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Performance Based Cont Method

PERFORMANCE ANALYSIS AND FORECASTING FOR WSDOT HIGHWAY PROJECTS

by

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16. ABSTRACT

Improving the way that WSDOT performs business is an important objective to pursue. The objectives of this research were to develop tools that will monitor the contractor's performance during construction in order to detect any unsatisfactory progress, and to develop tools that will improve the time and cost prediction of highway projects in order to reduce time and cost overruns.

To achieve the first objective, the research surveyed other state DOTs about how they measure and evaluate work progress and contractor performance. The survey showed that a formal progress measurement and performance evaluation process is lacking in many states, and that there is an apparent lack of progress charts for measuring contractor performance.

By using WSDOT historical project data on actual payment estimates and the elapsed working days of each estimate in each project, the current research developed *minimum performance bounds* and *average performance bounds* for a set of successfully completed projects using regression analysis. Performance bounds were developed for all projects and for clusters of projects grouped in categories based on quantities of asphalt concrete pavement/hot mix asphalt (ACP/HMA), contract value, project duration, and project miles.

Time and cost prediction models were developed through the application of general multiple regression analysis, ridge regression analysis, and nonlinear partial least-square regression analysis on WSDOT historical project data. The models were developed on the basis of a number of major variables in pavement projects, including project duration (working days), final contract value (paid-to-contractor dollars), ACP/HMA quantity (tons), grading (tons, cy), surfacing (ton), and the number of project highway miles.

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EXECUTIVE SUMMARY

Improving the way that WSDOT performs business is an important objective to pursue. The objectives of this research were to develop tools that will monitor the contractor's performance during construction in order to detect any unsatisfactory progress, and to develop tools that will improve the time and cost prediction of highway projects in order to reduce time and cost overruns.

To achieve the first objective, the research started by surveying other state DOTs about how they measure and evaluate work progress and contractor performance. The survey showed that a formal progress measurement and performance evaluation process is lacking in many states, and that there is an apparent lack of progress charts for measuring contractor performance.

By using WSDOT historical project data on actual payment estimates and the elapsed working days of each estimate, the current research developed *minimum and average performance bounds* for highway projects. Performance bounds were developed for all projects and for clusters of projects grouped in categories based on quantities of asphalt concrete pavement/hot mix asphalt (ACP/HMA), contract value, project duration, and project miles. The bounds were developed using (1) regression analysis with polynomial functions, and (2) regression analysis with "Logit" transformation. Contractors' actual performance, measured as percentage of work completed to percentage of time completed, can be evaluated as unsatisfactory if it is below the minimum benchmark performance bound.

Performance bounds charts would be an excellent addition to the standard specifications/construction manual of WSDOT. This would establish a benchmark performance that contractors must not cross without being subjected to penalties or default. A completed performance chart would also be a good addition to the pre-qualification performance report/file.

To achieve the second objective in improving time and cost prediction, WSDOT time and cost performances were checked first. Cost growth (overrun), award growth, estimate growth, and time growth performance measures were evaluated. The review showed that WSDOT achieved a very good average, within 10 percent on these measures; however, the range of variation between the minimum and maximum values of the measures were 25 percent if measured at the 5th and 95th percentiles and wider than that at the zero and 100th percentiles. The range of variation for the time performance measure was substantial, although it has improved since 2000.

Time and cost prediction models were developed through the application of general multiple regression analysis, ridge regression analysis, and nonlinear partial least-square regression analysis on WSDOT historical project data. The models were developed on the basis of a number of major variables in pavement projects, including project duration (working days), final contract value (paid-to-contractor dollars), ACP/HMA quantity (tons), grading (tons, cy), surfacing (ton), and the number of project highway miles.

Along with prediction models, time and cost characteristic prediction tables were developed to provide the average, minimum (5th percentile), maximum (95th percentile), and deviation for the time and cost of projects.

Both the time and cost characteristic tables and prediction models were checked against actual projects and the results were satisfactory. Both tools are able to provide good time and cost prediction before more detailed methods are used.

All time and cost prediction models and the performance bounds developed in this research were coded in spreadsheets (Excel files) to facilitate the implementation and use of the research results by the WSDOT.

CHAPTER 1
INTRODUCTION

1.1. Research Background

Evaluating the performance of highway projects is an important project management function to the Washington State Department of Transportation (WSDOT). In some cases project managers are faced with projects which are completed with unexpected time and cost figures or whose time and cost progress during construction are irregular. For example, during construction the actual project cash flow may significantly deviate from the original cash flow profile, which would signify problems with the contractor's performance and the possibility of time and cost overruns. Similarly, a project may reach completion with time and costs that are significantly different from those of similar projects. Therefore, project managers need tools that will assist them in predicting and monitoring the contractor's performance during construction and in predicting the time and cost of projects.

1.2. Research Objectives

The objective of this research was to develop tools that would assist in predicting the time and costs of projects and in evaluating the performance of projects:

- Develop a benchmark performance profile(s), e.g., construction performance chart(s), to help compare the contractor's actual performance at any time during construction to a benchmark performance and allow corrective actions to be taken as necessary.
- Develop characteristic tables and prediction models that will assist in predicting the time and costs of projects. Such prediction formulas will assist in preparing budgets, in

predicting the time and costs of new projects, and in predicting contractors' bids before bid submission.

1.3. Research Methodology

Historical records of projects can be used to predict the time and costs of future projects, as well as to develop performance/progress profiles. This assumption has been used in several research studies for forecasting project cash flows and was adopted for the current study.

1. Performance profiles

   A questionnaire of U.S. states was developed, and results were analyzed in order to investigate how different states currently measure and assess the performance of contractors. A literature survey was also conducted to investigate the statistical methods used in development of performance profiles.

   For the development of performance profiles, detailed data for elapsed time and progress estimates during construction were collected and analyzed. These data formed the basis for the development of *minimum performance bounds* and *average performance bounds* for WSDOT highway projects. Performance bounds were obtained by using statistical techniques that included (1) regression analysis with polynomial functions, and (2) regression analysis with "Logit" functions. The minimum and average performance bounds were developed for a set of projects, referred to as successfully completed projects, and for groups (clusters) of the projects.

2. Time and cost prediction

   A literature review was conducted to investigate methods used for predicting the time and costs of projects. For the development of time and cost prediction models, WSDOT historical records were analyzed. Data of interest included (1) cost data – quantities of asphalt concrete pavement (ACP)/hot mix asphalt (HMA), grading, and surfacing, (2) time data – workable charged days of projects, and (3) geometric data – centerline miles of projects. Statistical measures, e.g. minimum, maximum, 5th and 95th percentiles, average, and standard deviation of grouped data, were the basis for the development of two-dimensional characteristic tables for predicting project time. The data were then subjected to regression analysis to develop prediction formulas for the time and costs of projects; this included the use of (1) ordinary general multiple regression analysis (GRM), (2) "Ridge" regression analysis, and (3) general partial least square regression analysis (PLS).

1.4. Research Data Profiles

1.4.1. Data Collection

Data for WSDOT projects were collected from the *construction contract information system* (CCIS) and the *contract administration and payment systems* (CAPS) databases. The total number of projects reported in CCIS was 2725 for the period between May 1990 and March 2005. The types of projects included paving, electrical, signal, lighting, erosion control, landscaping, facilities, bridge, and mixed projects. Highway pavement projects were chosen as representative for the scope of the research study. With no prior classification codes for the different types of projects, the pavement projects were isolated by (1) reading the description of each project, and (2) checking the types of the highest 20 percent of the standard bid items, which represent around 80 percent of a project cost. Through this process, pavement projects were identified, and they represented 41 percent (1105 projects) of the total number of projects.

Once identified, the pavement projects were analyzed to determine whether they were sufficient to be included in the statistical analysis of the research. Several records had insufficient time and cost data and had to be excluded from the analysis; for example there were records of payment estimates with no working days, projects with no duration, payments with negative values, and payment estimates with a substantially higher number of working days than one calendar month could contain. The WSDOT on-line files[1] in "State Highway Contracts" were checked to obtain some of the missing information, particularly data regarding the number of project miles that were not recorded in the databases. At the conclusion of this process, 964 workable projects (87 percent of the pavement projects) were chosen to represent WSDOT highway pavement projects for the current research. Table 1.1 and Figure 1.1 contain a brief summary of the these projects for every year in the study period.

Table 1.1: Workable pavement projects in the study

Award Year	# of Projects	Prime Bid Amount ($2005)	Paid to Contractors ($2005)	ACP (HMA) Tons/year	Placement $/ton ($2005)
1990	9	$16,066,283.86	$18,067,485.98	61,408	$294.22
1991	62	$127,071,553.19	$131,976,420.86	913,725	$144.44
1992	58	$134,409,467.46	$147,130,155.37	879,238	$167.34
1993	89	$350,888,111.68	$393,721,946.61	1,521,790	$258.72
1994	71	$168,205,047.80	$177,515,738.84	793,745	$223.64
1995	63	$172,503,466.93	$173,014,346.67	895,059	$193.30
1996	79	$184,337,527.38	$194,605,808.97	1,352,263	$143.91
1997	104	$209,902,022.99	$218,525,481.32	1,310,364	$166.77
1998	68	$153,203,371.26	$159,885,827.87	649,217	$246.27
1999	70	$182,461,951.91	$197,097,133.17	752,430	$261.95
2000	60	$105,636,796.16	$106,436,791.89	571,904	$186.11
2001	73	$203,346,701.37	$213,050,240.93	1,312,139	$162.37
2002	55	$123,588,258.75	$125,371,280.92	981,318	$127.76
2003	57	$184,030,627.83	$199,260,935.09	1,266,465	$157.34
2004	46	$96,717,464.17	$97,181,066.59	729,997	$133.13
Total	**964**	**$2,412,368,652.74**	**$2,552,840,661.07**		
Average	**64.3**	**$160,824,576.85**	**$170,189,377.40**	**932,737**	**$191.15**

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[1] Contract records at http://www.wsdot.wa.gov/eesc/design/projectdev/AdReady/ContractRec.htm

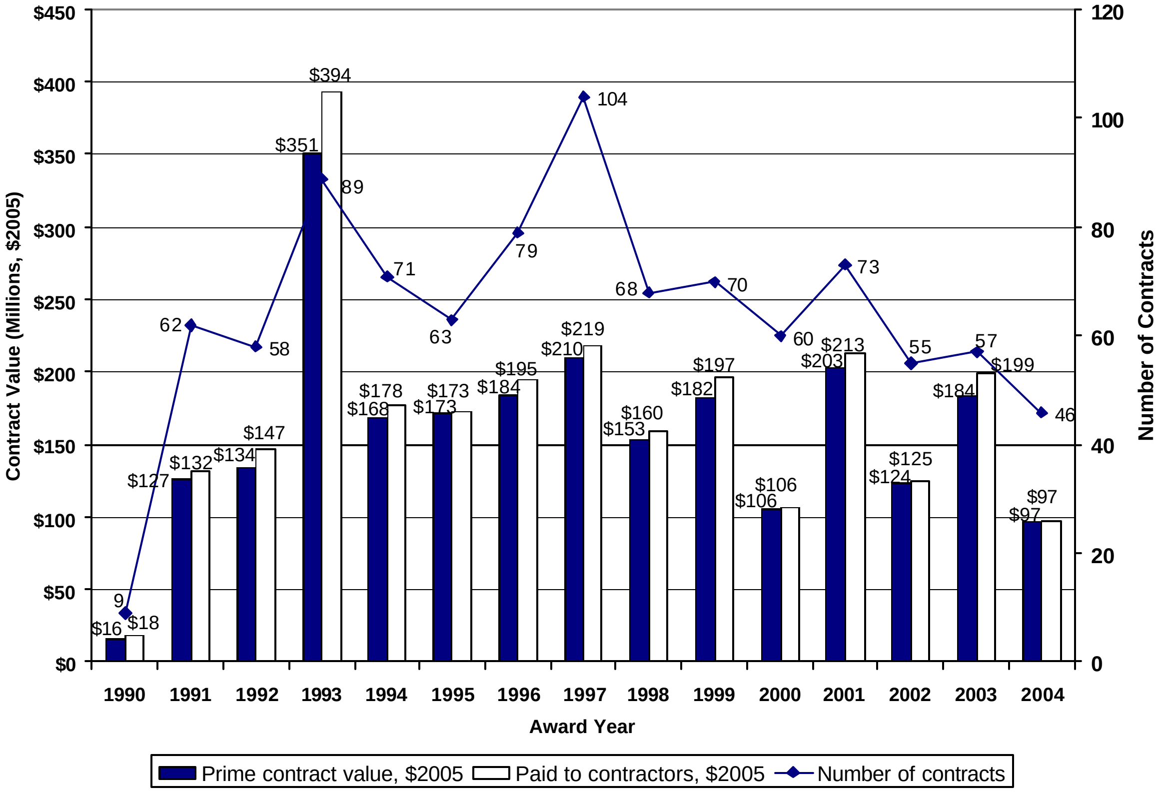


Figure 1.1: Summary of contract values and number of projects in the study period

1.4.2. Data Profile

The collected data included variables covering time, cost, and geometric information about the projects. Some of the variables included the prime bid amounts, total working days, project miles, and the ACP/HMA quantities. These variables are given below.

1. **Prime bid amount**

Contract prime bid amounts for all the projects were converted to 2005 dollars through the WSDOT Construction Cost Index. Figure 1.2 illustrates that nearly 60 percent of the pavement projects were under $2 million, 38 percent of the projects were between $2 million to $10 million, and 2 percent of the projects were larger than $10 million. The average contract value was $2.54 million, and the maximum was $55.96 million.

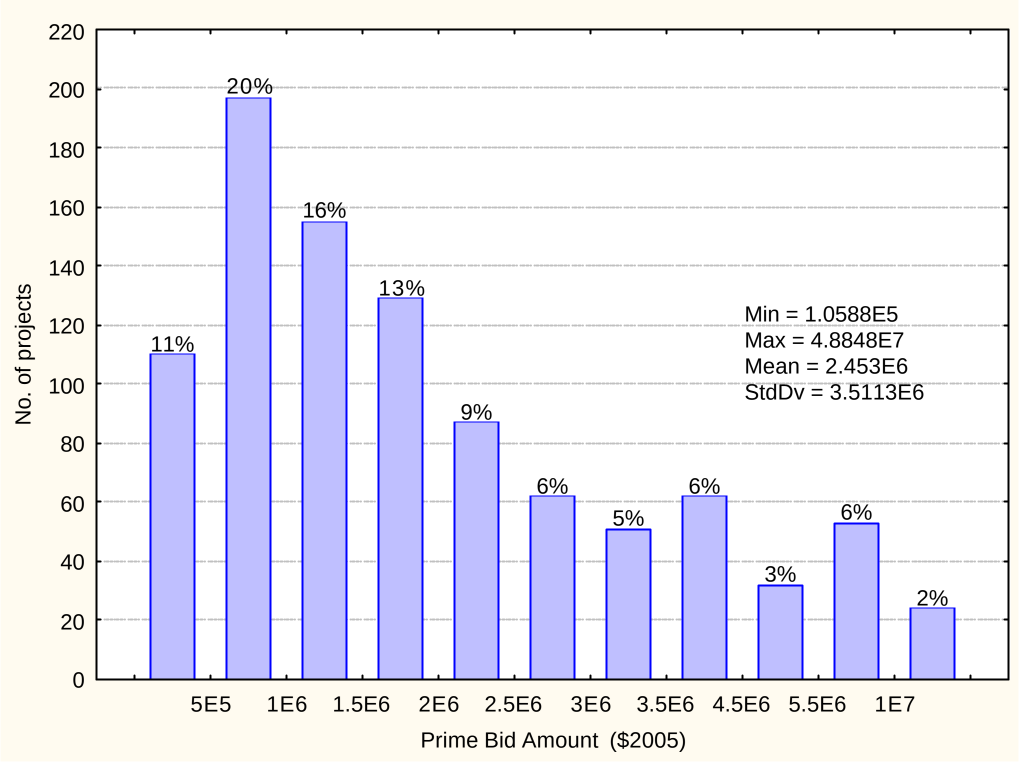


Figure 1.2: Number and percentage of projects for specified range of contract value

2. Total working days

Figure 1.3 illustrates that 77 percent of the pavement projects had less than 150 working days, 17 percent of the projects had between 100 and 200 working days, and 6 percent of the projects had more than 250 working days.

3. Highway miles of projects

No standard lane-miles equivalents were recorded for projects in the databases, and therefore only the centerline miles were available to determine the highway miles per project. Figure 1.4 illustrates that 83 percent of the pavement projects had less than 10 miles, 13 percent of the projects had between 10 and 20 miles, and 4 percent of the projects had more than 20 miles. The average length of projects was 6 miles.

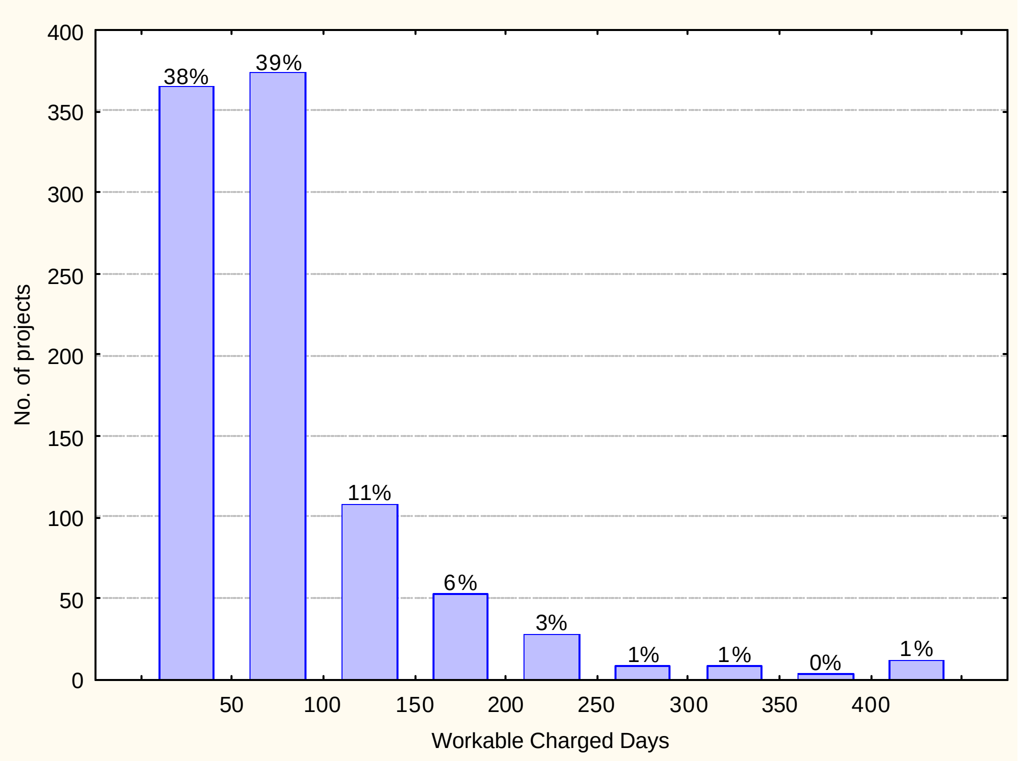


Figure 1.3: Number and percentage of projects for specified range of working days

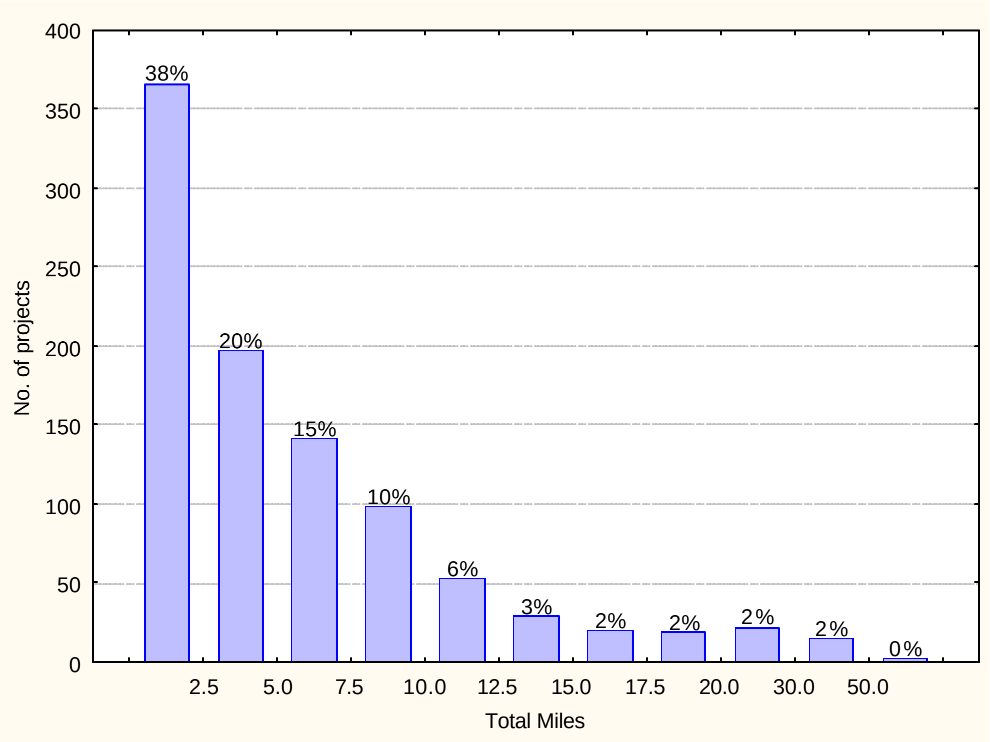


Figure 1.4 Number and percentage of projects for specified range of highway mileage

4. **Quantities of work**

Project data included the ACP/HMA, grading and surfacing quantities. The quantities were recorded on the basis of the Standard Bid Items (SBI) used by WSDOT. Tables 1.2, 1.3, and 1.4 show the SBIs. For example, quantities (tons) were aggregated for ACP/HMA as used in the different classes of asphalt concrete pavement, pre-leveling, approaches, and repair of projects. The quantities for metric standard items were also collected and converted to English equivalents. Figure 1.5 illustrates that 74 percent of the projects were in the range of less than 20,000 tons, 18 percent of the projects were between 20,000 and 40,000 tons, and 8 percent of the projects had more than 40,000 tons. The average ton per contract was 14,381 tons, and the maximum was 157,293 tons.

Table 1.2: English and metric Standard Bid Items for ACP/HMA

English				**Metric**			
ACP/HMA Classes	**Pre-leveling**	**Approaches**	**Repair**	**ACP/HMA Classes**	**Pre-leveling**	**Approaches**	**Repair**
5751	5716	5854	5737	8822	8851	8888	8865
5752	5717	5872	5738	8823	8852	8881	8866
5753	5718	5873	5739	8824	8853	8882	8867
5754	5726	5874	5740	8825	8855	8883	8868
5756	5729	5875		8826	8856	8884	
5757	5731			8827	8857		
5758	5732			8828	8858		
5760	5733			8876	8859		
5761	5734			8877	8860		
5762	5741			8878	8861		
5764	5742			8870	8862		
5765	5743			8871	8863		
5766	5744			8841	8864		
5767				8842			
5768				8843			
5769				-			
5775				8872			
5780				8873			
5787				8874			
5790				8875			
5797				8880			
5799				8885			

Table 1.3: English and metric Standard Bid Items for grading

Grading, cy		Grading, ton	
English	**Metric**	**English**	**Metric**
0300	2940	0408	2974
0310	2945	0431	2979
0320	2950		
0330	2955		
0360			
0405	2972		
0409	2975		
0421	2977		
0460	2987		
0470	2990		

Table 1.4: English and metric Standards Bid Items for surfacing

Surfacing, ton	
English	**Metric**
5047	8665
5090	8671
5100	8673
5110	8675
5120	8677

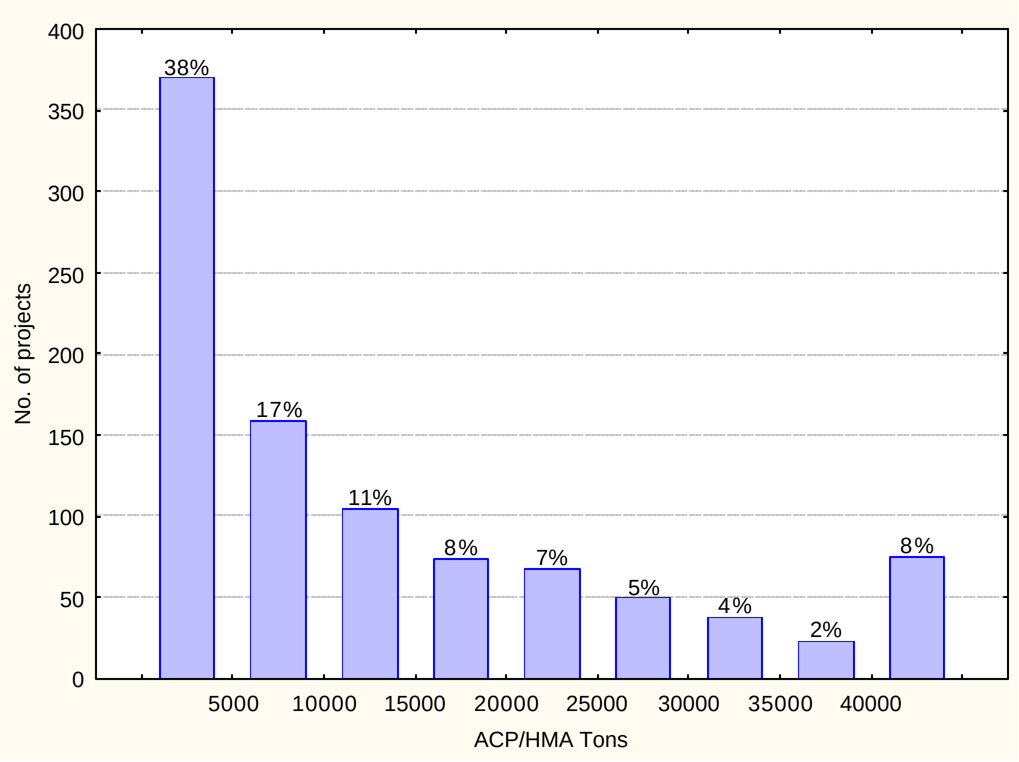


Figure 1.5: Number and percentage of projects for specified range of ACP/HMA tons

CHAPTER 2
PERFORMANCE EVALUATION AND MODELING

2.1 Introduction

A number of tools can be used to evaluate the progress of construction work and the performance of contractors. Following the determination of construction methods and sequence of operations, a construction schedule can be developed. When the schedule is developed with an appropriate level of detail and sufficient time and cost data (i.e,. resource loaded schedules) for the construction operations/activities, the construction schedule can serve as a comprehensive tool for evaluating the progress of work during construction. Intermediate and final milestones can be defined in the schedule network, and project progress can be evaluated on the basis of whether the milestones have been met. Milestones help in assessing the time objectives of the projects, and they usually serve as a basis for assessing the liquidated damages from the contractor when intermediate and completion times have not been met.

Quantity sheets can serve in assessing the progress of work by comparing the actual quantities put in place to the originally budgeted (planned) quantities. Percentage of work completion can be determined on the basis of the actual and budgeted quantities.

The amount of expenditure in a project can also serve in assessing the progress of work. During construction, the actual progress payments can be assessed against the total budgeted cost (or the authorized revised budget), and thus completion percentage can be determined on the basis of the actual and budgeted cost.

As explained above, project time, quantities, and cost can serve in measuring the progress of work. When these three project variables are collectively assessed at one point of time during the construction duration, e.g., during the monthly progress payment estimate, they can help in assessing not only the progress of work but also the performance of the project, i.e,. the performance of the contractor. The collective measure for these variables represents the project cash flow. A project cash flow represents the cumulative amount of money spent up to a particular point of time, the elapsed time, during the life of a project; i.e., the percentage of completion compared against the elapsed time. The cash flow is important because it reflects the project time, the quantities put in place, and how much has been spent on these quantities and the project. The cash flow is also a representation of the cumulative progress payments during construction; sometimes it is called payout curve. The actual project cash flow generated during construction can be compared to the original (or revised) cash flow to assess the performance of the project or the contractor. The performance can also be used to predict the likely completion cost of the project if the performance continues in a manner similar to that estimated at the reference point (progress payment estimate date). For example, if at the progress payment date the actual cash flow was below the originally estimated cash flow, the performance could be assessed as unsatisfactory because the quantities and/or cumulative expenditure would be less than planned. The size of the difference between the actual and original cash flow required to declare the project unsatisfactory varies among agencies; as explained later, one state may use 10 percent and another 15 percent.

Similarly to assessing performance on the basis of the percentage of project cash flow complete, other variables, such as time and quantities, can be used to measure the percentage of completion. For example, the percentage of completion can be determined on the basis of the actual duration of project activities, and in this case the measure becomes schedule performance. Percentage of completion can also be assessed on the basis of the actual quantities placed at the time of the progress payment estimate. This percentage of completion can be compared to the original percentage of completion based on the quantities of work, and thus it can measure work performance. Percentage of completion based on cash flow is considered to have the effect of measuring both duration of completion and quantity of completion.

With percentage of completion determined based on the basis of time, quantity, and/or cash flow, performance can be assessed when the percentage of completion is plotted against the elapsed time of the project, making a "construction performance profile/chart." Software packages such as Primavera Project Planner can produce such performance charts by resource loading the network activities. Contractors can generate construction progress charts or payment schedules for highway agencies by which they can assess performance during construction by comparing actual performance to planned performance. As explained later, a number of highway agencies surveyed in this research have used contractor-developed construction progress charts to assess the progress of work during construction.

When a sufficient number of projects is available, construction progress charts (performance profiles) can be produced that are representative, or average, among all projects of similar types and sizes. Once such a representative performance chart is developed, it can be used as a benchmark to which the performance of new projects can be compared. One of the objectives of this research was to develop such benchmark performance profiles for WSDOT highway projects.

In the next sections the current practice of the US states for measuring and evaluating the performance of projects will be surveyed. This will be followed by a literature review for the different statistical methods that could be used to develop such performance charts. This will be followed by the development of performance chart(s) for WSDOT projects using the collected project data. The performance charts/profiles will be a significant tool in judging the performance of contractors during construction of projects. Project managers could use the charts to monitor the performance of contractors, issue warnings for unsatisfactory progress, and/or asses penalties for continued unsatisfactory performance.

2.2 Current Practices Survey

A structured questionnaire was administered to solicit information about the current practices of state DOTs in measuring and evaluating performance during construction. The questionnaire (Appendix A) was developed with the WebQ survey software, part of the Catalyst package at the University of Washington. All U.S. state DOTs were e-mailed with the survey website, where state engineers could respond only through the on-line version of the questionnaire. The survey was designed to be brief and user friendly, with multiple choices and yes/no answers. The questionnaire had two parts relating to (1) performance evaluation, and (2) development and use of progress charts. Twenty-four states responded to the online survey, producing a response rate of 46 percent.

2.2.1 Performance Evaluation

The first part of the survey concerned the measurement and evaluation of project performance and addressed (1) measuring progress and performance during construction, (2) measuring performance at completion, and (3) administrating the progress evaluation process. These are explained in below.

2.2.1.1 Measuring Progress During Construction

The first question asked about current practice in measuring the progress of work during construction, as shown in Table 2.1. Comparing actual project quantities to planned quantities was the method most commonly used, chosen by 71 percent of the respondents. Around 54 percent of the respondents preferred to use a schedule to compare actual completion time with the original schedule. Around 50 percent pointed out that both schedule and cash flow were used in measuring performance, with 25 percent preferring to use cash flows (comparing actual and planned cash flows). Two respondents indicated other methods, including (1) the use of quantities and calendar days, and (2) number of calendar days used (percentage of contract time allocated).

Table 2.1: Methods for measuring the progress of work

1. During construction, for measuring the progress of work the agency analyzes the following (choose all that apply):			
Numeric value	Answer	Frequency	Percentage
1	Schedule – Comparing the actual project schedule to the original/revised schedules	13	54.17%
2	Cash Flow – Comparing the actual project cash flow to the planned cash requirements	6	25.00%
3	Both (a) and (b), i.e. schedule and cash flow	12	50.00%
4	Quantities – Comparing the actual project quantities to the planned quantities of work	17	70.83%
5	Labor Hours – Comparing the actual labor hours to the planned labor requirements	0	0%
6	All above, i.e. schedule, cash flow, quantities and labor hours	2	8.33%
7	Other, please specify	2	8.33%

In dealing with unsatisfactory schedule progress, e.g., failure to meet milestones, Table 2.2 shows that small percentage, 8 percent, of the state respondents did nothing, probably expecting the contractor to reschedule and finish on time or relying on liquidated damages at contract completion. One third of the respondents identified performance penalties as a consequence taken by the states. However, a significant percentage, 60 percent, of the respondents identified other strategies for addressing unsatisfactory schedule progress, including

(1) require updated schedule and plan to get back on track (16.7 percent; 4 respondents)
(2) correspond and hold meeting with contractor (12.5 percent; 3 respondents)
(3) disqualify contractor for bidding on further work if schedule deviation is 25 percent or more (8.3 percent; 2 respondents)
(4) apply incentive/disincentive for intermediate completion dates (8.3 percent; 2 respondents)
(5) withhold anticipated liquidated damages (8.3 percent; 2 respondents)
(6) suspend work if schedule deviation pattern is continued (4 percent; 1 respondent)

Table 2.2: Consequences for unsatisfactory schedule progress

4. During construction, an unsatisfactory progress with project schedule , e.g. not meeting intermediate milestones, may trigger the agency to:			
Numeric value	Answer	Frequency	Percentage
1	Charge performance penalties to the contractor	8	33.33%
2	Increase the retainage percentage of progress payments	0	0.00%
3	Do nothing	2	8.33%
4	Other, please specify	14	58.33%

In dealing with unsatisfactory cash flow progress, 46 percent of the respondents identified “do nothing” (see Table 2.3). Some respondents identified other strategies; for example, three respondents replied with “N/A Not Applicable” or emphasized that cash flow is generally on the department’s end, i.e., under its control. Increasing retainage percentage or charging performance penalties were also mentioned, but by a low percentage of respondents. The other strategies mentioned by 41 percent of the respondents included methods similar to those for schedule deviation:

(1) put contractor in default

(2) limit future bidding and withhold anticipated liquidated damages
(3) require an updated schedule
(4) correspond with the contractor on progress
(5) withhold money from the contractor

Table 2.3: Consequences for unsatisfactory cash flow performance

5. During construction, an unsatisfactory progress with project cash flow , e.g. not meeting cash flow expenditure, may trigger the agency to:			
Numeric value	Answer	Frequency	Percentage
1	Charge performance penalties to the contractor	1	4.55%
2	Increase the retainage percentage of progress payments	2	9.09%
3	Do nothing	10	45.45%
4	Other, please specify	9	40.91%

2.2.1.2 Measuring Performance at Completion

Measuring the performance at completion was addressed through a number of questions. The first question addressed the methods used to measure performance at completion. The two major methods identified were cost growth percentage (deviation from original contract amount), selected by 67 percent of respondents, and time growth percentage (deviation from original contract days), chosen by 50 percent of respondents (see Table 2.4). Award growth was selected by 8 percent of respondents and construction placement by 17 percent of respondents. Some respondents (21 percent; 5 respondents) identified other methods, including the quality of the contractor's work, safety, and project timelines.

A number of questions were posed to the respondents in order to establish a percentage below which a project would be considered completed successfully or satisfactorily. The first question tried to establish the basis for success, whether it was considered to be related to meeting contract value, completion time, or both.

