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16. Abstract

This study presents new estimates of project completion times, construction engineering costs for project overruns, and motorist costs for project overruns. A theoretical model is developed for evaluating alternative strategies for using bonuses and liquidated damages. Research results indicate that the preferred strategy is to use a procedure whereby contractors bid working days. For critical projects it is recommended that a bonus be paid. For other projects, it is recommended that contractors also be required to bid project working days and pay liquidated damages for overruns but receive no bonus for early completion. It is estimated that the total cost for completing projects will be decreased substantially by using improved bidding strategies and larger liquidated damages.

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PROJECT COMPLETION TIMES AND EVALUATION OF BIDDING STRATEGIES WITH BONUSES AND LIQUIDATED DAMAGES

by

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Research Report 412-1F
Research Study Number 2-6-85-412
Project Completion Time and Project Overruns

Sponsored by

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Texas Transportation Institute
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College Station, Texas

PREFACE

The authors are indebted to John Finley and Jerry Selby of the Texas State Department of Highways and Public Transportation (SDHPT) for their assistance throughout this project. They also are indebted to many individuals in SDHPT districts for providing detailed construction project data that are used in the statistical analysis in Chapters II and III.

The Texas Transportation Institute staff that assisted with this project includes Jesse L. Buffington, who assisted with the literature review and data collection. John B. Rollins performed the statistical analysis of project completion times and construction engineering costs and wrote Chapters II and III. Raymond A. Krammes developed the analysis of road user costs and wrote Chapter IV. Jeffery L. Memmott assisted with the theoretical modeling in Chapters IV and V. Margaret K. Chui assisted with Chapter V. Patricia Holmstrom served as Economics Program secretary, assisted with data entry, and typed the research report. Olga Pendleton assisted with the statistical analysis in Chapters II and III. Mohammad R. Sholevar assisted with the literature review and he and Jose Acosta assisted with data entry. William F. McFarland served as study supervisor and developed the theoretical models in Chapter V.

SUMMARY OF FINDINGS

The objectives of this research are to develop new techniques for estimating project completion times and construction engineering and motorist costs associated with project overruns and to evaluate alternative strategies for paying bonuses.

New statistical relationships are provided for estimating project completion times as a function of project cost and type of project.

New estimates are presented of the costs of project overruns. The costs include construction engineering costs and motorists' time and vehicle operating costs from extended construction activity. It is recommended that new values be used for liquidated damages and bonuses equal to the construction engineering costs plus 15 percent of motorist costs. It is not recommended that full motorist costs be used because of the shortage of highway funds for paying for reducing project completion time.

An analysis of alternative strategies for paying bonuses and/or bidding working days produced several interesting results. It was shown that current procedures of setting contract working days and charging liquidated damages do not minimize total cost unless two conditions are met: (1) it is necessary that the liquidated damages rate be set high enough; (2) it is necessary that contract working days be set equal to or less than the number of days for which the rate of increase in construction cost from reducing working days equals the rate of decrease in other Department and motorist costs from reducing the number of working days. Since there is no way for the Department to know the shape of the cost curves for contractors that will bid on a job, it is difficult to implement an optimal strategy with the current approach. This research does indicate, however, that an optimal solution might be provided with current procedures if the contract days are set with a very tight schedule and the correct liquidated damages are used.

Analysis of the procedure of having contractors bid on working days indicates that this is a very good strategy for minimizing total costs. Based on the analysis, it is recommended that this procedure with payment of bonuses be used for an increased number of critical projects. It further is recommended that this procedure without payment of bonuses be trial tested for use on other projects.

IMPLEMENTATION STATEMENT

This research produced several results that can be implemented by the Texas State Department of Highways and Public Transportation and also may be of interest to other agencies.

Project Completion Time Estimation

Statistical equations were developed for predicting project completion times in working days. It is recommended that districts test the use of these equations. Graphs and tables have been provided for ease of use.

Daily Rates for Liquidated Damages and Bonuses

New estimates have been made of the cost to the Department and motorists for project overruns. It is recommended that the new values for Department cost in Chapter III be added to 15 percent of the motorist costs in Chapter IV to obtain rates for liquidated damages and bonuses.

Bidding Strategies

The discussion presented in Chapter V indicates that a new approach to construction project bidding will lead to substantial benefits in terms of reduced total costs for projects. For projects with large motorist delays during construction and for other critical projects it is recommended that contractors be required to bid project working days and be paid a bonus for early completion and charged liquidated damages for late completion. This strategy already is being used on some projects and it is recommended that its use be expanded.

Perhaps the most interesting conclusion of the analysis in Chapter V is that having contractors bid working days and charging liquidated damages for overruns was found to give very good results even when there is no bonus. The potential benefit of using this approach on all projects is so large that it is recommended that this approach be tested on a variety of projects in the near future, with the possible future goal of using this approach on almost all projects, other than those where bidding working days with a bonus is used.

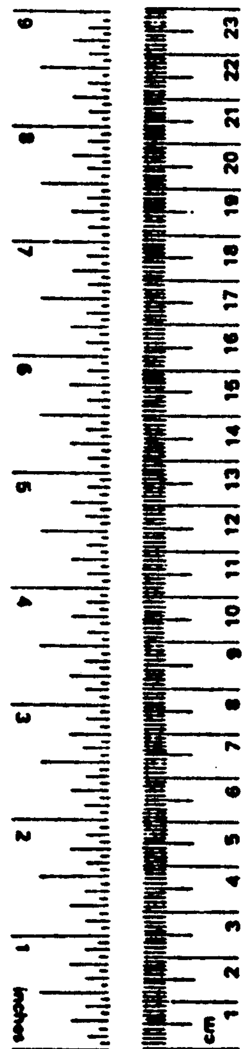
Using improved bidding strategies together with the higher liquidated damages rates is strongly recommended.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

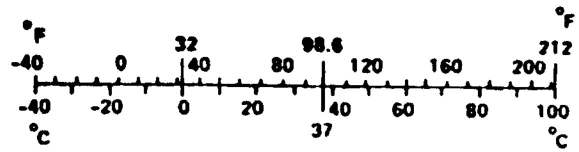
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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CHAPTER I. INTRODUCTION

Objectives

Delays in completion of construction projects increase costs to the State Department of Highways and Public Transportation and to the public. It may be possible to reduce these delays and costs by more accurately estimating project completion times; by using a different schedule of liquidated damages; or by using a different strategy such as paying bonuses for early completion or letting contractors bid the number of working days (with or without bonuses). To investigate these possibilities, this study has three objectives:

1. Develop a uniform method for estimating completion times for various types of construction activities in different geographical parts of the state.

2. Determine costs to the public of project overruns and recommend liquidated damages for projects.

3. Study the feasibility of paying bonuses to contractors for completing a project ahead of time.

Current Practices

To determine current practices, a review was made of relevant literature, and several states and all 24 Department districts in Texas were surveyed. This survey emphasized: (1) techniques for calculating project completion times, in either calendar days or working days, and (2) schedules for liquidated damages.

Estimation of Project Completion Times

Two methods are widely used for estimating project completion times: (1) use of a plot of working days versus project construction and type, and (2) use of production quantities, with calculations made on a worksheet or plotted on a bar chart [1]. One or both of these techniques are used by all 24 districts in Texas, together with judgment and past experience. Some states also use some type of Critical Path Method (CPM). A computerized CPM procedure is used in Michigan. A few of the large urban districts in Texas use CPM on large projects where timing of activities is especially critical. In this study, emphasis was placed on development of statistical equations for estimating working days as a function of construction cost and project type. These results are presented in Chapter II.

Liquidated Damages Schedules

The American Association of State Highway and Transportation Officials periodically publishes a schedule of liquidated damages for projects with different construction costs [2]. Two schedules are published, one by calendar days and one by working days. Most states follow these AASHTO schedules very closely. Some states use a slightly different schedule, with the most important differences being that their schedule continues increasing for higher cost projects, and some states now use higher values than those in the AASHTO Guide. The currently-used Texas schedule is based on working days and is shown in Table 1.

Payment of Bonuses

According to a recent survey made by the New Jersey Department of Transportation, a large number of states has experimented with use of bonuses, especially for such conditions as a bridge out of service, a lengthy detour, or excessive disruption of traffic [8]. Reported bonuses range up to $10,000 per day and liquidated damages often are of a comparable amount.

One ingenious strategy for paying a bonus, which is currently used in Texas and is based on a concept used previously in Mississippi, is a procedure whereby a contractor bidding on a job bids not only the construction cost but also the number of working days. This bid number of working days is multiplied by the bonus/liquidated damages rate and the result is added to the contractor's construction cost bid to obtain his total bid. The contractor with the lowest total bid is awarded the contract. He is paid his construction cost bid plus a bonus if he completes the job in less days than his bid number of days or is charged liquidated damages if he runs over his bid number of days.

One of the primary contributions of the present research is the development of a theoretical model for analyzing alternative bidding strategies, including this strategy of bidding working days, with and without the use of a bonus.

Table 1. Texas Schedule for Liquidated Damages

Contract Amount		Amount of Liquidated Damages Per Working Day
From More Than	To and Including	
$ 0	$ 25,000	$ 63
25,000	50,000	105
50,000	100,000	154
100,000	500,000	210
500,000	1,000,000	315
1,000,000	2,000,000	420
2,000,000	5,000,000	630
5,000,000	10,000,000	840
10,000,000	15,000,000	1,050
15,000,000	20,000,000	1,260
20,000,000	Over 20,000,000	1,500

Source: Reference 3, p. 30.

Contents of Report

Chapter II of the report presents the results of the statistical analysis of project completion times. Chapters III and IV present the results for estimating Department and motorist, or road user, cost associated with project overruns. Chapter III gives figures and tables for estimating the Department's construction engineering costs and Chapter IV gives tables of road user costs for different types of construction projects. Chapter V presents theoretical models that can be used to evaluate different strategies for project bidding. The study conclusions and recommendations are summarized in Chapter VI.

CHAPTER II. ESTIMATION OF WORKING DAYS

Before a construction project can be funded, the number of working days required for its completion must be estimated. The estimate of working days specified in the contract for a particular project provides a basis for bidding, work scheduling, and the assessing of liquidated damages against a contractor when the number of working days required for completion of the project exceeds the number of contract working days plus any additional days granted. One objective of this study was to develop an estimation technique that would facilitate the procedure for estimating working days for construction projects.

An equation for estimating working days was developed from data on construction projects. Two data sets were used, the first consisting of very detailed information on 300 projects, and the second consisting of less detailed data on 2,201 other projects. The first data set was used in evaluating the importance of many different factors in determining working days. The second data set was used in developing an equation for estimating working days as a function of the factors found to be most important.

