	A+B I/D	2.346	3.235	37.9	3.235	NA	NA
10	W. Belt 8 Houston	A+B I/D	48.246	59.342	23.0	46.754	NA	NA
11	US 59 Houston	CPM	62.937	61.057	(3.1)	59.071	59.724	1.1
12	US 59 Houston	CPM	51.564	47.826	(7.4)	46.974	48.99	3.7
13	US 59 Houston	CPM	47.914	48.285	0.8	47.499	48 .16	2.1
14	US 59 Houston	CPM	40.884	40.629	(0.6)	40.123	39.468	(1.6)

* Definitions:

1. A+B, I/D indicates use of A+B bidding with incentive/disincentive contract provisions.
2. Standard means the conventional type of bidding and/or project, with standard liquidated damages and no incentive/disincentive provision in the contract.
3. CPM denotes a contracting specification or method similar to TxDOT Special Provisions, Item 8, 008--223, (2-93). In general, this provision requires a contractor to submit a detailed critical path schedule for approval, then adhere to it. Regular monthly meetings between contractor and TxDOT scheduling personnel are required, along with continual monitoring of actual progress compared to the approved schedule. If a contractor falls behind schedule, he must submit a new schedule showing how he will catch up. Failure to do so results in withholding of progress payments.

Table 21. Case Study, Duration-Cost Comparisons

Case Study No.	Highway Location	Methods Used*	Contract Amount $ Millions	Final Amount $ Millions	Contract Duration Months	Average Rate $ Millions per month
1	US 75 Dallas	A+B I/D 10,000 Cal-7H LD 1500	39.83	40.78	36	1.13
2	US 75 Dallas	A+B I/D 10,000 Cal-6H LD 1500	39.78	40.39	28	1.44
3	US 75 Dallas	STD Cal-6H LD 2800	41.50	41.22	37	1.12
4	US 75 Dallas	STD Cal-6H LD 2500	23.58	23.72	30	0.79
5	IH 45 Houston	A+B I/D 5000 Cal-7 LD 5000	8.19	NA	9 I/D 15 Final	0.55 Est
6	IH 45 Houston	A+B I/D 6/12K Cal-6H LD 12K	43.36	NA	27	1.61 Est
7	IH 45 Houston	STD Cal-7H LD 3328	67.87	72.96	50	1.46
8	SH 289 Dallas	A+B I/D 10,000 CAL-6H LD 1500	15.87	16.18	21	0.77
9	IH 35 Austin	A+B I/D 10,000 CAL-7H LD 10,000	3.23	NA	1.4	2.31 Est
10	W. Belt 8 Houston	A+B I/D 10,000 Cal-6H LD 10,000	46.75	NA	19	2.46 Est
11	US 59 Houston	CPM Cal-7H LD 15,10,15K	59.07	59.72	44	1.35
12	US 59 Houston	CPM Cal-7H LD 15,000	46.97	48.70	47	1.04
13	US 59 Houston	CPM Cal-7H LD 15,000	47.50	48.52	47	1.03
14	US 59 Houston	CPM Cal-7H LD 15,10,15K	40.12	39.47	40	0.99

<u>Range:</u>
1. A+B, I/D: $0.55 to $2.46 Million per month
2. CPM: $0.99 to $1.35 Million per month
3. STD: $0.79 to $1.46 Million per month

* Definitions:

1. CPM denotes a contracting specification or method similar to TxDOT Special Provision, Item 8, 008–223, (2-93). In general, this provision requires a contractor to submit a detailed critical path schedule for approval, then adhere to it. Regular monthly meetings between contractor and TxDOT scheduling personnel are required, along with continual monitoring of actual progress compared to the approved schedule. If a contractor falls behind schedule, he must submit a new schedule showing how he will catch up. Failure to do so results in withholding of progress payments.
2. STD indicates standard, or conventional, type of bidding and/or project.
3. For Incentive-Disincentive Contracts, including A+B contracts, the following abbreviated style is used: I/D 10K 60 = $10,000 per day I/D with maximum incentives of 60 days, or $600,000.
4. CAL-7, CAL-7H, CAL-6, etc. specify the method of determining contract time. CAL means a calendar day, 7 or 6 means Sundays are or are not included, and H means that holidays are not included. For example, CAL-7 means 365 contract days per year. CAL-6H means a six-day week with contractually specified holidays off.
5. LD-$1500 or LD-$10K means liquidated damages of $1,500 per day or of $10,000 per day.

Table 22 includes a summary of information on the Case Study projects using A+B bidding. Major findings of the case studies are as follows:

* With the exception of two of the three "standard" projects, the other case studies finished on time or earlier.