Table 2.4: Methods for measuring performance at project completion

7. At project completion, the agency uses the following for measuring the performance of a project (choose all that apply):			
Numeric value	Answer	Frequency	Percentage
1	Deviation from engineer's estimate (Award Growth), i.e. (Original Contract Amount – Engineers' Estimate) / Engineers ' Estimate	2	8.33%
2	Deviation from original contract amount (Cost Growth), i.e. (Final Contract Amount – Original Contract Amount) / Original Contract Amount	16	66.67%
3	Deviation from original contract days (Time Growth), i.e. (Final Contract Days – Original Contract Days) / Original Contract Days	12	50.00%
4	Construction Placement, i.e. Final Construction Contract Cost / Final Construction Contract Days	4	16.67%
5	Other, please Specify	5	20.83%

For a project to be considered successfully completed, the majority of the respondents, 73 percent, stated that the project should be within a reasonable percentage of both the bid price and completion time, while 18 percent of the respondents were restricted to the original contract price and completion time (see Table 2.5). Table 2.6 shows that a significant percentage of the respondents, 42 percent, established a range of 5 percent to 10 percent to be reasonable for contract value. An increased cost deviation, e.g., between 10 percent and 20 percent, was not favored by the respondents; only 5 percent would consider a project satisfactorily completed in this range. One state respondent mentioned that the range was below 3 percent, and another respondent explained that projects were not rated as successful or unsuccessful on the basis of a specific rate, but project engineers have to explain all under/over runs beyond 10 percent. In summary, around 70 percent of the respondents reported that 10 percent or less is a reasonable percentage for judging a project to be successfully completed project within budget.

As for completion time, Table 2.7 shows that 55 percent of the respondents required finishing on time within a 10 percent allowance. This was further emphasized by half (20 percent) of the respondents who specified other percentages than those posed in the question (see Table 2.7); those respondents were restrictive about finishing on time. The other half (20 percent) explained that there was no established percentage, and one respondent mentioned no liquidated damages for time overrun.

Table 2.5: Criteria for satisfactorily completed projects

8. At project completion, a project would be successful or satisfactory if it was completed:			
Numeric value	Answer	Frequency	Percentage
1	At the award bid price (or authorized adjustments)	0	0.00%
2	At the required completion time (or authorized working days)	0	0.00%
3	At both the award bid price and completion time	4	18.18%
4	Within a reasonable percentage of the bid price	2	9.09%
5	Within a reasonable percentage of the completion time	0	0.00%
6	Within a reasonable percentage of both the bid price and completion time	16	72.73%

Table 2.6: Percentage range for successfully completed projects on budget

9. If a reasonable percentage of "bid price" is selected for a project to be successful (as in previous question), the percentage would be:			
Numeric value	Answer	Frequency	Percentage
1	Less than 5%	5	26.32%
2	Between 5% - 10%	8	42.11%
3	Between 10% - 20%	1	5.26%
4	Other, please specify	5	26.32%

Table 2.7: Percentage range for successfully completed projects on time

10. If a reasonable percentage of completion time is selected for a project to be successful (as in previous question), the percentage would be:			
Numeric value	Answer	Frequency	Percentage
1	Less than 5%	7	35.00%
2	Between 5% - 10%	4	20.00%
3	Between 10% - 20%	1	5.00%
4	Other, please specify	8	40.00%

2.2.1.3 Administration of the Progress Evaluation Process

A surprising result from the questionnaire was that 71 percent of the state respondents (17 out of 24 respondents) had no official documents to explain the progress evaluation process (Table 2.8). Of the states responding, 28 percent had documents related to progress evaluation; these documents included standard specifications and construction manuals. Three respondents mentioned that progress was measured on the basis of the contractor's updated progress schedules, but no official internal documents were mentioned.

Table 2.8: Availability of progress evaluation documents

11. Does the agency have an official document, or part of document, that describe the progress evaluation process?			
Numeric value	Answer	Frequency	Percentage
1	No.	17	70.83%
2	Yes. (Please specify the document title and where it could be located	7	29.17%

In the next question, state DOTs were asked about the tools for measuring work progress, and nearly half of the respondents, 46 percent, reported using reports, 17 percent (four respondents) used progress charts, and 17 percent used both reports and charts (see Table 2.9). Seven respondents indicated other methods, including the use of the critical path method (CPM).

Table 2.9: Measuring progress of work

2. During construction, the agency uses the following tools for measuring the progress of work			
Numeric			
Value	Answer	Frequency	Percentage
1	Progress reports	11	45.83%
2	Progress charts (or curves)	4	16.67%
3	Both progress reports and progress curves (charts)	4	16.67%
4	Other, please specify	7	29.17%

How states record the progress of work was another survey question. In answer, 75 percent of the states reported using software or spreadsheets for recording progress, while 25 percent used paper work (Table 2.10). The respondents identified the following systems:

(1) internal construction management or payment systems (33.33 percent; 8 respondents)
(2) Primavera Project Planner (25 percent; 6 respondents),
(3) ASHTO's SiteManager (17 percent; 4 respondents),
(4) Sure Trak (4 percent; 1 respondent), MS Project (4 percent; 1 respondent), and Sciforma's PS8 (4 percent; 1 respondent)

Table 2.10: Media type for recording the progress of work

6. During construction, does the agency use a specific software or spreadsheet to record the work progress?			
Numeric value	Answer	Frequency	Percentage
1	No; paper work is used instead.	6	25.00%
2	Yes, please specify if possible	18	75.00%

The frequency of measuring the progress of work was reported by 38 percent of the respondents to be at every progress payment; 38 percent of the respondents reported monthly periods, and 13 percent weekly periods (Table 2.11). Still another 13 percent used other periods, including (1) monthly and mid-monthly estimates, (2) ad hoc, when an issue arose, and (3) frequently, varying between daily to monthly.

Table 2.11: Frequency in measuring progress of work

3. During construction, the frequency for measuring the progress of work is:			
Numeric value	Answer	Frequency	Percentage
1	With every progress payment, pay request, or voucher	9	37.50%
2	Daily	0	0.00%
3	Weekly	3	12.50%
4	Monthly	9	37.50%
5	Quarterly	0	0.00%
6	Semi-annually	0	0.00%
7	Annually	0	0.00%
8	On-demand for special events (e.g. analysis of claims)	0	0.00%
9	Other, please specify	3	12.50%

2.2.2 Progress Charts

A construction progress chart is a profile (graph or table) of the percentage of construction completion compared with the construction elapsed time. Generally, progress charts are depicted as an S cumulative curve, with a slow start, then steep progress, then a slow finish near completion. If construction project duration is divided into three periods, then in a progress chart 80 percent of the work is expected to be done within the middle third, and the other 20 percent of work is divided between the first and third periods. This section reviews the state respondents' accounts of how progress charts are developed and their use and effectiveness in managing the performance of contractors.

2.2.2.1 Development of Progress Charts

The survey addressed the development and use of progress charts through a number of questions. The first question inquired about the use of these charts, and 38 percent (9 respondents) indicated that they used progress charts, while 67 percent (16 respondents) reported no use of progress charts. Four respondents (31 percent) said they had an official document that explains the process or a chart that explains how the progress is measured. The documents mentioned by the respondents were the respective DOTs' standard specifications. A check of the documents of the four states showed that progress analysis was generally explained through Division 100 "General Provisions" Subsection 108 "Prosecution and Progress." The process generally required updated schedules in which the actual contractor progress or project progress was measured against the contractor's submitted schedules. No specific progress curve was used.

The nine state respondents who used progress charts described different methods for establishing a progress chart (see Table 2.12): (1) based on cash flow (4 respondents), (2) based on schedule completion (2 respondents), and (3) based on quantities of work (1 respondent). Progress charts, however, were not developed by the state agencies. A significant percentage (67 percent; 6 respondents) of the nine state respondents used a progress chart submitted by the contractor after bid award; generally, that was a chart developed by the scheduling software. One state respondent mentioned using a percentage profile developed internally by the agency (see Table 2.13).

Table 2.12: Basis for progress charts

14. As used by the agency, the construction progress chart (curve) reflects:			
Numeric value	Answer	Frequency	Percentage
1	Progress with project cash flow, e.g. the percentage of money spent (dollars-paid-to-contractor) against the elapsed time	4	44.44%
2	Progress with project time, e.g. the percentage of time/ schedule completion against the elapsed time	2	22.22%
3	Progress with project quantities, e.g. the percentage of quantities put in place against the elapsed time	1	11.11%
4	Progress with project labor hours, e.g. the percentage of labor hours used against the elapsed time	0	0.00%
5	Other, please specify	2	22.22%

Table 2.13: Development method for progress charts (I)

15. As used by the agency, the construction progress curve/chart(s) represents:			
Numeric value	Answer	Frequency	Percentage
1	A chart (or curve) statistically driven from records of progress on several past projects	0	0.00%
2	A standard cumulative chart (or curve) in the form of an S-curve	0	0.00%
3	A progress chart (or curve) submitted by the contractor after contract award	6	66.67%
4	A specific progress profile, e.g. 0.5% work during the 1st month, 1% during the 2nd month, 5% during the 3rd month, etc	1	11.11%
5	Other, please specify	2	22.22%

Table 2.13 shows that most states rely on the contractor submitting cash flow/time schedules from which the contractor's performance is evaluated. This is further emphasized in Table 2.14, which shows that only one respondent reported using past records. The majority of the respondents (89 percent) reported establishing the progress chart on the basis of the contractor's submitted schedules. The results shown in Table 2.15 further indicate that categorizing projects into successful and unsuccessful projects is not typically a factor in developing the progress charts; the charts are mainly produced by the contractor (78 percent in Table 2.15). Because progress charts are contractor-generated, they become project-specific; this is indicated by the 78 percent for the "other" charts in Table 2.16.

Table 2.14: Development method of progress charts (II)

16. The progress curves/charts were developed based on:			
Numeric value	Answer	Frequency	Percentage
1	Average progress of past projects	1	11.11%
2	Lower limit of progress of past projects	0	0.00%
3	Upper limit of progress of past projects	0	0.00%
4	Other, please specify	8	88.89%

Table 2.15: Project types for progress charts

17. The progress charts (or curves) were developed based on projects that were:			
Numeric value	Answer	Frequency	Percentage
1	Satisfactorily completed projects	1	11.11%
2	All satisfactorily and less-than satisfactorily completed projects	1	11.11%
3	Other, please specify	7	77.78%

Table 2.16: Types of progress charts

18. The agency uses for measuring progress:			
Numeric value	Answer	Frequency	Percentage
1	One construction progress chart for all projects	1	11.11%
2	A number of classified progress charts based on project type and other criteria	1	11.11%
3	Other, please specify	7	77.78%

2.2.2.2 Use and Effectiveness of Progress Charts

As shown in tables 2.13 to 2.16, progress charts are mainly cash flow and schedule charts delivered by the contractor. States receive these charts and use them as benchmarks against which to check the actual progress. Only one respondent indicated the use of state experience and records to develop a progress chart.

The use of progress charts is not limited to a specific contract size. Table 2.17 shows that 56 percent of the state respondents have no price limit for use of progress charts. The other respondents (33.33 percent; 3 respondents) indicated no specific limit, with one respondent mentioning that the use of progress charts in the form of CPM schedules is required on vertical construction, complicated/ interrelated corridor projects, and mega projects.

Table 2.17: Progress charts and project size

19. The project progress chart (or curve) is used if the project value...???			
Numeric value	Answer	Frequency	Percentage
1	No price limit	5	55.56%
2	Projects over $10,000	0	0.00%
3	Projects over $100,000	0	0.00%
4	Projects over $500,000	1	11.11%
5	Other, please specify	3	33.33%

As indicated earlier, progress charts are used to check the progress of contractors against their own developed schedules and cash flows, or against historical records, as indicated by one state respondent. When the charts show the contractor's performance/progress becoming unsatisfactory, highway agencies would be expected to apply certain procedures to warn and perhaps penalize the contractor. Table 2.18 shows that "continued" unsatisfactory progress triggers several parallel actions, including declaring contractor default (56 percent of respondents), informing the surety company and charging performance penalties (33.33 percent of respondents), ranking the contractor lower in future prequalification of bids (22 percent of respondents), and/or retaining a higher percentage of progress payments (11 percent of respondents). Other actions mentioned by the respondents included asking the contractor for a revised schedule and choosing the action most suitable with how far behind the contractor is. While continued unsatisfactory progress triggers the above actions, temporary (one or two periods) unsatisfactory progress generally provokes no action; two respondents mentioned issuing a warning to the contractor.

Table 2.18: Actions for the continued unsatisfactory performance

<table>
<tr><th colspan="4">22. A continued unsatisfactory progress may trigger the agency to (choose all that apply):</th></tr>
<tr><th>Numeric value</th><th>Answer</th><th>Frequency</th><th>Percentage</th></tr>
<tr><td>1</td><td>Charge performance penalties (e.g. dollar deductions) to the contractor</td><td>3</td><td>33.33%</td></tr>
<tr><td>2</td><td>Retain a higher percentage of the progress payment</td><td>1</td><td>11.11%</td></tr>
<tr><td>3</td><td>Inform the surety company of the contractor</td><td>3</td><td>33.33%</td></tr>
<tr><td>4</td><td>Declare the contractor in default</td><td>5</td><td>55.56%</td></tr>
<tr><td>5</td><td>Rank the contractor at a lower prequalification level for future bids</td><td>2</td><td>22.22%</td></tr>
<tr><td>6</td><td>Other, please specify</td><td>6</td><td>66.67%</td></tr>
</table>

While the above actions would be enforced with “continued” unsatisfactory progress, state respondents were not clear about how long it take before progress is considered unsatisfactory. One out of the eight respondents who reported using progress charts/schedules indicated that two periods are sufficient to declare unsatisfactory progress (Table 2.19). The rest of the respondents indicated no period; one respondent mentioned that progress is unsatisfactory if the project is 15 percent behind schedule.

To assess whether progress charts are useful, respondents were asked about their experiences. Nearly half of the respondents agreed that progress charts are useful; the rest were neutral. When asked about suggestions for performance evaluation, the respondents mentioned:

(1) One respondent suggested changing the specification to require that the baseline and updated schedule be monitored during construction. One respondent mentioned the use of schedules but with no real ties to performance; liquidated damages would be enforced only at the end for late completion.

(2) When interim milestones are established, they should be implemented with an incentives/disincentive clause

(3) One respondent suggested that the highway agency track the percentage of time against the percentage of completion without charting the results into a curve.

Table 2.19: Timelines for unsatisfactory progress

20. A progress is considered unsatisfactory if the actual progress is continued to be less than the expected progress for:			
Numeric value	Answer	Frequency	Percentage
1	Two sequential/successive periods on the progress chart	1	12.50%
2	Three sequential/successive periods on the progress chart	0	0.00%
3	Other, please specify	7	87.50%

2.2.3 Specific Practices for Performance Evaluation

As revealed by the survey, few states use progress charts to measure the contractor's performance, and only one or two states have developed their own progress charts. Some of the states' requirements are described below for California, Virginia, North Carolina, and Alabama.

2.2.3.1 California DOT

The California Department of Transportation (Caltrans) may be the only state DOT that has full articulation and use of progress charts. Caltrans, however, did not participate in the current survey. Fortunately, Caltrans' Standard Specifications and Construction Manual explains all about the state's process of performance evaluation (Caltrans 2006).

Caltrans uses a progress chart to evaluate the progress and performance of contractors. The chart, Figure 2.1, was developed by Caltrans on the basis of experience with past projects; details can be found in Section 3-805B "Progress of Work" of the Construction Manual. After each progress estimate, progress is considered unsatisfactory if the contractor's progress curve (using the formula given in Figure 2.1) falls below the curve of the contract progress chart or when successive points on the contractor's progress curve indicate that the contractor's progress rate will soon fall below the curve. The percentage of work completed is determined by dividing the amount of the total work completed by the authorized final cost. The percentage of contract time elapsed is determined by dividing the number of working days elapsed up to the date of the progress estimate by the original working days plus the time extension approved to the date

Alternatively, on federally funded contracts, unsatisfactory progress is determined when

- The number of working days charged to the contract exceeds 75 percent of the working days in the current time of completion, and
- The percent of working days elapsed exceeds the percentage of work completed by more than 15 percentage points.

Actions Caltrans will take for unsatisfactory progress includes (briefly) the following:

- Whenever the contractor fails to conduct the work adequately, the resident engineer must notify the contractor of the apparent lack of progress.
- If the resident engineer judges that the work on the original schedule will not be completed by the original due date, the resident engineer must request the contractor to submit a revised schedule showing how the balance of the work will be carried out.
- When sufficient reasons are found, the resident engineer may notify the district that the contractor's bonding company should be notified of the unsatisfactory progress.
- "Termination for control" may be invoked by the district. This occurs when the contractor fails to supply an adequate work force; this is defined by Caltrans when the percentage of the contract completed is more than 25 percent behind the percentage of

time elapsed. If the project is terminated for control, the surety (bonding company) assumes the responsibility for completing the contract.

- The resident engineer may start deducting an amount sufficient to cover probable liquidated damages. The deduction is made in lieu of retention for unsatisfactory progress. On federally funded projects, a 10 percent deduction is made.

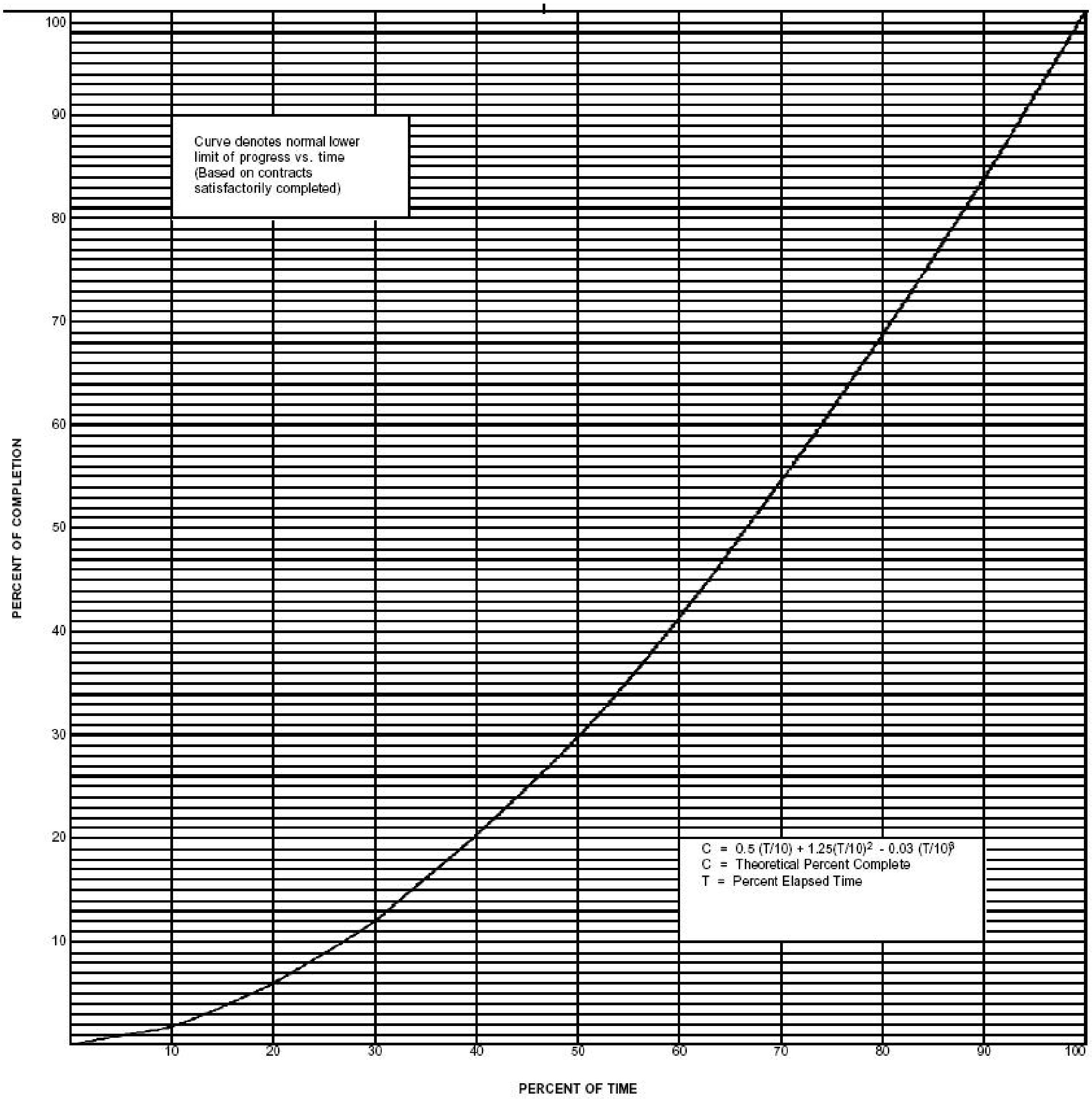


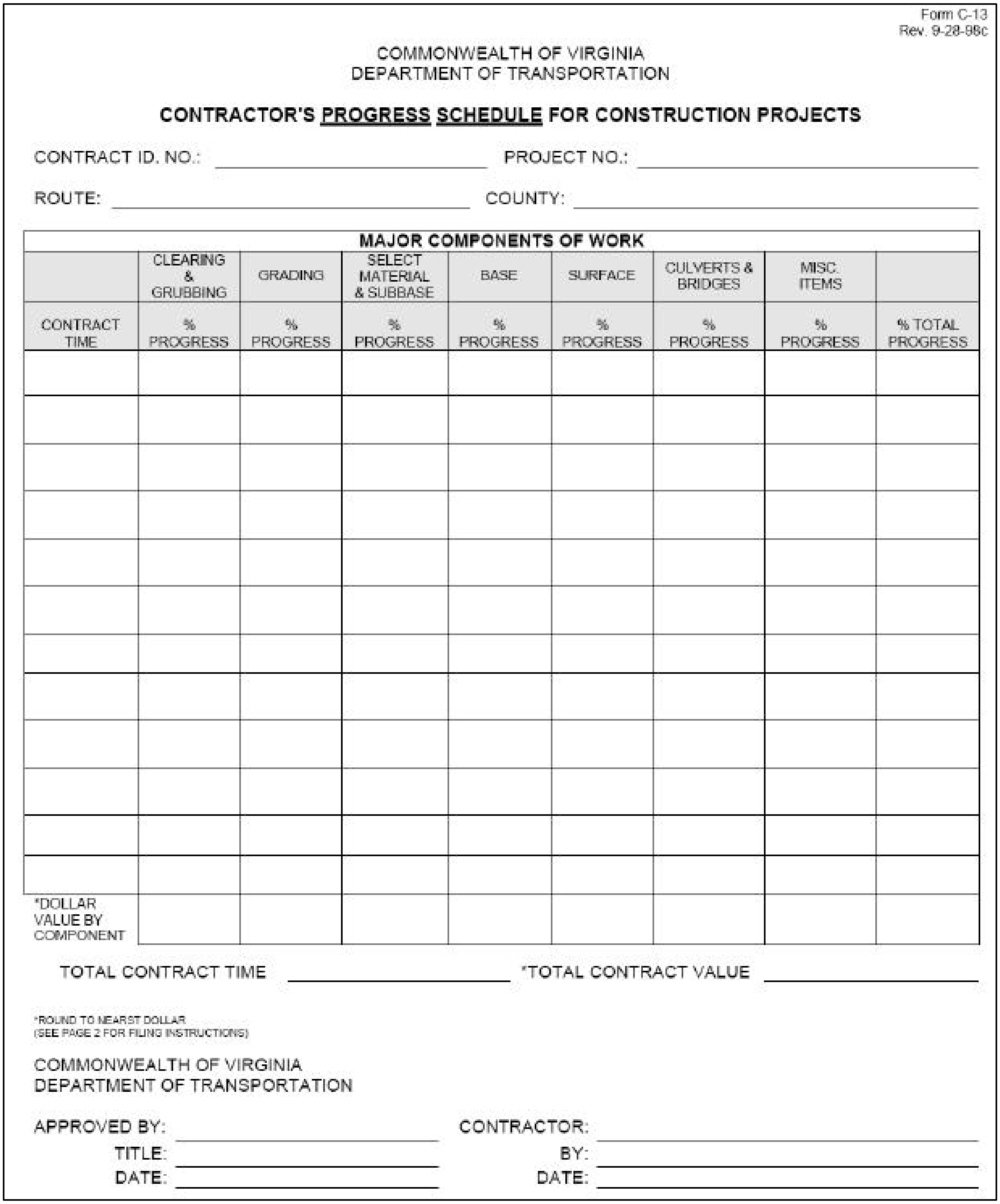
Figure 2.1: Caltrans progress chart

2.2.3.2 Virginia DOT

The Virginia Department of Transportation (VDOT) uses a construction progress chart, Figure 2.2, or other contractor-generated charts, to measure contractor progress during construction. This schedule defines the contract work by major components and indicates anticipated progress in percentages for each time period.

Progress is evaluated by comparing the actual work completed to date with the contractor's anticipated progress shown on the latest accepted schedule or progress chart (Figure 2.2). The progress schedule indicates the amount of work to be performed within given time periods as percentages of the contract dollar value.

When the percentage of time used exceeds the percentage of work completed by more than 10 percent, the contractor is notified that if the next monthly progress estimate shows a delinquency of more than 10 percent, progress will be considered unsatisfactory, and 5 percent retainage will be withheld on either bonded or unbonded contracts for each month the percentage of time used exceeds the percentage of work completed by more than 10 percent. A similar retainage is held if the contractor’s progress falls more than 10 percent behind the latest approved progress schedule (VDOT 2005).



Form C-13
Rev. 9-28-98c

COMMONWEALTH OF VIRGINIA
DEPARTMENT OF TRANSPORTATION

CONTRACTOR'S PROGRESS SCHEDULE FOR CONSTRUCTION PROJECTS

CONTRACT ID. NO.: ____________ PROJECT NO.: ____________

ROUTE: ____________ COUNTY: ____________

MAJOR COMPONENTS OF WORK								
	CLEARING & GRUBBING	GRADING	SELECT MATERIAL & SUBBASE	BASE	SURFACE	CULVERTS & BRIDGES	MISC. ITEMS	
CONTRACT TIME	% PROGRESS	% PROGRESS	% PROGRESS	% PROGRESS	% PROGRESS	% PROGRESS	% PROGRESS	% TOTAL PROGRESS
*DOLLAR VALUE BY COMPONENT								

TOTAL CONTRACT TIME ____________ *TOTAL CONTRACT VALUE ____________

*ROUND TO NEARST DOLLAR
(SEE PAGE 2 FOR FILING INSTRUCTIONS)

COMMONWEALTH OF VIRGINIA
DEPARTMENT OF TRANSPORTATION

APPROVED BY: ____________ CONTRACTOR: ____________
TITLE: ____________ BY: ____________
DATE: ____________ DATE: ____________

Figure 2.2: Virginia construction progress schedule

2.2.3.3 North Carolina DOT

The North Carolina Department of Transportation (NCDOT), one of the states that participated in the survey, uses progress charts submitted by the contractors. Section 108 “Prosecution and Progress” of its standard specifications provides that the contractor’s progress is considered unsatisfactory if (NCDOT 2006)

- The dollar value of the work completed is less than the dollar value of the work that should have been completed, as determined by the contractor's approved progress schedule, by more than 15 percent of the current contract amount.
- The percentage of the work completed is less than the percentage of contract time elapsed on the work by more than 15 percentage points. The percentage of work completed is the dollar value of the work completed divided by the current contract amount as defined above. The percentage of contract time elapsed is the number of calendar days elapsed, as shown in the latest pay estimate, divided by the total contract time in calendar days.
- The engineer anticipates the contractor will not complete the work described in the contract by the intermediate contract time or the contract completion date.

When the contractor's progress is found to be unsatisfactory, the state engineer may demand that the contractor state in writing the reason for the unsatisfactory progress. If the Contractor cannot satisfactorily justify the unsatisfactory progress, the state engineer may invoke one or more of the following sanctions:

- withhold anticipated liquidated damages from amounts currently due or that become due
- remove the contractor and all firms pre-qualified under the contractor's prequalification number from the department's Pre-qualified Bidders List.

The specifications also allow the use of liquidated damages if the contractor fails to complete the work by any of the applicable completion dates, intermediate completion dates, or intermediate completion times shown in the contract. The liquidated damage is an amount stipulated in the contract and is applied for each and every calendar day, for each and every hour, or portion thereof, that the work or any portion of the work remains uncompleted after the expiration of any completion date, intermediate completion date, or intermediate completion time applicable to the uncompleted work. This amount is deducted from any money due the contractor or his surety under the contract, and the contractor and his surety are liable for any liquidated damages in excess of the amount due.

2.2.3.4 Alabama DOT

The Alabama Department of Transportation (ALDOT), one of the states that participated in the survey, uses a progress chart that implies a linear trend (y = x; 45 degree line) in which the percentage of work completed proceeds at the same pace as the percentage of time elapsed. Section 108 “Prosecution and Progress” of its standard specifications provides that the contractor’s unsatisfactory progress will invoke the following sequence (ALDOT 2006):

(1) After preparation of the contractor's monthly estimate, the department will review work progress. The percentage of work performed is based on the dollar amount of work performed and the total contract amount. This is compared to the percentage of contract time elapsed. If the percentage of work performed, as compared to the percentage of contract time elapsed, is behind by more than 25 percentage points, a warning notice of possible disqualification is sent to the contractor.

(2) The warning notice states that ten days will be allowed to bring the progress within the required 25 percent, complete the project, or furnish acceptable reasons why the contractor should not be given a final notice of disqualification.

(3) At the end of the 10-day period, if the contractor's progress is not within the required percentage, nor has an acceptable reason been furnished to waive final disqualification, the department will issue a final notice of disqualification.

At completion, a contractor’s failure to complete on time triggers the use of liquidated damages based on a schedule of values in the specifications. Common clauses for termination for default on the contractor’s part are included in the specs.

2.2.4 Summary and Conclusions on Survey Data

The analysis of the survey results led to a number of conclusions.

(1) A formal progress measurement and performance evaluation process is lacking in many states.

Surprisingly, around 71 percent of state respondents indicated the unavailability of any document that describes a progress evaluation process (see Table 2.8). Progress reports are the major way to record work progress for 46 percent of the states (Table 2.9), and within these reports, which measuring work quantities (71 percent) and the work schedule (54 percent) are major factors (Table 2.1). Surprisingly again, 25 percent of the states use paper work to record work progress (Table 2.10); other states use internal management systems, as well as commercial systems such as Primavera Project Planner and AASHTO’s SiteManager.

(2) There is an apparent lack of progress charts for measuring contractor performance. Most states own and manage records of thousands of projects; however, no progress charts have been developed on the basis of this experience except for one or two states. Contractor-built progress charts are used by the states to check the contractor’s progress.

As mentioned in (1) above and in Table 2.1, for measuring work progress, some states analyze quantities of work (71 percent; 17 respondents), time schedules (54 percent; 13 respondents), and cash flow (25 percent; 6 respondents). However, only nine of 24 states indicated the use of progress charts. Only one of those states (Utah) uses past experience to develop progress charts (UDOT 2006), and the other states use contractor-submitted charts after project award (Table 2.13). (Caltrans also develops progress charts from experience with past projects.)

One state respondent mentioned that the DOT tracks the percentage of time against the percentage of completion without charting the results. Also, one state indicated that CPM schedules are used, but with no real ties to performance.

(3) States tend to evaluate projects as satisfactory if they are completed within a reasonable time and cost overrun.

Tables 2.5 to 2.7 show that around 73 percent of the state respondents reported that satisfactory projects should be completed within a reasonable percentage of both the contract value and completion time; 70 percent of the respondents establish the reasonable percentage at 10 percent or less, while around 30 percent or the respondents establish the percentage at 5 percent or less.

(4) Methods and limits for establishing the unsatisfactory status of a project vary among states.

In three state DOTs (ALDOT, NCDOT, VDOT), if the percentage of work complete (based on dollar value) is less than the percentage of time comple (elapsed time) by a specific tolerance value, then progress is deemed unsatisfactory. One state uses a 10 percent tolerance value, another uses 15 percent, and the third uses 25 percent. This method implies that actual completion is compared to a linear line in which work completed equals time completed (i.e., y = x).

Two of the three states (NCDOT, VDOT) also use another method in which a tolerance value is applied to actual work completion versus planned work completion; a value of 10 percent is used in one state and 15 percent in the other state.

A third method is used by California, in which the percentage of work complete at the associated percentage of time complete is compared to a benchmark historical progress chart/curve. No tolerance value is used; instead, once the actual progress is below the progress chart, the progress is deemed unsatisfactory. The progress curve thus acts as a minimum performance level.

(5) States measure work progress in terms of schedule time and project quantities more than they measure the performance of contractors by using cash flow.

Table 2.1 shows that comparing actual project schedule (time) to originally planned time, as well as comparing actual quantities to planned quantities, are the “progress” measurement factors most commonly used (54 percent and 71 percent, respectively) by the state respondents. Comparing actual cash flow to planned cash flow, which establishes the work done per unit of time, was selected by only 25 percent of the respondents. Tables 2.2 and 2.3 emphasize this point, showing that the percentage of respondents choosing the “do nothing” option was higher for unsatisfactory cash flow (46 percent) than for unsatisfactory schedule (8 percent). Also, the percentage of respondents who said that there are performance penalties for an unsatisfactory schedule (33 percent) was larger than those who reported penalties for unsatisfactory cash flow (5 percent). Furthermore, the percentage of respondents explaining other strategies for dealing with unsatisfactory schedule was larger than that for unsatisfactory cash flow.

Measuring *progress* means comparing actual construction work (time units and work quantities), e.g., actual times/schedules for interim milestones and quantities placed, to the established or planned work, e.g., target completion times and budgeted quantities. However, measuring *performance* requires comparing the actual work done in a unit of time to an established or planned set of work per unit of time along the duration of a project. Measuring *performance* can explain whether the contractor is on the right track to finish on time and within budget long before the project has been completed. It can determine whether the contractor is going to meet an interim or completion milestone before reaching those milestones. Measuring the “*progress*” of work can’t provide such information. For example, a milestone that has not been met on time becomes known on the milestone date, i.e., after it has not been met. *Performance* measurement at any time during the project duration can help in taking precautionary actions before any unsatisfactory time or cost problems have materialized.

The progress of schedule/time, quantities, and cost should not be measured in isolation of each other. Measuring performance allows project parameters to be related in a graph that always has time along one axis and the other factors, e.g., proportion of elapsed time, proportion of quantities placed, or proportion of money spent, along the other axis.

2.3 Performance Modeling Methodology

Contractors are more interested than client agencies in developing cash flow profiles to better plan for the size and timing of the funds required to support the development of a project and to prepare for project financing. The difference between the cash out and cash in profiles represents the amount that contractors will need to finance, given the client's retention percentage and the time lag between submitting a progress payment and the day it will be paid.

Most of the literature on time/cost cash flow supports the assumption that the cumulative capital expenditure over time will resemble an s-shaped envelope that normally has a slow build-up period, then a relatively steady load/rise period, followed by a final slow tail-off period. Various studies have been conducted to establish a mathematical formula that can model the s-shaped curve. These efforts can be classified into three main approaches.

The first approach is the development of a "standard s-curve" through a specially developed mathematical formula, or by using an existing one, such as the Normal or Gamma distribution. The parameters of such mathematical formulae are obtained on the basis of matching or comparison of the developed s-curve/formula with actual project time/cost cumulative cash flow (De La Mare 1979; Miskawi 1989; Hwee and Tiong 2002). The approach is generally referred to as the nomothetic approach because it generally tries to discover a general curve/law to be used with different types of projects. Once the parameters have been determined, the formula can be used with future project cash flow forecasting.

The second approach develops s-curves by using Logit transformation. The transformation of sigmoid (S) curves can produce linear function; the parameters of the linear function are determined through linear regression of data from actual projects; and then the parameters of the sigmoid Logit formula are determined through transformation (Kaka and Price 1993; Kaka 1996;

Kenley and Wilson 1986, 1989). The approach uses historical data to determine two parameters, and the approach is considered superior to the first standard s-curve approach. The approach is generally referred to as the idiographic approach because it tries to establish specific laws pertaining to individual projects.

The third approach reflects the application of polynomial regression analysis to actual project historical data to obtain a forecasting formula for future projects (Peer 1982; Navon 1996; Nassar et al 2005; Shapanka and Allen 1984).

While most of the work cited has reflected deterministic-type analysis, a small number of studies, on cash flow forecasting for contractors, has explained efforts to use earned value analysis and stochastic s-curves via Monte Carlo simulation to expand the deterministic analysis into probabilistic forecasting (Barraza et al 2000, 2004; Isidore and Back 2002).