Description of the Data

Two sets of data on construction projects completed between late 1981 and early 1985 were compiled from D-6's monthly construction reports. The first data set was used to identify the factors most useful in estimating working days for a particular project. From the extensive amount of data collected on the 300 projects in this data set, the following factors were evaluated:

1. SDHPT district
2. Rural or urban area
3. ADT level (present ADT, ADT at project letting, estimated future ADT)
4. Type of improvement (added capacity, rehabilitation, new location)
5. Number of structures involved
6. Type of terrain
7. Type of soil
8. Amount of rainfall
9. Average wintertime temperature
10. Number of winter seasons during course of project
11. Project cost
12. Type of work done

Only the last two factors were found to affect working days by more than about one day. Therefore, the second data set, which included project cost and type of work done (project type) for 2,201 projects, was used in developing an equation for estimating working days as a function of project cost and type of project.

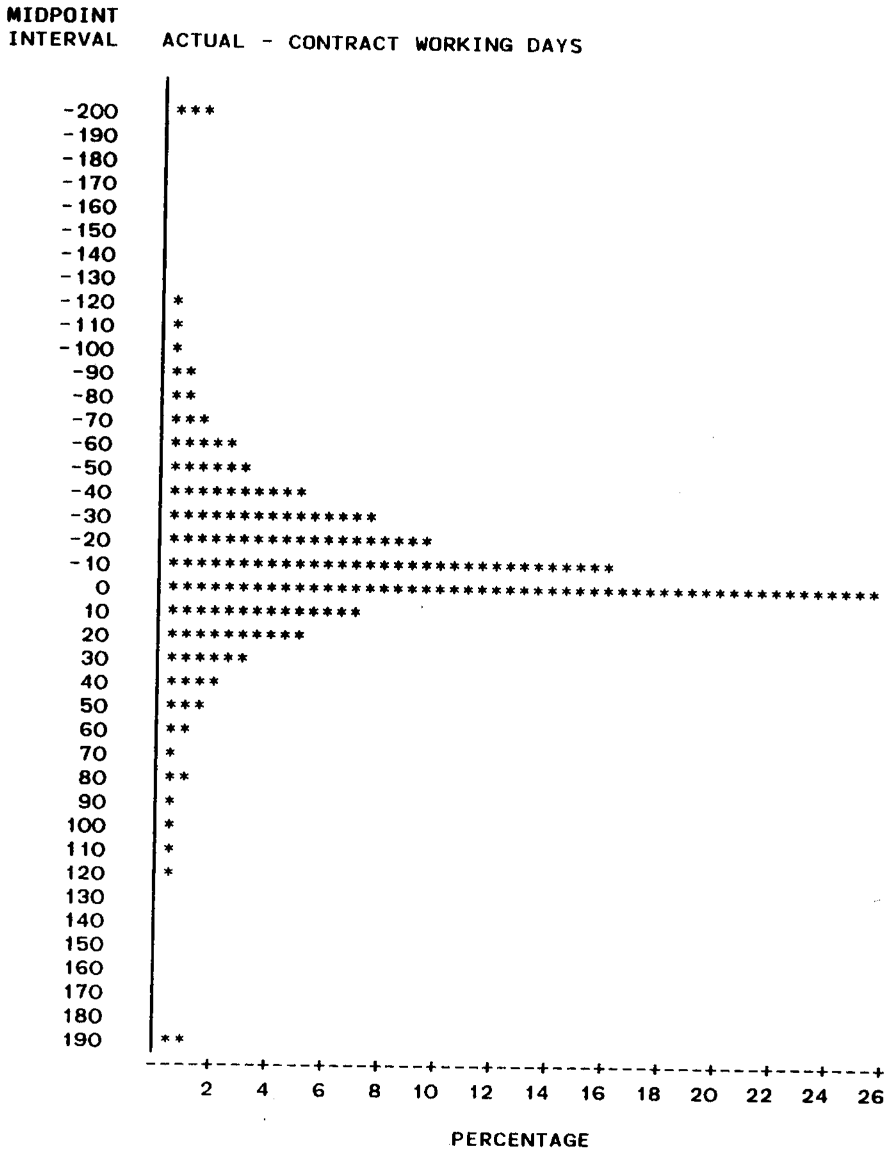
Project types in the set of 2,201 construction projects were defined similarly to the descriptions of the type of work done on construction projects in the monthly construction reports. Project types used in estimating working days were defined as follows:

1. Type 1 - grading, base, flexible base, and pavement, with structures (715 projects)
2. Type 2 - bridge or overpass (241 projects)
3. Type 3 - grading, base, flexible base, and pavement, without structures (192 projects)
4. Type 4 - hot-mix asphaltic concrete pavement only (132 projects)
5. Type 5 - seal coat only (173 projects)
6. Type 6 - pavement repairs, lighting, markings, landscaping, and miscellaneous types of work not included in one of the other five categories (748 projects)

Equation for Estimating Working Days

Using the data set of 2,201 projects, an equation for estimating project working days was developed. Because contractors have to pay liquidated damages on time overruns but not on underruns, the distribution of overruns and underruns (actual working days minus contract working days) is not normally distributed. This distribution is shown as a histogram in Figure 1, with underruns (negative differences) and overruns (positive differences) plotted by cumulative percentages. It should be noted that, in Figure 1, the midpoints (not upper limits) of the intervals of underruns and overruns are given; hence, the cumulative percentage for the interal centered on 0 (from five days underrun to five days overrun) is 75.60 percent, although the cumulative percentage of total underruns is 65 percent, i.e., 35 percent overruns.

Because it fit the data much better than a simple linear model, a logarithmic model relating working days to project cost and type was developed using the set of 2,201 projects. All of the estimated coefficients in the model were significant at the 1 percent significance level, and the goodness-of-fit statistic R^2 had a value of 0.69 (i.e., the model explained 69 percent



MIDPOINT INTERVAL	FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
-200	32	32	1.45	1.45
-190	2	34	0.09	1.54
-180	1	35	0.05	1.59
-170	2	37	0.09	1.68
-160	1	38	0.05	1.73
-150	2	40	0.09	1.82
-140	4	44	0.18	2.00
-130	5	49	0.23	2.23
-120	7	56	0.32	2.54
-110	9	65	0.41	2.95
-100	14	79	0.64	3.59
-90	18	97	0.82	4.41
-80	24	121	1.09	5.50
-70	35	156	1.59	7.09
-60	52	208	2.36	9.45
-50	65	273	2.95	12.40
-40	105	378	4.77	17.17
-30	165	543	7.50	24.67
-20	211	754	9.59	34.26
-10	347	1101	15.77	50.02
0	563	1664	25.58	75.60
10	159	1823	7.22	82.83
20	109	1932	4.95	87.78
30	65	1997	2.95	90.73
40	41	2038	1.86	92.59
50	31	2069	1.41	94.00
60	23	2092	1.04	95.05
70	13	2105	0.59	95.64
80	20	2125	0.91	96.55
90	14	2139	0.64	97.18
100	8	2147	0.36	97.55
110	9	2156	0.41	97.96
120	7	2163	0.32	98.27
130	3	2166	0.14	98.41
140	4	2170	0.18	98.59
150	2	2172	0.09	98.68
160	1	2173	0.05	98.73
170	4	2177	0.18	98.91
180	3	2180	0.14	99.05
190	21	2201	0.95	100.00

Figure 1. Actual Distribution of Project Underruns and Overruns.

of the variation in working days). The following equation, based on the assumption of a normal distribution of overruns and underruns, was estimated:

$$
\begin{aligned}
(1)\quad \ln \text{WORKDAYS} = {} & 4.632 \\
& +0.410\ \text{TYPE1} \\
& +0.667\ \text{TYPE2} \\
& +0.142\ \text{TYPE3} \\
& -0.455\ \text{TYPE4} \\
& -0.760\ \text{TYPE5} \\
& +0.120\ \text{TYPE1} \times \ln \text{COST} \\
& +0.217\ \text{TYPE2} \times \ln \text{COST} \\
& +0.146\ \text{TYPE3} \times \ln \text{COST} \\
& +0.359\ \text{TYPE4} \times \ln \text{COST} \\
& +0.125\ \text{TYPE5} \times \ln \text{COST} \\
& +0.341\ \ln \text{COST}
\end{aligned}
$$

where the variables were defined as:

ln WORKDAYS = natural logarithm of working days

ln COST = natural logarithm of project cost, i.e., total work done (millions of dollars, deflated by the construction cost component of the Highway Cost Index)

TYPE1 = 1 if Type 1 project
= 0 otherwise

TYPE2 = 1 if Type 2 project
= 0 otherwise

TYPE3 = 1 if Type 3 project
= 0 otherwise

TYPE4 = 1 if Type 4 project
= 0 otherwise

TYPE5 = 1 if Type 5 project
= 0 if otherwise

To exclude the effects of inflation on the estimate of working days, project cost was deflated using the construction cost component of the Highway Cost Index (12-month moving average, August 1979 = 100 percent). The equation pertained to a Type 0 project whenever all five variables for project type were equal to zero.

In order to maintain consistency between estimated working days and present SDHPT practice regarding the proportion of project overruns allowed, an overrun rate of 35 percent was used in developing the equation for estimating working days. In the data set of 2,201 construction projects used in estimating equation (1), time overruns occurred for 35 percent of the projects, although the rate of overruns that resulted in the assessment of liquidated damages against contractors (i.e., working days exceeded the sum of contract working days and additional days granted) was 24 percent. Since contract working days reprsented the original estimate of the time required to complete a project, the 35 percent proportion was used as the basis for estimating working days in equations (1) and (2).

To account for this 35 percent proportion of overruns, the log of the upper prediction interval (ln UPI) was calculated as:

$$\begin{aligned}(2)\quad \ln \text{UPI} &= \ln \text{WORKDAYS} + ts(1 + 1/n)^{0.5}\\ &= \ln \text{WORKDAYS} + (0.3854)(0.5213)(1 + 1/2{,}201)^{0.5}\\ &= \ln \text{WORKDAYS} + 0.2009\end{aligned}$$

where t is the t-statistic for a one-tail prediction interval of 35 percent for a normal distribution, s is the root mean square error of the regression equation, and n is the sample size. The number of working days was then estimated as:

$$\begin{aligned}(3)\quad \text{WORKDAYS} &= \text{EXP}(\ln \text{UPI})\\ &= \text{EXP}(\ln \text{WORKDAYS} + 0.2009)\\ &= 1.21\ \text{EXP}(\ln \text{WORKDAYS})\end{aligned}$$

The predicted distribution of overruns and underruns (actual working days minus predicted working days) based on equations (1) and (3) is shown in Figure 2. A distribution of estimated working days with an overrun rate of 35 percent, consistent with present SDHPT practice, was obtained for the sample of construction projects. In Figure 2, the cumulative percentage for the interval centered on 0 is given as 70.20 percent, although the cumulative percentage of underruns is 65 percent, i.e., 35 percent overruns, as in Figure 1.