* On all of the incentive contracts where the contractors selected contract time (A+B bidding), the contractors earned the maximum bonus allowed.

* The CPM provision used on the four Southwest Freeway projects ended with a substantially "on-time, under-budget" result. TxDOT/METRO staff estimate that use of CPM reduced overall combined project duration from five years to three years.

* Where A+B bidding was employed, in only one of seven cases was the low bidder determined by the time-bid.

Conclusions

Regardless of the type of contract provision used, computation of working time is critical. More training in estimating time (preferable by CPM) should be employed, with feedback from field personnel.

Whatever technique is used to minimize project duration, *TxDOT must provide enough trained field personnel* to match the effort the contractor is required to exert to meet the project schedule. If the project is urgent enough to warrant an accelerating technique, it also warrants TxDOT to devote commensurate resources. This applies not only to project staff but also to district and headquarters personnel.

Since the World War II, techniques such as PERT and CPM have been widely used to schedule project elements and estimate project duration. But their use was hampered by the effort needed for rigorous application. In the 1980s, two advances took place: (1) development of moderately-priced, readily-learned, computer software capable of handling CPM scheduling and monitoring on major highway projects; and (2) development of moderately-priced personal computers with multi-megabyte random-access memories (RAM) and hard discs capable of storing hundreds of megabytes, as well as peripheral equipment appropriate to the task. These developments have made use of CPM analyses for both project planning and construction viable. With adequate training, more widespread use by TxDOT can benefit Texas motorists considerably more than the cost.

No single contracting provision assures that a given contractor will complete an

Table 22. Summary of A+B Incentive/Disincentive Projects

Case Study No.	Locale	Contract Amount $ Millions	Time Bid(B)	Incentive			Time Used	Incentive Earned Days	Incentive Earned $	Percent of Contract
			Days	Max Days	$/Day	Max $ Allowed	Days			
1	Dallas	39.834	1010	60	10,000	600,000	950	60	600,000	1.5
2	Dallas	39.781	850	60	10,000	600,000	698	152	600,000	1.5
5	Houston	8.187	360	90	5,000	450,000	269	91	450,000	5.5
6	Houston	43.361	870*	170	6,000	1,020,000	700	170	1,020,000	2.4
8	Dallas	15.868	525	60	10,000	600,000	465	60	600,000	3.8
9	Austin	3.235	61	?	10,000	?	42	19	190,000	5.9
10	Houston	46.754	791	60	10,000	600,000	579	112	600,000	1.2

* Contractor bid 750 days and was allowed 120 additional days for a field change, giving a total of 870 days.

urgent project as fast as the contracting agency desires. For that matter, no combination of techniques can guarantee that end. But, by selecting a blend of contract provisions tailored to a specific project (rather than a blanket policy), the odds of getting on-time project completions are greatly improved.

There is one major proviso. To meet a tight project schedule, the contractor often will have to work more than one shift and use a six or seven day week. Then, the contracting agency must have a sufficient number of qualified, trained engineering/inspection personnel on hand to assure specification compliance without overworking such personnel. Headquarters personnel must be available to support the field personnel.

The case study projects reviewed in this study are limited to major projects on heavily traveled highways in urban areas, and how such projects can be constructed quickly. The study focuses on contract provisions and techniques, not on design, plan-preparation or construction methods to achieve the same end.

The techniques studied fall into the two traditional "carrot and stick" categories: providing a financial reward for the contractor who is able to complete a project ahead of a stated schedule, and charging a contractor who fails to meet the contract time. The case studies and previous discussions identify several contract provisions in both categories.

Recommendations

When should a specific strategy be used? Each project must be viewed on its own. However, the data and experiences gathered in this study suggest the following general recommendations:

* Based on the case studies and the experience in Texas, it is concluded that incentive/disincentive provisions, with or without A+B bidding, should *not* be used routinely in Texas at this time. They should be reserved for special cases that: are of great urgency; are of short duration; have a "clean" set of plans; and have little chance of field changes.

* For the type of project discussed in this study, liquidated damages should include user costs; so should incentives and disincentives.

* A+B bidding is a technique that does *not* have to be tied to I/D provisions. It can be used alone, although it has not been tested this way in Texas. There appears to be no impediment to using A+B bidding along with a CPM specification.

* The CPM specification which as been employed by some TxDOT Districts should be used more often. The success of the four concurrent, abutting projects on the Southwest Freeway in Houston (circa 1989-93) amply demonstrates its effectiveness, even on complex, interrelated projects.

* There are many other contract provisions/techniques applicable to construction projects. These include, for example, pre-qualification restrictions, partnering, and end-result specifications. However, while these may help expedite progress, avoid problems, and improve quality, their basic intent is not to shorten project duration.

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