In the literature, no single approach provides a better forecasting formula over the other. The effectiveness of such approaches reflects the scarcity of project records to develop more accurate models, the level of detail used in the analysis (e.g., the grouping of projects into a general category and development of a single general forecasting formula or development of formulae for projects of similar sizes and types), and the number of variables used in the analysis. The techniques commonly used have been polynomial regression analysis and Logit transformation.

2.4 Performance Modeling Approach

As outlined in the Chapter I, one of the objectives of this research was to develop a representative, benchmark performance profile(s) that could be used for evaluating the performance of contractors in future projects. The characteristics and conditions for this development include the following:

(1) Performance profile type

As discussed earlier, a performance profile explains the percentage of completion of a project in comparison to the elapsed time from the start of the project. The percentage of completion can be determined on the basis of schedule/time, quantities, or cash flow. By using a project's progress estimates and the number of working days for all projects in WSDOT databases, the cash flow percentage of completion can be determined, and this is the approach that was adopted in this research.

(2) Performance model methodology

The statistical techniques used in developing the model(s) for the current research included both (a) regression analysis with polynomial functions and (b) regression analysis with "Logit" functions.

(3) Performance model base and tolerance value

As revealed by the current practice survey and described by the specific practices section, a performance model and the tolerance value for unsatisfactory performance can be established by (a) comparing actual work completion to actual time completion with a tolerance value of 10 percent to 25 percent, (b) comparing actual work completion to planned work completion (based on a contractor-generated progress chart) with a tolerance value of 10 percent to 15 percent, and (c) comparing both actual work and time completion to an established agency-generated progress curve, with no tolerance value if the curve is a minimum curve or use of a tolerance value otherwise.

The current research developed *minimum performance bounds* as well as *average performance bounds* by using data from WSDOT highway projects. The minimum and average performance bounds were developed for a set of projects, referred to as successfully completed projects, and for groups (clusters) of the projects that were classified on the basis of quantities of ACP/HMA, contract value, project duration, and project miles.

2.5 Development of Performance Profiles

2.5.1 Successfully Completed Projects

The benchmark performance model needed to be developed on the basis of a set of successfully completed projects. Table 2.20 shows the number of WSDOT projects completed at different levels of time and cost overrun. For example, at 0 percent time overrun (Workable Charged Days—Total Authorized Days/Total Authorized Days), 72.72 percent of the projects were completed on time. At 0 percent cost overrun (Paid-to-Contractor—Original Bid Price/Original Bid Price), 42.84 percent of the projects were completed within the bid price. At 0 percent both time and cost overrun, 33.16 percent of the projects were successfully completed at the planned time and cost, but 66.84 percent experienced time and cost overruns.

For performance model development, a 5 percent time and cost overrun was considered as a limit, and therefore, 497 projects (51.56 percent of all projects) were considered to have been successfully completed and were used as the basis for model development. For each of these projects, data collected included progress payment estimates and the number of working days recorded at each payment estimate. From these data, work and time percentage complete were obtained. Figure 2.3 illustrates the progress of 133 of the successfully completed projects.

Table 2.20: Number and percentage of projects at different levels of time and cost overrun

% Overrun	No. of Projects at indicated % of **Time Overrun** (WCD – TAD)/TAD	No. of Projects at indicated % of **Cost Overrun** (PTC – OBP)/OBP	No. of Projects at indicated % of **Time and Cost overrun**
0%	710 (72.72%)	413 (42.84%)	310 (32.16%)
5%	731 (75.83%)	636 (65.98%)	**497 (51.56%)**
10%	753 (78.11%)	751 (77.90%)	583 (60.48%)
15%	777 (80.60%)	828 (85.89%)	667 (69.19%)
20%	799 (82.88%)	878 (91.08%)	726 (75.31%)
25%	817 (84.75%)	902 (93.57%)	764 (79.25%)
30%	825 (85.58%)	927 (96.16%)	792 (82.16%)

WCD - Workable Charged Days, **TAD** - Total Authorized Days, **PTC** – Paid-to-Contractor, **OBP** – Original Bid Pric

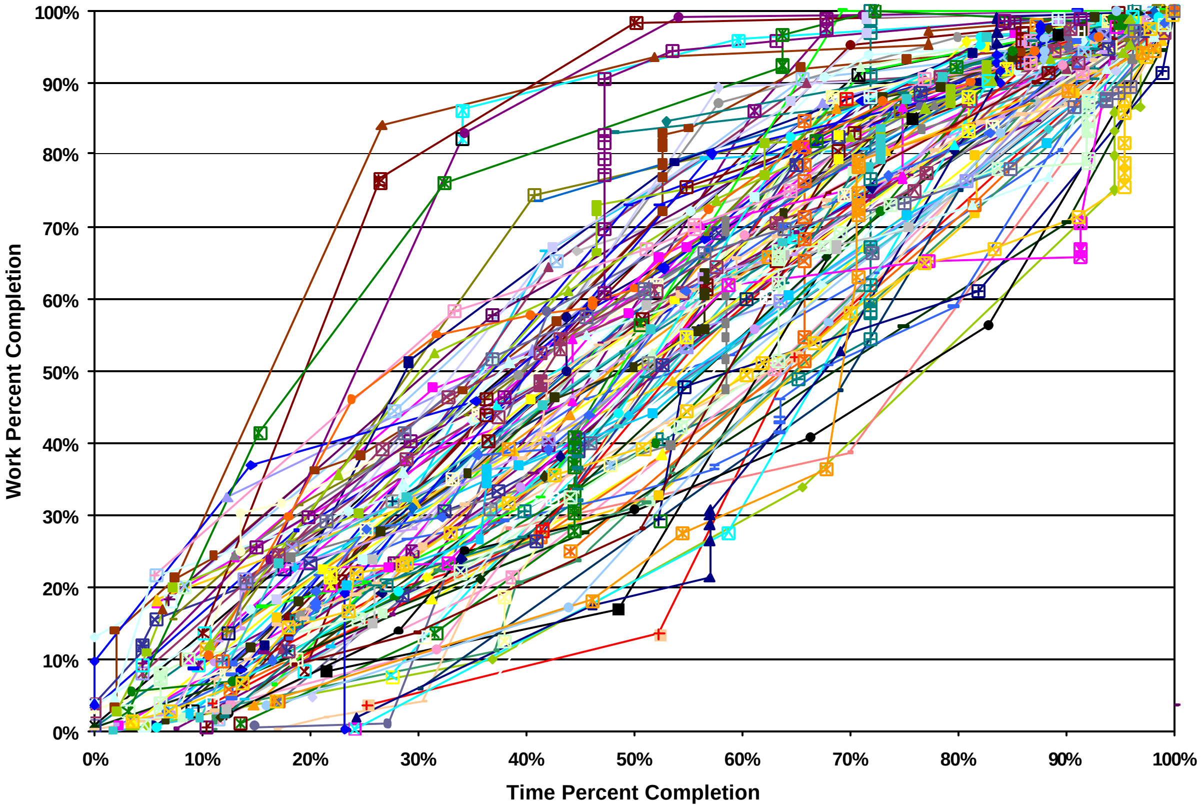


Figure 2.3: Progress profiles of a sample of 133 successfully completed projects

Figure 2.3 illustrates the wide range of progress that may be experienced in a project. The lower part of the figure shows that some projects experienced slow progress, in that after almost

25 percent of elapsed time, the work started to proceed at a slow pace. In contrast, the upper part of the figure shows that some projects had a quick start and proceeded at a fast pace. The majority of the projects fall into the middle part of the figure, where the work and time percentage of completion seem to cluster around an average progress, shown by a 45 degree line (linear model y = x) between zero and 100. The range between average and slow progress is around 35 percent. This helps explain why some states choose to measure the limit for unsatisfactory progress at between 10 percent and 25 percent from the average linear line. On the other hand, Caltrans works with the minimum performance level without a tolerance value. That is also the approach contemplated in this current research.

2.5.2 Performance Models for Project Groups - All Projects

2.5.2.1 Average Performance Bound

To develop an average performance profile for the projects, polynomial regression analysis of the 3rd, 4th, and 5th degree and logit regression analysis were performed. The dependent variable in the analysis was the percentage of work completed, and the independent variable was the percentage of time completed. The analysis did not explain significant differences among the three models. In developing the models, two constraints were imposed on the model design: to have no intercept in the final model and to have the sum of the three regression coefficients equal unity. These constraints were defined in the *loss function* of the regression analysis. The regression model for the 3rd polynomial and *logit* function under these constraints was solved by using three methods: Quasi-Newton, Simplex, and the Rosenbrock pattern search (Brent 1973; Gill and Murray 1974; Peressini et al. 1988; and Wilde and Beightler 1967).

The results of the three models for each regression were analyzed to determine whether any of the profiles would produce negative values at the lower extreme of the percentage of time completed. The results for the logit regression were nearly identical with an R^2 value (coefficient of determination) of 81.630 percent. The results for the polynomial regression were very close to each other: 86.602 percent (Quasi-Newton), 86.65 percent (Simplex), and 86.52 percent (Rosenbrock). Figure 2.4 illustrates how the models were close to each other in explaining the average performance and very close to the 45 degree linear line (y = x) at around a 5 percent difference. The Simplex regression result was chosen because it had the highest R^2:

$$Y = (.99762)*x + (.455684)*x\verb|^|2 + (-.45322)*x\verb|^|3 \tag{2.1}$$

where y is the percentage of work completed and x is the percentage of time completed.

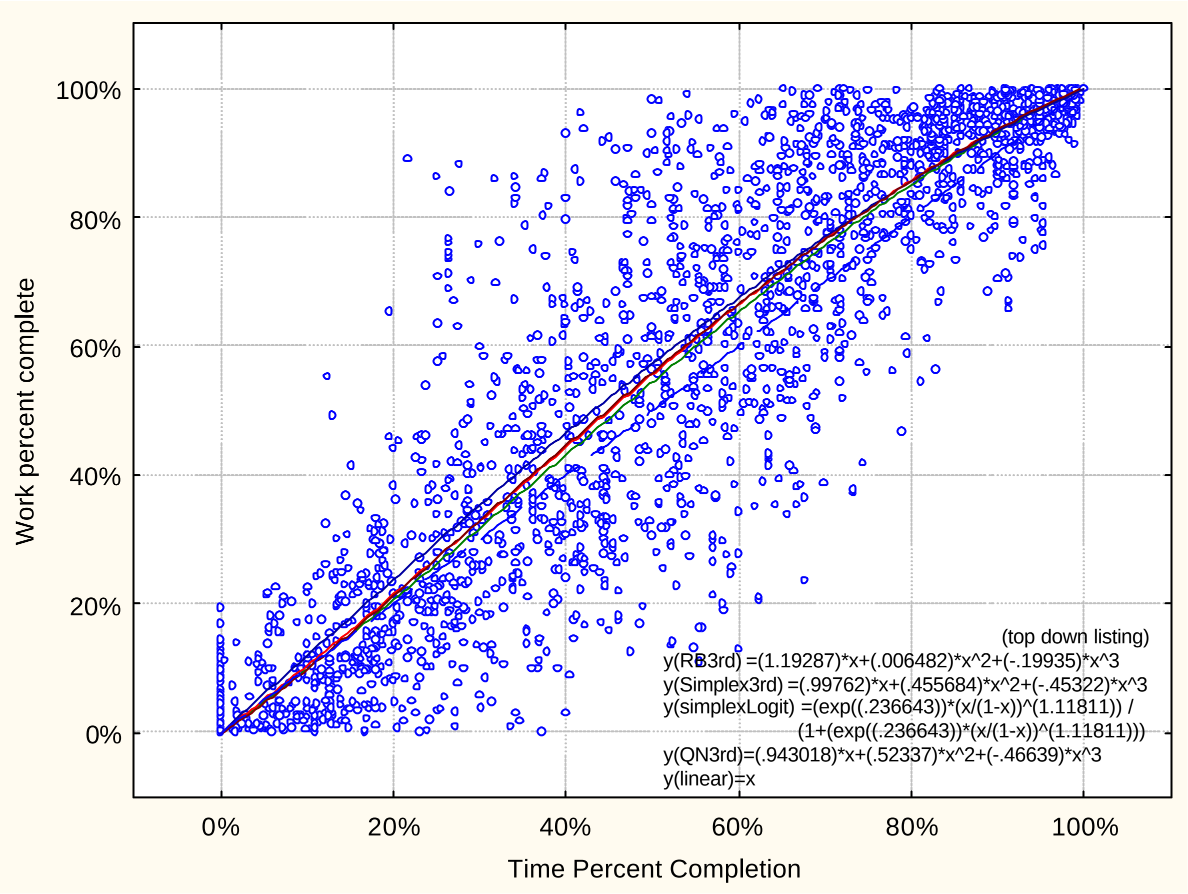


Figure 2.4: Average performance bounds for all successfully completed projects

The average performance profile considers all the successful projects and thus can be used with a tolerance value to establish an unsatisfactory progress level. There is no specific rule for determining a tolerance value, as it can be determined a number of ways:

(1) Visually: A visual inspection of the graph of performance profiles and projects (Figure 2.3 and 2.4). For example, at the mid point, 50 percent, the range is about 35 percent to 40 percent between the average line and the lower points. Assuming a 5 percent rejection for the lower projects, then the tolerance becomes 30 percent to 35 percent. This is equivalent to measuring the tolerance by using the 45-degree linear line.

(2) Statistically: The determination of the lower prediction interval for the developed average model (Simplex). For the successfully completed projects, and by using model Eq. 2.1, the average lower prediction interval was determined to be 24 percent.

A lower prediction interval can be determined by using the standard errors and the variance of the estimates (Dielman 2005). The variance of the prediction, Var_p, for any value x_m equals the variation around the regression line (called the MSE, or mean square error), Var_e, plus the square of the standard error of the estimate value, Var_m (for sample *n*):

$$\mathrm{Var}_p = \mathrm{Var}_e + \mathrm{Var}_m$$

$$\mathrm{Var}_p := \mathrm{Var}_e \cdot \left[1 + \frac{1}{n} + \frac{\left(x_p - \mu_x\right)^2}{(n-1)\cdot \mathrm{Var}_x} \right] \tag{2.2}$$

and the lower prediction interval becomes (where S_p is the square root of Var_p):

$$\text{lower prediction} = \text{prediction} - t_{a/2,n-2} * S_p \tag{2.3}$$

where $t_{a/2,n-2}$ is a value chosen from the *t* distribution with (1-a)100% prediction interval and (*n*-2) degrees of freedom.

In the current case, where *n* is very large and at a prediction interval of 95 percent, $t_{a/2,n-2}$ equals 1.96. In model Eq. 2.1, the variance around the regression line, Var_e, is 0.0149, so the average value of ($t_{a/2,n-2} * S_p$) for a percentage of time completed of 0.1, 0.7, and 0.9, representing minimum, average, and maximum values of x_m, respectively, becomes 24 percent.

Therefore, by using a lower prediction interval, the tolerance can be suggested at 24 percent measured from the average Simplex model line in Figure 2.4. Because the difference between the simplex line and the average linear line (y = x) is around 5 percent, it is also possible to assume a tolerance value of 19 percent measured from the linear line.

(3) Departmentally: Decision makers and project managers can also check Figure 2.4 and decide on a tolerance value. Choosing a large tolerance value, e.g., 45 percent or 50 percent, would send a wrong message to contractors, saying that lower performance is acceptable. Choosing a low tolerance value, e.g., 5 percent, would require steady progress almost on the average line (Figure 2.4) or the linear line, which would require the contractor to carefully control the construction work and the pace of operations.

2.5.2.2 Minimum Performance Bounds

Rather than using the average performance (or linear performance), use of minimum performance bounds would allow the tolerance value to be ignored and progress or contractor performance to be compared against a performance benchmark curve. Determination of the minimum performance bounds, however, is more complex than determination of the average performance bounds. The average boundary is calculated by the least square regression analysis that was performed on “all” successfully completed projects. However, calculating a “minimum” boundary or the “border” of the data requires further scrutiny. For example, in Figure 2.3, where the progress profiles are plotted, the lower boundary or border includes the progress profiles of several projects that intersect. The border itself can be considered a narrow strip that includes several projects or portions of several projects. Consequently, the determination of the lower or minimum bounds requires determination of the size of the border strip, the identification and isolation of the projects on the border strip, and identification of portions or performance points of projects in the strip.

One way to do that is by developing a regression line for each project (there were 497 successful projects in the research study) and then evaluating those regression lines at intermediate intervals between zero and 100 percent to get the values of the percentage of work completed in each interval and choose the minimum of these values. This is equivalent to getting the percentage of work completed for each interval or the percentage of time completed directly from the collected data instead of developing 497 regression equations. The problem in both methods, however, is how many intervals to work with. The number of intervals may have to be statistically significant to produce significant results. In the following analysis, the number of intervals was chosen to be 50, 100, 250, and 500. The number of intervals determined the number of projects in each interval, and the number of points equalled the number of intervals.

Along with determining the number of intervals, the minimum performance points in each interval has to be identified. However, looking back to Figure 2.3 and the performance profiles, one can visualize that in some intervals there will be a number of minimum performance points, and in other intervals there will be no performance points, or the performance points will have a large value that can not be considered a "minimum" when compared to the previous or next intervals. Therefore, it becomes necessary to work with absolute minimum points, referred to here as the zero percentile values, and other, slightly higher than minimum points, referred to here as the 5th and 7.5th percentiles. This also helps determine minimum performance of projects that do not accidentally have extremely low performance.

Figure 2.5 illustrates the minimum performance boundary with 50 intervals and points representing the minimum or zero percentile. The number of projects was 44. The boundary was developed with regression analysis by using the Quasi-Newton, Simplex, and Rosenbrock methods. The bounds from the three solution methods were nearly identical; however, the

Rosenbrock method was the only line that had all positive values at the lower percentage of time completed and, consequently, would be the one selected for the 50-point case. Figures 2.6, 2.7, and 2.8 illustrate the bounds for 100 (73 projects), 250 (168 projects), and 500 (264 projects) intervals; the unique projects in these intervals are shown in brackets.

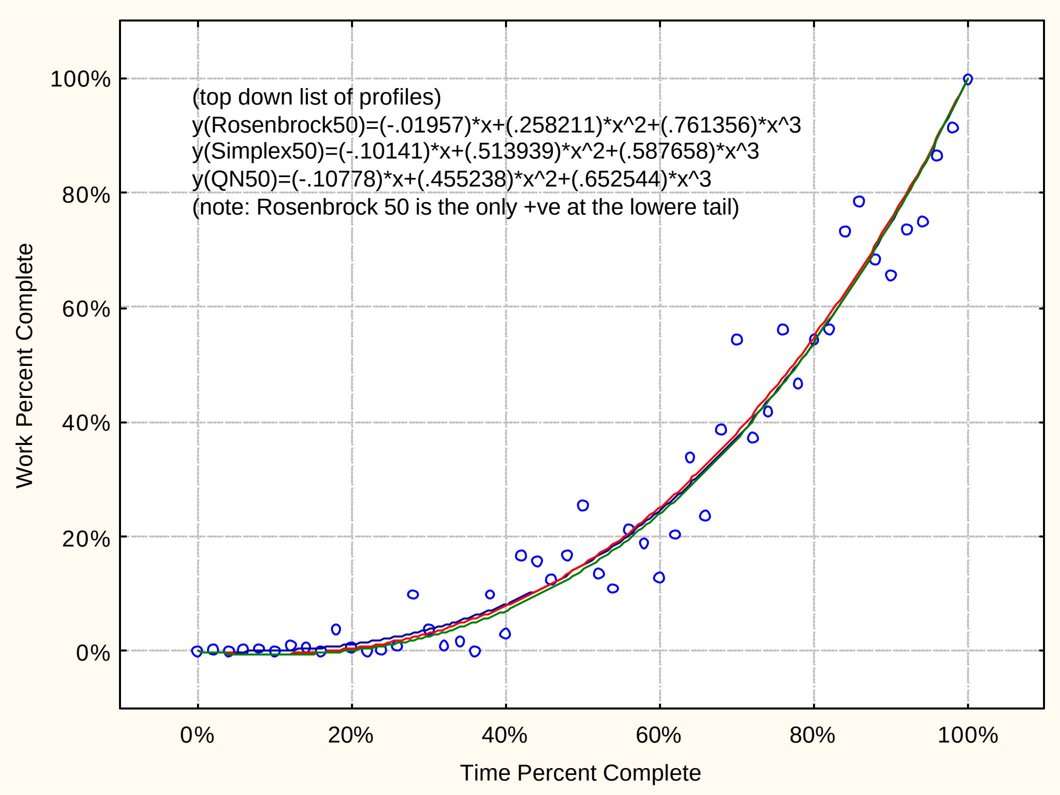


Figure 2.5: Minimum performance bounds for 50 intervals and zero percentile

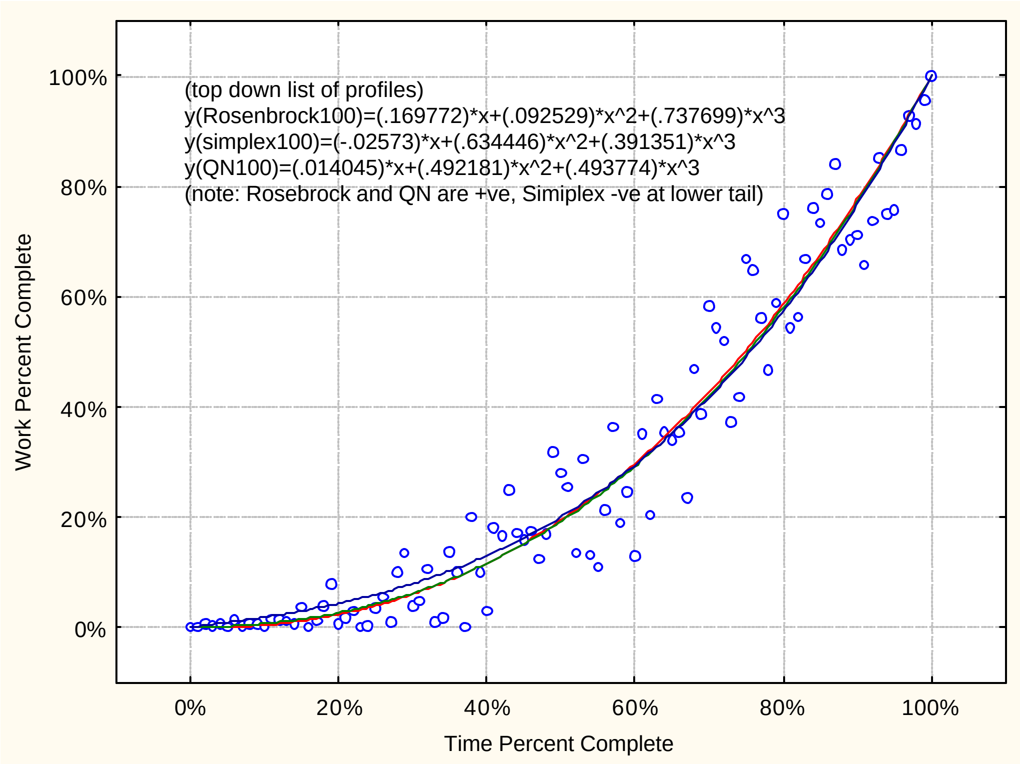


Figure 2.6: Minimum performance bounds for 100 intervals and zero percentile

Figure 2.7: Minimum performance bounds for 250 intervals and zero percentile

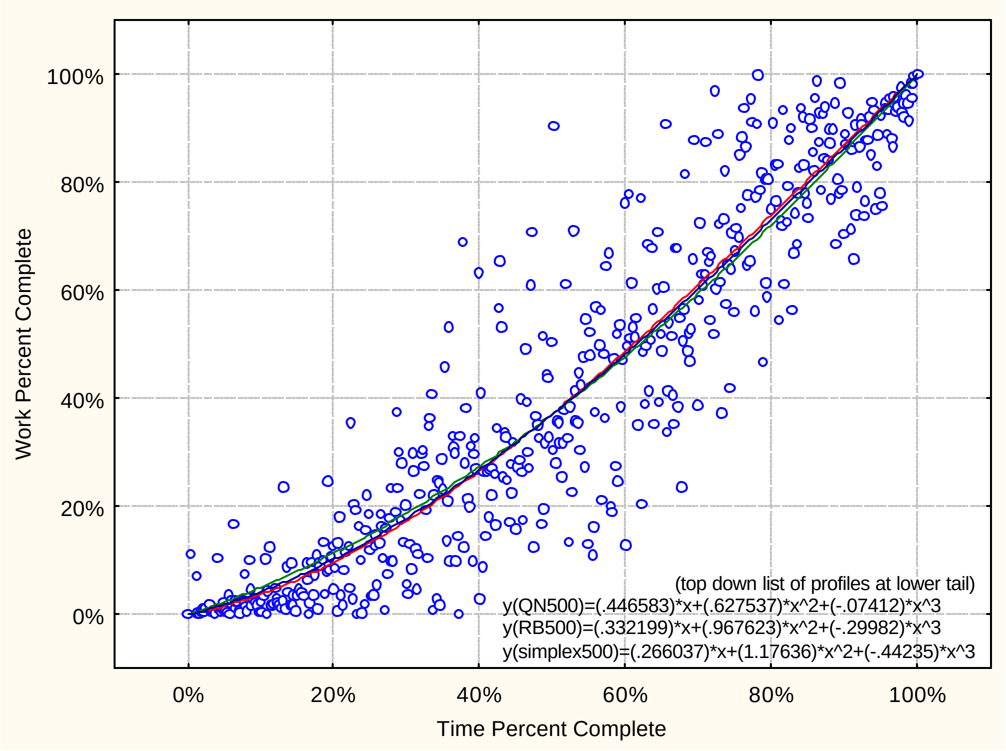


Figure 2.8: Minimum performance bounds for 500 intervals and zero percentile

Figure 2.9 illustrates a summary of the best model in each interval, as well as the average Simple model (Eq. 2.1; Figure 2.4), linear model (y=x), and the model Caltrans uses. The models are written/listed in the same order they appear in the figure. The more interval points, the more the minimum performance boundary moves toward the average line. The 50-point model (Rosenbrock) covers more of the slow performance at the start of projects and proceeds with a slow pace upward. The 100-point model (Quasi-Newton QN) is similar, with a little better performance. Decision makers could choose one of these models in the graph, knowing that the 100-point and 250-point models would be better than the 50-point model, since they would require contractors to maintain faster progress.

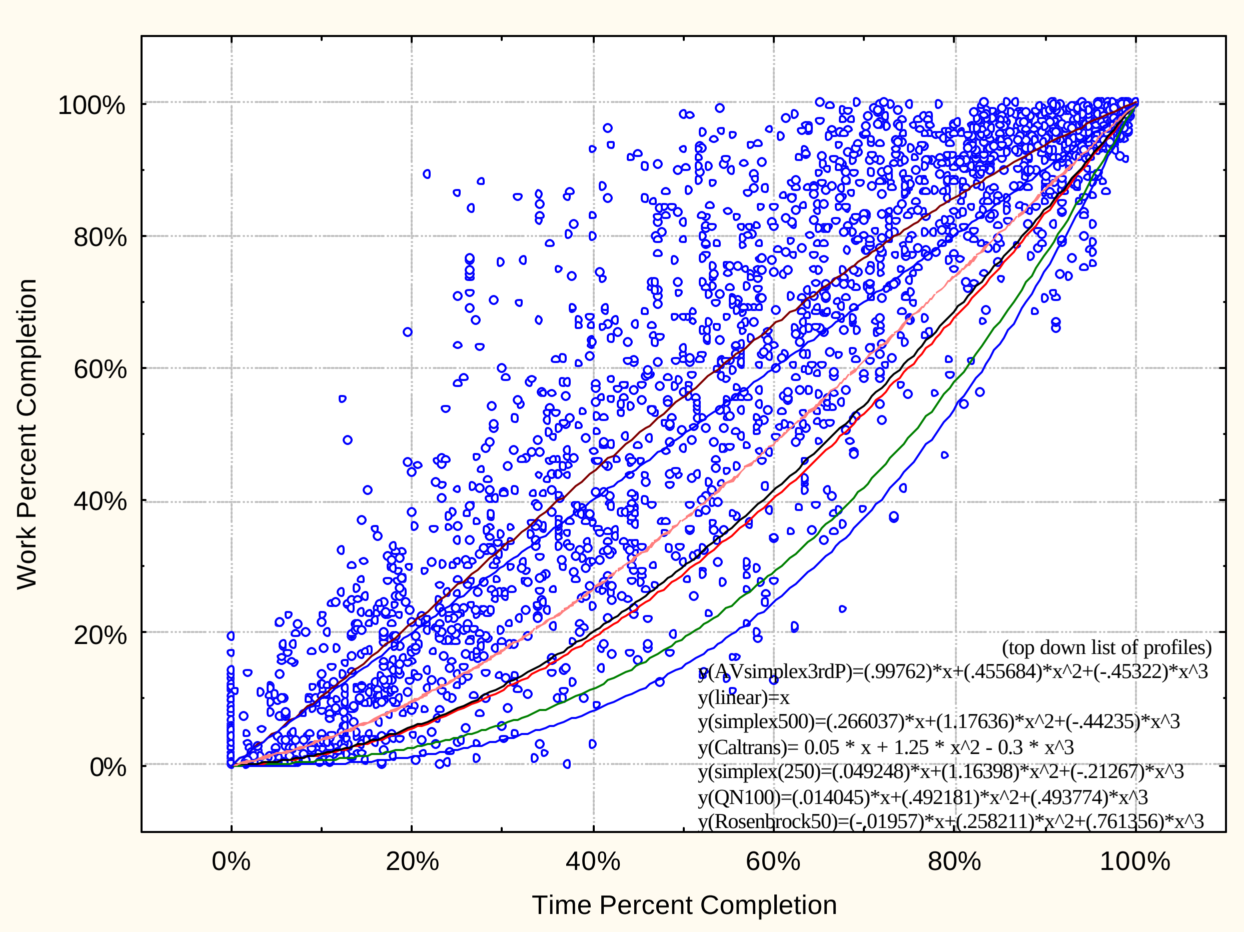


Figure 2.9: Minimum performance bounds for successful projects (zero percentile)

Figure 2.10 illustrates the results of producing minimum performance bounds by using the 5th percentile points in each interval. The absolute minimum points (zero percentiles) were not considered in model development. This could also be considered a way to remove any projects with extremely low performance from development of the benchmark minimum performance models. Of note in this graph is the closeness of the 50- and 100-point models to each other; more consistency is produced by the 5th percentile. Decision makers could choose any of the models; however, the 50-point and 100-point models would provide a more reasonable rate of work progress. These two models represent an average between the 100- and

250-point zero percentile models of Figure 2.9. Therefore, they provide minimum performance bounds with reasonable progress.

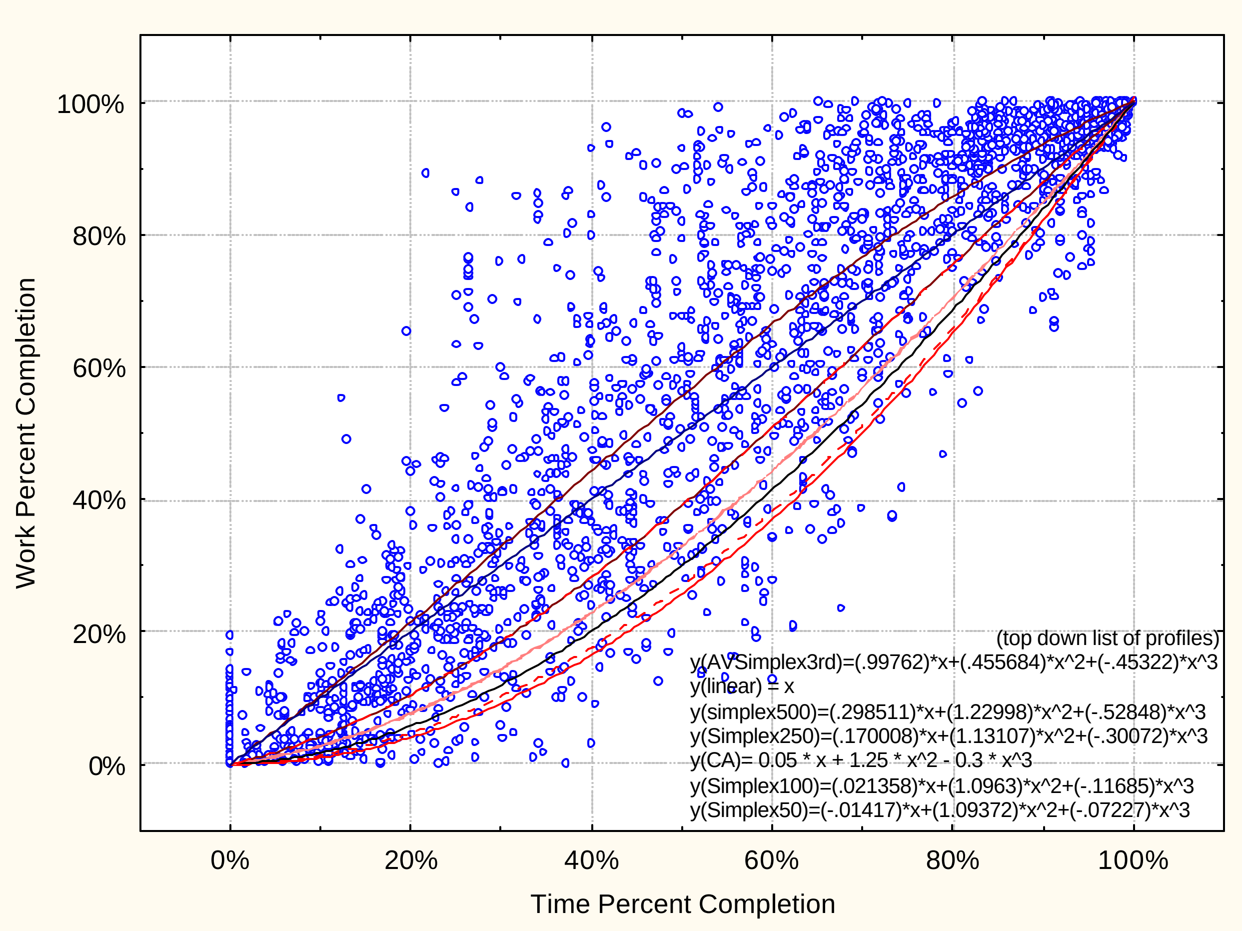


Figure 2.10: Minimum performance bounds for successful projects (5th percentile)

Figure 2.11 illustrates the results for the minimum performance bounds for the different interval points with 7.5 percentile points in each interval. In this case, the absolute minimum points (zero percentile) and the 5th percentile points were not considered in the regression model development. Again, this could be considered a way to remove any projects with extremely low performance from development of the benchmark minimum performance models. In this graph, the 50- and 100-point models match the Caltrans model, leaving many of the projects in the minimum bound strip. These two models show greater progress for minimum performance than the 5th percentile models. Decision makers could choose any of the models; however, the 5th percentile models would be more representative of minimum performance.