The distribution of overruns and underruns based on working days predicted from equations (1) and (3), shown in Figure 2, has a modal interval centered on -10, suggesting that contractors would most commonly underrun by about 10 working days when equations (1) and (3) are used to estimate working days. This is because the distribution in Figure 2 is based on a lognormal model, while actual underruns and overruns in the data sample are not quite normally distributed, as shown in Figure 1. Contractors often use all of the contract working days allotted rather than underrunning by a few days, as a means of making their own work schedules more flexible and thereby reducing their operating costs. Hence, it is expected that, in practice, the distribution of overruns and underruns resulting from estimating working days from equations (1) and (3)

MIDPOINT INTERVAL	ACTUAL - PREDICTED WORKING DAYS	FREQ	CUM. FREQ	PERCENT	CUM. PERCENT
-200	***	34	34	1.54	1.54
-190		1	35	0.05	1.59
-180	*	6	41	0.27	1.86
-170	*	8	49	0.36	2.23
-160	*	6	55	0.27	2.50
-150	*	8	63	0.36	2.86
-140		4	67	0.18	3.04
-130	*	8	75	0.36	3.41
-120	*	8	83	0.36	3.77
-110	**	17	100	0.77	4.54
-100	**	20	120	0.91	5.45
-90	**	22	142	1.00	6.45
-80	****	45	187	2.04	8.50
-70	*****	55	242	2.50	11.00
-60	*******	77	319	3.50	14.49
-50	**********	107	426	4.86	19.35
-40	**************	153	579	6.95	26.31
-30	******************	199	778	9.04	35.35
-20	***********************	258	1036	11.72	47.07
-10	**************************	283	1319	12.86	59.93
0	*********************	226	1545	10.27	70.20
10	***************	166	1711	7.54	77.74
20	*************	138	1849	6.27	84.01
30	*******	77	1926	3.50	87.51
40	******	61	1987	2.77	90.28
50	****	43	2030	1.95	92.23
60	***	34	2064	1.54	93.78
70	**	19	2083	0.86	94.64
80	**	20	2103	0.91	95.55
90	**	21	2124	0.95	96.50
100	*	7	2131	0.32	96.82
110	*	12	2143	0.55	97.36
120	*	13	2156	0.59	97.96
130	*	8	2164	0.36	98.32
140		2	2166	0.09	98.41
150		4	2170	0.18	98.59
160		3	2173	0.14	98.73
170		2	2175	0.09	98.82
180		3	2178	0.14	98.96
190	**	23	2201	1.04	100.00

2 4 6 8 10 12 14 16 18 20 22 24 26

PERCENTAGE

Figure 2. Predicted Distribution of Project Underruns and Overruns.

would closely approximate the distribution shown in Figure 1, with a modal interval centered on 0.

Working days for any project type and constant-dollar cost can be estimated using equations (1) and (3). Working days by project type and cost are presented in Table 2 and depicted graphically in Figure 3. If the desired project cost is not given in Table 2, then working days can be obtained by interpolation.

For purposes of comparing estimates of working days by project type and cost vs. estimates by project cost only, the following equation was developed:

(4) ln WORKDAYS = 4.800 + 0.453 ln COST

The R^2 value was 0.51, compared with 0.69 for equation (1). Because equation (4) does not account for project type, it is less precise than equation (1) in estimating working days. With a root mean square error of 0.6555, equation (4) leads to the following equation for working days, obtained similarly to equation (3):

(5) WORKDAYS = 1.28 EXP(ln WORKDAYS)

Estimates of working days for all project types combined, based on equation (8), are shown in Table 2 for comparison with working days by project type. However, because equation (6) is less precise than equation (1), estimates of working days should always be made by project type and cost, not project cost alone.

Adjustment of Overrun Rate

A change in the overrun rate from 35 percent to some other rate can be accomplished by altering the t value in equation (2) and thereby adjusting the factor 1.21 in equation (3). Adjusting this factor has the effect of shifting the distribution in Figure 2, thereby either increasing or decreasing the percentage of overruns. This is illustrated by the following range of overrun rates and corresponding factors:

20 percent: WORKDAYS = 1.47 EXP(ln WORKDAYS)
25 percent: WORKDAYS = 1.37 EXP(ln WORKDAYS)
30 percent: WORKDAYS = 1.29 EXP(ln WORKDAYS)
35 percent: WORKDAYS = 1.21 EXP(ln WORKDAYS)
40 percent: WORKDAYS = 1.14 EXP(ln WORKDAYS)

Table 2. **Working Days by Project Cost and Type.**

Project Cost[a] (Constant $)	Working Days by Project Type[b]						
	0	1	2	3	4	5	All
$ 50,000	45	47	46	33	10	14	43
100,000	57	65	67	47	16	20	59
200,000	72	89	99	65	26	27	81
300,000	82	108	124	80	34	33	97
400,000	91	123	145	92	42	38	111
500,000	98	136	164	102	49	42	122
600,000	104	148	182	112	55	46	133
700,000	110	159	198	120	61	49	143
800,000	115	169	214	129	67	52	152
900,000	120	178	228	136	73	55	160
1 Million	124	187	242	143	79	58	168
2 Million	157	258	357	201	128	80	230
3 Million	181	311	447	245	170	97	276
4 Million	199	355	525	281	208	111	314
5 Million	215	393	594	314	243	123	348
6 Million	229	428	658	343	276	-	378
7 Million	241	459	717	370	308	-	405
8 Million	253	488	773	394	338	-	430
9 Million	263	516	825	418	367	-	454
10 Million	273	541	875	440	395	-	476
15 Million	313	653	1,097	536	-	-	572
20 Million	-	745	-	-	-	-	-
25 Million	-	826	-	-	-	-	-
30 Million	-	898	-	-	-	-	-

[a]Deflated using construction cost component of Highway Cost Index (Aug 1979=100)

[b]Project types are defined as:

0 - pavement repairs, lighting, markings, landscaping, miscellaneous
1 - grading, base, flexible base, and pavement, **with** structures
2 - bridge or overpass
3 - grading, base, flexible base, and pavement, **without** structures
4 - hot-mix asphaltic concrete pavement only
5 - seal coat only

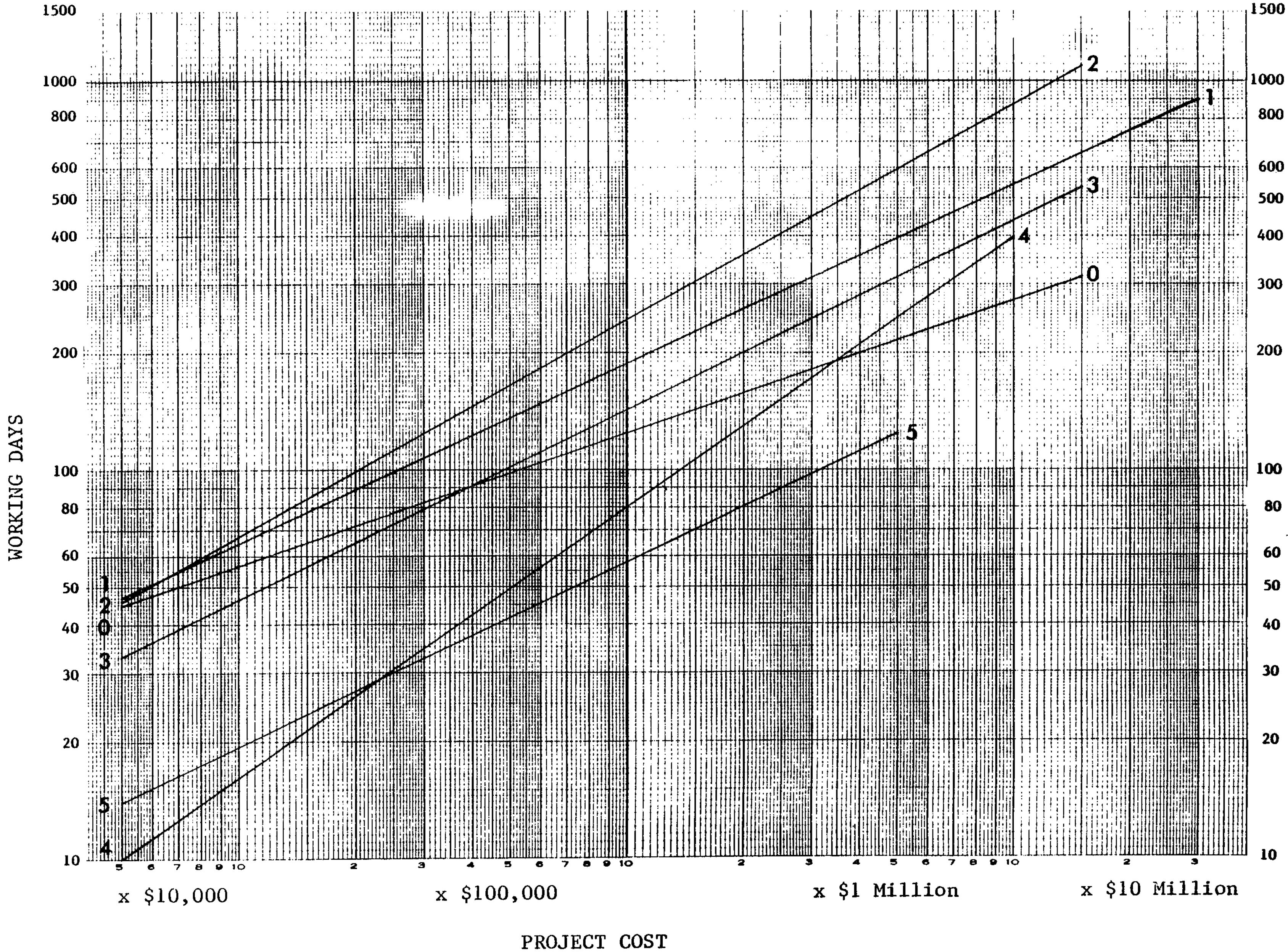


Figure 3. Working Days by Project Type and Cost (Constant Dollars).

These factors and the corresponding overrun rates are based on current practices by SDHPT in managing construction projects and by contractors in conducting their work.

Limitations of Estimation Procedure

The procedure for estimating working days for construction projects has the advantage that working days can be readily obtained either from Table 2 or from equations (1) and (3), maintaining consistency with present SDHPT practice regarding the rate of time overruns. However, like any estimation procedure, the technique cannot predict the exact number of working days that will be required for a particular construction project. Because many factors that cannot be accounted for in equation (1) have some influence on the amount of time needed to complete a project, the number of working days for a construction project of a given cost and type is estimated on the basis of a probability distribution. Hence, it is possible that the actual number of working days required to complete a project may differ substantially from the estimated number of working days, whether that estimate is developed from a procedure such as that used by SDHPT or from the procedure presented here.