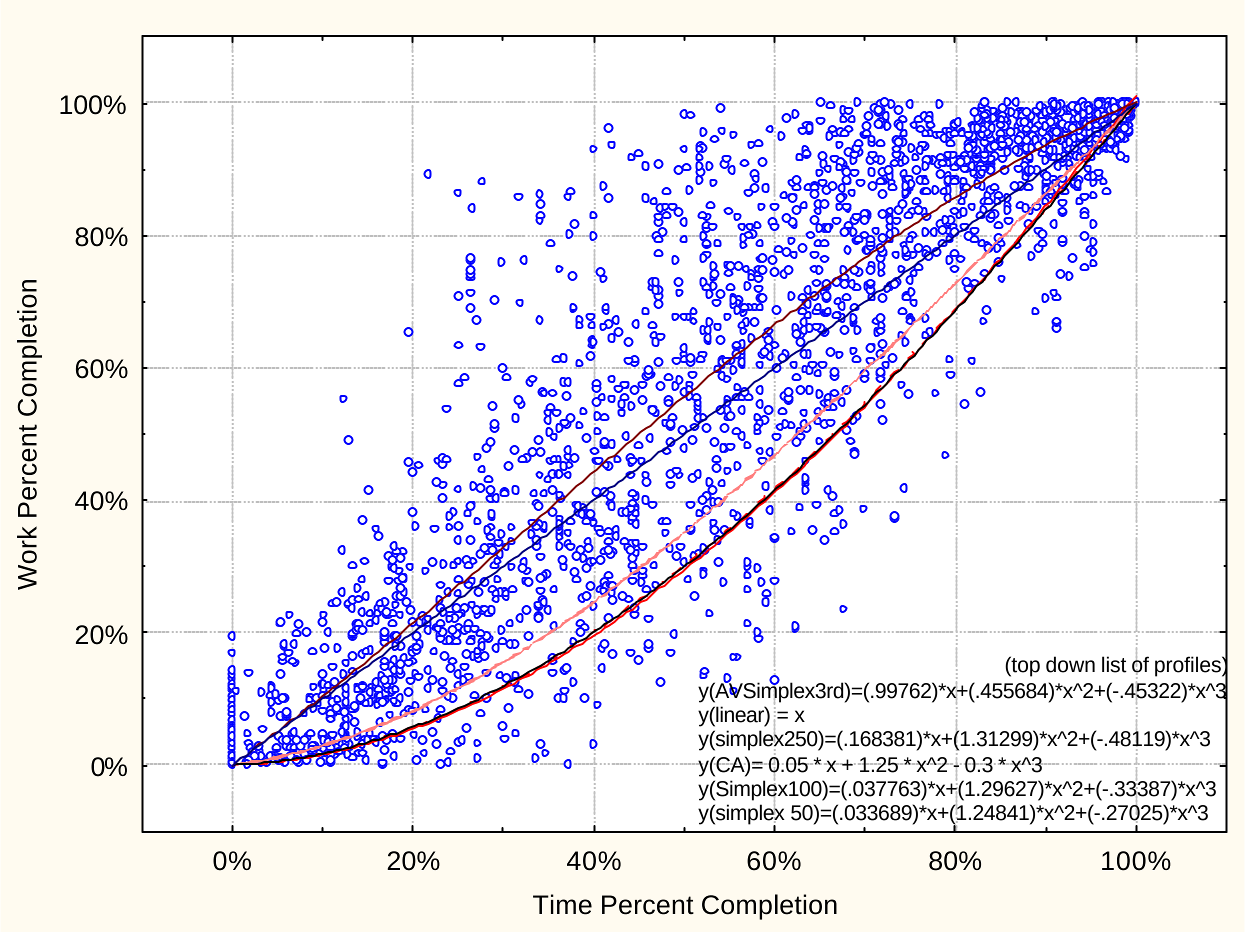


Figure 2.11: Minimum performance bounds for successful projects (7.5 percentile)

2.5.3 Performance Models for Project Groups - ACP/HMA

The above analysis developed average and minimum performance models by using the full sample of successfully completed projects (497 projects). In this analysis, further models were developed for groups of projects classified on the basis of quantities of ACP/HMA. The groups were formed with cluster analysis, an analysis that tries to develop groups of similar data by minimizing the variance within the group and maximizing the variance between the groups. K-means clustering was used, and Table 2.21 illustrates the statistics of the three clusters that included all the successfully completed projects.

Table 2.21: ACP/HMA clusters for the successfully completed projects

Cluster #	# of projects	Min ACP/HMA	Max ACP/HMA	Mean	Standard Deviation	Variance
3	342	0.00	16,753.74	4,978.590	4,986.134	24,861,530
2	129	16,927.26	48,767.96	28,764.12	8,153.351	6,647,7130
1	26	51,338.70	99,426.20	69,997.30	16,447.71	270,527,300

The analysis and model development for the minimum performance bounds and average performance bounds for each ACP/HMA cluster were conducted as explained for all cases of successfully completed projects. Figure 2.12 illustrates the results for the 0k- to 17k-ton HMA cluster, which contained the majority of the projects (342 projects); the model for 100 points (Simplex) was most representative of the minimum performance bounds. Figure 2.13 shows that for the 17k- to 51k-ton HMA cluster (129 projects,) the 100-point (Simplex) model also produced good minimum performance bounds. Figure 2.14 illustrates a unique cluster of 26 projects that ranged from 51k tons of HMA and above. The average and minimum performance bounds were close to each other. The 50-point (Simplex) model would be chosen as the minimum performance bounds. (A summary graph is shown in Figure 2.15.)

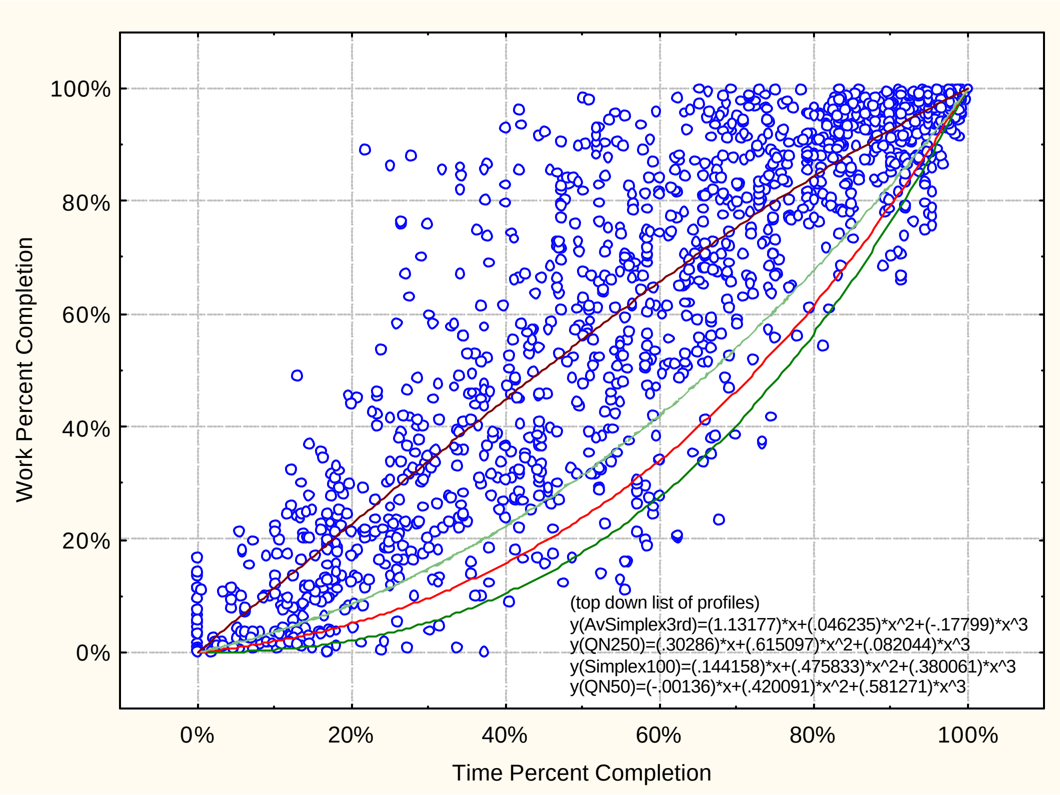


Figure 2.12: Minimum and average performance bounds - HMA Cluster (0k to 17k tons)

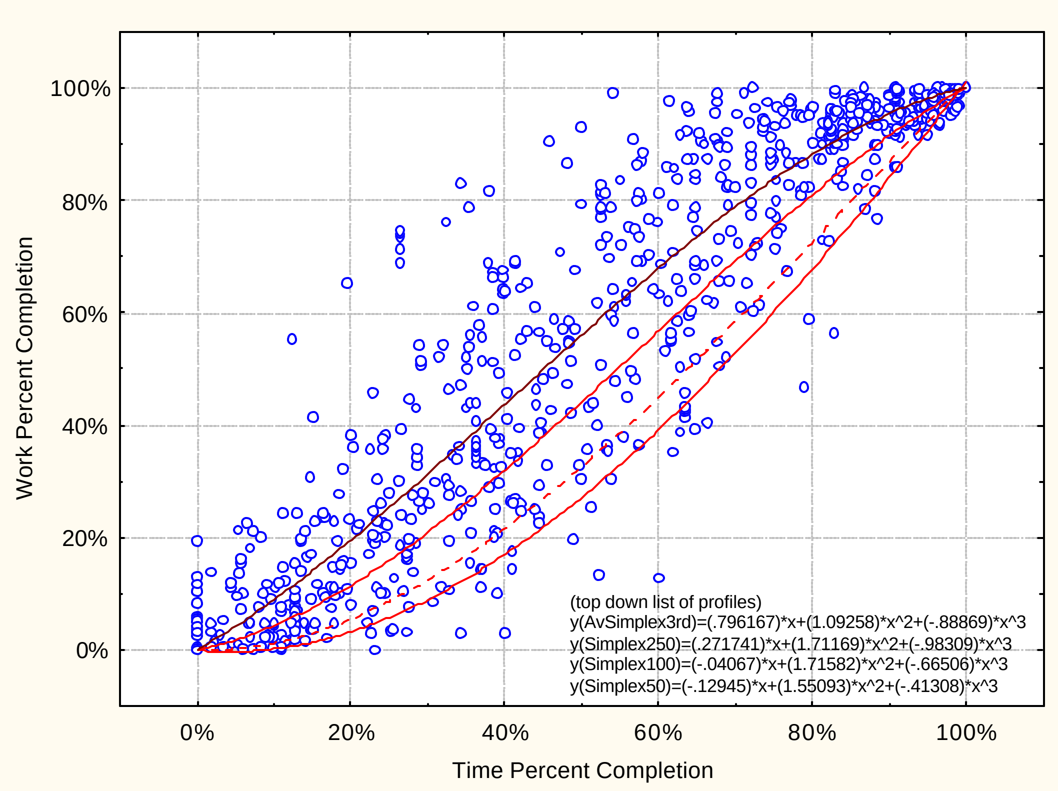


Figure 2.13: Minimum and average performance bounds - HMA Cluster (17k to 51k tons)

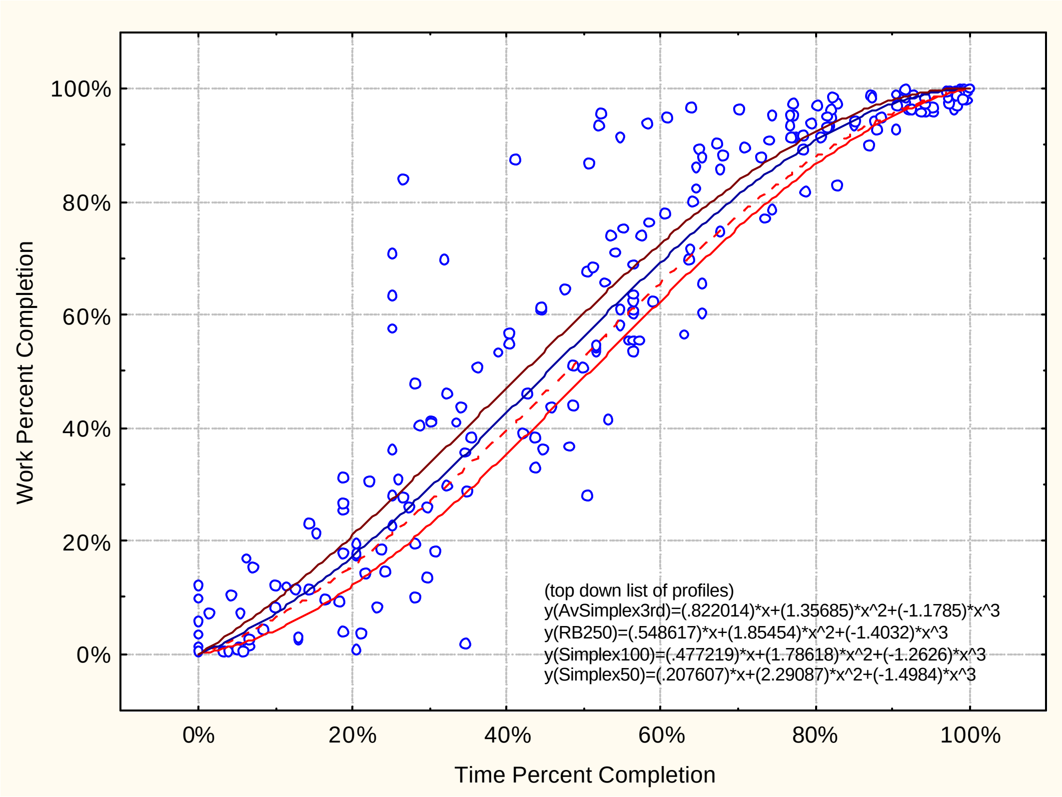


Figure 2.14: Minimum and average performance bounds - HMA Cluster (51k and above)

Figure 2.15 is a summary graph that includes the selected minimum performance models for each of the three clusters, along with the associated average performance bounds. The average in the model envelope for each cluster is the upper line, and the minimum is the lower line. Each envelope explains the position of the projects and their associated cluster relative to all the successfully completed projects. Cluster 3 projects with fewer HMA tons tended to have a slower progress pace than projects with a medium amount of HMA in cluster 2, which had a slower progress rate than projects with the largest amounts of HMA in cluster 1.

While the 50- and 100-point models in Figure 2.10 were previously suggested as the best representative minimum performance bounds for all the successfully completed projects, Figure 2.15 provides more tools for monitoring and controlling progress, given specific quantities of ACP/HMA in a project.

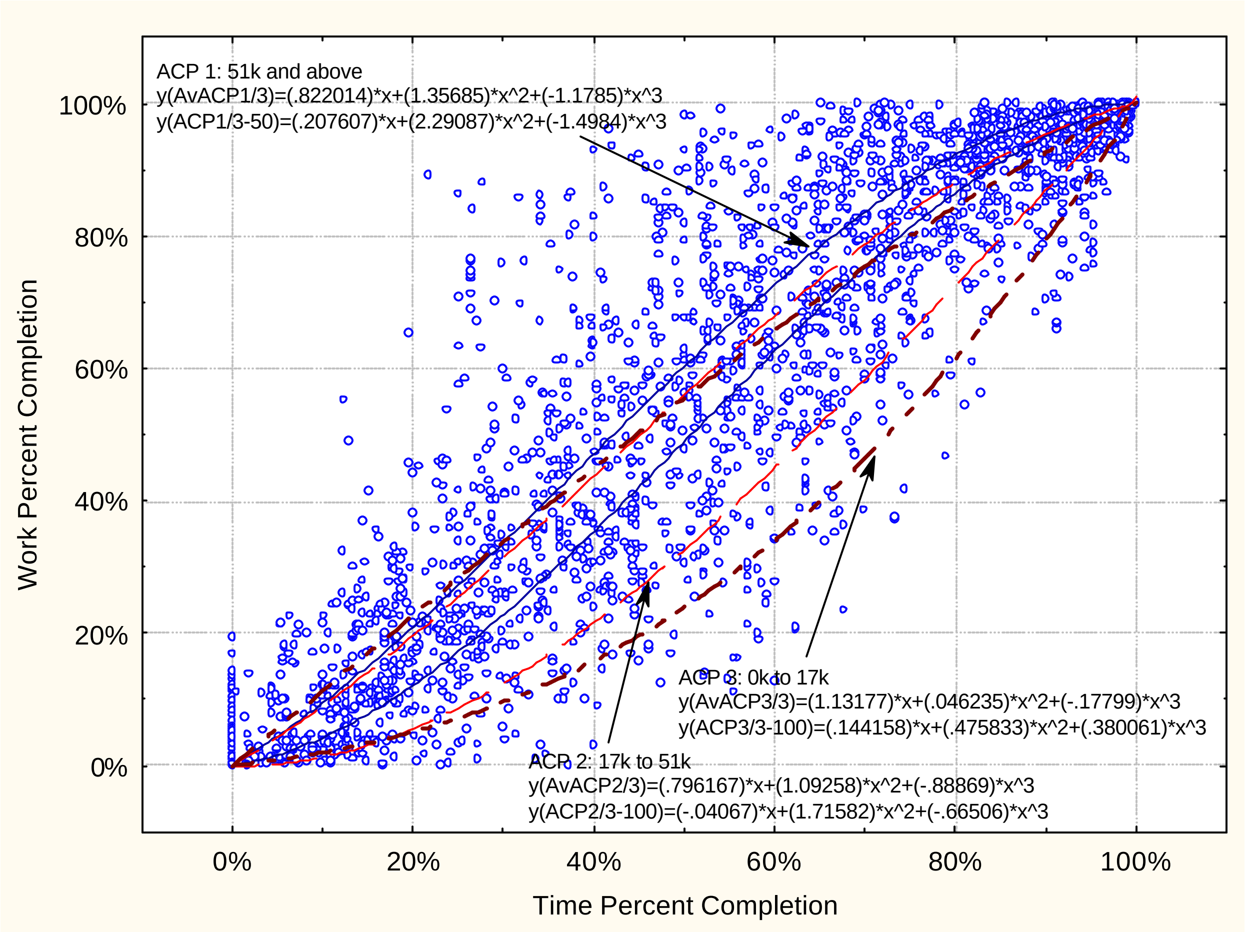


Figure 2.15: Summary minimum and average performance bounds – ACP/HMA Clusters

Both figures 2.10 and 2.15 could be used in monitoring work progress. Contractors could be generally required to be within the average and lower bounds of Figure 2.10 and/or to satisfy the specific requirements of their ACP/HMA group performance bounds.

2.5.4 Performance Models for Project Groups - Contract Value

In the current analysis, further models were developed for groups of projects classified on the basis of the contract value, i.e., paid-to-contractor dollars (in 2005 dollars). Table 2.22 illustrates the statistics of the four clusters that included all the successfully completed projects. Cluster 1 was ignored because of the small number of projects.

Table 2.22: Contract value clusters for the successfully completed projects

Cluster #	# of projects	Min Contract value	Max Contract Value	Mean	Standard Deviation	Variance
4	348	$105,018.58	$2,321,238.82	1073383	600158.0	3.602E+11
3	128	$2,357,167.46	$6,495,159.59	3612667	1031118	1.063E+12
2	19	$6,638,740.47	$18,715,549.56	9484181	3368837	1.135E+13
1	2	$30,304,343.08	$49,787,911.29	40046130	13776960	1.898E+14

The analysis and model development for the minimum performance bounds and average performance bounds for each contract value cluster were conducted as explained for all cases of successfully completed projects. Figure 2.16 illustrates the results for the up-to-$2.3 million cluster, which contained the majority of the projects (348 projects); the model for 100 points (Simplex) was most representative of the minimum performance bounds. Figure 2.17 shows that for the $2.3 million to $6.5 million cluster (128 projects), the 100-point (Rosenbrock) model also produced good minimum performance bounds. Figure 2.18 illustrates a cluster of 19 projects that had a range of $6.5 million and above. The average and minimum performance bounds were close to each other. The 50-point (Simplex) model would be chosen as the minimum performance bounds. (A summary graph is shown in Figure 2.19.)

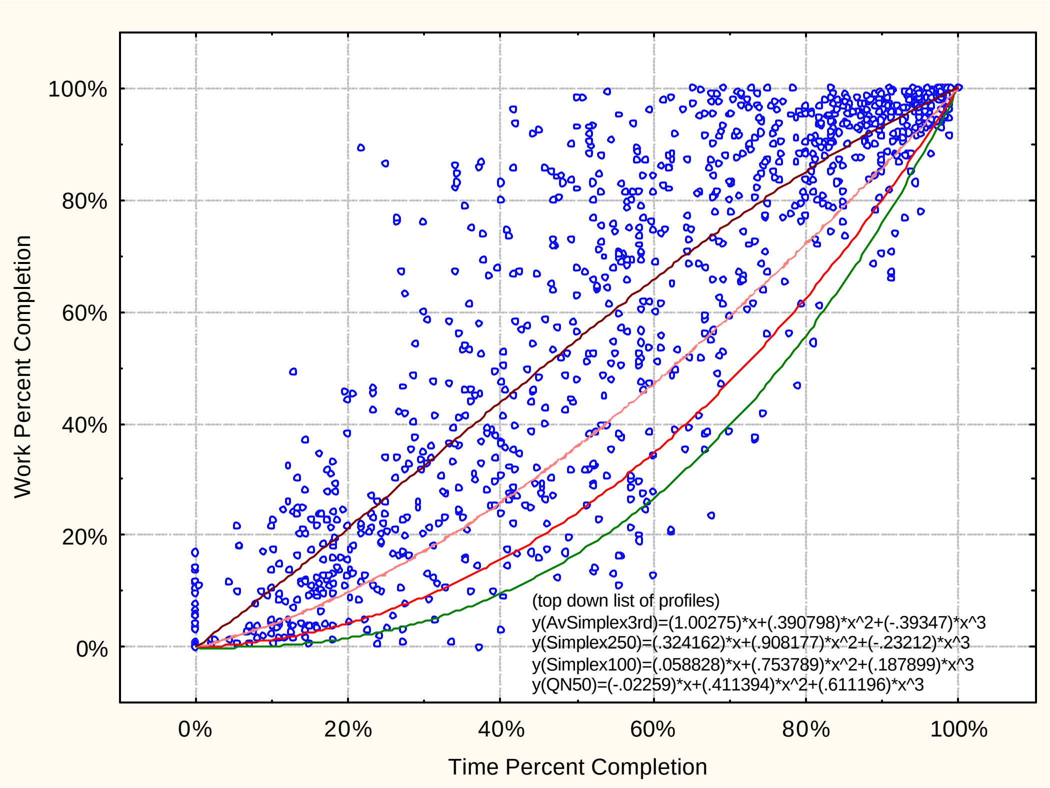


Figure 2.16: Minimum and average performance bounds - Contracts (up to $2.3 million)

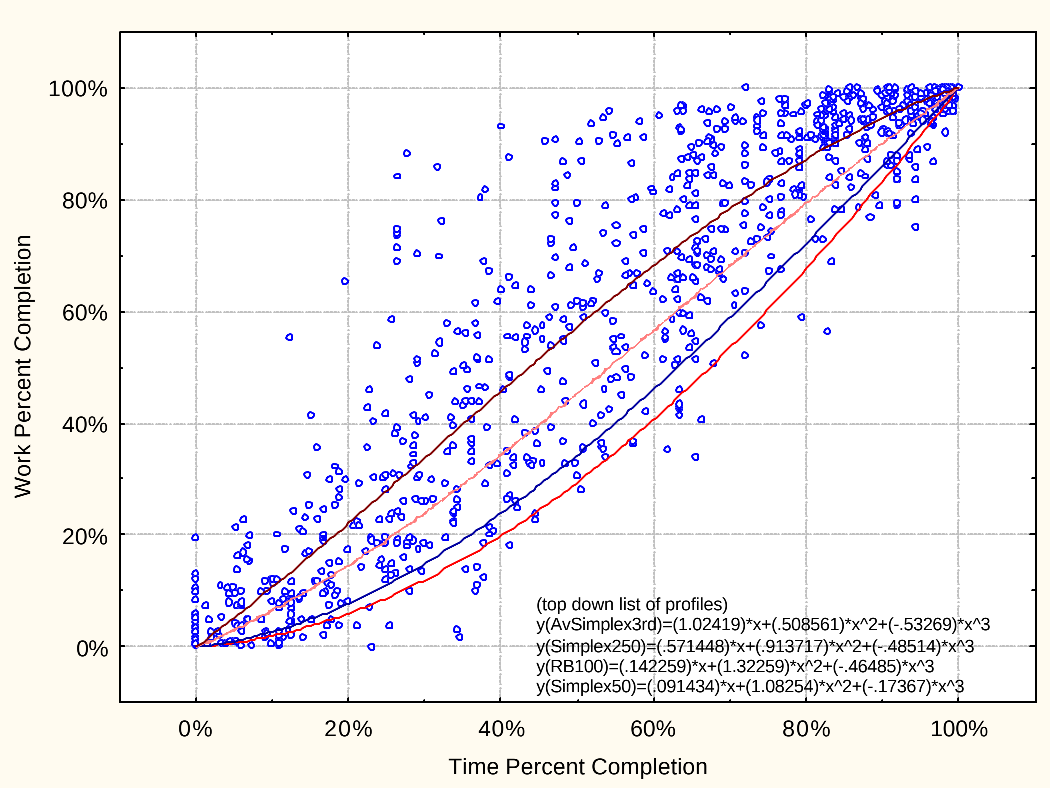


Figure 2.17: Minimum and average performance bounds - Contracts ($2.3 million – $6.5 million)

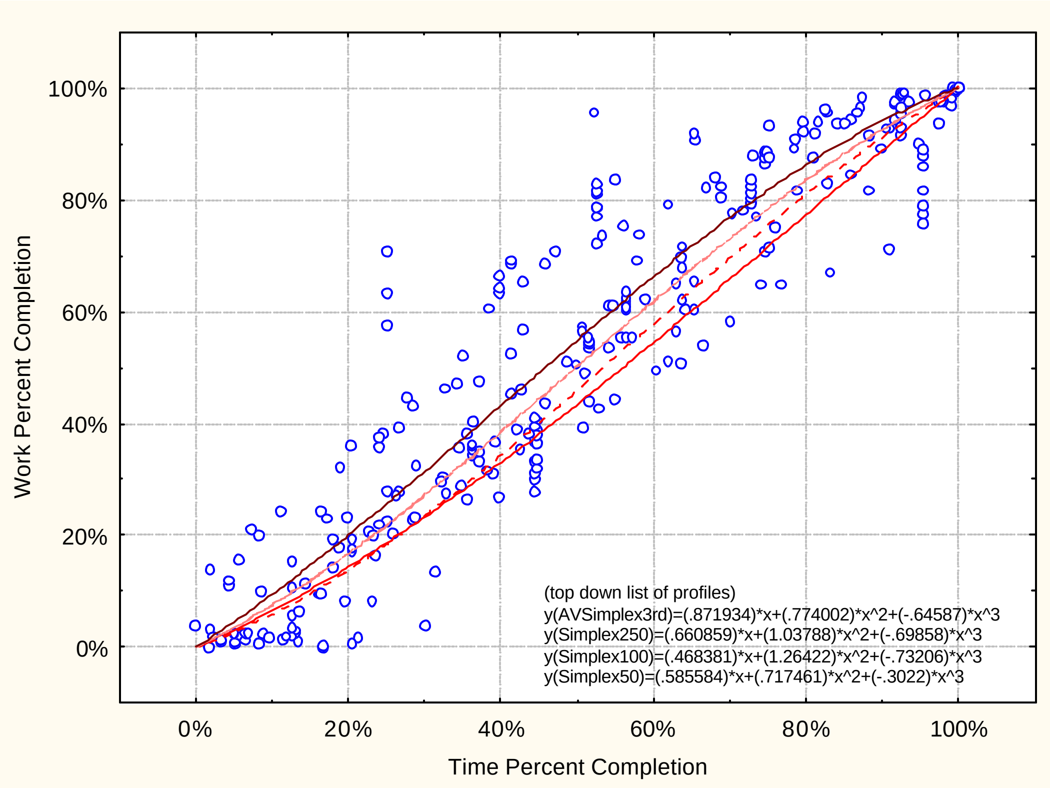


Figure 2.18: Minimum and average performance bounds - Contracts ($6.5 million and above)

Figure 2.19 is a summary graph that includes the selected minimum performance models for each of the three clusters, along with the associated average performance bounds. The average in the model envelope for each cluster is the upper line, and the minimum is the lower line. Each envelope explains the position of the projects and their associated cluster relative to all the successfully completed projects. Cluster 4 projects with the smallest contract values (up to $2.3 million) tended to have a slower progress pace than projects with medium contract values ($2.3 million-$6.5 million) in cluster 3, which had a slower progress rate than projects with the largest contract values ($6.5 million and above) in cluster 2. These clusters coincided with the results of the ACP clusters. Figure 2.19 provides more tools for monitoring and controlling progress, given the contract value of a project.

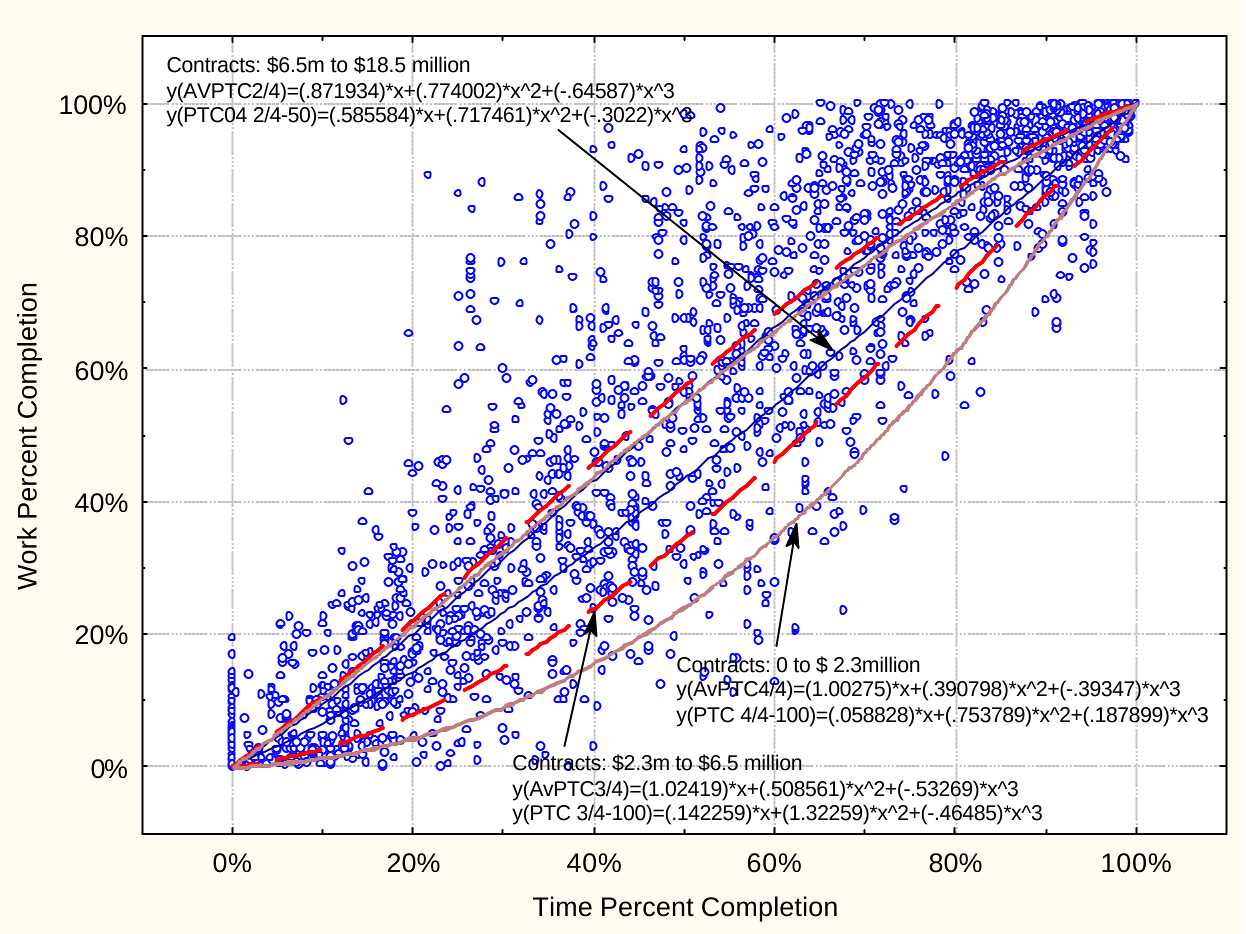


Figure 2.19: Summary minimum and average performance bounds – contract clusters

2.5.5 Performance Models for Project Groups - Duration

In the current analysis, further models were developed for groups of projects classified on the basis of contract duration, i.e., workable charged days. Table 2.23 illustrates the statistics of the clusters that included all the successfully completed projects.

Table 2.23: Duration clusters for the successfully completed projects

Cluster #	# of projects	Min Duration (WCD)	Max Duration (WCD)	Mean	Standard Deviation	Variance
3	331	3	64	39.81873	13.75843	189.2943
2	143	65	146.5	89.01748	20.44104	417.8360
1	23	154	615.5	212.0217	96.55574	9323.011

The analysis and model development for the minimum performance bounds and average performance bounds for each contract value cluster were conducted as explained for all cases of successfully completed projects. Figure 2.20 illustrates the results for the up-to-65 days cluster, which contained the majority of the projects (331 projects); the model for 100 points (Simplex) was most representative of the minimum performance bounds. Figure 2.21 shows that for the 65- to 150-days cluster (143 projects), the 100-point (Simplex) model also produced good minimum performance bounds. Figure 2.22 illustrates a cluster of 23 projects that had a range of 150 days and above. The average and minimum performance bounds were close to each other. The 50-point (Simplex) model would be chosen as the minimum performance bounds. (A summary graph is shown in Figure 2.23.)

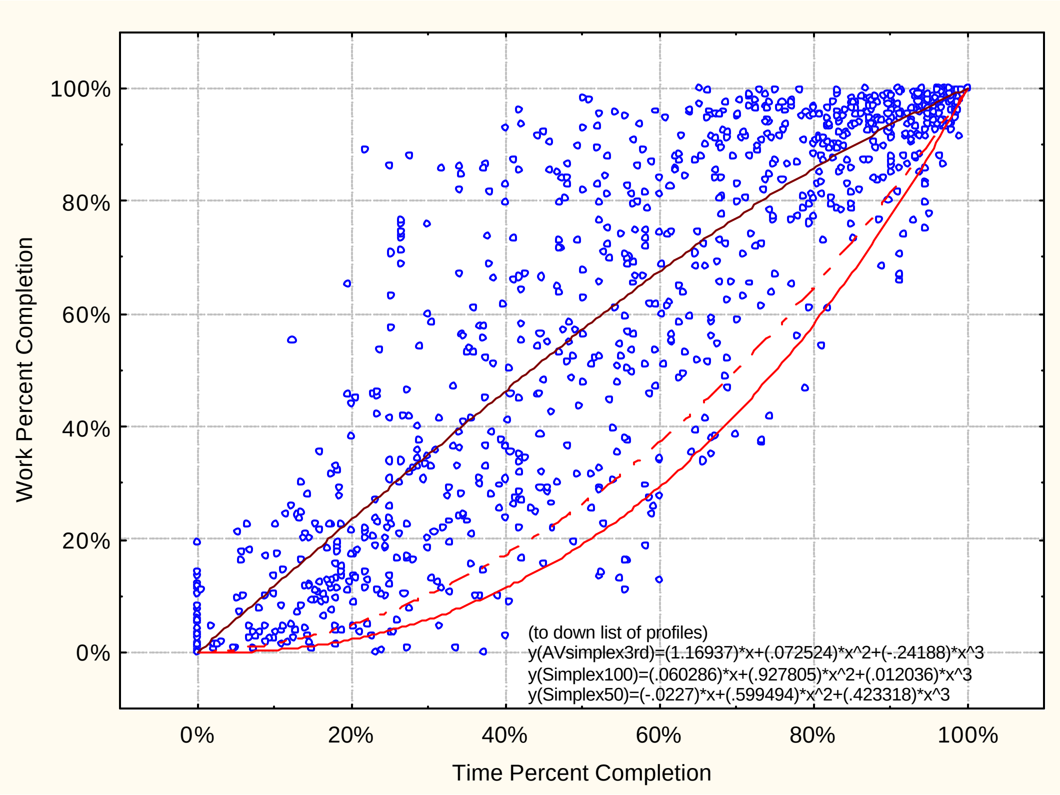


Figure 2.20: Minimum and average performance bounds – Duration (0 – 65 days)

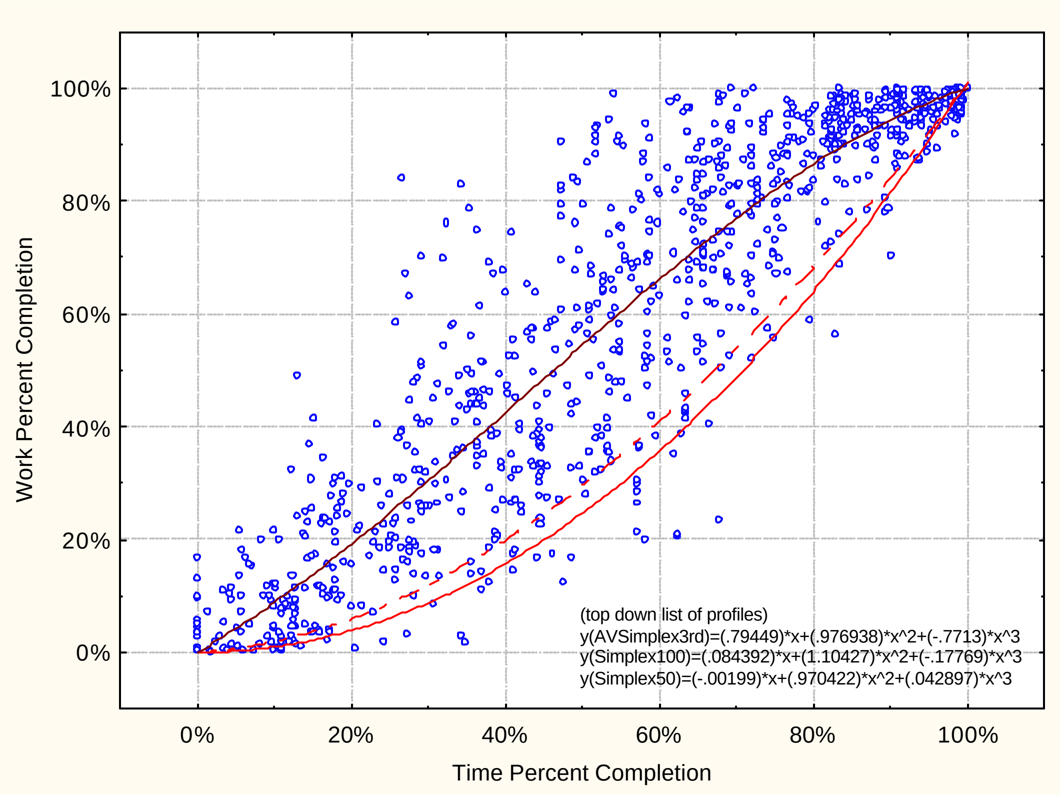


Figure 2.21: Minimum and average performance bounds – Duration (65 – 150 days)

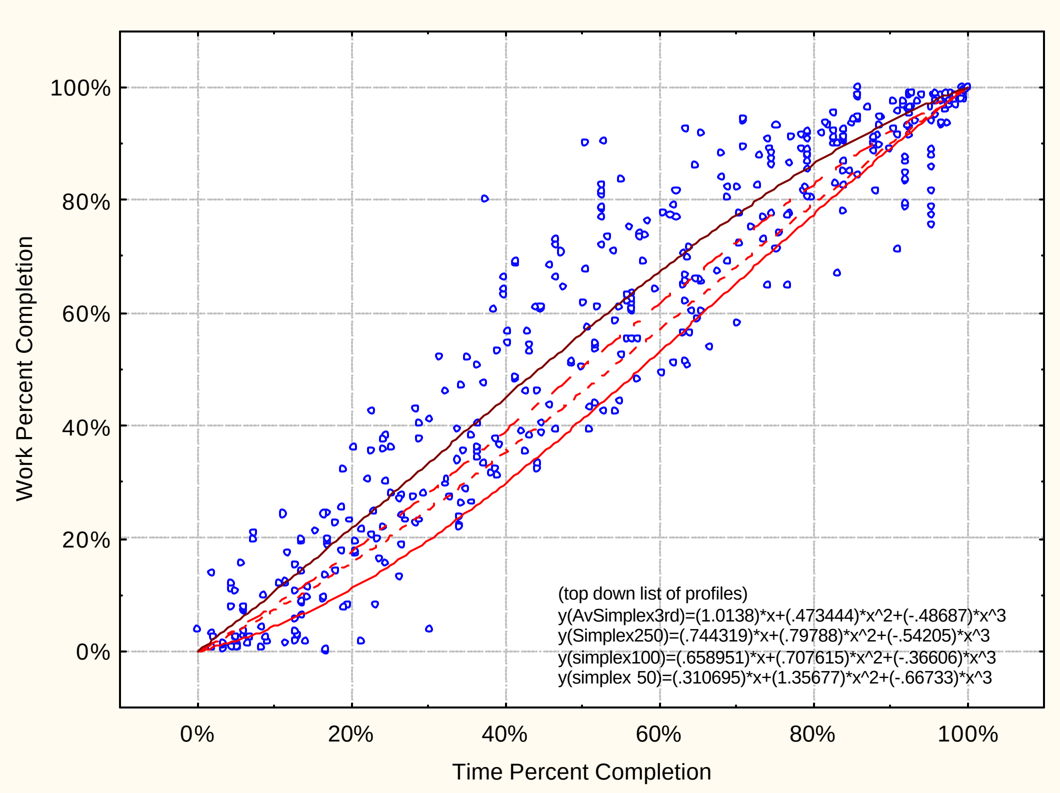


Figure 2.22: Minimum and average performance bounds – Duration (150 days and above)

Figure 2.23 is a summary graph that includes the selected minimum performance models for each of the three clusters, along with the associated average performance bounds. The average in the model envelope for each cluster is the upper line, and the minimum is the lower line. Each envelope explains the position of the projects and their associated cluster relative to all the successfully completed projects. Cluster 3 projects with the fewest working days (up-to 65 days) tended to have a slower progress pace than projects of medium duration (65 to 150 days) in cluster 2, which had a slower progress rate than the longest projects (150 days and above) in cluster 1. Figure 2.23 provides more tools for monitoring and controlling progress, given the duration of a project.

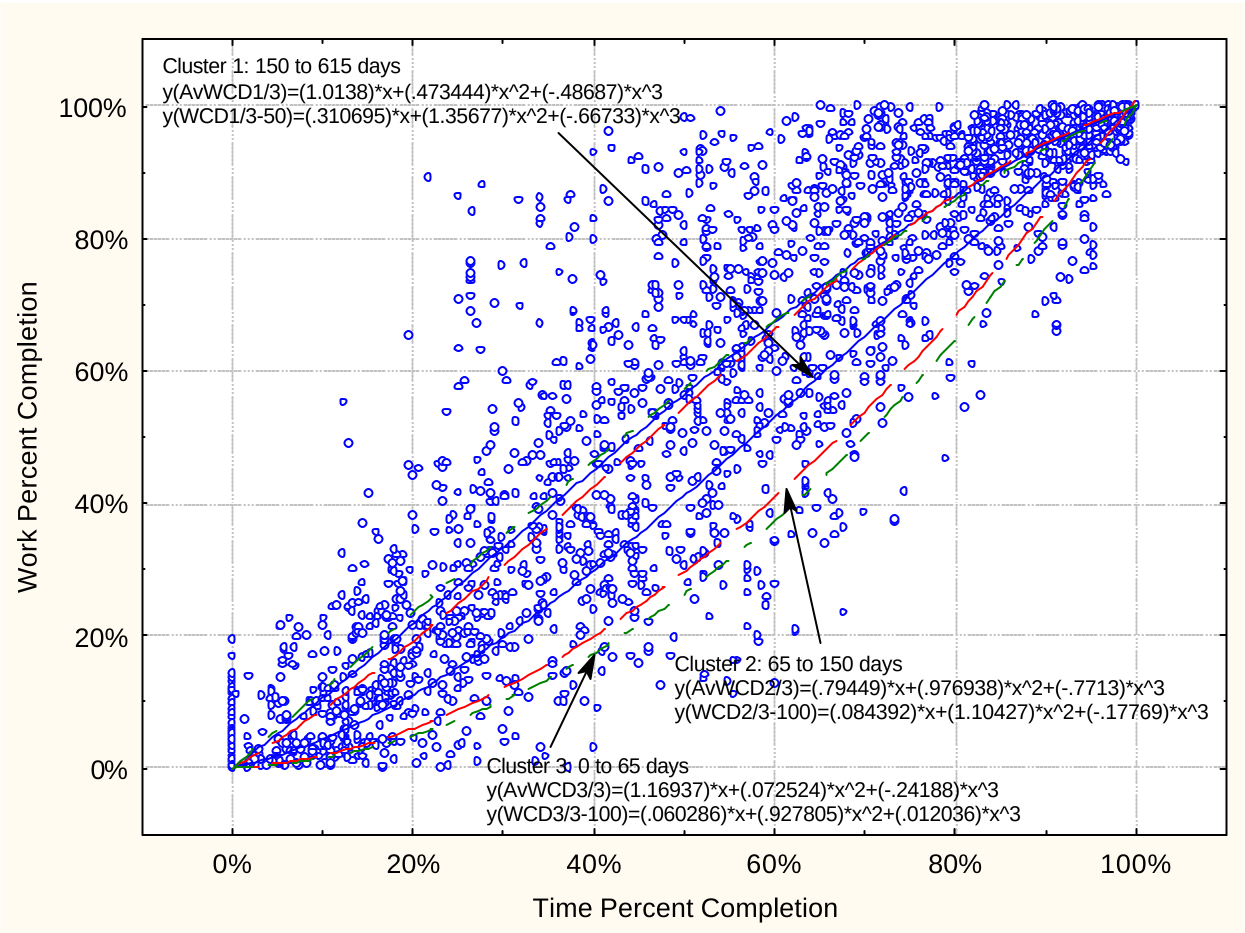


Figure 2.23: Summary minimum and average performance bounds – Duration cluster

2.5.6 Performance Models for Project Groups - Project Miles

In the current analysis, further models were developed for groups of projects classified on the basis of project length, measured in miles. Table 2.24 illustrates the statistics of the clusters that included all the successfully completed projects.

Table 2.24: Miles clusters for the successfully completed projects

Cluster #	# of projects	Min Miles	Max Miles	Mean	Standard Deviation	Variance
3	326	0.01	6.27999973	2.380509	1.737348	3.018379
2	145	6.4	18.9500008	10.37874	3.238595	10.48849
1	26	20.113	52.1700011	28.10381	7.845677	61.55465

The analysis and model development for the minimum performance bounds and average performance bounds for each miles cluster were conducted as explained for all cases of successfully completed projects. Figure 2.24 illustrates the results for the up-to-6.4 miles cluster, which contained the majority of the projects (326 projects); the model for 100 points (Simplex) was most representative of the minimum performance bounds. Figure 2.25 shows that for the 6.4- to 20-miles cluster (145 projects), the 100-point (Simplex) model also produced good minimum performance bounds. Figure 2.26 illustrates a cluster of 26 projects that had a range of 20 miles and above. The average and minimum performance bounds were close to each other. The 50-point (Simplex) model would be chosen as the minimum performance bounds. (A summary graph is given in Figure 2.27.)

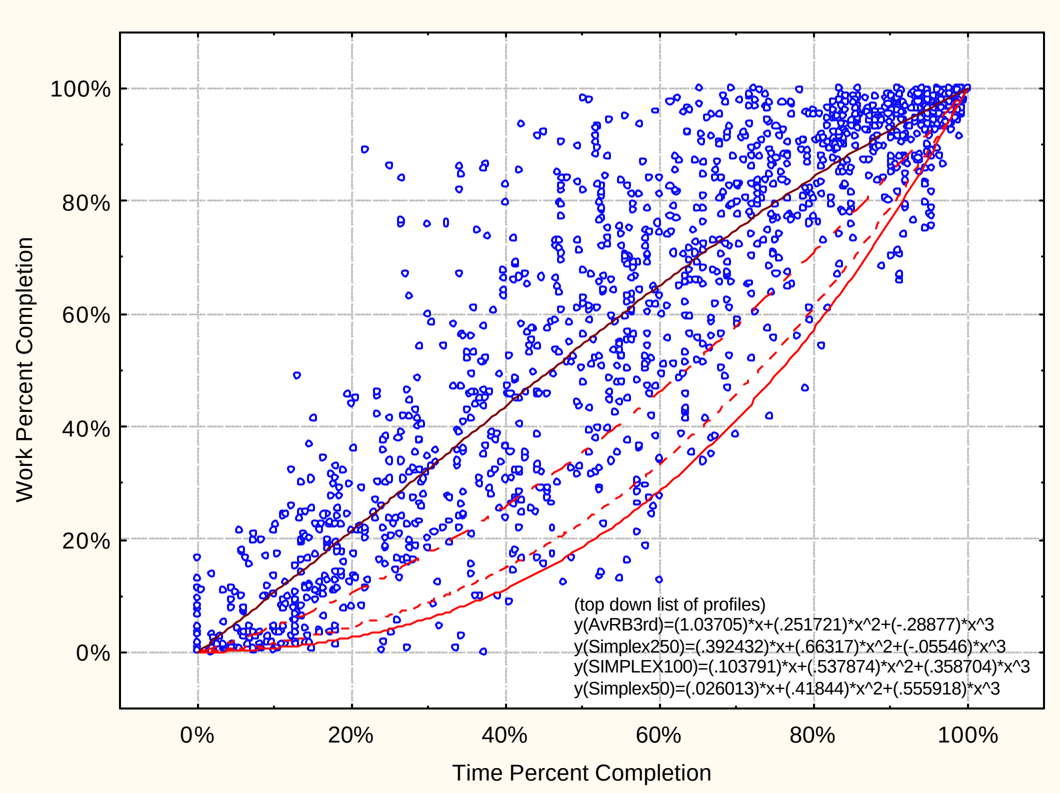


Figure 2.24: Minimum and average performance bounds – Miles (20 miles and above)

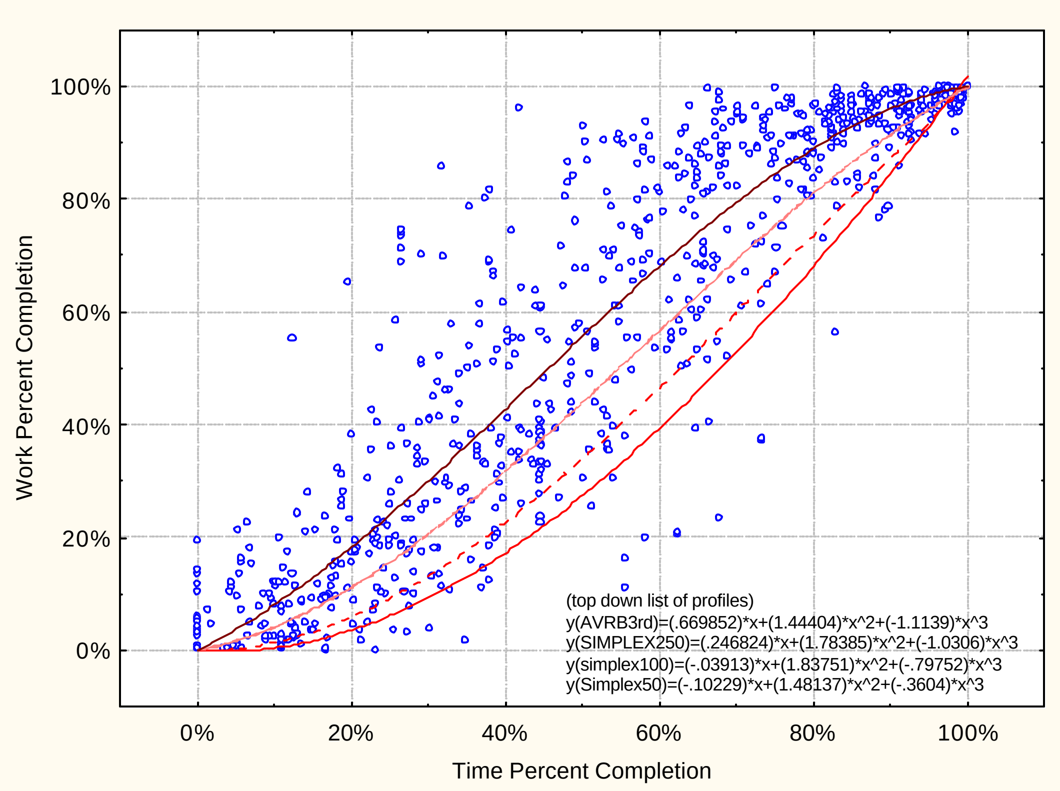


Figure 2.25: Minimum and average performance bounds – Miles (6.4 miles to 20 miles)

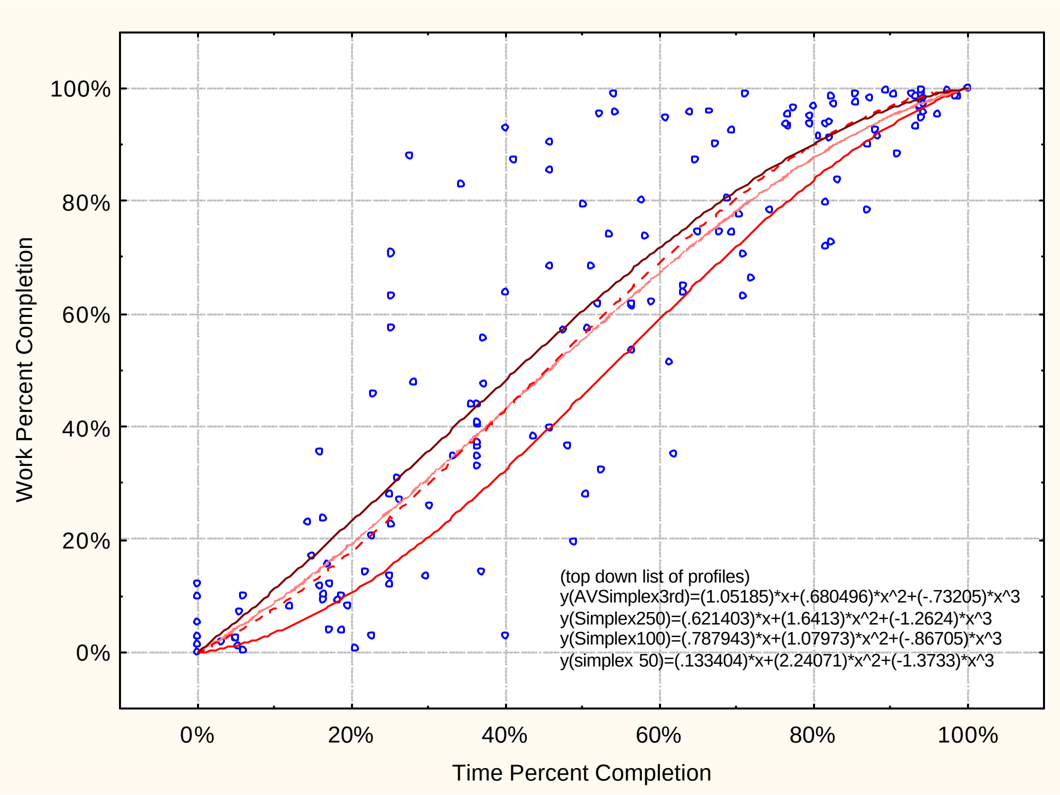


Figure 2.26: Minimum and average performance bounds – Miles (0 miles to 6.4 miles)

Figure 2.27 is a summary graph that includes the selected minimum performance models for each of the three clusters, along with the associated average performance bounds. The average of the model envelope for each cluster is the upper line, and the minimum is the lower line. Each envelope explains the position of the projects and their associated cluster relative to all the successfully completed projects. Cluster 3 projects with the smallest number of miles (up to 6.4 miles) tended to have a slower progress pace than projects with a medium numbers of miles (6.4 to 20 miles) in cluster 2, which ehad a slower progress rate than projects with the most miles (20 miles and above) in cluster 1. Figure 2.27 provides more tools for monitoring and controlling progress, given project mileage.

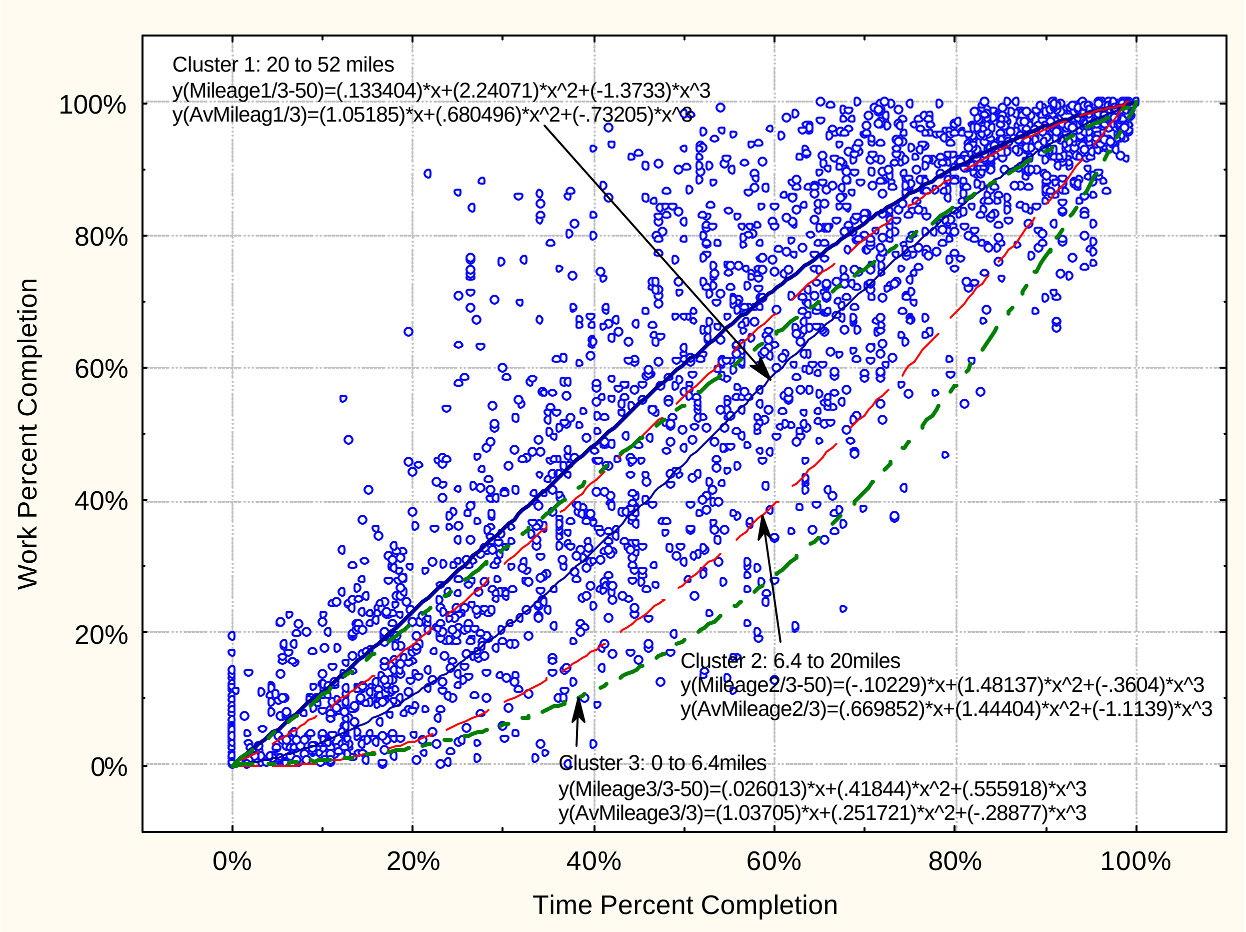


Figure 2.27: Summary minimum and average performance bounds – Miles cluster

2.6 Conclusions

This chapter provided a survey on how state DOTs evaluate the progress and performance of contractors during construction and at project completion. The analysis determined that only a few states (four out of 25) analyze the performance of contractors by using a linear relation (y = x) that relates work completion to time completion and a tolerance value beyond which performance is deemed unsatisfactory. Only one of those states, California, has a true performance chart that describes a minimum boundary for performance without a tolerance value. The majority of other states measure work progress in lieu of performance.

In this research, average and minimum performance bounds were developed on the basis of data from a number of successfully completed projects (497 projects that had time and cost overruns of less than 5 percent). On the basis of the analysis, the performance bounds in Figure 2.28 are suggested for evaluating the performance of contractors. However, other bounds could be used, such as the minimum bounds shown in figures 2.9, 2.10, and 2.11. Figure 2.28 is a subset of Figure 2.10. In using the average bounds, a tolerance value of between 20 percent and 24 percent could be used to identify unsatisfactory status. In using the minimum bounds, the performance would be unsatisfactory if actual performance was below the minimum bounds.

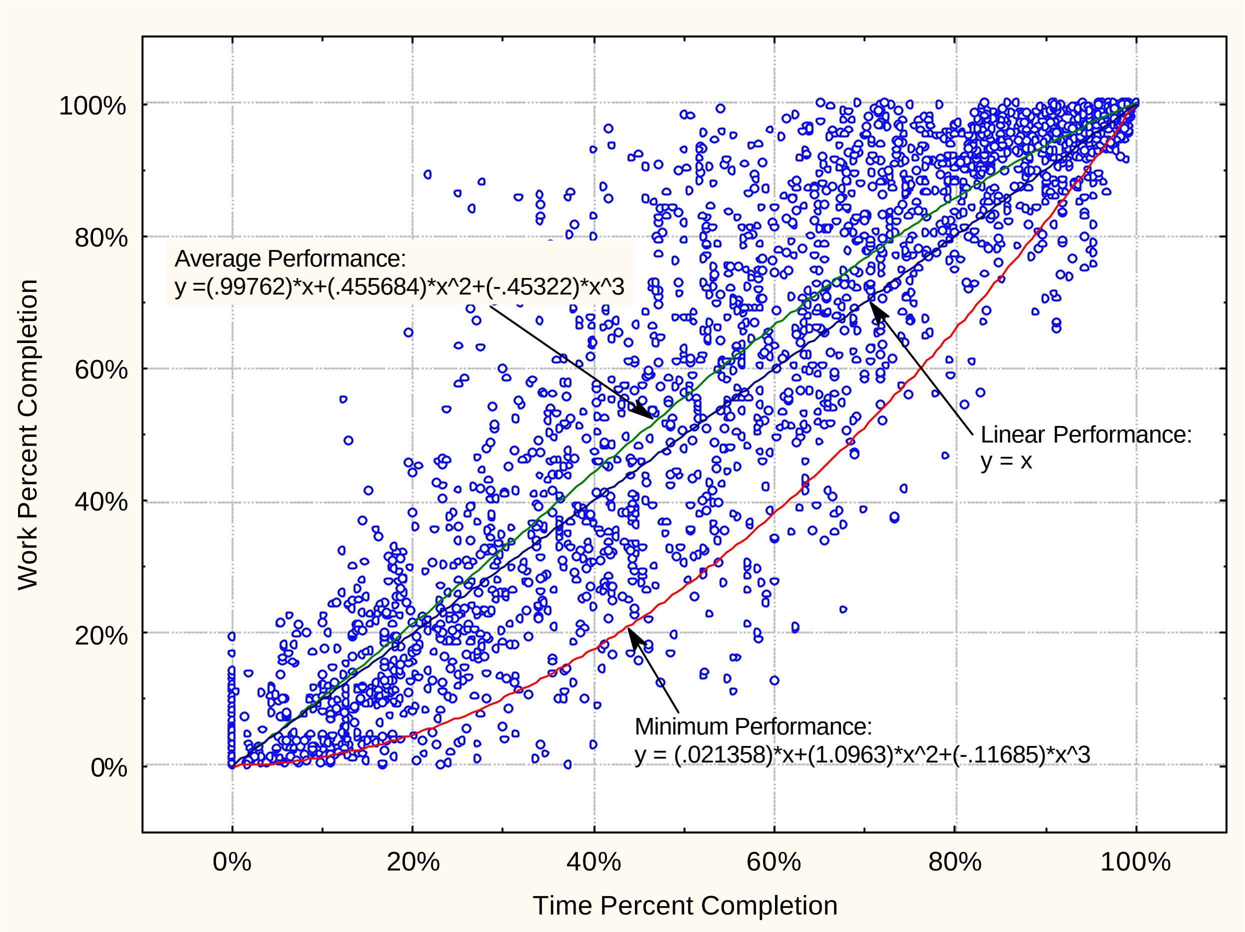


Figure 2.28: Average and minimum performance bounds for WSDOT projects

Average and minimum performance bounds were also developed for groups of projects that were clustered on the basis of four data categories: quantities of ACP/HMA, value of contracts, duration of construction, and length of project (in miles) (see figures 2.15, 2.19, 2.23, and 2.27). Cluster analysis segregated the projects into three groups that could be referred to as small, medium, and large. The performance bounds for the small projects clusters shown in Table 2.25 were significantly close to each other, even among the different categories of miles, days, value, and amount of HMA. This is illustrated in Figure 2.29.

Table 2.25: Small projects clusters (cluster # 3 in each category) ($2005)

Category	# of projects	Min value	Max Value	Mean	Standard Deviation	Variance
Miles	326	0.01	6.27999973	2.380509	1.737348	3.018379
Days	331	3	64	39.81873	13.75843	189.2943
Value	348	$105,018.58	$2,321,238.82	$1,073,383	$600,158	$3.602E+11
HMA	342	0.00	16,753.74	4,978.590	4,986.134	24,861,530

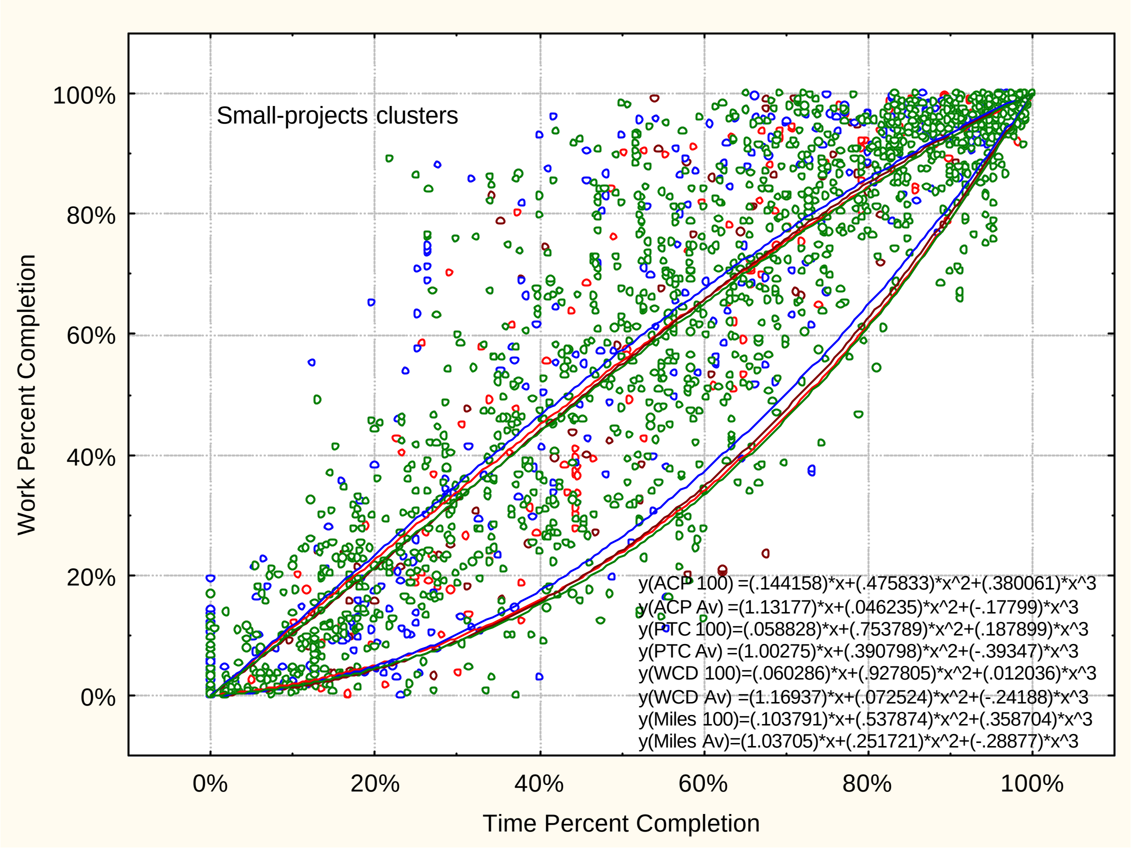


Figure 2.29: Average and minimum performance bounds for the small projects clusters

Table 2.26 shows the medium projects clusters; the values for these clusters are higher than those for the small projects clusters. The performance bounds, minimum, and average are illustrated in Figure 2.30. A project that would be categorized as a medium project could then be evaluated on the basis of any of the performance profiles in Figure 2.30. For example, a project that had 40,000 tons of HMA, a 15-mile length, a $5 million value (based on 2005 dollars), or a duration of 100 working days could be evaluated with Figure 2.30.

Table 2.26: Medium projects clusters (cluster # 2 in each category) ($2005)

Category	# of projects	Min value	Max Value	Mean	Standard Deviation	Variance
Miles	145	6.4	18.9500008	10.37874	3.238595	10.48849
Days	143	65	146.5	89.01748	20.44104	417.8360
Value	128	$2,357,167.46	$6,495,159.59	$3,612,667	$1,031,118	$1.063E+12
HMA	129	16,927.26	48,767.96	28,764.12	8,153.351	6,647,7130

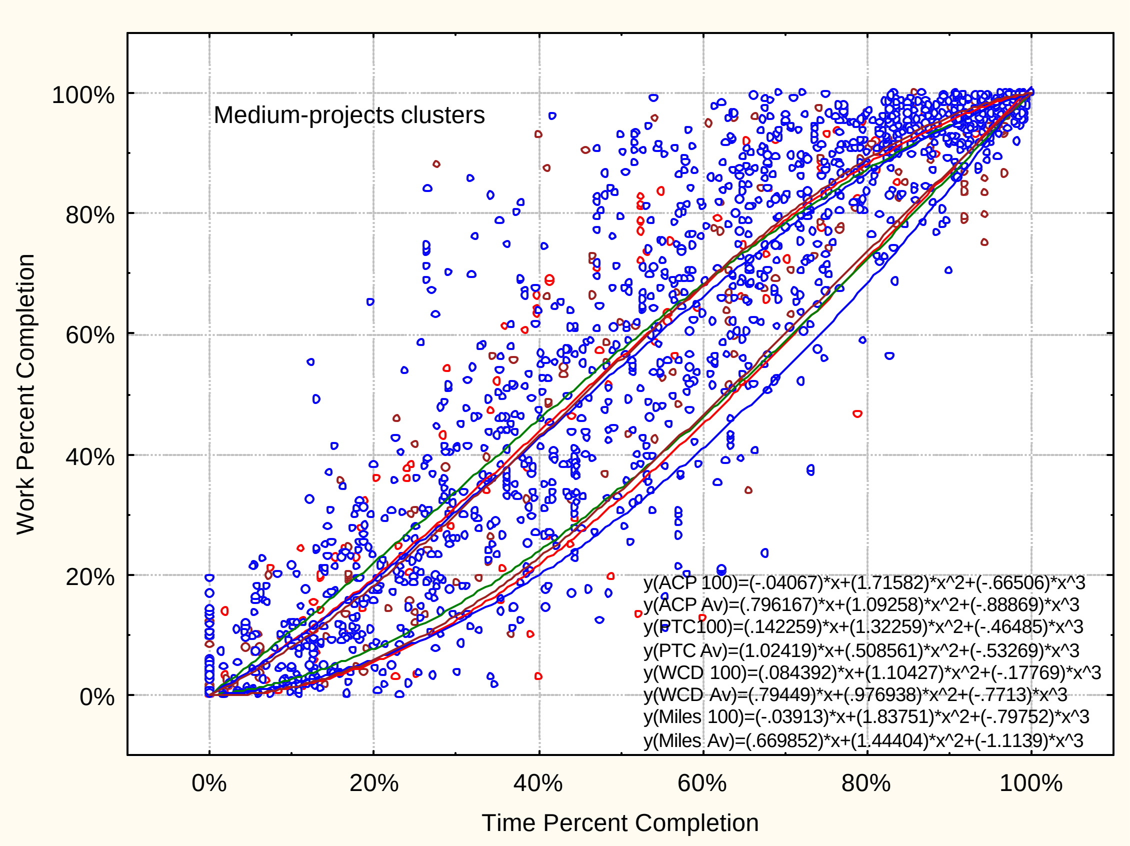


Figure 2.30: Average and minimum performance bounds for the medium projects clusters

Table 2.27 shows the large projects clusters; the values in this cluster were higher than those in the small and medium projects clusters. The performance bounds, minimum, and average are illustrated in Figure 2.31. A project that would be categorized as a large project could then be evaluated on the basis of any of the performance profiles in Figure 2.31. For example, a project that had 70,000 tons of HMA, a 40-mile length, a $15 million value (based on 2005 dollars), or a duration of 200 working days could be evaluated with Figure 2.31.