Example Calculation of Working Days

As an example of how equations (1) and (3) can be used in estimating working days, suppose that the number of working days is to be estimated for a project involving structures and surface treatment (Type 1 project). Let the estimated cost of the project be \$2.5 million, which must be converted to constant dollars using the Highway Cost Index (HCI). The appropriate HCI value to use in deflating the estimated project cost is the value for the month in which the project is to be let; if this value is unavailable, then the most recent value available should be used. By expressing project costs in terms of constant dollars, the deflation procedure excludes the influence of future inflation rates on the estimate of working days. In this example, supposing the correct HCI value to be 131.0, the constant-dollar cost of the project is \$2.5 million / 1.31 = \$1.91 million. The number of working days to be allowed for the project (*i.e.*, contract working days) is estimated as follows, using equations (1) and (3):

$$
\begin{aligned}
(1)\quad \ln \text{WORKDAYS} = {} & 4.632 \\
& +0.410\ (1) \\
& +0.667\ (0) \\
& +0.142\ (0) \\
& -0.455\ (0) \\
& -0.760\ (0) \\
& +0.120\ (1) \times \ln 1.91 \\
& +0.217\ (0) \times \ln 1.91 \\
& +0.146\ (0) \times \ln 1.91 \\
& +0.359\ (0) \times \ln 1.91 \\
& +0.125\ (0) \times \ln 1.91 \\
& +0.341 \ln 1.91 \\
= {} & 4.632 + 0.410 + 0.120 \ln 1.91 + 0.341 \ln 1.91 \\
= {} & 5.340
\end{aligned}
$$

$$
\begin{aligned}
(3)\quad \text{WORKDAYS} & = 1.21\ \text{EXP}(\ln \text{WORKDAYS}) \\
& = 1.21\ \text{EXP}(5.340) \\
& = 252 \text{ working days}
\end{aligned}
$$

The number of working days could have been obtained from Table 2, interpolating between 187 days at a cost of $1 million and 258 days at $2 million, giving an estimate of 252 working days at $1.91 million for a Type 1 project. The same estimate can be read from Figure 3 for comparison.

CHAPTER III. CONSTRUCTION ENGINEERING COST COMPONENT OF LIQUIDATED DAMAGES

An important component of liquidated damages is the additional construction engineering costs incurred by the Department whenever a construction project overruns the number of working days allocated for the project (contract working days plus addtional days granted). These additional construction engineering costs include monitoring, inspection, and testing costs. An objective of this study was to develop a technique for estimating the daily rate of additional construction engineering costs caused by project overruns.

An equation for estimating the construction engineering costs associated with a construction project was developed using a set of data on 300 construction projects, described in Chapter II. The factors found to be most useful in determining the construction engineering costs for a project were the cost of the project and the number of working days required to complete the project.

Procedure for Estimating Construction Engineering Costs

A linear regression model was used to relate construction engineering costs to project cost and working days. A logarithmic model fit the data much better than did a simple linear model. The estimted coefficients for working days and project cost were significant at the 1 percent and 5 percent significance levels, respectively, the goodness-of-fit statistic R^2 had a value of 0.54, and the root mean square error, s, was equal to 0.9695. The equation for estimating construction engineering costs (ENGCOST) was developed as follows:

$$(6) \quad \ln \text{ENGCOST} = 0.096 + 0.894 \ln \text{WORKDAYS} + 0.358 \ln \text{COST}$$

where ln WORKDAYS is the natural logarithm of working days obtained from either Table 2 or equation (3) in Chapter II, and ln COST is the log of the project cost (in millions of constant dollars). Because ln WORKDAYS is a function of project type, ln ENGCOST pertains to construction engineering costs by type of project.

Although a simultaneous estimation procedure may be appropriate whenever two or more equations are interdependent, as are the equations for working days and construction engineering costs, such a procedure could not be used in this case. The data set used to develop equation (1) did not include information on construction engineering costs, while the data set used for equation (6) did not include projects of type 4 or 5. Therefore, equations (1) and (6) had to be estimated separately. However, substituting project type (types 0 through 3 only) for working days in equation (6) did not improve the value of either R^2 or the mean square error, suggesting that no improvement in estimation precision could be gained by simultaneously estimating the equations for working days and construction engineering costs.

Because equation (6) was developed from data on project types 0 through 3, it is not valid for estimating construction engineering costs for project types 4 and 5. Thus, the current liquidated damages schedule in Table 1 appears to give more accurate estimates of construction engineering costs for project types 4 and 5 than obtained using equation (6). Hence, equation (6) was used in estimating daily rates of construction engineering costs due to overruns for project types 0 through 3, and the current schedule was used for project types 4 and 5.

The total amount of construction engineering costs associated with a construction project was estimated as:

$$(7)\quad \text{ENGCOST} = \text{EXP}(\ln \text{ENGCOST} + s^2/2)$$
$$= \text{EXP}(\ln \text{ENGCOST} + 0.9399/2)$$
$$= 1.60\ \text{EXP}(\ln \text{ENGCOST})$$

where the factor 1.60 was derived from the reverse log transformation, and ln ENGCOST was obtained from equation (6). The term s^2 was necessary in equation (7) because that equation was used to estimate the expected value of the variable ENGCOST, which was lognormally distributed. Since the lognormal distribution is not symmetrical, this adjustment term was needed to account for the skewness of the distribution. The adjustment was necessary in equation (3) since an upper interval, not the expected value, of working days was of interest [9].

The daily rate of construction engineering costs due to time overruns was estimated for each project type (types 0 through 3) on the basis of the difference between total construction engineering costs if a project is completed on time and total construction engineering costs if the project overruns by the average percent time for that project type. Dividing this difference by the number of working days of overrun produced the daily rate for each project type. It should be noted that the average percent time overrun refers here to the average ratio of days overrun to contract working days for each project type, not to the overrun rate (percentage of projects that overran by one or more days) discussed in Chapter II. The average percent time overruns by project types in the data sample were:

Project Type	Percent Time Overrun
0	35
1	23
2	24
3	20

A schedule of daily rates of construction engineering costs due to construction project time overruns is presented in Table 3 by project cost and type. Rates for project types 0 through 3 were estimated on the basis of equations (6) and (7), while rates for types 4 and 5 were obtained from the current liquidated damages schedule in Table 1. Rates for project types 0 through 3 are also shown graphically in Figure 4. Because rates vary only slightly by type, the rates for all project types combined (types 0 through 3) in Table 3 may be used for any type 0, 1, 2, or 3 project. The daily rate of construction engineering costs in current dollars, which is the amount used in assessing liquidated damages against contractors, is obtained for any project type by multiplying the constant-dollar cost from Table 3 by the most recently available HCI value.

If the constant-dollar cost of a construction project of interest falls between cost values given in Table 3, then the daily rate of construction engineering costs due to a time overrun can be obtained by interpolating between values in the table. Use of Table 3 with interpolation provides daily rates that are approximately as accurate as those obtained using equations (6) and (7) for project types 0 through 3.

Example Calculation of Construction Engineering Cost Rate

The procedure by which the rates of construction engineering costs in Table 3 were calculated for project types 0 through 3 can be illustrated using an example. First, total construction engineering costs are estimated on the assumption that a project is completed in the number of working days allowed, obtained from equation (3). Second, total construction engineering costs are estimated for the same project cost and a greater number of working days representing the average percent time overrun for that type of project. The difference in construction engineering costs, divided by the additional days due to the time overrun, gives the rate of construction engineering costs due to the overrun.

For example, for a Type 1 construction project (grading, base, flexible base, and pavement, with structures) costing $5 million in constant dollars

Table 3. Construction Engineering Cost per Working Day by Project Cost and Type.

Project Cost[a] (Constant $)	Cost per Day by Project Type (Constant Dollars)[b]						
	0	1	2	3	4[c]	5[c]	All[d]
$ 50,000	$ 354	$ 354	$ 355	$ 368	$ 105	$ 105	$ 359
100,000	443	439	437	455	154	154	445
200,000	553	544	538	563	210	210	552
300,000	630	616	607	637	210	210	626
400,000	692	673	661	696	210	210	684
500,000	743	722	707	745	210	210	734
600,000	788	763	746	788	315	315	776
700,000	828	801	782	826	315	315	814
800,000	864	834	813	860	315	315	849
900,000	898	865	843	892	315	315	880
1 Million	929	894	870	921	315	315	909
2 Million	1,161	1,108	1,070	1,139	420	420	1,127
3 Million	1,323	1,256	1,208	1,290	630	630	1,278
4 Million	1,451	1,372	1,316	1,408	630	630	1,397
5 Million	1,559	1,470	1,407	1,508	630	630	1,498
6 Million	1,653	1,556	1,485	1,595	840	-	1,585
7 Million	1,737	1,632	1,556	1,672	840	-	1,662
8 Million	1,814	1,700	1,619	1,742	840	-	1,732
9 Million	1,884	1,763	1,677	1,806	840	-	1,797
10 Million	1,949	1,822	1,730	1,865	840	-	1,857
15 Million	2,220	2,065	1,953	2,112	-	-	2,105
20 Million	-	2,257	-	-	-	-	-
25 Million	-	2,418	-	-	-	-	-
30 Million	-	2,558	-	-	-	-	-

[a]Deflated using construction cost component of Highway Cost Index (Aug 1979=100)

[b]Project types are defined as:

0 - pavement repairs, lighting, markings, landscaping, miscellaneous
1 - grading, base, flexible base, and pavement, **with** structures
2 - bridge or overpass
3 - grading, base, flexible base, and pavement, **without** structures
4 - hot-mix asphaltic concrete pavement only
5 - seal coat only