Table 2.27: Large projects clusters (cluster # 1 in each category) ($2005)

Category	# of projects	Min value	Max Value	Mean	Standard Deviation	Variance
Miles	26	20.113	52.1700011	28.10381	7.845677	61.55465
Days	23	154	615.5	212.0217	96.55574	9323.011
Value	19	$6,638,740.47	$18,715,549.56	$9,484,181	$3,368,837	$1.135E+13
HMA	26	51,338.70	99,426.20	69,997.30	16,447.71	270,527,300

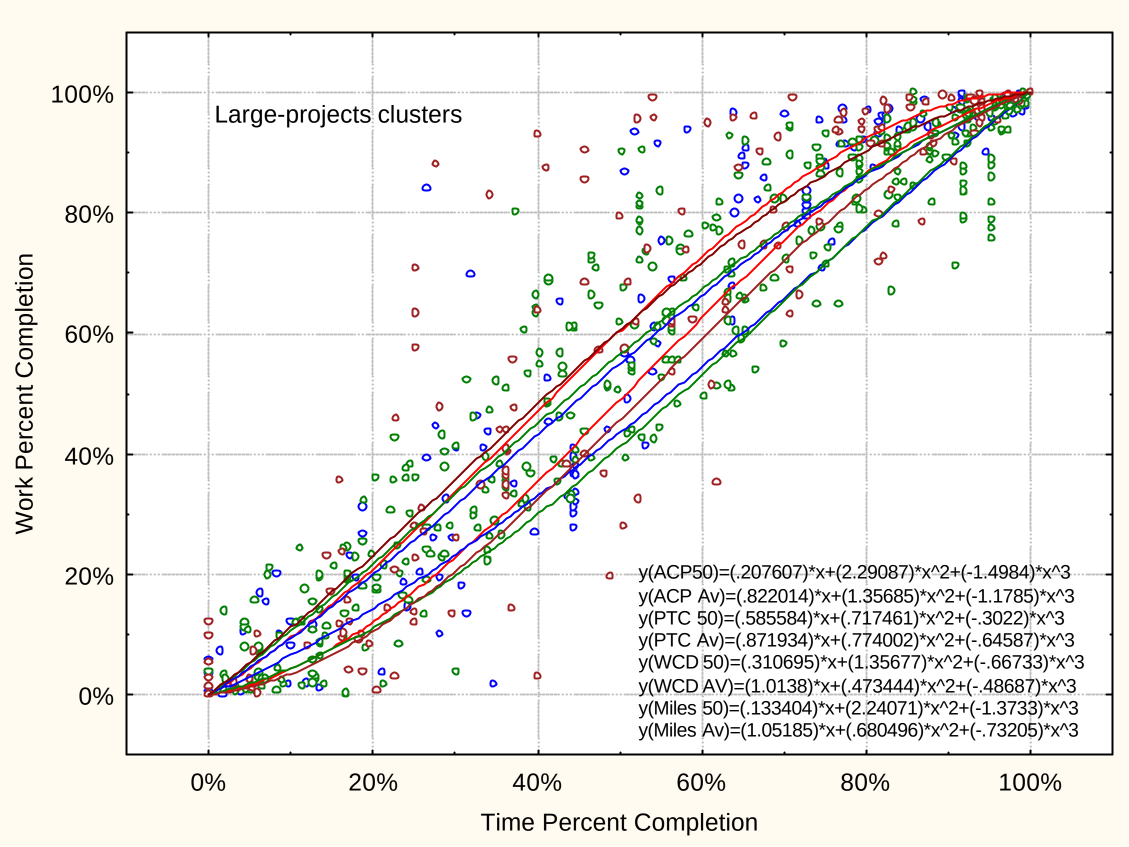


Figure 2.31: Average and minimum performance bounds for the large projects clusters

2.7 Recommendations

The analysis and conclusions explained a number of average and minimum performance bounds for categories of projects that includede (1) all projects, (2) three clusters of projects based on the quantities of ACP/HMA, number of highway miles, contract value, and number of working days. It is recommended that WSDOT use the average and minimum performance bounds to assess the performance of contractors during construction.

- The actual performance of contractors would be estimated at every payment estimate or at the discretion of the WSDOT management office.
- The performance would be assessed by measuring the percentage of time completed (ratio of elapsed time to original or authorized duration) and the percentage of completed (ratio of the cumulative payment to the contract amount or the authorized value). Both values represent a single point that could be plotted on one or all of the performance curves (figures 2.28 to 2.31) (or other bounds, as selected by WSDOT from those in figures 2.9, 2.10, and 2.11).
- When performance curves were made available to the contractors (e.g., through standard specifications, special provisions, or the construction manual), contractors would be required to remain near the average performance curve. Contractors would be warned if an actual performance curve moved toward the minimum performance bounds.
- If the contractor's performance moved below the minimum bounds, then the performance would become "unsatisfactory," and suitable WSDOT action would be taken. A phased consequence would be to alert the contractor if performance had not improved within a specific period (e.g., in a month), and then a performance penalty would be imposed. Such penalties might include, for example, holding more percentage retainage of the

payments, holding liquidated damages in anticipation of delay, charging a performance deduction, acknowledging the surety company, and at the extreme, declaring the contractor in default.

- WSDOT could use the overall performance curve (Figure 2.28), as well as the categorized performance curve, in assessing the contractor's performance.

The performance of the contractor during construction would be plotted directly on the performance curve. The final completed curve (actual and officially planned) would be added to the contractor's qualification file for use in future projects.

While the average performance curve was developed to evaluate the contractor's performance, it could also be used by WSDOT as a "payout curve," or as a standard payment schedule, for deciding how much would be needed to pay out during every month of construction. In particular, the categorized average performance in figures 2.29 to 2.31 of the project cluster curves could be used to establish the funding requirements for small, medium, and large projects. Once an average curve had been selected, the percentage could be determined by using the formulas given on the curves. Then working days could be converted into calendar days, given WSDOT's standard list of working days of every calendar month.

2.8 Implementation

It is suggested that the performance curves be included in the WSDOT Standard Specifications and/or the WSDOT Construction Manual. Official charts could be developed explaining the process of evaluating performance, along with the performance bounds established in figures 2.28 to 2.31. The developed models in this research were coded in an Excel file to facilitate the implementation and use of the performance bounds, see Appendix C.

CHAPTER 3
TIME PERFORMANCE AND PREDICTION

3.1 Introduction

The aim of time prediction is to forecast the most likely number of working days required to complete a project. There are a number of methods for determining the duration of a project. The most accurate way of predicting project duration is to develop a *critical path method* (CPM) network, which defines all project activities, establishes the sequence/logic between the activities, and determines the duration of the activities on the basis of the quantities of work and the production rates of the work crews. However, in the planning stages, sufficient information may not be available to apply a full scale CPM analysis. Highway agencies usually record information about the planned and actual duration of a project, the quantities of work, the costs, the weather conditions during construction, and the number of miles. By applying a set of statistical methods, e.g., regression analysis methods, to these historical records, they can be used to predict the duration of a project.

Applying statistical methods to these data can help predict the approximate duration of a project, where the quality of the prediction will depend on the quality of the data (some project data may not be recorded for a project), variability of the data, sufficiency of the number of projects, variability of project sizes, and variability in weather conditions during a project life time and between projects, among other factors. Although the time predicted is approximate, it is still useful because it can be obtained very early in a project life, when data insufficiency is usually the case.

This chapter starts with a literature review on methods for estimating the duration of projects. Next is an analysis of the time performance of WSDOT projects. The chapter then explains the methodology/approach for developing time prediction characteristic tables and developing time prediction models. The characteristic tables were developed on the basis of statistical analysis of WSDOT's historical project records. The prediction models were developed by using a holistic approach that considered final project duration and the associated quantities of work (ACP/HMA, grading, and surfacing), project miles, and project contract value.

The models will support the current tools and methods WSDOT uses to estimate the duration of highway projects.

3.2 Current Practices Literature Review

A number of research studies have attempted to determine and/or predict the duration of transportation projects. In 1984, Shapanka and Allen (1984) developed methods for forecasting payments on construction contracts for the Florida Department of Transportation. Along with forecasting payments, the research used regression analysis to develop a formula for forecasting contract duration. A formula was developed to predict the project duration in months on the basis of the original contract amount, the month in which the contract is signed, the road system, and project type. The authors reported that the contract amount was the most important factor in determining project duration.

In 1995, the National Cooperative Highway Research Program (NCHRP) endorsed a study to identify the methods used by state DOTs to determine contract time for highway construction (Herbsman and Ellis 1995). The research was based on interviews and a survey of practitioners in highway agencies and private contracting firms. The researchers found that manual methods involving the use of spreadsheets and computer systems, developed internally and commercially, were used to determine time. Basically, the systems used a predefined set of controlling activities with a predefined logic and production rates to determine the duration of activities, then added activities, or performed CPM calculations, to determine completion time. The research emphasized the importance of considering the impact of specific factors in determining project duration, including geophysical conditions, construction operations (e.g., mobilization, utility relocation, traffic), project characteristics (type and dominant operations), and economic/legal factors (e.g., letting time and permits). The research recommended development of historical data to support production rate determination and suggested the development of a statistical database for determining contract time, as well as using expert systems to support professional judgment.

In 2000, Hancher and Werkmeister (2000) developed a system for determining contract time for the Kentucky Transportation Cabinet (KyTC). The system determines the time for a new project by relying on a predefined project template comprising a set of controlling activities linked via a specific logic/sequence. Six project templates were defined to reflect the work type of six project classifications: reconstruction limited access, reconstruction open access, new route, relocation, bridge rehabilitation, and bridge replacement. The duration of activities in the template is determined by the associated production rates for each activity; lower, average, and maximum production rates were determined on the basis of analysis by managers of KyTC. The system runs on the software package MS Project.

In 2002, the Federal Highway Administration produced a brief guide on procedures for determining contract times (FHWA 2002). In this guide, FHWA mentioned a number of methods, including CPM calculation with a software package, bar charts, and the “estimated cost method.” CPM was labeled the most accurate method. The estimated cost methods rely on historical information gathered in tables to illustrate project cost versus project time for different project types, traffic volumes, and geographic locations. However, contract time is developed solely on the basis of the engineer’s estimate.

In 2006, Stoll et al. (2006) conducted research for the South Carolina Department of Transportation (SCDOT) to identify the best practices for predicting duration estimates, evaluate current methods, and suggest improvements to SCDOT’s current methods for time prediction. Similarly to the project template system developed for Kentucky, five project templates were defined to reflect work types in five project categories: bridge replacement, intersection improvement, primary and interstate improvements, resurfacing, and secondary road improvements. For each template, critical activities and CPM logic were defined and combined with SCDOT’s recorded production rates. Primavera Project Planners is the software package used for running the system templates.

3.3 Time Performance Analysis of WSDOT Projects

> “The State Transportation Agency (STA) should periodically review its procedures for determining contract time, which should include a comparison of the actual construction time against the estimated completion time for several projects to ascertain whether its procedures result in appropriate contract times.” (FHWA 2002)

WSDOT uses CPM to estimate project duration. Duration of activities is determined on the basis of actual duration of similar activities, expert judgment guided by historical information of similar projects, and use of work quantities and historical production rates.

In a 1998 performance audit by the State of Washington Joint Legislative Audit and Review Committee (JLARC), the JLARC found that WSDOT highway construction contract work days exceeded bid work days by 3 percent (JLARC 2005). In a 2005 review, the JLARC analyzed data for fiscal years 2003 and 2004 and found that the contract days exceeded the bid work days by 8 percent. The current research was not a performance audit; rather, it was an investigation of time performance at the project level and whether there is a relationship between changes in performance and changes in major project parameters such as contract value, ACP/HMA quantities, project miles, and project duration. The objective was to review the relationship between project duration and those project parameters to develop time prediction formulas. However, Appendix B provides a review of time growth (overruns) for the WSDOT projects from which data for the current study were taken. Time performance needs considerable attention (prediction and control); however, the range of variation is narrowing.

Project time performance at completion can be evaluated through a performance measure that relates the completion time (duration) to the original contract duration. The following subsections review the time performance of WSDOT highway projects and analyze the relationships that exist between the duration of a project and the variables in a project.

3.3.1 Time Growth Percentage Measure

Time performance measurement can be established on the basis of a relationship among a number of project time variables, such as original contract days, authorized working days, workable charged days, and total working days. The performance measure adopted in this study is the “time growth” percentage, which measures the deviation of a project’s workable charged days from the original number of contract bid days:

Time Growth = 100 x (workable charged days – original contract days) / original contract days

The time growth percentage chart in Figure 3.1 shows a substantial range in the growth of completed projects. Of all the projects, 53.3 percent finished later than originally planned (greater than zero, with 37.2 percent having a time growth of larger than 10 percent. Around 47.7 percent of the projects finished earlier than originally planned duration, with 34.3 percent finishing within 10 percent earlier than the planned duration. This reflects the high variance of the projects, for which the average time growth was 21 percent, the standard deviation was 55.78 percent, and the coefficient of variation was 264.86 percent.

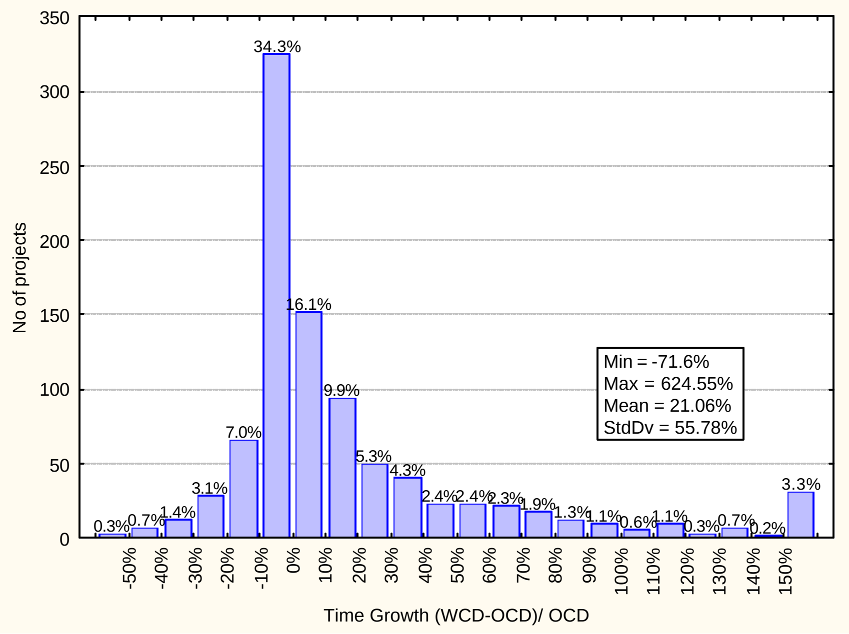


Figure 3.1: Distribution of projects with respect to the time growth percentage

To further analyze time performance, Figure 3.2 shows the change of the average time growth percentage in relation to the brackets/ranges of the prime bid amounts of the studied projects. For example, the $2.0 million to $2.5 million bracket has an average the time growth of 30.91 percent. The “maximum” time growth percentage has substantially extreme valuesm with an average of 353.4 percent. While the maximum growth line represents the maximum time growth in each bid bracket, it represents extreme cases that should not be used for making decision. The 95th percentile line is a more reasonable and representative substitute for the maximum line. The 95th percentile line, however, still shows that projects had a substantial average time growth of 109.6 percent. Figures 3.1 and 3.2 and Table 3.1 illustrate that projects tend to exceed the original contract durations.

Similarly wide ranges of variation in time growth percentages can also be illustrated if the growth percentage is plotted in relation to the main project variables. Figures 3.3 and 3.4 illustrate this variation with respect to ACP/HMA quantities and project miles.

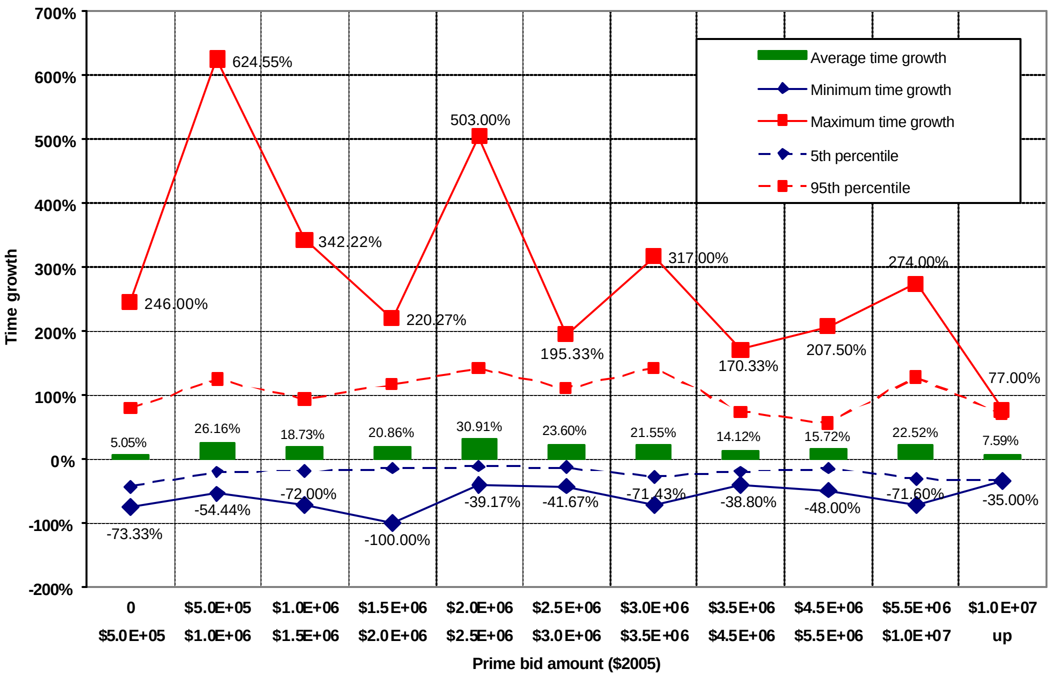


Figure 3.2: Time growth percentages for specified prime bid amount

Table 3.1: Statistics of the time performance measure

Measure	**Average**	**Std. Dev.**	**Coeff. of Variation**	**Min.**	**Max.**	**Av of 5th Percentile**	**Av of 95th Percentile**
Time Growth	21.06%	55.78%	264.86%	-71.6%	624.55%	-21.57%	109.62%

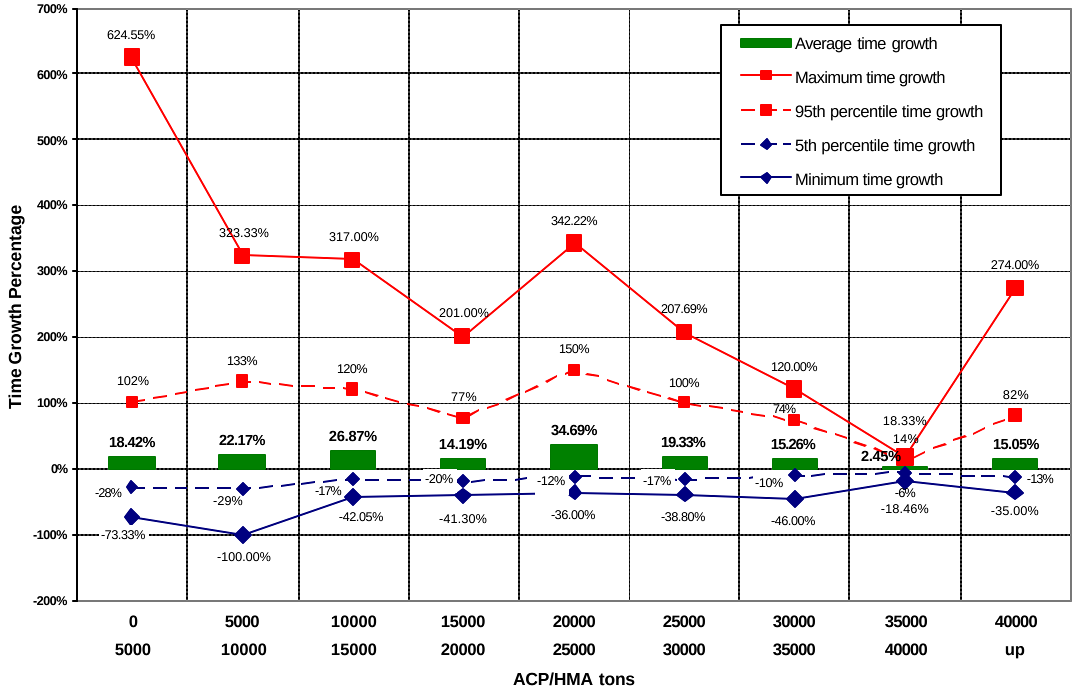


Figure 3.3: Time growth percentages for specified ACP/HMA quantities

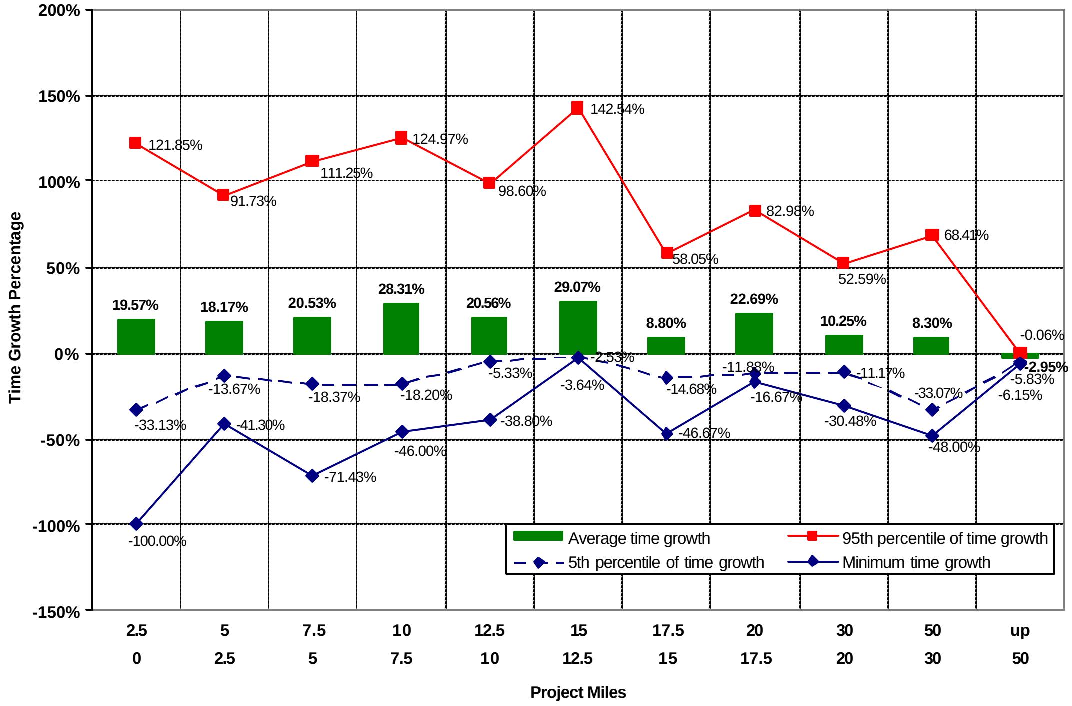


Figure 3.4: Time growth percentages for specified project miles

3.3.2 Elapsed Days to Start Work

WSDOT's Standard Specifications establish that the "contract time shall begin on the first working day following the 10th calendar day after the date the contracting agency executes the contract. The contact provisions may specify another starting date for contract time, in which case, time will begin on the starting date specified." The December 4, 2006, revisions to the General Special Provisions extended the 10 calendar days to 21 calendar days in recognition of all preparatory work that a contractor must do to mobilize and begin work.

The WSDOT databases (CCIS) define three dates for starting work: contract execution date (ED), time-started date (TSD) (e.g., official date to start work or to start counting the working days), and work-started date (WSD) (e.g., contractor's first day of work). Figure 3.5 shows that 65 percent of the projects followed the specifications for starting after 10 (21) days, while 35 percent of the projects were beyond that, and some did not begin until more than 100 days out. This, however, does not necessarily mean a contractor's delay in starting work because the time-started date is a function of WSDOT. However, contractors did start projects late. Figure 3.6 shows the elapsed time between the contractor's start of work and the contract time-started date. In this figure, 30 percent of the projects did not start on time, and 13 percent of those started more than 10 days beyond the TSD. Collectively, this can be explained by relating the contractor's start of work to the execution date. Figure 3.7 shows that 46 percent of the projects started more than 21 days beyond the execution date.

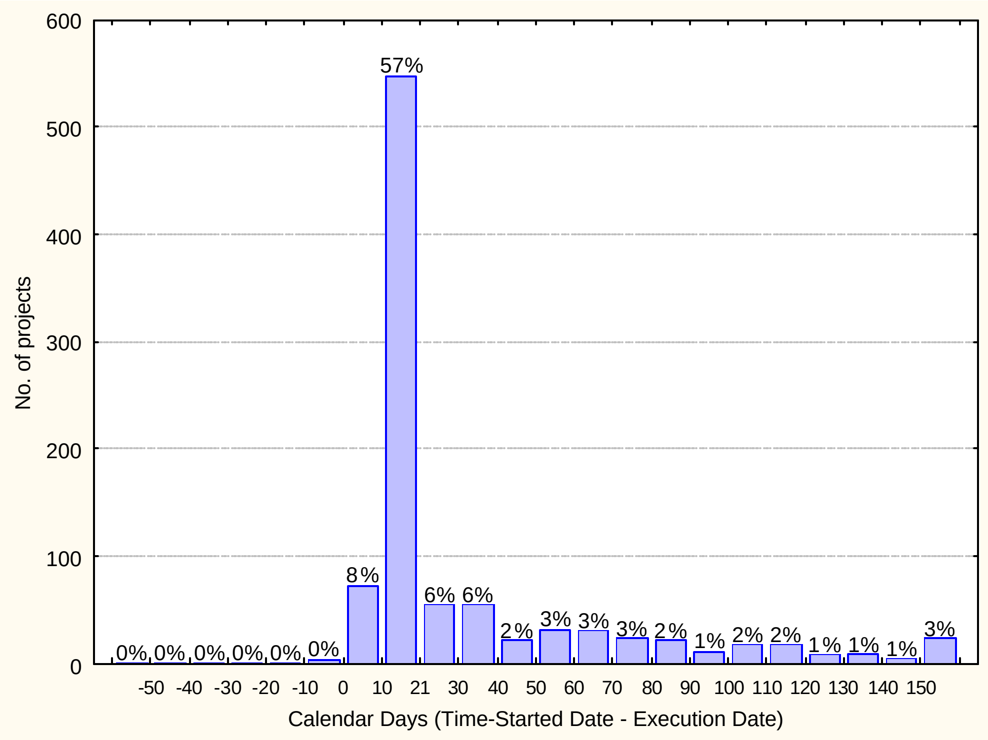


Figure 3.5 Number of days between contract execution and the time to start work

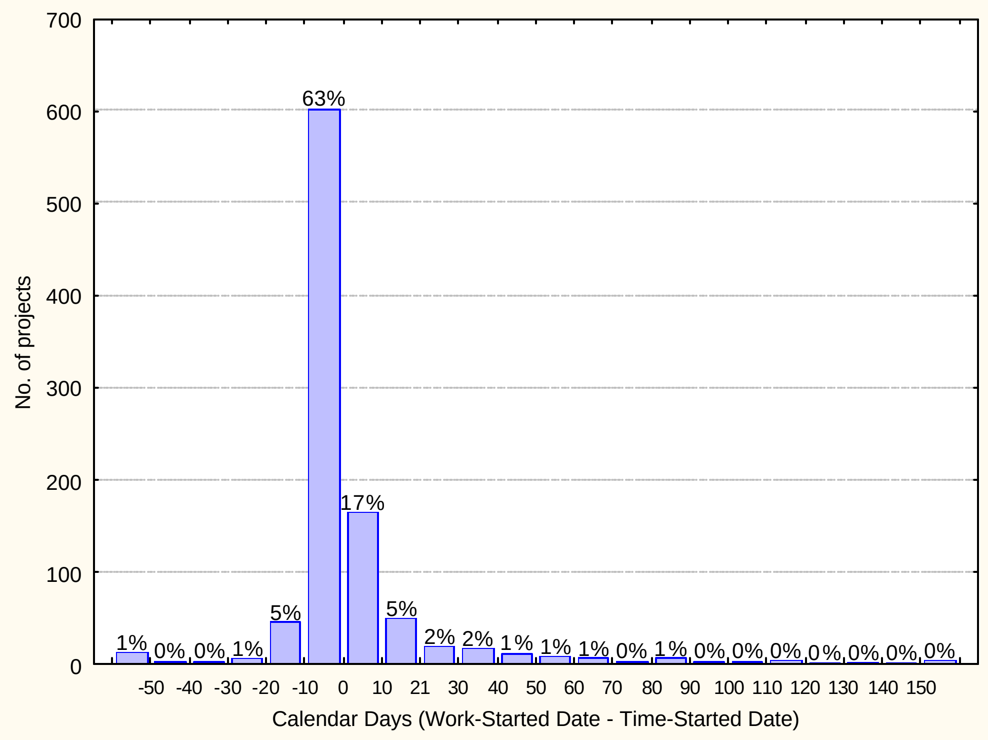


Figure 3.6 Days between the contractor’s start of work and the contract-date to start work

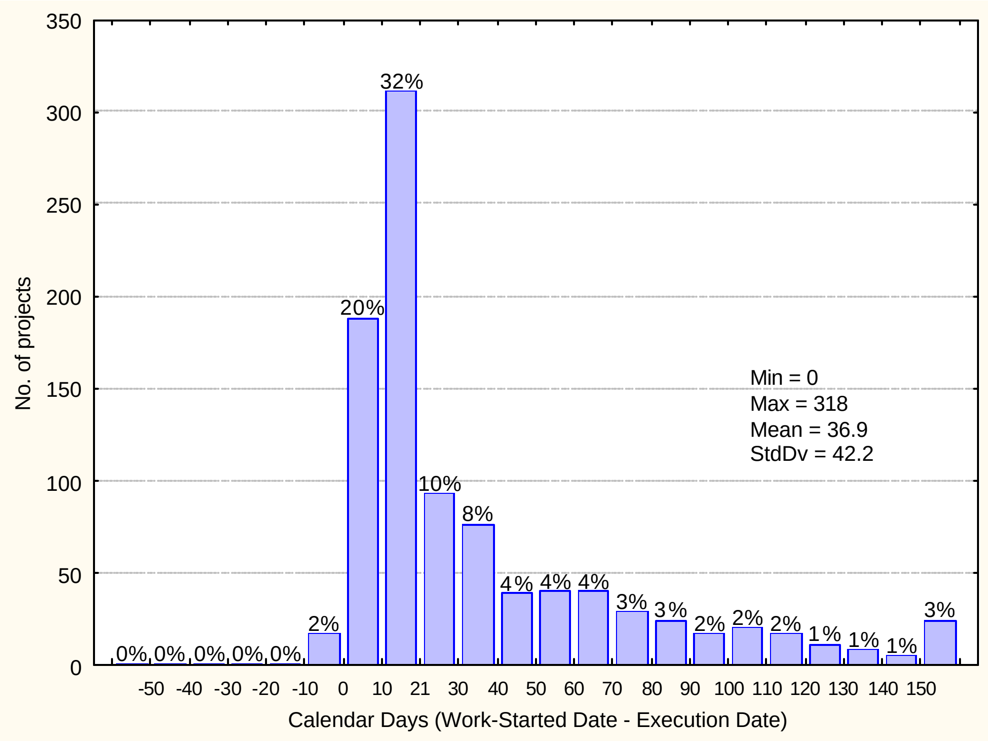


Figure 3.7 Days between the contractor’s start of work and the contract execution date

Figure 3.8 shows a decreasing trend in elapsed days with an increase in the prime bid amount. The maximum and 95th percentile graphs show how far the elapsed days reached for each prime bid bracket. However, plotting the elapsed days in relation to quantities of ACP/HMA, in Figure 3.9, shows that the average and 95th percentile nearly leveled for the different ACP brackets.

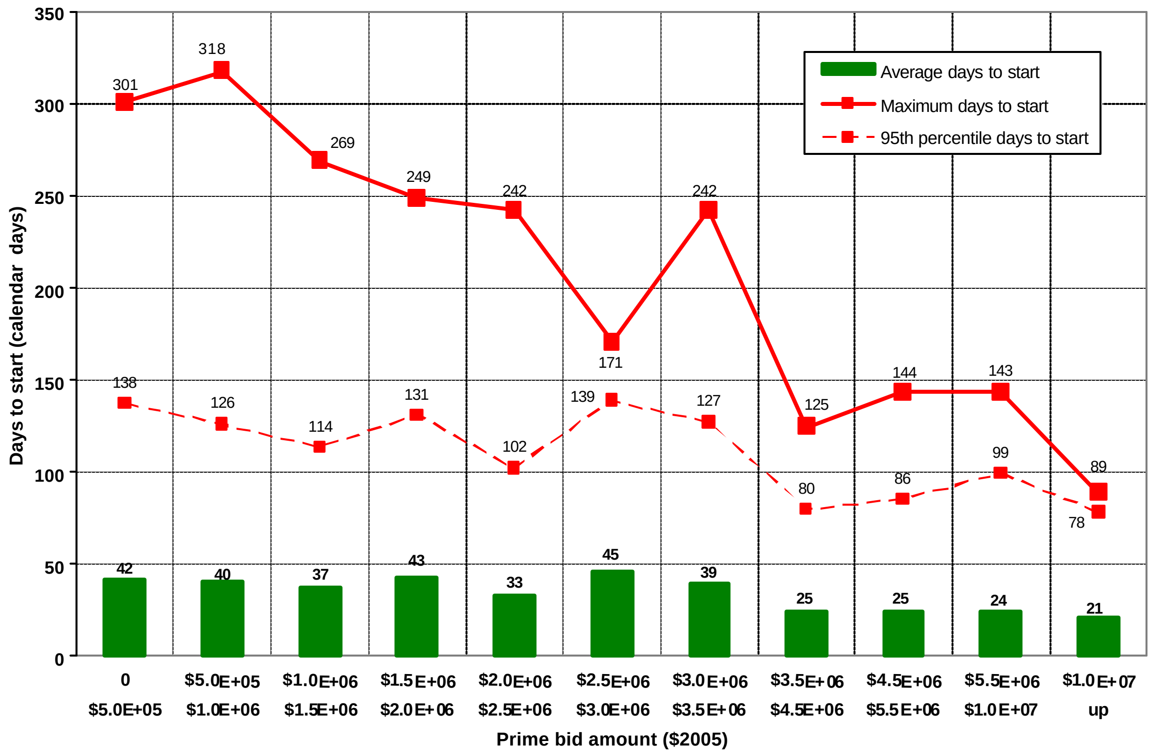


Figure 3.8 Elapsed days to start work (WSD – ED) in relation to prime bid amounts

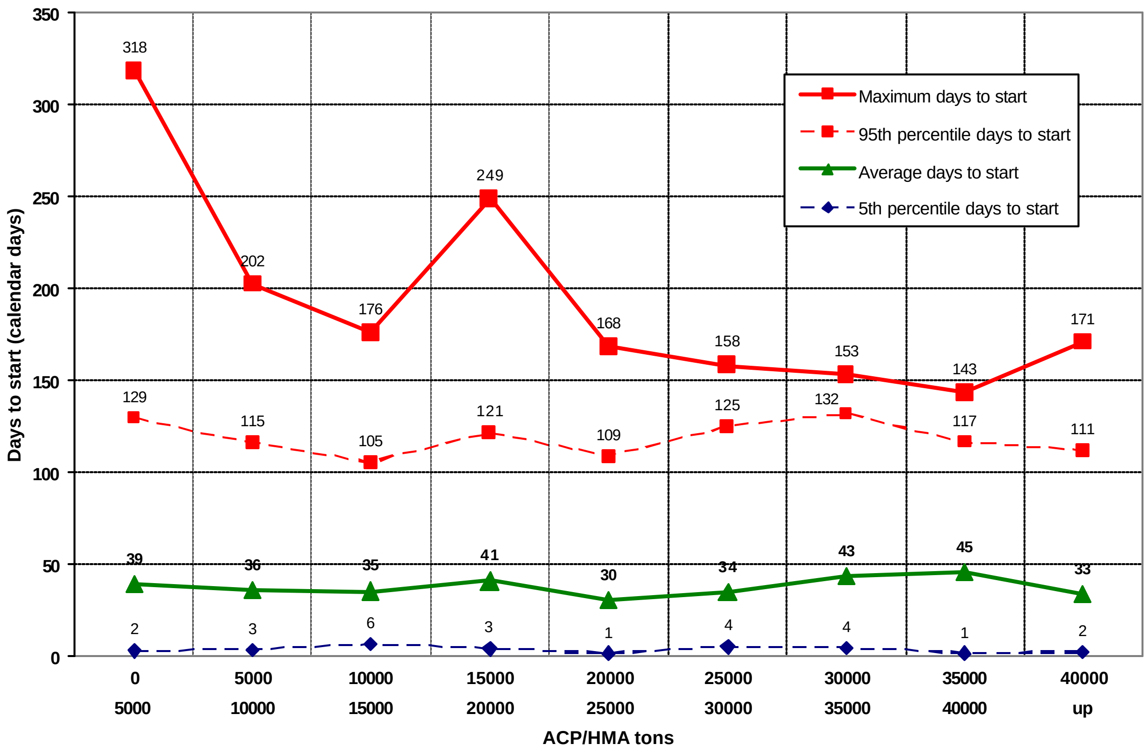


Figure 3.9: Elapsed days to start work (WSD – ED) in relation to ACP/HMA quantities

3.3.3 Workable Charged Days

Figure 3.10 illustrates how the workable charged days (WCD) of projects varied in relation to the prime bid amounts (PBA). The average coefficient of variation was significant at 65 percent. A slight and steady increasing trend can be noted between the WCDs and the PBAs. The range of variation for each prime bid bracket is still substantial.

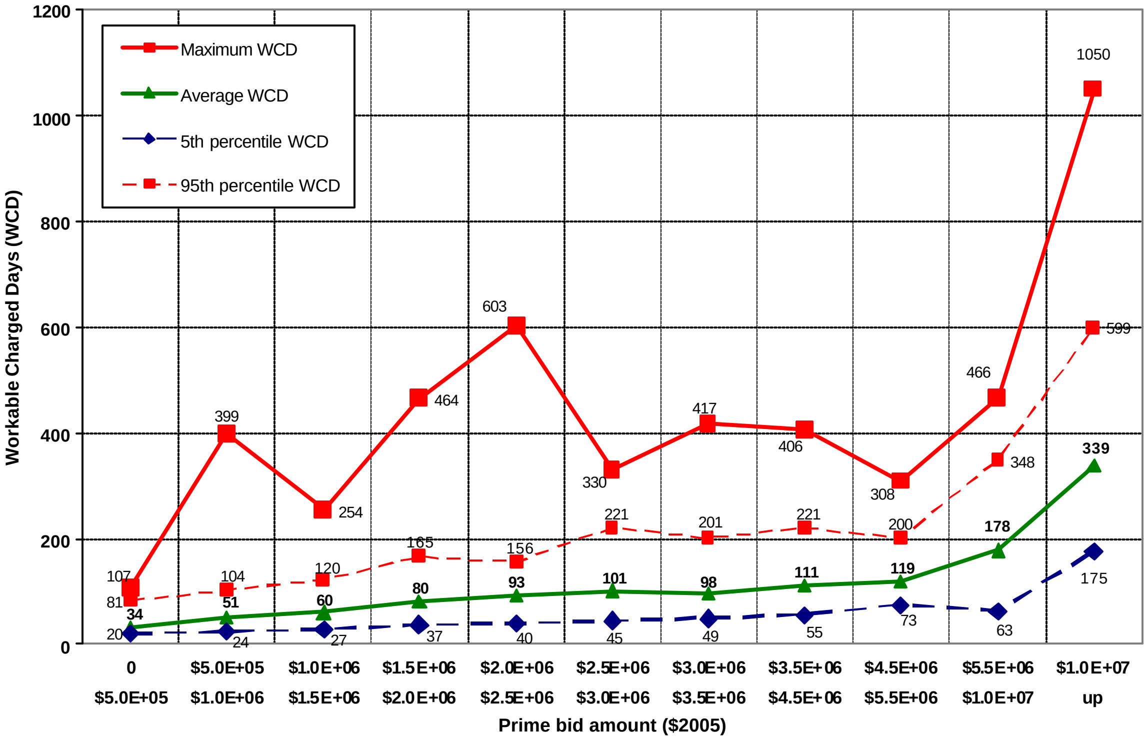


Figure 3.10: Variation of workable charged days against the prime bid amounts

The relationship between the WCDs and the length of projects (miles), in Figure 3.11, showed a surprisingly level/flat average WCD value for the various lengths/miles of projects, i.e., a weak relationship in which WCD did not change much with variations in project miles or ACP/HMA tons. A similar pattern is shown in Figure 3.12, in which WCD did not change with an increase or decrease in ACP/HMA quantities. Thus, WCD is more related to a project's value/amount than to any other project variable.

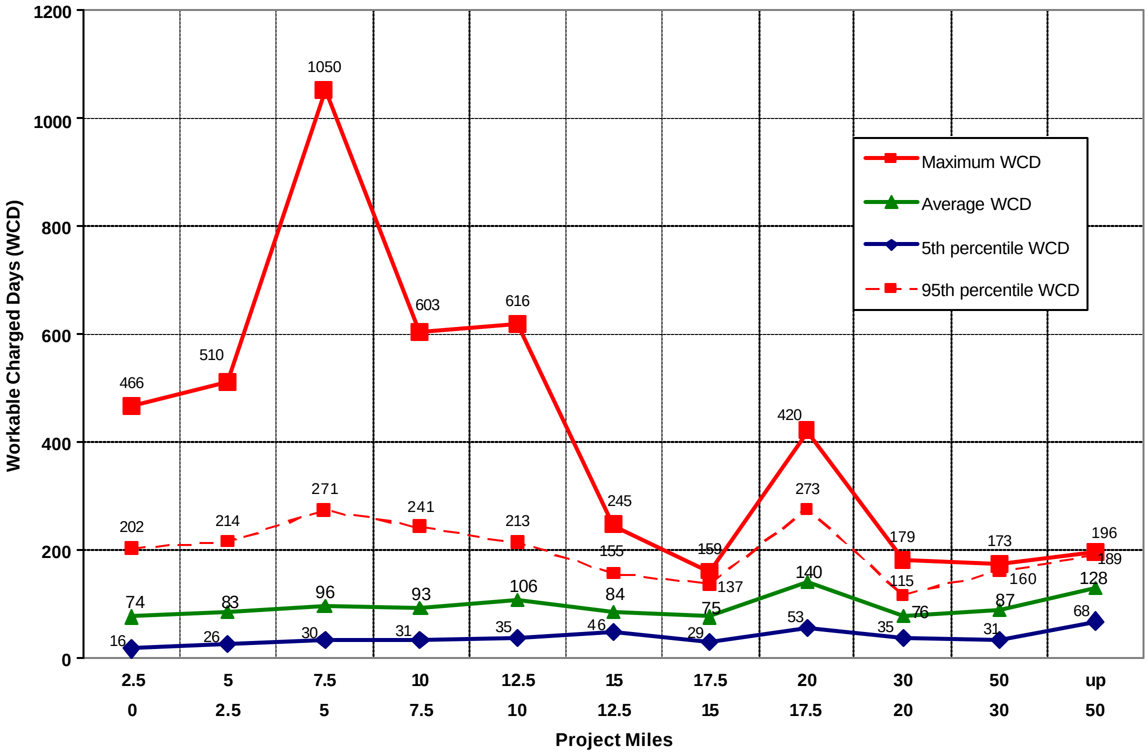


Figure 3.11 Variation of workable charged days in relation to project length

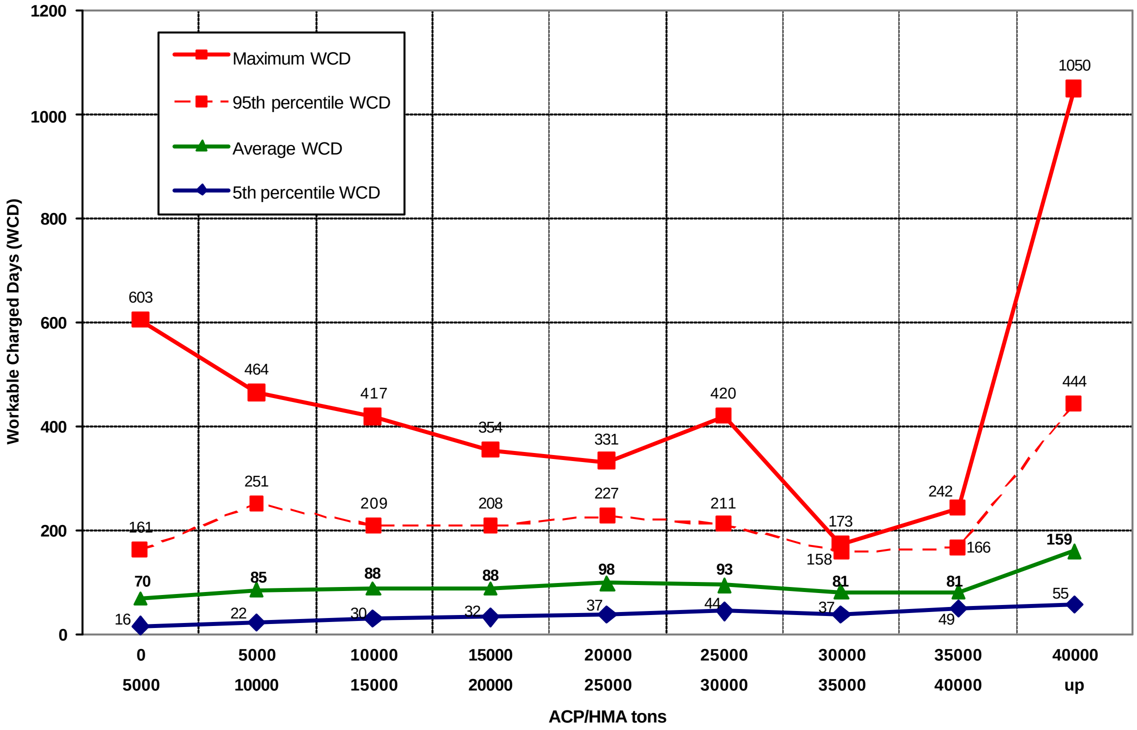


Figure 3.12 Variation of workable charged days in relation to quantities of ACP (HMA)

3.4 Research Approach for Time Prediction

As explained in the analysis of time performance, WSDOT uses CPM, production rates, and historical data to estimate the duration of activities and projects. This research was intended to supplement WSDOT work by using historical data to predict project duration. However, this research was based on a holistic method that relied on the recorded final project duration and the associated contract value, quantities of work, and the number of miles of highway to predict the duration of new projects. The work quantities utilized in the development of the prediction models were the quantities of asphalt concrete pavement (ACP)/hot mix asphalt (HMA), grading, and surfacing. Project data and the quantities of work were collected for each project (964 projects; Table 1.1) by using WSDOT standard bid items (tables 1.2 –to 1.4). With data for projects awarded between 1990 and 2004, the total project costs were converted to the 2005 dollars by using WSDOT's cost index before the prediction development process began.

The data were then subjected to statistical analysis in order to develop

1. time characteristic tables—statistical measures, e.g., minimum, maximum, 5th and 95th percentiles, average, and standard deviation of grouped data, were the basis for the development of two-dimensional tables for predicting project time.
2. time prediction models—this included the use of (a) ordinary general multiple regression analysis (GRM), (b) "Ridge" regression analysis, and (c) general partial least square regression analysis (PLS).

3.5 Time Prediction for WSDOT Projects—Characteristic Tables

The charts in figures 3.10 and 3.11 explain the relationship between workable charged days and a single variable at a time. These two-dimensional charts have a nearly level/flat average for WCDs. Thus, the charts provide little help in predicting project duration. A better method is to use three-dimensional matrixes, or characteristic tables, for prediction. A three-dimensional table gives the duration of a project when two variables change at a time. This better establishes the relationship between WCD and project variables. For example, Table 3.2 gives an average value of 84 working days when 15,000 to 20,000 tons of ACP/HMA are planned and the project length is 2.5 to 5 miles. Tables 3.2 and 3.3 give the WCD for a combination of project cost and ACP/HMA quantity. Similarly, Table 3.4 gives the duration for a combination of project cost and project miles.

The duration information given in tables 3.2 to 3.4 includes the following:

- average duration (first line)
- minimum and maximum values (second line)
- standard deviation and the number of contracts in this category (third line).

For the same example given above (15,000-20,000 ACP/HMA and 2.5-5 miles),

- The average value is 84 working days.
- The minimum and maximum values are 37 and 155 working days, respectively.
- The standard deviation is 47 working days, and the number of projects is 17.

Figures 3.10 to 3.12 represent valuable time prediction tools at the early stages of a project.

Table 3.2: Working days information for specific ACP/HMA tons and specific miles

	ACP	**0**	**5,000**	**10,000**	**15,000**	**20,000**	**25,000**	**30,000**	**35,000**		**WCD for Miles**
Miles		**5,000**	**10,000**	**15,000**	**20,000**	**25,000**	**30,000**	**35,000**	**40,000**	**>40,000**	
0	2.5	59, 15, 148, 58 , 231	83, 24, 230, 66 , 74	103, 37, 192, 52 , 27	128, 37, 337, 101 , 20	168, 52, 290, 92 , 7	149, 60, 203, 91 , 3	37, 28, 45, 13 , 2	N/A	95, 64, 126, 48 , 2	74, 16, 202, 67 , 366
2.5	5	66, 24, 125, 59 , 50	66, 24, 168, 47 , 45	70, 29, 147, 46 , 44	84, 37, 155, 47 , 17	90, 47, 163, 43 , 15	95, 45, 174, 49 , 11	117, 80, 153, 41 , 3	137, 86, 226, 73 , 4	296, 79, 479, 161 , 8	83, 26, 214, 74 , 197
5	7.5	74, 26, 152, 44 , 33	142, 29, 428, 145 , 15	59, 26, 126, 35 , 18	56, 30, 89, 22 , 21	92, 36, 208, 68 , 21	76, 44, 144, 40 , 15	82, 47, 137, 40 , 6	68, 50, 96, 29 , 3	283, 63, 792, 295 , 11	96, 30, 271, 115 , 143
7.5	10	101, 39, 232, 113 , 27	81, 26, 230, 86 , 10	186, 47, 391, 154 , 6	58, 35, 95, 25 , 8	89, 32, 217, 65 , 12	64, 44, 91, 18 , 9	73, 36, 108, 25 , 16	100, 55, 160, 62 , 3	119, 60, 189, 54 , 7	93, 31, 241, 84 , 98
10	12.5	76, 29, 171, 53 , 12	73, 40, 93, 34 , 3	117, 37, 169, 67 , 5	131, 51, 200, 72 , 4	105, 46, 170, 59 , 4	104, 48, 201, 64 , 7	92, 61, 122, 48 , 2	57, 50, 64, 8 , 3	144, 59, 374, 148 , 13	106, 35, 213, 89 , 53
12.5	15	78, 53, 100, 20 , 7	67, 67, 67, 0 , 1	44, 44, 44, 0 , 1	112, 77, 147, 54 , 2	73, 42, 104, 31 , 4	60, 60, 60, 0 , 1	94, 61, 128, 53 , 2	60, 50, 74, 10 , 6	132, 81, 227, 70 , 5	84, 46, 155, 43 , 29
15	17.5	N/A	77, 11, 135, 67 , 4	52, 52, 52, 0 , 1	55, 55, 55, 0 , 1	N/A	N/A	76, 42, 141, 45 , 6	87, 65, 108, 33 , 2	78, 61, 106, 19 , 6	75, 29, 137, 38 , 20
17.5	20	72, 55, 99, 28 , 3	41, 41, 41, 0 , 1	257, 257, 257, 0 , 1	55, 55, 55, 0 , 1	184, 184, 184, 0 , 1	420, 420, 420, 0 , 1	N/A	N/A	135, 77, 238, 67 , 11	140, 53, 273, 98 , 19
20	30	61, 36, 94, 34 , 3	96, 66, 162, 44 , 6	35, 35, 35, 0 , 1	N/A	61, 51, 76, 15 , 3	77, 46, 108, 34 , 3	N/A	55, 55, 55, 0 , 1	83, 61, 111, 23 , 5	76, 35, 115, 33 , 22
30	50	94, 53, 146, 54 , 3	13, 13, 13, 0 , 1	119, 119, 119, 0 , 1	N/A	45, 45, 45, 0 , 1	N/A	173, 173, 173, 0 , 1	61, 61, 61, 0 , 1	88, 41, 145, 42 , 7	87, 31, 160, 48 , 15
50	up	196, 196, 196, 0 , 1	N/A	N/A	N/A	N/A	N/A	N/A	N/A	61, 61, 61, 0 , 1	128, 68, 189, 95 , 2
WCD for ACP/HMA		66, 16, 161, 62 , 370	83, 22, 251, 74 , 160	87, 30, 209, 66 , 105	88, 32, 208, 67 , 74	98, 37, 227, 65 , 68	93, 44, 211, 67 , 50	81, 37, 158, 38 , 38	81, 49, 166, 46 , 23	159, 55, 444, 158 , 76	

Table 3.3: Working days information for specific project cost and ACP/HMA tons

PTC ACP		0	500,000	1000,000	1,500,000	2,000,000	2,500,000	3,000,000	3,500,000	4,500,000	5,500,000	>10,000,000	WCD for ACP
		500,000	1,000,000	1,500,000	2,000,000	2,500,000	3,000,000	3,500,000	4,500,000	5,500,000	10,000,000		
0	**5,000**	33, 13, 78, 20 , 105	57, 21, 119, 48 , 100	56, 20, 95, 30 , 62	67, 36, 131, 29 , 26	109, 59, 203, 55 , 25	127, 40, 322, 141 , 14	74, 46, 118, 31 , 7	118, 71, 185, 40 , 11	215, 82, 382, 171 , 3	157, 87, 327, 104 , 12	219, 131, 317, 81 , 5	66, 16, 161, 62 , 370
5,000	**10,000**	28, 13, 42, 11 , 9	51, 22, 105, 37 , 52	62, 29, 108, 30 , 28	87, 35, 162, 38 , 22	119, 39, 288, 111 , 13	125, 62, 263, 85 , 9	139, 25, 304, 111 , 10	87, 64, 102, 18 , 5	109, 19, 226, 120 , 3	205, 87, 385, 127 , 6	234, 183, 297, 65 , 3	83, 22, 251, 74 , 160
10,000	**15,000**	N/A	51, 27, 116, 27 , 25	55, 29, 102, 24 , 32	82, 35, 148, 40 , 16	105, 56, 154, 49 , 4	116, 67, 148, 37 , 5	68, 59, 74, 9 , 3	169, 67, 300, 92 , 13	179, 160, 205, 26 , 3	201, 131, 298, 99 , 3	257, 257, 257, 0 , 1	87, 30, 209, 66 , 105
15,000	**20,000**	N/A	50, 29, 117, 44 , 7	53, 34, 86, 18 , 19	64, 33, 112, 34 , 15	70, 39, 96, 20 , 11	133, 95, 187, 42 , 5	88, 72, 107, 20 , 3	121, 82, 176, 40 , 6	119, 75, 188, 70 , 3	288, 288, 288, 0 , 1	277, 207, 351, 79 , 4	88, 32, 208, 67 , 74
20,000	**25,000**	N/A	N/A	64, 27, 160, 53 , 10	74, 36, 148, 40 , 13	85, 41, 147, 42 , 16	95, 72, 151, 33 , 8	89, 55, 143, 45 , 4	108, 50, 208, 65 , 8	211, 146, 295, 86 , 3	183, 61, 312, 110 , 5	175, 175, 175, 0 , 1	98, 37, 227, 65 , 68
25,000	**30,000**	N/A	N/A	57, 46, 68, 12 , 3	59, 44, 86, 16 , 12	67, 42, 103, 23 , 13	109, 51, 199, 62 , 6	102, 83, 116, 20 , 3	102, 57, 186, 57 , 7	85, 85, 85, 0 , 1	180, 114, 215, 54 , 4	420, 420, 420, 0 , 1	93, 44, 211, 67 , 50
30,000	**35,000**	N/A	N/A	57, 46, 67, 17 , 2	66, 34, 103, 26 , 12	64, 43, 91, 20 , 7	61, 30, 96, 29 , 5	57, 57, 57, 0 , 1	111, 80, 148, 27 , 8	N/A	155, 151, 159, 6 , 2	173, 173, 173, 0 , 1	81, 37, 158, 38 , 38
35,000	**40,000**	N/A	N/A	N/A	56, 50, 62, 6 , 4	59, 57, 61, 3 , 2	62, 50, 77, 12 , 7	76, 53, 106, 30 , 3	67, 51, 84, 26 , 2	95, 90, 100, 8 , 2	181, 136, 235, 56 , 3	N/A	81, 49, 166, 46 , 23
40,000	**Up**	N/A	N/A	N/A	N/A	95, 95, 95, 0 , 1	80, 53, 102, 20 , 6	75, 48, 104, 25 , 18	88, 61, 122, 24 , 11	111, 78, 166, 35 , 11	158, 67, 284, 84 , 15	399, 202, 768, 231 , 14	159, 55, 444, 158 , 76
WCD for contract value		33, 12, 75, 19 , 114	54, 22, 118, 42 , 184	57, 24, 107, 29 , 156	72, 35, 145, 33 , 120	91, 40, 163, 58 , 92	104, 44, 193, 80 , 65	90, 47, 202, 58 , 52	116, 58, 215, 59 , 71	138, 72, 282, 81 , 29	174, 76, 353, 91 , 51	317, 173, 579, 183 , 30	

Table 3.4: Working days information for specific project cost and project miles

PTC		0	500,000	1000,000	1,500,000	2,000,000	2,500,000	3,000,000	3,500,000	4,500,000	5,500,000	>10,000,000	WCD for Miles
Miles		**500,000**	**1,000,000**	**1,500,000**	**2,000,000**	**2,500,000**	**3,000,000**	**3,500,000**	**4,500,000**	**5,500,000**	**10,000,000**		
0	**2.5**	34, 13, 77, 19 , 109	61, 22, 131, 52 , 101	63, 25, 99, 30 , 53	73, 41, 104, 21 , 25	117, 27, 225, 69 , 19	131, 79, 231, 66 , 16	187, 97, 316, 94 , 6	143, 76, 227, 54 , 17	161, 74, 281, 86 , 6	201, 100, 395, 116 , 9	286, 195, 350, 76 , 5	74, 16, 202, 67 , 366
2.5	**5**	27, 24, 30, 4 , 2	46, 26, 99, 23 , 52	52, 22, 95, 28 , 43	69, 29, 148, 36 , 26	91, 56, 135, 26 , 18	102, 50, 152, 40 , 15	90, 53, 125 , 28 , 8	117, 64, 213, 49 , 15	179, 76, 373, 145 , 5	200 , 115, 341, 101 , 6	317, 183, 483, 131 , 7	83, 26, 214, 74 , 197
5	**7.5**	23, 23, 23, 0 , 1	41, 20, 67, 23 , 19	57, 35, 114, 25 , 32	70, 34, 140, 35 , 27	100, 50, 195, 84 , 24	76, 54, 100, 17 , 9	90, 26, 202, 68 , 9	97, 52, 174, 49 , 8	101, 101, 101, 0 , 1	242, 143, 388, 106 , 7	448, 211, 921, 318 , 6	96, 30, 271, 115 , 143
7.5	**10**	23, 23, 23, 0 , 1	49, 25, 68, 22 , 4	60, 28, 118, 41 , 16	63, 36, 112, 25 , 27	69, 40, 106, 24 , 10	128, 37, 377, 168 , 10	66, 46, 91, 18 , 7	128, 60, 305, 106 , 10	167, 103, 207, 53 , 4	188, 108, 294, 77 , 6	227, 130, 301, 99 , 3	93, 31, 241, 84 , 98
10	**12.5**	N/A	47, 35, 61, 12 , 5	31, 21, 40, 10 , 3	131, 59, 176, 56 , 5	63, 42, 89, 20 , 6	97, 46, 191, 65 , 6	63, 44, 73, 13 , 6	107, 52, 146, 35 , 9	117, 75, 162, 39 , 5	153, 103, 213, 51 , 6	411, 226, 595, 290 , 2	106, 35, 213, 89 , 53
12.5	**15**	N/A	103, 59, 146, 68 , 2	55, 45, 65, 11 , 3	49, 41, 56, 12 , 2	72, 57, 95, 17 , 5	68, 50, 87, 17 , 5	88, 54, 144, 42 , 5	104, 88, 128, 24 , 3	74, 74, 74, 0 , 1	150, 101, 231, 82 , 3	N/A	84, 46, 155, 43 , 29
15	**17.5**	8, 8, 8, 0 , 1	31, 31, 31, 0 , 1	N/A	94, 65, 128, 36 , 3	49, 42, 55, 6 , 4	54, 45, 63, 14 , 2	81, 61, 106, 26 , 3	89, 74, 110, 22 , 3	83, 83, 83, 0 , 1	147, 137, 158, 17 , 2	N/A	75, 29, 137, 38 , 20
17.5	**20**	N/A	N/A	50, 42, 55, 8 , 3	N/A	N/A	78, 78, 78, 0 , 1	70, 58, 82, 19 , 2	87, 76, 97, 16 , 2	132, 104, 176, 45 , 3	147, 83, 233, 74 , 4	282, 224, 395, 93 , 4	140, 53, 273, 98 , 19
20	**30**	N/A	N/A	55, 37, 73, 29 , 2	44, 36, 54, 10 , 3	91, 66, 111, 24 , 4	78, 78, 78, 0 , 1	65, 50, 75, 11 , 5	77, 57, 97, 31 , 2	106, 97, 114, 13 , 2	61, 51, 71, 16 , 2	179, 179, 179, 0 , 1	76, 35, 115, 33 , 22
30	**50**	N/A	N/A	50, 50, 50, 0 , 1	98, 79, 116, 30 , 2	53, 46, 60, 11 , 2	N/A	49, 49, 49, 0 , 1	60, 60, 60, 0 , 1	13, 13, 13, 0 , 1	110, 50, 154, 44 , 6	173, 173, 173, 0 , 1	87, 31, 160, 48 , 15
50	**up**	N/A	N/A	N/A	N/A	N/A	N/A	N/A	61, 61, 61, 0 , 1	N/A	N/A	196, 196, 196, 0 , 1	128, 68, 189, 95 , 2
WCD for Cont. Value		33, 12, 75, 19 , 114	54, 22, 118, 42 , 184	57, 24, 107, 29 , 156	72, 35, 145, 33 , 120	91, 40, 163, 58 , 92	104, 44, 193, 80 , 65	90, 47, 202, 58 , 52	116, 58, 215, 59 , 71	138, 72, 282, 81 , 29	174, 76, 353, 91 , 51	317, 173, 579, 183 , 30	

3.6 Time Prediction for WSDOT Projects—Prediction Models

3.6.1 Introduction

The analysis of project time performance found that completion times among projects were highly variable. Several variables may have contributed to that variability, including, for example, a change in the work quantities of the major operation, such as surfacing, grading, and ACP/HMA pavement; a change in the number of work crews and their production rates; the weather conditions during construction, particularly if the weather affected the critical path activities; logistics and delays in the procurement of materials; and inefficient resource management or lack of labor or equipment. With so many factors contributing to completion time variability, predicting completion times for future projects is complex and difficult. For example, a project with 5,000 tons of ACP placed by a crew that has a production rate of 50 ton per day would require 100 working days. However, if two crews were used, then the time would be around 50 days. So in predicting the completion time of a future project of similar size, the range would be between 50 and 100 working days, which is too wide to make sound decision about completion time.

Adding more variables into the prediction equation will help in reducing prediction errors. However, for the highway agency side, the number of variables is generally limited to those under its control and supervision, e.g., work quantities. The number of crews, production rates, logistics, and resource availability are mainly the contractor's responsibility and are not usually recorded in highway agency databases. Therefore, time prediction equations will have to be used with the understanding that prediction errors will be encountered because of the many factors that affect completion time and because prediction equations will have only a limited number of variables. The variables that were considered in this research included work quantities of ACP/HMA (tons), grading (tons), grading (cy), surfacing (tons), project length (centerline miles), and contract value (paid to contractor, dollars).

The following subsections explain the development of the time prediction equations. In phase one, the statistical characteristics of the variables were investigated, and a preliminary regression analysis was conducted. In the subsequent phases, a number of regression analysis techniques were used to develop prediction equations that would attain reasonable *mean absolute percentage error* (MAPE) values. The MAPE is used to check prediction error by comparing predicted duration to actual duration.

3.6.2 Phase I Development

By using historical project data, the relationship between project completion time and project variables can be partially explained through graphical representation (e.g., scatter plots) and through a study of the correlation between variables. Figures 3.11 and 3.12 illustrate that, for categorized data, the average workable charged days (WCD) for projects did not change significantly with a change in project miles and ACP/HMA quantities. This can be further explained through figures 3.13 and 3.14, in which the correlation coefficient is 0.08 for project miles and 0.38 for ACP/HMA quantities. Each dot on these two graphs represents a project. The graphs and the low correlations clearly establish that the relationship between project completion and the two variables is not strong.

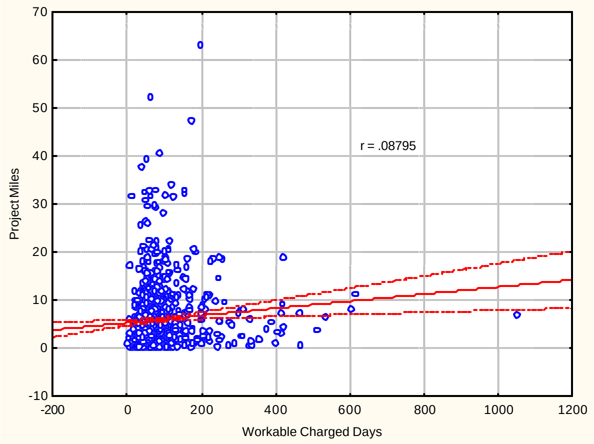


Figure 3.13: WCD in relation to project miles

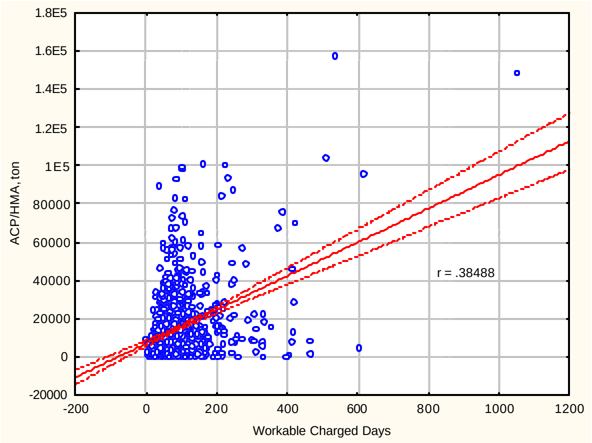


Figure 3.14: WCD in relation to ACP/HMA

However, an important finding from these graphs is that the relationship between WCD and the other variables may be better explained if the variables are transformed with the natural logarithms. For example, figures 3.15 and 316 illustrate a better linear relationship between ln(WCD) and ln(ACP) and between ln(WCD) and ln(Miles). This means that transformed variables, rather than raw variables, should be considered in the prediction equations.

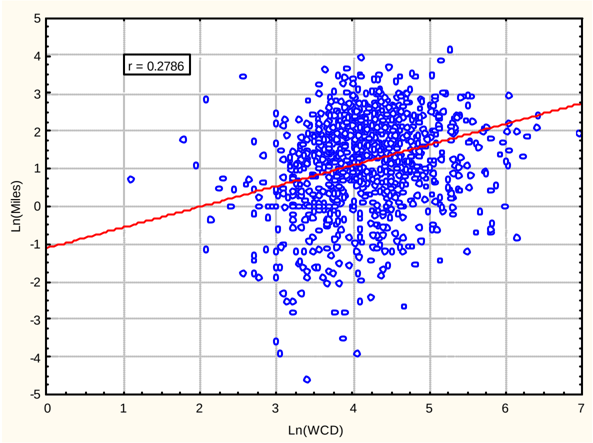


Figure 3.15: ln(WCD) in relation to ln(Miles)

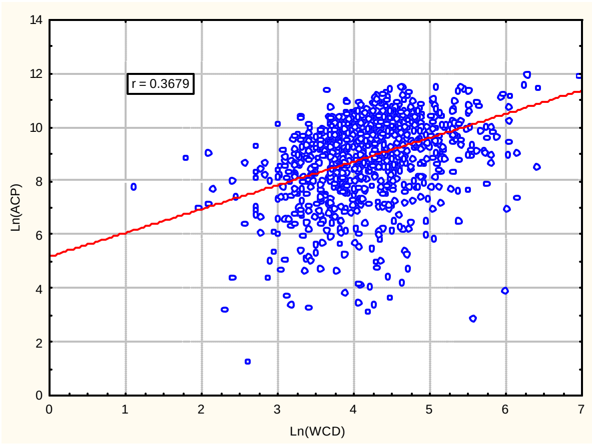


Figure 3.16: ln(WCD) in relation to ln(ACP)

While the above variables are mainly physical variables (e.g., quantities of work, project miles) related to tangible components of projects, the contract value, *paid-to-contractor*, also contributes to the determination of completion time. Figures 3.17 and 3.18 illustrate the relationship between completion time, WCD, and the contract value before and after transformation. Figure 3.18 shows the strong correlation between PTC and WCD, which suggests that PTC is a better factor than the other variables in predicting completion time. Similarly, figures 3.19 to 3.21 suggest that the natural logarithms of grading (cy), grading (ton), and surfacing (ton), with their linear trend and correlation, can contribute to time prediction.