[c]From Table 1

[d]Types 0 thru 3 combined

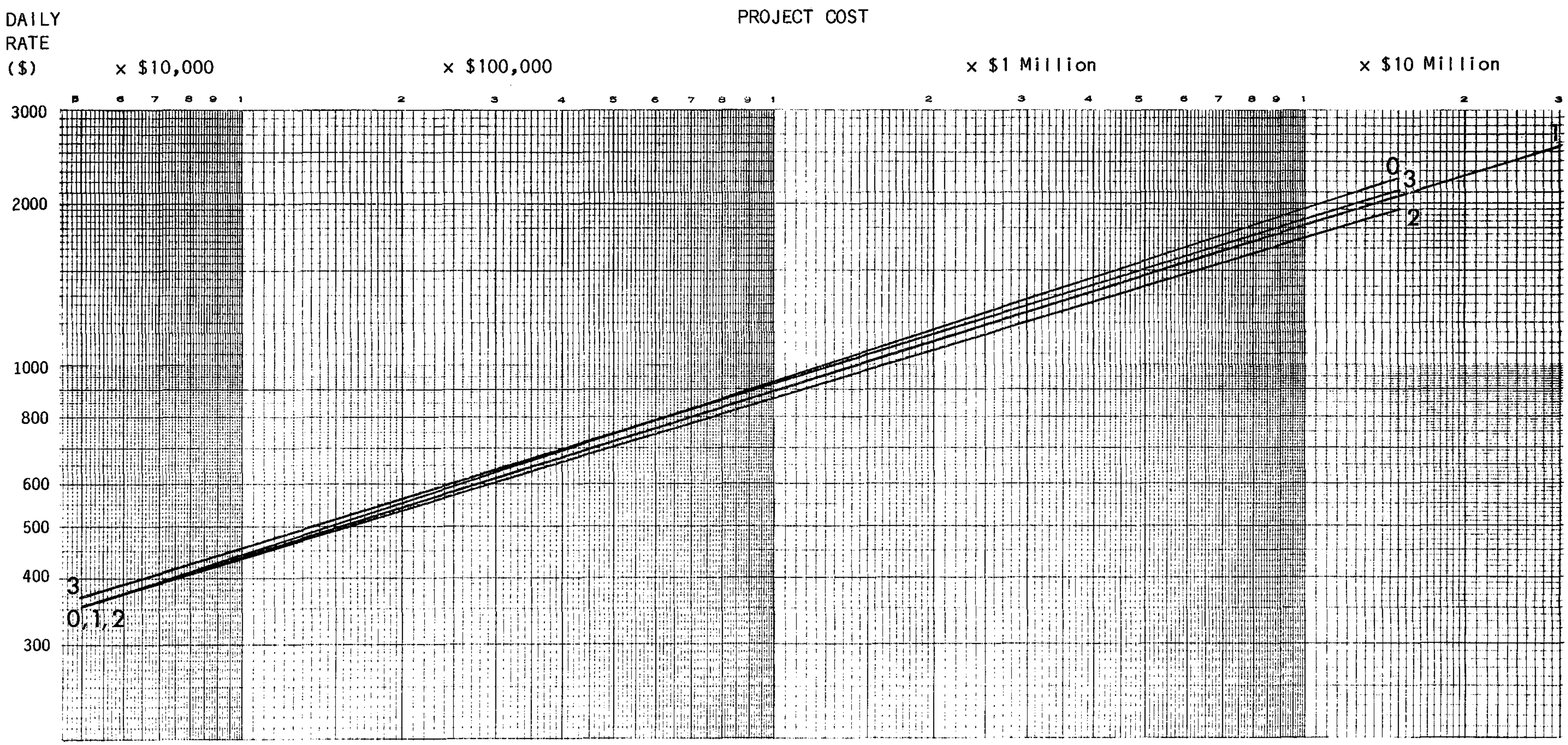


Figure 4. Construction Engineering Cost Per Day Due to Overrun, by Project Type and Cost (Constant Dollars).

(deflated using the Highway Cost Index, as described in Chapter II), the calculations are as follows. The number of working days for this project type and cost is found in Table 2 or, alternatively, from equations (1) and (3):

(1) $\ln \text{WORKDAYS} = 4.632 + 0.410\,(1) + 0.120\,(1) \ln \text{COST} + 0.341 \ln \text{COST}$
$= 5.042 + 0.461 \ln (5)$
$= 5.784$

(3) $\text{WORKDAYS} = 1.21\ \text{EXP}(\ln \text{WORKDAYS})$
$= 1.21\ \text{EXP}(5.784)$
$= 393$ working days

Then equation (6) becomes:

(6) $\ln \text{ENGCOST} = 0.096 + 0.894 \ln \text{WORKDAYS} + 0.358 \ln \text{COST}$
$= 0.096 + 0.894 \ln (393) + 0.358 \ln (5)$
$= 6.013$

The construction engineering costs associated with this project completed within the allotted number of contract working days are:

(7) $\text{ENGCOST} = 1.60\ \text{EXP}(6.013)$
$= \$654$ thousand

Actual working days for a Type 1 project exceeded contract working days by an average of 23 percent in the data sample. Thus, for this example project, the number of working days for an average overrun of 23 percent is 1.23 x 393 = 483 working days. Hence:

(6) $\ln \text{ENGCOST23} = 0.096 + 0.894 \ln \text{WORKDAYS23} + 0.358 \ln \text{COST}$
$= 0.096 + 0.894 \ln (483) + 0.358 \ln (5)$
$= 6.197$

where ENGCOST23 and WORKDAYS23 represent, respectively, construction engineering costs and working days reflecting a 23 percent time overrun. Then total construction engineering costs for a 23 percent overrun are:

(7) $\text{ENGCOST23} = 1.60\ \text{EXP}(6.197)$
$= \$786$ thousand

The daily rate of construction engineering costs, in constant dollars, due to an average 23 percent time overrun is then calculated as follows:

(8) Daily Rate = (ENGCOST23 - ENGCOST)/(0.23 x 393)
= ($786 - 654 thousand)/90
= $1,470 per day (constant dollars)

The daily rate in current dollars is equal to the constant-dollar rate times the most recently available HCI value. For example, if the appropriate HCI value is 131.0, then the daily rate is equal to $1,470 x 1.31 = $1,926 in current dollars.

All of the values in Table 3 for project types 0 through 3 were developed using the procedure shown in this example. For each project type, the corresponding average percent time overrun was used. For project types 0 through 3 combined, equations (4) and (5) were used instead of equations (1) and (3). Rates can be expressed in current dollars using the HCI.

CHAPTER IV. ROAD USER COST COMPONENT OF LIQUIDATED DAMAGES

The effect on motorists should be considered in evaluating delays in the completion of a highway construction project, and the additional road user costs should be included in the liquidated damages assessed to the contractor for the delay in completion. The additional road user costs are the difference between the cost of operating through the construction zone and the cost of operating through the same highway segment with the construction project completed.

This chapter provides estimates of the additional road user costs associated with the delayed completion of several types of highway construction projects. The methodology for developing the estimates is described, and the estimates are then presented in tabular form.

Methodology for Estimating Additional Road User Costs

The three basic components of road user costs are vehicle running costs, travel time costs, and accident costs. The estimates of additional road user costs presented in this chapter include only the first two components: additional vehicle running costs and additional travel time costs.

Changes in accident costs are not included in the estimates of additional road user costs because of the lack of data on changes in accident rates through work zones. Since the mid-1970's, studies of vehicle accident characteristics in work zones have been conducted in Texas [11], as well as in Virginia [12], Ohio [13], and North Carolina [14]; however, these studies reported only the frequency of accidents by type in highway work zones. Graham, Paulsen, and Glennon [15] examined accident rates on highway segments before and during construction projects at 79 work zones in seven states. They reported an average increase of 6.8 percent in accident rates during construction. However, there was considerable variability in the changes in accident rates from project to project: 31 percent of the projects had decreased accident rates during construction, but 24 percent of the projects had increases of 50 percent or more [15]. Since the available data did not permit reasonable estimates of changes in accident costs to be made, accident costs were not included in the analysis.

QUEWZ [10] was used to estimate the additional vehicle running and travel time costs that would result from the delayed completion of a construction project. QUEWZ is a computer model that was developed in 1982 to analyze traffic flows through work zones and estimate the queue lengths and additional road user costs that would result. The original QUEWZ model was modified so that it could be used to analyze two-lane two-way highways. The speed-volume relationships in the model were updated to correspond to the relationships shown in the 1985 Highway Capacity Manual [16]. Queue length calculations were revised to reflect the effect of the percentage of trucks. Finally, an algorithm was added to account for the fact that traffic will divert away from the work zone when delays become excessive. It was assumed that traffic diversion would occur such that delays to motorists never exceeded 20 minutes during construction.

The modified version of QUEWZ that was used in this analysis estimates additional vehicle running and travel time costs both for traffic traveling through the work zone and for traffic diverting away from the work zone. The additional costs for diverting traffic are estimated by assuming that (1) the distance traveled by diverting traffic equals the length of the work zone plus the length of queue, (2) the travel time for diverting traffic equals the time required by a vehicle at the end of the queue to travel through both the queue and the work zone, (3) the diverting traffic maintains a constant speed equal to the length of the diversion divided by the travel time, and (4) trucks do not divert. The sum of the additional costs to diverting traffic plus the additional costs to traffic traveling through the work zone equals the total additional road user costs that would result from the delayed completion of a construction project.

Additional road user costs per day were estimated for 14 cases. Table 4 summarizes the roadway configuration and conditions before, during, and after construction for each case. Roadway conditions refer to the effect of lane and shoulder width on highway capacity and are defined as unrestricted, restricted, or very restricted. Unrestricted indicates ideal geometry, which from a highway capacity viewpoint implies lanes 12 feet wide and shoulders at least 6 feet wide. Restricted indicates that lane and shoulder widths are such that the prevailing capacity is only 90 percent of the capacity with ideal geometry. Very restricted indicates that lane and shoulder widths are such that the

Table 4. Summary of Assumed Roadway Configurations and Conditions for Construction Projects.

Case	Before Construction	During Construction	After Construction
1	Two-lane two-way (restricted)	Two-lane two-way (very restricted)	Two-lane two way (unrestricted)
2	Two-lane two-way (unrestricted)	Two-lane two-way (restricted)	Two-lane two-way (unrestricted)
3	Two-lane two-way (unrestricted)	Two-lane two-way (restricted)	4-lane undivided (unrestricted)
4	Two-lane two-way (unrestricted)	Two-lane two-way (unrestricted)	4-lane divided (unrestricted)
5	4-lane undivided (unrestricted)	Two-lane two-way (restricted)	4-lane undivided (unrestricted)
6	4-lane divided (unrestricted)	Two-lane two-way (unrestricted)	4-lane divided (unrestricted)
7	4-lane undivided (unrestricted)	4-lane undivided (restricted)	6-lane divided (unrestricted)
8	4-lane divided (unrestricted)	4-lane divided (restricted)	4-lane freeway (unrestricted)
9	4-lane divided (unrestricted)	4-lane divided (restricted)	6-lane divided (unrestricted)
10	4-lane freeway (unrestricted)	4-lane freeway (restricted)	6-lane freeway (unrestricted)
11	4-lane freeway (unrestricted)	4-lane freeway (restricted)	8-lane freeway (unrestricted)
12	6-lane freeway (unrestricted)	6-lane freeway (restricted)	8-lane freeway (unrestricted)
13	6-lane freeway (unrestricted)	6-lane freeway (restricted)	10-lane freeway (unrestricted)
14	8-lane freeway (unrestricted)	8-lane freeway (restricted)	10-lane freeway (unrestricted)

prevailing capacity is only 80 percent of the capacity with ideal geometry. The lane and shoulder widths corresponding to restricted and very restricted roadway conditions vary according to roadway configuration and are presented in Table 5. For two-lane two-way highways, the percentage of no-passing zones is also shown.

Table 6 provides the per-lane capacities for level terrain that correspond to the roadway conditions presented in Table 5. Cases 1 through 7, which have two- or four-lane undivided configurations during construction, apply to rural locations. Cases 8 through 14, which have multilane divided or freeway configurations during construction, apply to urban locations. For rural locations, estimates are made for 5, 10, and 20 percent trucks. For urban locations, estimates are made for 5 and 10 percent trucks. It is assumed that the restricted capacities during construction are in effect 24 hours a day.

Estimates of additional road user costs per day were made for a range of average annual daily traffic (AADT). For cases 1 through 6, estimates were made at 5,000 vehicle per day increments. For cases 7 through 14 estimates were made at 10,000 vehicle per day increments. The lower end of the range is the AADT at which additional costs are approximately $0.01 per vehicle. The upper end is the AADT at which additional costs would exceed $1.00 per vehicle for most combinations of work zone length and percentage of trucks and at which significant traffic diversion would start occurring.

Typical hourly volume distributions of AADT were used in estimating additional road user costs. These typical distributions were derived using data from Automatic Traffic Recorder (ATR) stations throughout Texas for October 1985. For cases 1 through 7, the average percentage of AADT for each hour of each day at the 54 ATR stations on rural, undivided highways was used to estimate hourly volumes from AADT. Since the ATR data provide only total hourly volumes in both directions for undivided highways, it was not possible to determine an average directional distribution. Therefore, for each hour a 50/50 directional split was assumed. For cases 8 through 14, the average percentage of AADT for each hour of each day in each direction at the 37 ATR stations on urban Interstate highways was used.

Additional road user costs per day were computed for each day of the week. The estimates presented in this chapter are averages of the costs for each day of the week.

Table 5. Lane and Shoulder Widths Corresponding to Various Roadway Conditions

	Roadway Configuration			
Roadway Condition	Two-Lane Two-Way	Multilane Undivided	Multilane Divided	Freeway
Unrestricted	12 ft. lanes & 6 ft. shoulders (0% No Passing)	12 ft. lanes & 6 ft. shoulders	12 ft. lanes & 6 ft. shoulders	12 ft. lanes & 6 ft. shoulders
Restricted	12 ft. lanes & 1 ft. shoulders (100% No Passing) or 11 ft. lanes & 3 ft. shoulders (100% No Passing)	12 ft. lanes & 1 ft. shoulders or 11 ft. lanes & 2 ft. shoulders	12 ft. lanes & 1 ft. shoulders or 11 ft. lanes & 2 ft. shoulders or 10 ft. lanes & 6 ft. shoulders	12 ft. lanes & 1 ft. shoulders or 11 ft. lanes & 2 ft. shoulders or 10 ft. lanes & 5 ft. shoulders
Very Restricted	11 ft. lanes & 0 ft. shoulders or 10 ft. lanes & 1 ft. shoulders (100% No Passing)	-[a]	-	-

Source: Highway Capacity Manual, Special Report 209, Washington, D. C.: Transportation Researach Board, 1985, pp. 3-13, 7-8, and 8-9.

[a]Condition not used for this configuration.

Table 6. Per-lane Capacities for Various Roadway Configurations and Conditions (vehicles per hour per lane).

Roadway Conditions/ % Trucks	Roadway Configuration: Two-Lane Two-Way	Multilane Undivided	Multilane Divided, Rural	Multilane Divided, Urban	Freeway
Unrestricted					
5% Trucks	1330	1840	1940	1740	1940
10% Trucks	1270	1780	1870	1680	1870
20% Trucks	1160	1670	1760	-[a]	-
Restricted					
5% Trucks	1190	1650	-	1560	1740
10% Trucks	1140	1600	-	1500	1680
20% Trucks	1040	1500	-	-	-
Very Restricted					
5% Trucks	1070	-	-	-	-
10% Trucks	1020	-	-	-	-
20% Trucks	930	-	-	-	-

[a]Condition not used for this configuration.

A review of the estimated additional road user costs per day for each case indicated that there were only small differences in the costs per day for cases with the same roadway configuration during construction. For example, the estimates for cases 2, 3, and 5, all of which had restricted two-lane two-way configurations during construction, were very similar within the range of AADT's considered. The conclusion that can be drawn is that the additional road user costs per day are not significantly affected by the roadway configuration after construction, so long as that configuration has adequate capacity to maintain a high level of service (essentially, free flow operations) after construction. This is because at high levels of service, with low volume-to-capacity ratios, the mean speed of the traffic stream is virtually unaffected by small changes in the volume-to-capacity ratio. Since user costs are closely related to speed, the small differences in speeds among configurations after construction result in only small differences in user costs.

Estimated Additional Daily Road User Costs

It was found that additional road user costs are not significantly affected by the roadway configuration after construction, as long as the capacity of that configuration is great enough to maintain essentially free flow operations. On the basis of this finding, estimates of the additional road user costs per day resulting from the delayed completion of a construction project are presented in tabular form for the following roadway locations, configurations, and conditions during construction:

Table 7: Rural two-lane two-way (very restricted)
Table 8: Rural two-lane two-way (restricted)
Table 9: Rural two-lane two-way (unrestricted)
Table 10: Rural four-lane undivided (restricted)
Table 11: Urban four-lane divided (restricted)
Table 12: Urban four-lane freeway (restricted)
Table 13: Urban six-lane freeway (restricted)
Table 14: Urban eight-lane freeway (restricted)

These estimates can be assumed to apply to any roadway configuration after construction that has adequate capacity to maintain free flow operations at the relevant AADT after construction.

Table 7. Estimated Additional Daily Road User Costs Due to the Delayed Completion of a Project with a Very Restricted Two-Lane Two-Way Work Zone During Construction.

AADT	1 Mile Long			5 Miles Long		
	5% Trucks	10% Trucks	20% Trucks	5% Trucks	10% Trucks	20% Trucks
5,000	$ 0	$ 0	$ 100	$ 0	$ 0	$ 100
10,000	100	200	200	200	200	300
15,000	400	400	600	500	700	800
20,000	800	1,100	1,700	1,200	1,400	2,100
25,000	3,800	6,400	17,200	4,500	7,100	18,000
30,000	26,800	44,800	97,800	27,600	45,600	104,900

Table 8. Estimated Additional Daily Road User Costs Due to the Delayed Completion of a Project with a Restricted Two-Lane Two-Way Work Zone During Construction.

AADT	1 Mile Long			5 Miles Long		
	5% Trucks	10% Trucks	20% Trucks	5% Trucks	10% Trucks	20% Trucks
5,000	$ 100	$ 100	$ 100	$ 100	$ 100	$ 100
10,000	200	200	300	300	300	100
15,000	500	600	800	800	900	1,100
20,000	1,000	1,200	1,700	1,800	2,000	2,600
25,000	2,100	3,000	2,200	3,500	4,500	7,300
30,000	7,000	9,700	24,900	9,400	12,200	27,200
35,000	28,800	35,900	58,200	31,500	38,400	60,400

Table 9. Estimated Additional Daily Road User Costs Due to the Delayed Completion of a Project with an Unrestricted Two-Lane Two-Way Work Zone During Construction.

AADT	1 Mile Long			5 Miles Long		
	5% Trucks	10% Trucks	20% Trucks	5% Trucks	10% Trucks	20% Trucks
5,000	$ 0	$ 100	$ 100	$ 100	$ 100	$ 100
10,000	200	200	300	200	300	300
15,000	400	500	700	700	700	900
20,000	900	1,000	1,400	1,400	1,600	2,100
25,000	1,600	1,900	3,000	2,700	3,100	4,400
30,000	4,200	5,600	9,300	6,200	7,600	11,700
35,000	10,600	16,700	35,700	13,500	19,700	38,200
40,000	35,700	43,800	79,500	38,700	46,700	81,700

Table 10. Estimated Additional Daily Road User Costs Due to the Delayed Completion of a Project with a Restricted Four-Lane Undivided Work Zone During Construction.

AADT	1 Mile Long			5 Miles Long		
	5% Trucks	10% Trucks	20% Trucks	5% Trucks	10% Trucks	20% Trucks
20,000	$ 100	$ 100	$ 200	$ 100	$ 100	$ 200
30,000	300	300	500	300	400	500
40,000	700	800	1,200	900	1,100	1,500
50,000	1,500	1,800	2,500	2,200	2,500	3,400
60,000	2,800	3,400	4,900	4,500	5,300	7,900
70,000	5,800	8,100	16,000	10,500	13,600	24,000
80,000	21,000	29,500	53,000	31,900	42,600	68,200
90,000	58,600	82,200	171,100	78,800	103,100	197,700

Table 11. Estimated Additional Daily Road User Costs Due to the Delayed Completion of a Project with a Restricted Four-Lane Divided Work Zone During Construction.

AADT	1 Mile		5 Miles	
	5% Trucks	10% Trucks	5% Trucks	10% Trucks
20,000	$ 100	$ 100	$ 100	$ 100
30,000	300	400	400	500
40,000	800	900	1,100	1,300
50,000	1,800	2,300	2,900	3,600
60,000	4,400	6,300	8,100	11,000
70,000	20,600	30,500	28,700	39,800
80,000	64,700	84,400	76,200	97,500

Table 12. Estimated Additional Daily Road User Costs Due to the Delayed Completion of a Project with a Restricted Four-Lane Freeway Work Zone During Construction.

AADT	1 Mile		5 Miles	
	5% Trucks	10% Trucks	5% Trucks	10% Trucks
30,000	$ 200	$ 200	$ 200	$ 200
40,000	400	600	500	600
50,000	1,000	1,200	1,300	1,500
60,000	2,000	2,500	2,900	3,600
70,000	6,500	10,000	11,300	15,700
80,000	28,100	39,500	37,500	49,600
90,000	71,300	90,700	82,900	100,300
100,000	136,600	178,700	146,900	182,900

Table 13. Estimated Additional Daily Road User Costs Due to the Delayed Completion of a Project with a Restricted Six-Lane Freeway Work Zone During Construction.

AADT	1 Mile		5 Miles	
	5% Trucks	10% Trucks	5% Trucks	10% Trucks
40,000	$ 200	$ 200	$ 200	$ 200
50,000	400	500	400	500
60,000	700	800	800	1,000
70,000	1,200	1,400	1,400	1,700
80,000	1,900	2,300	2,400	3,000
90,000	3,000	3,800	4,300	5,300
100,000	5,700	8,600	9,700	14,800
110,000	16,500	25,200	25,600	35,300
120,000	42,100	59,300	55,900	74,100
130,000	83,900	106,300	97,400	122,700
140,000	136,600	172,700	151,900	184,500

Table 14. Estimated Additional Daily Road User Costs Due to the Delayed Completion of a Project with a Restricted Eight-Lane Freeway Work Zone During Construction.

AADT	1 Mile		5 Miles	
	5% Trucks	10% Trucks	5% Trucks	10% Trucks
70,000	$ 600	$ 700	$ 600	$ 800
80,000	900	1,100	1,000	1,200
90,000	1,300	1,600	1,500	1,900
100,000	1,900	2,300	2,300	2,700
110,000	2,600	3,300	3,400	4,100
120,000	3,800	4,700	5,100	6,500
130,000	5,700	8,400	9,000	13,700
140,000	12,400	19,300	21,200	29,800
150,000	28,000	42,100	40,100	56,100
160,000	55,700	78,700	72,400	96,500
170,000	96,500	126,500	114,000	143,900
180,000	145,400	187,200	165,600	207,000
190,000	212,300	272,300	229,200	288,600

For rural locations, estimates are given for 5, 10, and 20 percent trucks at work zones both 1 and 5 miles long. For urban locations, estimates are provided for 5 and 10 percent trucks at work zones both 1 and 5 miles long. Estimates for other percentages of trucks or other work zone lengths may be determined by linear interpolation or extrapolation from the tables.

The lower end of the range of AADT's is the volume at which additional daily road user costs are approximately $0.01. For AADT's lower than the range provided, additional costs are negligible.

The upper end of the range of AADT is the volume at which additional daily road user costs start exceeding $1.00 per vehicle for most combinations of work zone length and percentage of trucks. Significant volumes of traffic are likely to divert away from the work zone at this AADT; and the roadway configuration in question is not likely to be used beyond this AADT. If the configuration is used at higher AADT's, much of the additional traffic is also likely to divert and, as a result, the user costs would not increase significantly beyond the maximum values presented in the tables. Therefore, for AADT's higher than the range provided, the maximum value in the appropriate table for the pertinent percentage of trucks and length of work zone should be used.

Application of Road User Costs

All of the user costs in Tables 7 through 14 are per calendar day. Therefore, if these user costs are used to determine a bonus or liquidated damages rate per working day, the values in the tables should be multiplied by the predicted ratio of calendar days to working days for the planned construction period.

Because of the scarcity of highway construction funds, it is recommended that only 15 percent of the values in the tables be used to determine a bonus or liquidated damages. This is discussed more fully in Chapter V.

If the construction project is 1 mile long or less, it is recommended that the values for 1-mile sections be used. If the project is 5 miles in length, then the value can also be read from the tables. For sections greater than 1 mile but less than 5 miles in length, or for sections greater than 5 miles in length, it is recommended that the values be estimated with the following equation:

$$DRUC_X = DRUC_1 + (X-1)(DRUC_5 - DRUC_1)/4$$

where:

$DRUC_X$ = daily road user cost for a construction project that is X miles long

$DRUC_1$ = daily road user costs for a construction project that is 1 mile long, from the relevant table for the specified AADT and percent trucks

$DRUC_5$ = daily road user costs for a construction project that is 5 miles long, from the relevant table for the specified AADT and percent trucks

X = project length in miles

For projects where AADT and/or percent trucks differ from specific values given in the tables, estimates of $DRUC_1$ and $DRUC_5$ can be derived by linear interpolation or extrapolation.

CHAPTER V. THEORETICAL BASIS FOR APPLICATION OF RESEARCH RESULTS

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 construction engineering costs in Chapter III, (3) the extra costs to motorists associated with construction activity, as estimated in Chapter IV, for different types of projects, and (4) the cost to businesses adjacent to the project, in terms of lost profits because of construction activity. The purpose of the discussion in this chapter is to discuss the theoretical basis for using the first three of these types of costs to establish liquidated damages schedules and bonuses for highway projects. It is beyond the scope of this study to attempt to estimate the cost to adjacent businesses; if procedures are developed for estimating these costs, then they should be included in the analysis in the same way that motorist costs are included.

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 5. The three lower curves in Figure 5 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

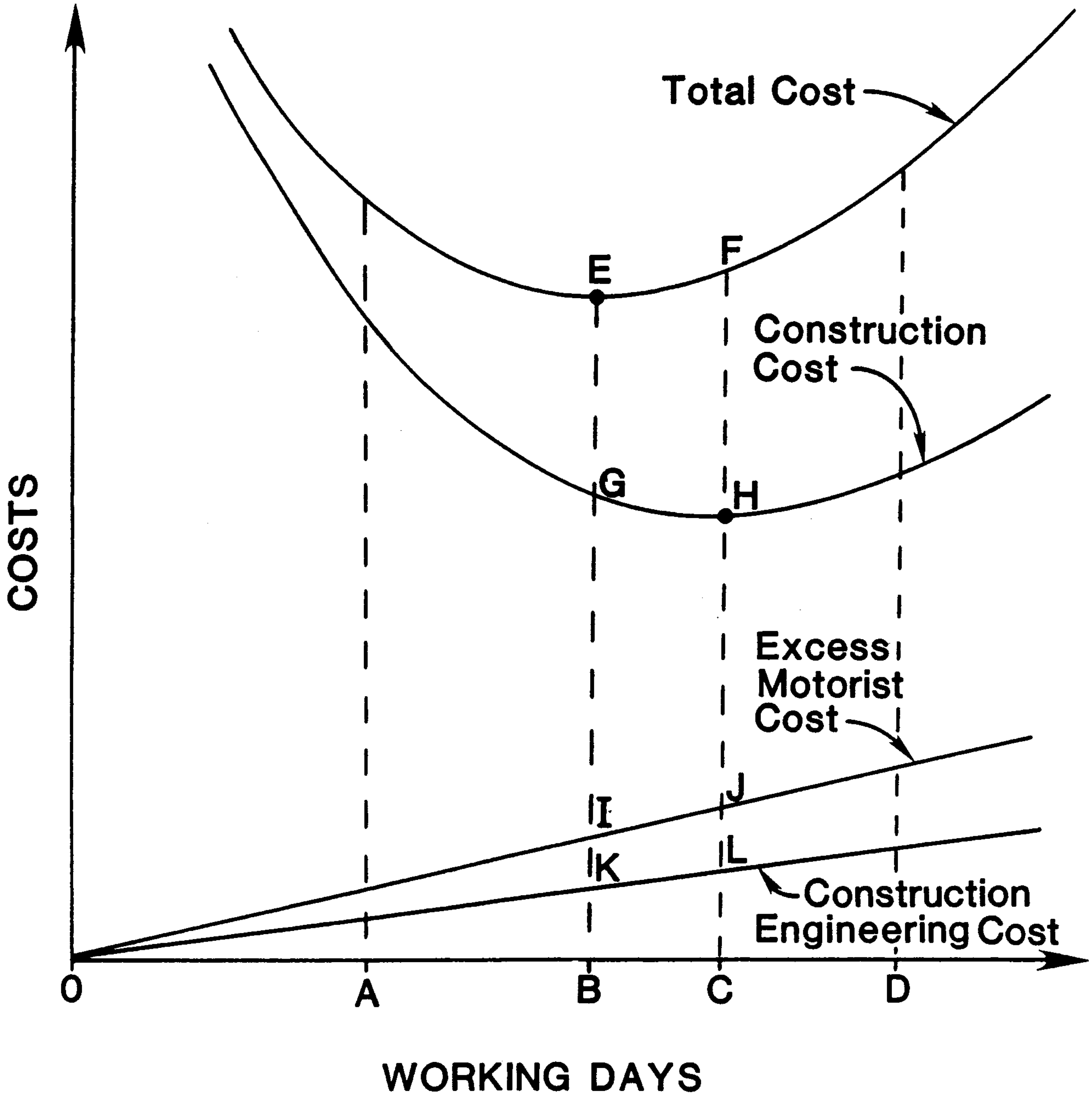


Figure 5. Costs by Type Related to Working Days.

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 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 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 5. 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 5, 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 5, 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 5 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 cost 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 5. 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 cost by simply charging liquidated damages for all working days from the beginning of the contract. In this case, in terms of Figure 5, 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 cost, 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 5, 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 6 which is based on the curves in Figure 5. Points A, B, C, and D in Figure 6 correspond to the same points in Figure 5. However, in Figure 6, it is assumed that D days in Figure 5 are taken as a reference point and the horizontal axis in Figure 6 measures the number of working days that the job is completed early with respect to D days. Three curves are shown in Figure 6. 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, increasses to zero at C days, and is positive beyond C days. The marginal construction cost curve is defined as the change in construction costs as working days are decreased below D days in Figure 5. Therefore, in Figure 6, 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 cost, 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 lexpect 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 6. 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

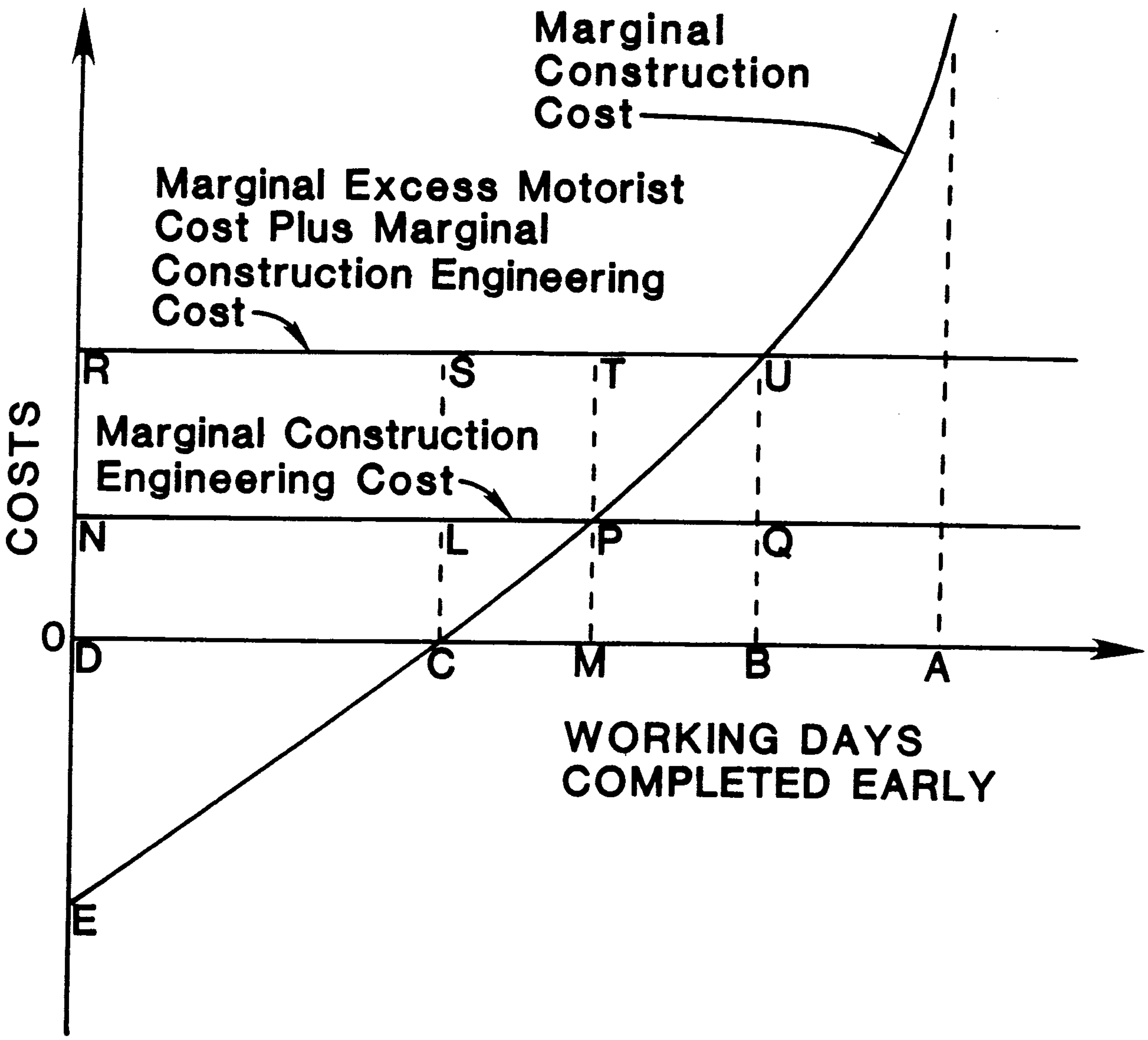


Figure 6. Marginal Costs Related to Working Days Completed Early.

cost curve is below the bonus rate (or below the marginal excess motorist cost plus marginal construction cost in Figure 6). 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 cost 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 is set equal to marginal construction engineering costs only. For ease of exposition, assume contract working days are set at C in Figure 5 and 6. 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 motorists 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 6, 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 increae in Department cost equal to Area PUQ to reduce motorist cost at Area PTUQ, with a net gain of Area PTU. If contractor costs increase at an increasing rate when the contractor completes the job faster, then the loss to motorists will be more than twice what the Department's additional cost would have been if motorist costs had been included in liquidated damages.

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.

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 Working Days

On some critical construction jobs where there would be high motorist costs associated with construction activity, SDHPT 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 contact 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 7. First, he estimates his construction cost curve, which is the same as that described previously for Figure 5. 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 7. Summing these two curves gives the top curve in Figure 7. The number of working days corresponding to

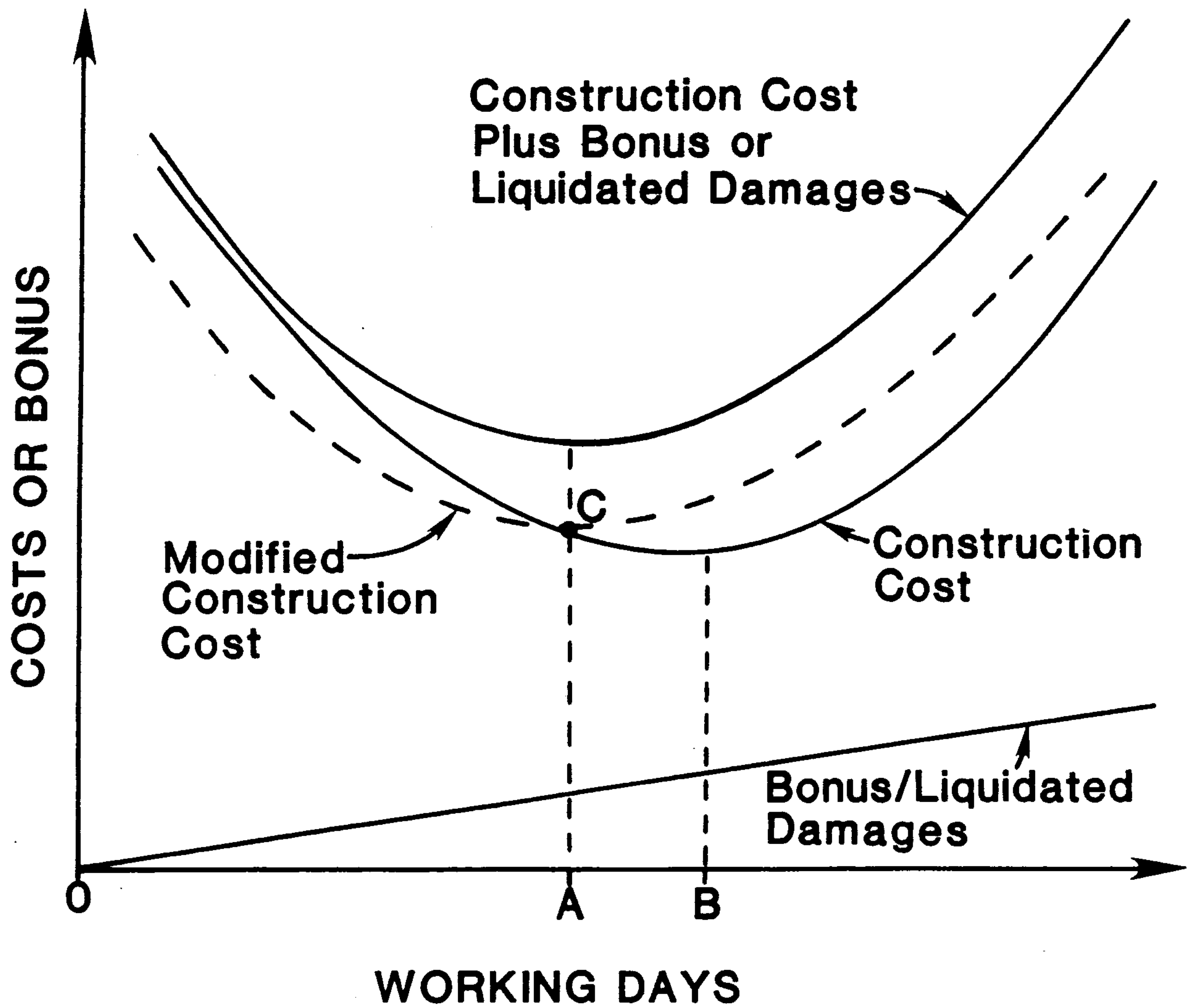


Figure 7. Costs and Bonus Related to Working Days.

the minimum point on this top curve is the number of working days that he should bid (A days in Figure 7). The construction cost 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 7 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 at the bonus strategy discussed in the preceding section as long as the bonus per day is the same.

Bidding Working 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 working 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 7. 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 certainly 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 cuves 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.

Qualification on Use of Motorist Costs

It was demonstrated in the bonus-strategy discussion that including motorist costs in liquidated damages can lead to a better solution with less total cost. 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 countractors' 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, since there is a shortage of highway construction funds, it is recommended that only part of motorist costs be included 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 6. As explained previously in Figure 6, the average benefit-cost ratio of completing a job B days early instead of M days early is at least 2 to 1. It is exactly 2 to 1 (Area PTUQ ÷ Area PUQ) 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 6, to completion of projects B days early. If only enough funds are available 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 6, where the marginal benefit- cost ratio for spending to reduce excess motorist cost is 2 to 1. In Texas, recent calculations [17] indicate that the marginal return to highway expenditures is about 8.7 to 1. Applying this ratio would lead to the recommendation that about 11 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 and considering that the discomfort and inconvenience from traveling through construction zones is probably above average, it is recommended that 15 percent of the motorist costs in Chapter IV be included in liquidated damages.

CHAPTER VI. CONCLUSIONS AND RECOMMENDATIONS

Statistical analyses presented in Chapter II developed new equations for estimating working days for different types of projects as a function of estimated project construction cost. Estimates of working days for different types of projects are provided for a wide range of construction costs, so that the number of working days to be allowed for a particular construction project can easily be estimated. The procedure gives results comparable to currently used methods, in terms of both accuracy and the percentage of project overruns. A procedure for altering the percentage of overruns is also provided.

Estimates of the extra construction engineering costs because of project overruns were developed and are presented in tables and figures in Chapter III. These costs are about double the current liquidated damages schedule for high-cost projects and more than double for low-cost projects. Estimates of excess motorist costs caused by construction activity are presented in Chapter IV for the most common types of highway construction projects. These costs are the costs per calendar day and must be converted to working days before adding them to construction engineering costs to get a bonus or liquidated damages rate. Because of the shortage of construction funds, it is recommended that only 15 percent of the values in Chapter IV be used in the liquidated damages or bonus rate per calendar day.

From the analysis presented in Chapter V, it was concluded that it is very difficult to minimize the total cost of a project with current procedures for setting contract working days and using liquidated damages for overruns. Only by setting a very tight schedule on contract working days and using correct liquidated damages is it possible to minimize total cost. Since it is not possible to know the cost curves for contractors that will bid on a specific job, it is not possible to know the contract working days (B days in Figure 5, Chapter V) that will yield an optimal solution. In general, however, it can probably be concluded that this optimal value often is considerably less than the currently-used values.

There are three strategies that appear preferable to the currently-used strategy:

1. Pay a bonus for each day the contract is completed early. This bonus should be the same rate per day as liquidated damages.

2. Have the contractor bid the number of working days and pay a bonus if he completes the job early and charge liquidated damages for overruns. The project is awarded to the contractor that has the lowest total bid including the bid working days multiplied by the liquidated damages rate. (This strategy is currently used on some contracts.)
3. Have the contractor bid the number of working days and charge liquidated damages for overruns. The contract is awarded to the low bidder for combined construction cost bid plus bid working days multiplied by the liquidated damages per day as in strategy number 2 above.

The second of these two strategies probably is preferable to the first in that the amount of bonus paid to the contractor would tend to be smaller (even though the bid for construction cost would be correspondingly larger). Because of the possible adverse publicity from paying large bonuses, strategy number 2 is probably preferable to strategy number 1, even though they should give similar results if there is effective competition. The third strategy is interesting in that it should give approximately the same results as the second strategy, without the possible disadvantage of adverse publicity from paying bonuses for early completion on all contracts.

In summary, the recommendations of this report are:

1. Charge liquidated damages and bonuses based on the estimates of construction engineering costs in Chapter III and 15 percent of the motorist costs in Chapter IV.
2. For critical projects, use strategy number 2 above, where contractors bid working days and are paid a bonus for early completion.
3. For all other projects, use strategy number 3 above, where contractors bid working days and are charged liquidated damages for overrunning their bid days. However no bonus is paid for early completion.

Since the benefits of this improved approach could be substantial, it is recommended that steps be taken to test this approach on selected projects in the near future. The Department may eventually want to use a strategy of bidding working days and paying a bonus for early completion on virtually all projects, since this is the best overall strategy.

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