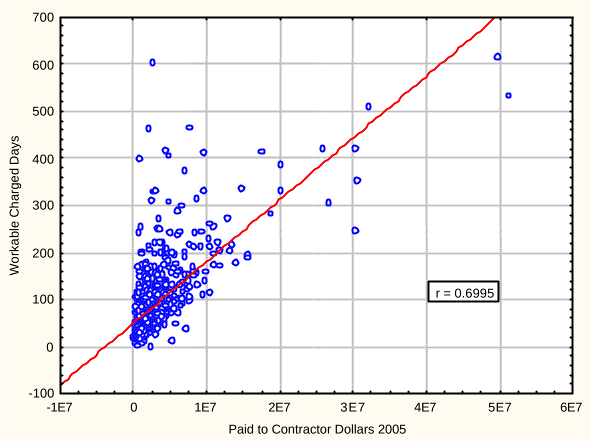


Figure 3.17: WCD in relation to PTC

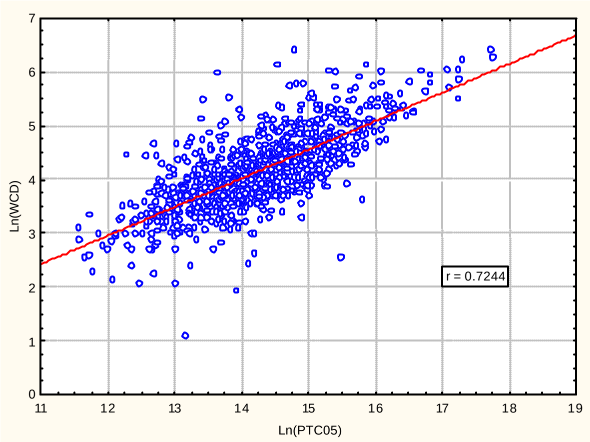


Figure 3.18: ln(WCD) in relation to ln(PTC)

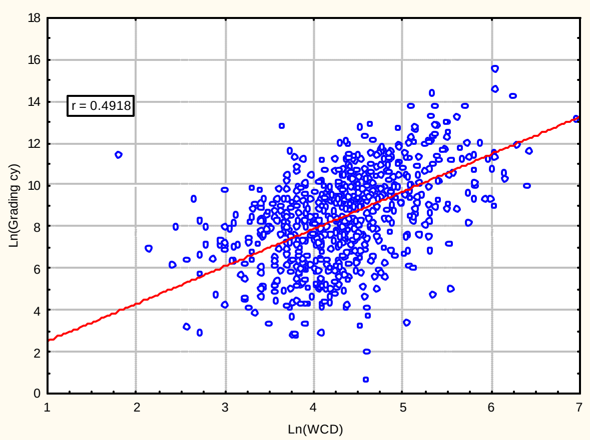


Figure 3.19: ln(WCD) in relation to ln(Grading cy)

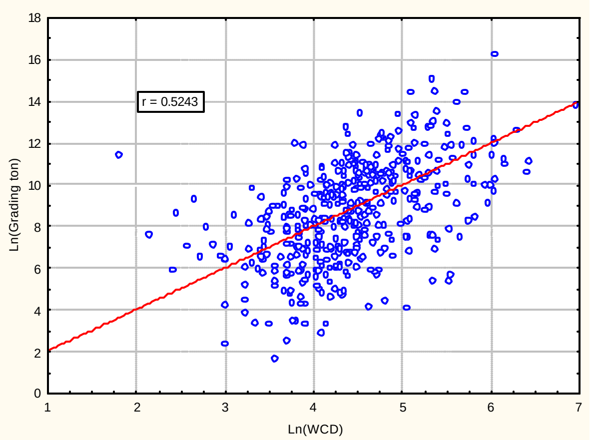


Figure 3.20: ln(WCD) in relation to ln(Grading ton)

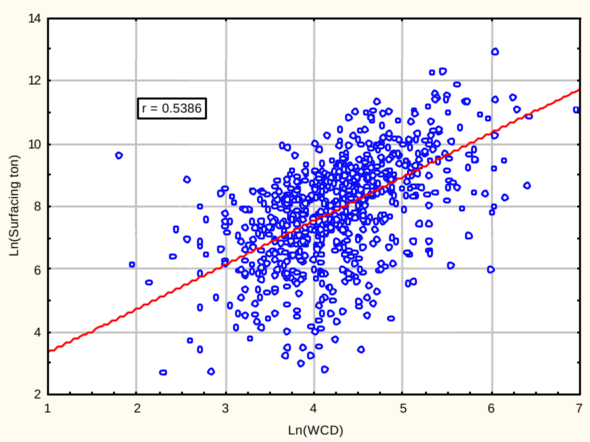


Figure 3.21: ln(WCD) in relation to ln(Surfacing ton)

The prediction models use formulas that have a dependent variable, *workable charged days, WCD*, the predicted values of which depend on the number and value of the independent variables (ACP/HMA quantity, grading (cy and ton), surfacing (ton), project miles, and value (paid-to-contractors)). The six independent variables could be used in the development of a large number of predication models. In total, 63 models could be developed by using one, two, three, four, five, or six of the independent variables. Both the completion time and contract value naturally depend on the other five variables, which represent five physical elements in any project. However because completion time is highly correlated to contract value, the time prediction models were developed in two groups, with and without the contract value.

With large number of models that could be developed, the objective was to choose the best among these models. The selection was based on how closely the time predicted through a model matched the actual time. This was tested by using the *mean absolute percentage error, MAPE,* statistic, which measures the deviation of predicted time from actual time.

In developing the time prediction models, formulas could be designed with or without an intercept, and the preference would be to have no intercept if it would not affect the value of MAPE. Regression analysis could produce prediction models with negative coefficients, but their meaning would be difficult to interpret, and therefore, models with negative coefficients were rejected. For example, if the ACP/HMA resulted in a negative coefficient in a model, it would mean that more quantities of ACP/HMA would produce a shorter completion time, which would not be reasonable. However, before a model was rejected for negative coefficients, the reasons for negativity were checked. For example, while correlation between the dependent variable, WCD, and the independent variables was highly preferred because it would produce better prediction, correlation between the independent variables would generally weaken the prediction model. Correlation between independent variables is referred to as *multicolinearity*, which needs to be treated if it is encountered in a model. Figures 3.22 and 3.23 illustrate examples of significant correlation between ACP/HMA and miles and between surfacing and grading. Negative coefficients can be produced if multicolinearity is found between variables.

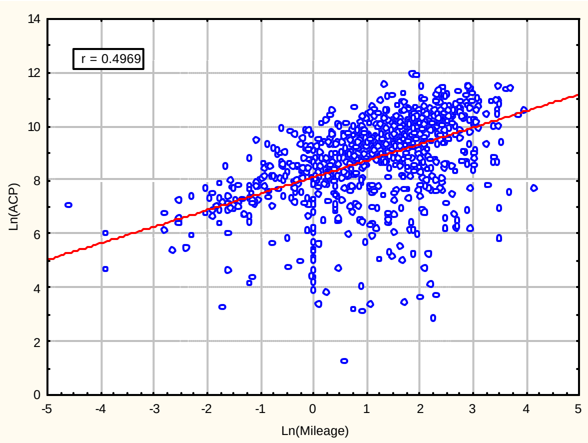


Figure 3.22: ln(ACP) in relation to ln(Miles)

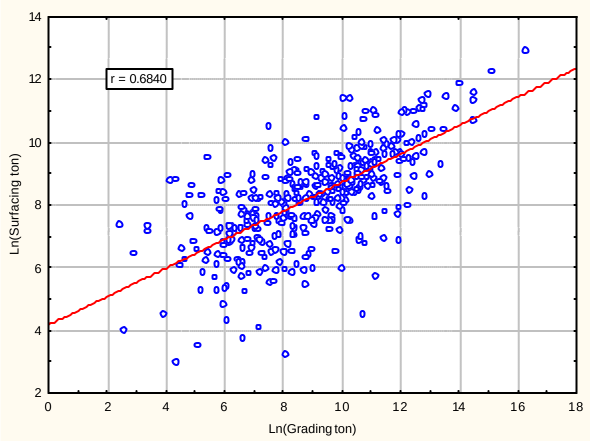


Figure 3.23: ln(Sufacing) in relation to ln(Grading)

In a first attempt at designing prediction models, a general multiple regression model (GRM) (Tabachnick et. al 2007; Dielman 2005; Makridakis et. al 1998) was applied to the original raw variables. A best subsets regression analysis was performed using GRM. The best subset regression runs all possible regressions between the dependent variable and all possible subsets of the independent variables. Subset models are then ranked in terms of the best fit by using the coefficient of determination, R^2, an adjusted R^2, or *Mallows* C_p statistic. Table 3.5 illustrates the results of the first ten best models. The table shows that eight out of ten models had negative coefficients, particularly for grading (ton and cy). Multicolinearity was suspected because grading (ton) and grading (cy) were highly correlated, as illustrated in Figure 3.24.

Table 3.5: Standardized coefficients using best subset regression (raw variables, no intercept)

Adj. R2	**Effects**	**Miles**	**PTC**	**ACP**	**grading ton**	**grading cy**	**surfacing**
0.67008	5	0.13431	0.62267	0.08968		-0.06532	0.12767
0.66974	6	0.13360	0.62416	0.09035	0.00834	-0.07230	0.12610
0.66939	5	0.13892	0.61297	0.09039	-0.04552		0.11360
0.66891	4	0.13596	0.61895	0.10023			0.07338
0.66728	4	0.17195	0.66228			-0.08125	0.14239
0.66695	5	0.17249	0.66005		-0.01036	-0.07243	0.14419
0.66660	4	0.17783	0.64885		-0.06432		0.13168
0.66602	4	0.13319	0.65111	0.10743	0.02693		
0.66578	5	0.13087	0.65710	0.10815	0.05098	-0.02811	

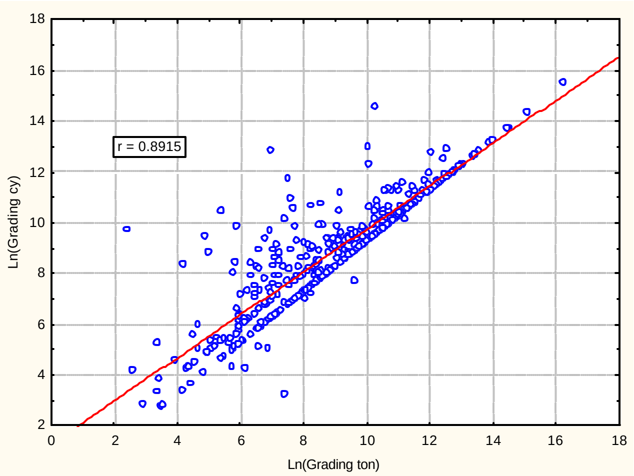
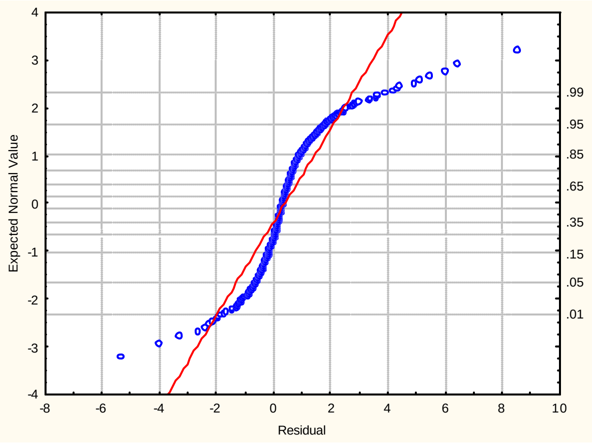


Figure 3.24: ln(Grading ton) in relation to ln(Gradig cy)

Figure 3.25 shows the normal probability plot of the six-variable model in the table; the plot shows a violation of the normality assumption in regression analysis. In addition, Figure 3.26 shows a cone-shaped standardized residual plot, suggesting another violation of the constant variance assumption of the regression model. The researchers concluded that the preliminary model using the original raw values of the variables was not appropriate for prediction because of the violations of assumptions. The results further confirmed that transformation of the variables with the natural logarithms would provide better models.



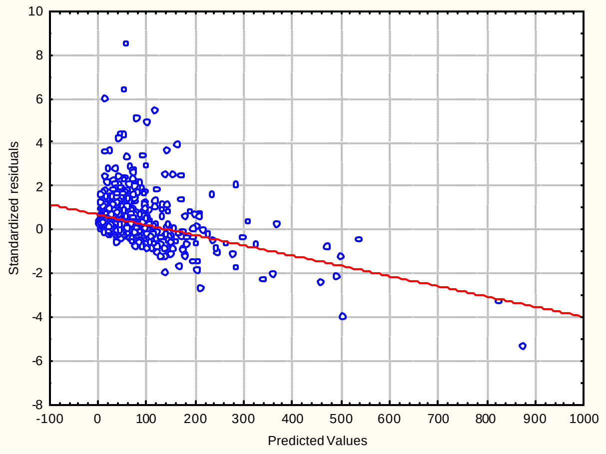


Figure 3.25: Normal probability plot

Figure 3.26: Predicted values vs. residuals

3.6.3 Phase II Development

In Phase II, both the dependent and explanatory variables were transformed with the natural logarithms. Tables 3.6 and 3.7 show the results of the first ten best subset models with and without the use of an intercept. In both models, the contract value had a higher weight than the other variables. The use of transformation thus helped in alleviating the non-normality and non-constant variance violations. For example, in Table 3.6, the six-variable model has a normal probability plot, and the residuals in figures 3.27 and 3.28 represent significant improvement over those in figures 3.25 and 3.26.

Table 3.6: Standardized coefficients produced by best subsets models using transformed variables (without intercept).

Adj R2	Effects	Ln (Miles)	Ln (PTC)	Ln (ACP)	Ln (grad. ton)	Ln (grad. cy)	Ln (surfacing)
0.98794	5	0.0128	0.8295	-0.0641	0.1751		0.0493
0.98793	4	0.0132	0.8518	-0.0565	0.1941		
0.98792	3	0.0090	0.7983		0.1943		
0.98791	4	0.0082	0.7746		0.1791		0.0395
0.98790	6	0.0126	0.8308	-0.0652	0.1838	-0.0125	0.0528
0.98790	3		0.7767		0.1748		0.0465
0.98790	5	0.0133	0.8500	-0.0561	0.1880	0.0075	
0.98790	2		0.8055		0.1925		
0.98789	4	0.0091	0.7962		0.1855	0.0108	
0.98789	4		0.8051	-0.0323	0.1716		0.0534

Table 3.7: Standardized coefficients produced by best subsets regression and transformed variables (with intercept).

Adj R2	Effects	Ln(Miles)	Ln(PTC)	Ln (ACP)	Ln(grading ton)	Ln(grading cy)	Ln(surfacing)
0.59918	5.00000	-0.13770	0.78639	-0.08906	0.29029	-0.10273	
0.59875	6.00000	-0.13929	0.77893	-0.09554	0.28584	-0.12251	0.04106
0.59822	4.00000	-0.12827	0.76721	-0.08495	0.20586		
0.59722	5.00000	-0.12819	0.76303	-0.08708	0.19810		0.01538
0.59615	4.00000	-0.16578	0.74410		0.28443	-0.09323	
0.59556	3.00000	-0.15601	0.72840		0.20772		
0.59524	5.00000	-0.16775	0.73840		0.28179	-0.10355	0.02220
0.59444	4.00000	-0.15608	0.72785		0.20691		0.00162
0.59029	3.00000		0.70846	-0.12900	0.22840		
0.59008	4.00000		0.71829	-0.13386	0.28532	-0.06791	

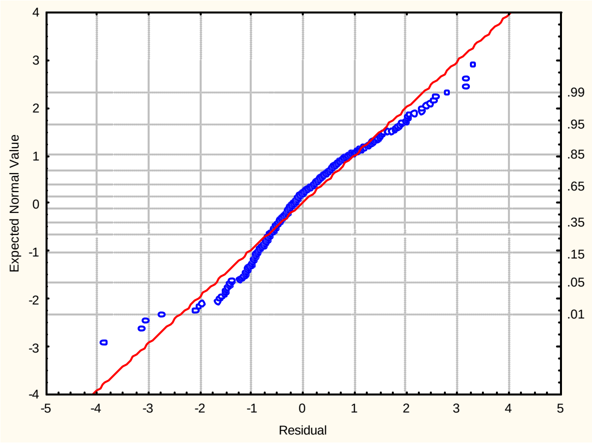


Figure 3.27: Normal probability plot

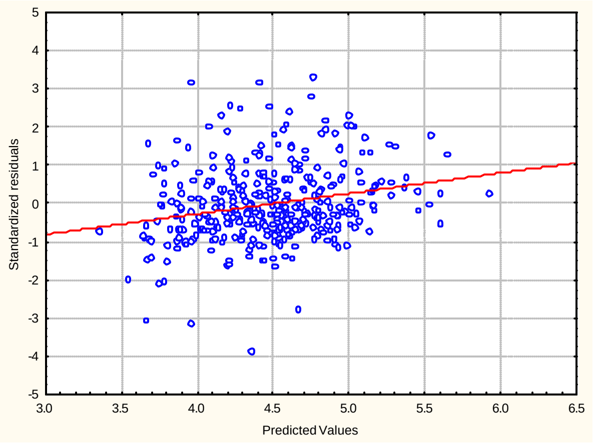


Figure 3.28: Predicted values vs. residuals

As shown in tables 3.6 and 3.7, the ACP/HMA, grading (cy), and miles variables still had negative coefficients, suggesting the existence of multicolinearity. For example, the six-variable model in Table 3.6 had tolerance values approaching zero and large variance-inflation-factor (VIF) values, which strongly suggests multicolinearity, Table 3.8.

Table 3.8: Multicolinearity in six-variables GRM model (no intercept)

Adj R2	**Tolerance**	**VIF**
Ln(Mileage)	0.502419	1.99037
Ln(PTC05)	0.010447	95.72163
Ln(ACP)	0.014435	69.27436
Ln(Grading ton)	0.012782	78.23704
Ln(Grading cy)	0.010106	98.94826
Ln(Surfacing ton)	0.013255	75.44112

One of the common methods for dealing with the multicolinearity effects is “Ridge” regression analysis (Dielman 2005; Kutner et al. 2005; Sen and Srivastava 1990). Ridge regression uses a procedure to artificially decrease the correlations between the variables so that more stable beta coefficients can be obtained. A constant (lambda) is added to the diagonal of the correlation matrix, which is then re-standardized, and the off-diagonal elements are divided by the constant. Lambda is a constant between zero and one. Therefore, the values of lambda are increased to the point at which multicolinearity is reduced. For example, Table 3.9 shows the results for the no-intercept six-variable model, which, when compared to Table 3.8, shows improvement in both tolerance and VIF when Ridge regression is applied with a lambda of 0.15.

Table 3.9: Six-variables Ridge model (no intercept; 0.15 lambda)

Adj R2	**Tolerance**	**VIF**	**Coefficient**
Ln(Mileage)	0.770404	1.29802082	0.064900
Ln(PTC05)	0.202697	4.93346962	0.073366
Ln(ACP)	0.209983	4.76228266	0.098155
Ln(Grading ton)	0.211642	4.72495776	0.083372
Ln(Grading cy)	0.207070	4.8292918	0.083268
Ln(Surfacing ton)	0.199047	5.02394257	0.099831

General nonlinear partial least square regression (PLS) is another regression analysis method. Although the GRM model has been extended in a number of ways (multivariate methods) to address more sophisticated data analysis problems, including the development of “Discriminant Analysis,” “Principal Component Analysis,” and “Canonical Correlation” (Tabachnick et. al 2007), the application of these methods has had restrictions. PLS is another extension of the GRM regression, but with fewer restrictions than the other multivariate methods (Rannar et. al 1994; de Jong, 1993; Geladi and Kowalsky 1986). PLS regression transforms the original predictor (independent) variables into factor scores by using linear combinations of the original predictors. The objective is to have no correlation between the factor score variables, which are then used in the predictive regression model. In this sense, multicolinearity is dealt with.

The development of time prediction models for the current research started with the general multiple regression models (GRM), and if negative parameters or multicollinearity was found, then Ridge regression was used with different lambda values until multicollinearity was removed. Then PLS regression was used to compare results with those of the Ridge regression. The best model was then selected on the basis of the best MAPE value, i.e., the best model at reducing prediction error. For example, Table 3.10 shows the results for the six-variable model. The last two "GRM" models were rejected because of their negative coefficients; the other three were ranked on the basis of MAPE, and the lowest was selected for its best prediction ability in the six-variable model category. The same process was repeated for every model combination of two, three, four, and five variables, and the best was selected for each category. Table 3.11 shows the best models when contract value (PTC) was not included in the model; similarly, Table 3.12 shows the best models when contract value was added to the model. The addition of contract value was expected to improve the prediction ability of the models. The best models were ranked on the basis of the lowest absolute percentage of error, MAPE. Each model was assigned a number (e.g., for model 4.3, 4 refers to four-variable models and 3 to the model number in this category), and a suffix (P means a model with PTC (contract value) included, e.g., P4.2 is an equivalent to model 4.2 but with PTC added).

Table 3.10: Regression results for the six-variable time prediction model

Regression	**Adj R2**	**MAPE**	**Inter-cept**	**Ln (Miles)**	**Ln (PTC)**	**Ln (ACP)**	**Ln (Grad. Ton)**	**Ln (Grad. Cy)**	**Ln (Grad. Cy)**
Ridge	0.4807	**0.3405**	0.1576	0.0146	0.2058	0.0306	0.0370	0.0316	0.0483
PLS	0.9906	**0.3642**	0.0126	0.0126	0.1647	0.0904	0.0382	0.0389	0.0605
Ridge	0.9540	**0.4016**		0.0649	0.0734	0.0982	0.0834	0.0833	0.0998
GRM	0.9879	**0.3980**		0.0344	0.2586	-0.032	0.0902	-0.006	0.0285
GRM	0.5987	**0.3472**	-3.66	-0.074	0.5522	-0.045	0.0893	-0.041	0.0194

Table 3.11: Best time prediction models without contract value

Model	Reg.	Adj R2	MAPE	Inter-cept	Ln (Miles)	Ln (PTC)	Ln (ACP)	Ln (Grad. Ton)	Ln (Grad. Cy)	Ln (Grad. Cy)
4.3	GRM	0.46399	**0.37709**	2.09200	0.06149		0.06855	0.10264		0.09002
5.1	GRM	0.45602	**0.38111**	2.06996	0.06165		0.07143	0.07527	0.03186	0.08547
3.1	Rdg.	0.43001	**0.38122**	1.92910			0.10522	0.08838		0.09362
4.1	GRM	0.45456	**0.38691**	1.72118			0.12223	0.07597	0.02500	0.08696
2.2	GRM	0.45011	**0.38704**	1.98808			0.13220	0.13893		
3.2	Rdg.	0.42121	**0.38728**	1.85634			0.10951		0.08285	0.09857
2.3	GRM	0.44389	**0.39153**	1.93251			0.12884		0.14727	
3.3	GRM	0.44542	**0.39666**	1.85635			0.13926	0.07386	0.07455	
2.1	GRM	0.41440	**0.40213**	1.88716			0.09476			0.19402
3.11	GRM	0.42645	**0.40345**	1.97274	0.05779		0.07522			0.19540
2.4	GRM	0.13941	**0.49191**	3.05272	0.05967		0.11536			
4.2	Rdg.	0.92545	**0.51837**		0.16850			0.13723	0.14096	0.18246

Table 3.12: Best time prediction models with contract value

Model	Reg.	Adj R2	MAPE	Inter-cept	Ln (Miles)	Ln (PTC)	Ln (ACP)	Ln (Grad. Ton)	Ln (Grad. Cy)	Ln (Grad. Cy)
P5.2	Rdg.	0.49931	**0.30707**	0.39454	0.03301	0.20628		0.03501	0.02802	0.04935
P4.2	Rdg.	0.44748	**0.33015**	0.22879		0.20399	0.04015		0.04309	0.05204
P5.3	Rdg.	0.47518	**0.33897**	0.06827	0.01128	0.21762	0.02922	0.04933		0.06072
P5.1	Rdg.	0.48088	**0.33955**	0.06851		0.21102	0.03394	0.03682	0.03104	0.04903
P6.1	Rdg.	0.48067	**0.34052**	0.15763	0.01464	0.20585	0.03064	0.03704	0.03164	0.04829
P4.1	Rdg.	0.46171	**0.34294**	0.11409		0.21471	0.03246	0.04793		0.05994
P4.3	Rdg.	0.46454	**0.34412**	0.06953		0.22788	0.03526	0.04270	0.04065	
P3.3	Rdg.	0.42825	**0.35089**	0.05581		0.23845	0.03663		0.05988	
P3.2	Rdg.	0.42453	**0.35211**	0.19493		0.23326	0.03597	0.05886		
P4.11	Rdg.	0.41689	**0.35453**	0.18487	0.01506	0.21959	0.03401			0.07248
P3.1	Rdg.	0.41202	**0.36614**	0.04268		0.23185	0.03227			0.07632
P3.4	Rdg.	0.32583	**0.39868**	0.05997	0.00556	0.26806	0.03041			
P2.2	Rdg.	0.30940	**0.40168**	0.25521		0.25400	0.03196			
P2.5	PLS	0.98635	**0.43158**	0.01343	0.00984	0.28804				

3.6.4 Phase III Development

Although the time prediction models in tables 3.11 and 3.12 would be sufficient for prediction, the researchers decided to further investigate avenues for enhancing the prediction ability of the models. Cluster analysis was considered. Cluster analysis allows a number of classification algorithms to organize observed data into meaningful structures. The *k-means* clustering algorithm produces *k* different clusters of greatest distinction by moving cases/projects in and out of groups (clusters) to get the most significant ANOVA results that (1) minimize the variability within the clusters and (2) maximize the variability between the clusters. Tables 3.13 and 3.14 show the results of cluster analysis. The table shows the number of projects in each cluster based on clustering the ACP/HMA quantities of projects. Working with two clusters, GRM, Ridge, and PLS regression analyses were performed, and prediction models were developed for various two-, three-, four-, five-, and six-variable models in each cluster.

Tables 3.15 to 3.18 show the time prediction models for cluster #1 (26k tons to 160k tons) and for cluster #2 (0 to 26k tons). Clustering of ACP/HMA quantities into two clusters slightly improved the MAPE values, but not with a significant difference between the population and the two clusters. Increasing the number clusters, e.g., to three or four, would have added better quality to the prediction; however, the number of projects (observations) necessary would have been problematic for obtaining good results. It is suggested that the two-cluster models be used to check the results of the other models developed in tables 3.11 and 3.12.

Table 3.13: Clustering based on ACP variance

ACP Clusters	Between SS	Within SS	# in C1	# in C2	# in C3	# in C4	# in C5	# in C6
2	1.893448E+11	1.151274E+11	173	789				
3	2.528505E+11	5.162170E+10	43	258	661			
4	2.729557E+11	3.151647E+10	24	124	267	547		
5	2.832719E+11	2.120033E+10	20	61	157	229	495	
6	2.898917E+11	1.458051E+10	14	33	103	162	230	420

Table 3.14: Characteristics of ACP/HMA clusters

ACP Clusters	Min	Max	Mean	SD	#
1	26,226.4	157,293.43	44,342.67	20,375.36	173
2	0	26,001.64	7,812.42	7,448.69	789

Table 3.15: Cluster #1 of 2 - Best time prediction models "without" contract value

Model	Reg.	Adj R2	MAPE	Inter-cept	Ln (Miles)	Ln (PTC)	Ln (ACP)	Ln (Grad. Ton)	Ln (Grad. Cy)	Ln (Grad. Cy)
3.1	Rdg	0.93701	**0.35754**				0.16323	0.13981		0.16192
2.1	Rdg	0.89629	**0.37680**				0.20377			0.23134
4.1	Rdg	0.93311	**0.37765**				0.13227	0.10279	0.10249	0.12746
3.2	Rdg	0.92152	**0.37823**				0.15482		0.14009	0.16033
2.3	Rdg	0.93662	**0.37948**				0.24323		0.20148	
2.2	Rdg	0.89320	**0.37974**				0.21870	0.20883		
3.3	Rdg	0.91719	**0.39112**				0.16984	0.13806	0.13842	
4.3	Rdg	0.94199	**0.39375**		0.29430		0.13745	0.12587		0.14037
5.1	Rdg	0.93874	**0.41505**		0.28178		0.11197	0.09215	0.09307	0.10987
3.11	Rdg	0.91275	**0.42100**		0.42869		0.15976			0.18647
2.4	Rdg	0.87150	**0.48239**		0.67014		0.23649			
4.2	Rdg	0.93430	**0.50054**		0.41021			0.11919	0.11914	0.15143

Table 3.16: Cluster #1 of 2 - Best time prediction models "with" contract value

Model	Reg.	Adj R2	MAPE	Inter-cept	Ln (Miles)	Ln (PTC)	Ln (ACP)	Ln (Grad. Ton)	Ln (Grad. Cy)	Ln (Grad. Cy)
P3.2	Rdg	0.94113	**0.30233**			0.10392	0.14543	0.14541		
P4.1	Rdg	0.95165	**0.32405**			0.08265	0.11555	0.10641		0.12013
P3.3	Rdg	0.94084	**0.33054**			0.10441	0.14566		0.14176	
P3.1	Rdg	0.94180	**0.33119**			0.10001	0.13775			0.16178
P4.3	Rdg	0.95020	**0.33453**			0.08749	0.12350	0.10098	0.10141	
P2.2	Rdg	0.91850	**0.33670**			0.14162	0.19485			
P5.1	Rdg	0.95658	**0.34155**			0.07332	0.10317	0.07922	0.07924	0.09865
P5.2	Rdg	0.95006	**0.40774**		0.26606	0.08515		0.08970	0.09009	0.11086
P5.3	Rdg	0.95370	**0.35643**		0.20184	0.07467	0.10233	0.10052		0.10921
P6.1	Rdg	0.95810	**0.37402**		0.17927	0.06685	0.09228	0.07487	0.07586	0.08973
P4.11	Rdg	0.94611	**0.38380**		0.25812	0.08789	0.11885			0.14366
P3.4	Rdg	0.92935	**0.40672**		0.37585	0.11627	0.15692			
P2.5	Rdg	0.89795	**0.46153**		0.63246	0.17875				

Table 3.17: Cluster #2 of 2 - Best time prediction models “without” contract value

Model	**Reg.**	**Adj R2**	**MAPE**	**Inter-cept**	**Ln (Miles)**	**Ln (PTC)**	**Ln (ACP)**	**Ln (Grad. Ton)**	**Ln (Grad. Cy)**	**Ln (Grad. Cy)**
5.1	Rdg.	0.47248	**0.34230**	2.18549	0.07907		0.07153	0.08476	0.01657	0.06971
4.3	GRM	0.48445	**0.34342**	2.14943	0.07957		0.07328	0.10105		0.07247
3.1	GRM	0.46089	**0.35032**	1.85084			0.11236	0.09519		0.08102
4.1	Rdg.	0.42638	**0.35185**	2.00006			0.10105	0.06771	0.02541	0.07695
4.2	Rdg.	0.42647	**0.35248**	2.72655	0.10363			0.06912	0.02805	0.08018
2.2	GRM	0.41552	**0.36390**	2.07506			0.13195	0.12455		
3.3	GRM	0.41142	**0.36924**	2.03202			0.12856	0.08615	0.04823	
3.2	GRM	0.38178	**0.39630**	1.78965			0.11413		0.09159	0.08959
2.3	GRM	0.35481	**0.39874**	2.10343			0.12533		0.12844	
2.1	GRM	0.37489	**0.40104**	1.90239			0.09044			0.19353
3.11	GRM	0.34276	**0.43286**	2.08449	0.06890		0.07398			0.17943
2.4	GRM	0.08935	**0.50293**	3.21619	0.06569		0.09326			

Table 3.18: Cluster #2 of 2 - Best time prediction models “with” contract value

Model	**Reg.**	**Adj R2**	**MAPE**	**Inter-cept**	**Ln (Miles)**	**Ln (PTC)**	**Ln (ACP)**	**Ln (Grad. Ton)**	**Ln (Grad. Cy)**	**Ln (Grad. Cy)**
P5.2	Rdg	0.44442	**0.31228**	0.61920	0.02945	0.19465		0.03681	0.02645	0.04280
P6.1	Rdg	0.42859	**0.32225**	0.46193	0.01544	0.18574	0.03272	0.03766	0.02604	0.04604
P5.3	Rdg	0.42300	**0.34998**	0.16399	0.02067	0.21438	0.02676	0.04634		0.05957
P3.2	Rdg	0.38932	**0.35209**	0.24315		0.22503	0.04737	0.05213		
P4.1	Rdg	0.37760	**0.36102**	0.27109		0.21381	0.02507	0.04544		0.05298
P4.3	Rdg	0.40053	**0.36187**	0.21235		0.21154	0.05033	0.03756	0.03793	
P3.3	Rdg	0.37704	**0.36907**	0.18835		0.22382	0.04362		0.05937	
P2.5	Rdg	0.28680	**0.37749**	0.48620	0.01454	0.25251				
P4.11	Rdg	0.35780	**0.38065**	0.19329	0.01489	0.22247	0.03066			0.07265
P2.2	Rdg	0.28173	**0.39965**	0.27909		0.24847	0.03219			
P3.1	Rdg	0.34189	**0.40293**	0.20678		0.21735	0.03792			0.07187
P5.1	Rdg	0.36141	**0.41209**	0.00614		0.22338	0.02405	0.04087	0.03014	0.04567
P3.4	Rdg	0.93494	**0.43754**		0.09033	0.14914	0.19538			

3.6.5 Examples for Using Time Prediction Models

Tables 3.11 and 3.12 show the best time prediction models. The following are examples of the application of those models. The first example is contract #5159 in 1995; the work quantities of the project are shown in Table 3.19, and the work was actually accomplished in **115** working days.

For a preliminary prediction, the miles/ACP characteristic table, Table 3.2, produced 83 working days for the miles and ACP/HMA quantity associated with the project. The ACP/PTC (contract value) characteristic table, Table 3.3, produced 111 working days, and the miles/PTC table produced 106 workings days. These compared very well with the actual 115 working days of the project.

By taking the natural logarithms of the project’s miles and quantities and multiplying the logarithmic values by the corresponding model’s coefficient, the results for the different models were obtained as shown in Table 3.20. For each model, the percentage of error (deviation of the predicated value from the original value) is shown next to the model results. The average value for the models with no contract value was 122 working days, and it was 112 days when the contract value was considered. The first had a MAPE of 6.46 percent, and the MAPE of the second was 2.62 percent. The predicted values compared well with the original values.

Table 3.19: Contract #5159 in 1995

year	Contract #	Miles	PTC 05	ACP/HMA	Grad. ton	Grad. cy	Surfacing Ton	WCD
1995	5159	22.26	5007423.24	45801.30	37246.43	18457.41	8281.66	**115**

Table 3.20: Predicted completion time for contract #5159 in 1995

Model #	Predicted WCD	MAPE	Model #	Predicted WCD	MAPE
4.3	**136**	18.07%	P5.2	**118**	2.36%
5.1	**135**	17.25%	P4.2	**110**	4.45%
3.1	**126**	9.22%	P5.3	**127**	10.09%
4.1	**129**	12.49%	P5.1	**124**	8.08%
2.2	**130**	13.22%	P6.1	**127**	10.38%
3.2	**114**	1.01%	P4.1	**124**	7.79%
2.3	**117**	1.70%	P4.3	**123**	6.94%
3.3	**129**	12.26%	P3.3	**112**	2.90%
2.1	**105**	8.65%	P3.2	**121**	5.54%
3.11	**112**	2.25%	P4.11	**103**	10.14%
2.4	**88**	23.59%	P3.1	**105**	8.67%
4.2	**148**	28.80%	P3.4	**94**	18.63%
			P2.2	**92**	20.41%
			P2.5	**89**	22.71%
Average	**122**	6.46%		**112**	2.62%
Std Dev.	16			14	

Another example represents contract # 6708 of 2004. The information for this contract is listed in Table 3.21. The project was completed in **110** working days.

Table 3.21: Contract #6708 in 2004

year	Contract #	Miles	PTC 05	ACP/HMA	Grad. ton	Grad. cy	Surfacing Ton	WCD
2004	6708	15.92	3382380.43	37618.30	91823.00	91823.00	1031.30	**110**

In a preliminary prediction, the miles/ACP characteristic table, Table 3.2, produced an average of **87** working days (minimum 65 to maximum 108) for the project's miles and ACP quantity; with the ACP quantity at the upper end, a value between the average and maximum days would be selected on the basis of interpolation (**around 97** days). The ACP/PTC (contract value) characteristic table, Table 3.3, produced an average of **76** working days (minimum 54 to maximum 106); with interpolation this would be **around 91** working days. The miles/PTC table, Table 3.4, produced an average of **81** workings days (minimum 61 to maximum 106); this would be around **92** days with interpolation. These values compared well with the actual **110** working days of the project.

By taking the natural logarithms of the values and multiplying them by the relevant model coefficient, the predicted time was reviewed, as shown in Table 3.22. The average for the no-contract-value models was **114** working days, and it was **100** working days when contract value was included. The MAPE for the first model was 4.06 percent and for the second 9.41 percent; both represented very good prediction in comparison to the original contract value. Thus, both the characteristics tables (tables 3.2 to 3.4) and the time prediction models could support each other in estimating a reasonable number of days for a project.

Table 3.22: Predicted completion time for contract #6708

Contract: 6708 in 2004					
Model #	**Predicted WCD**	**MAPE**	**Model #**	**Predicted WCD**	**MAPE**
4.3	**119**	8.49%	P5.2	**105**	4.93%
5.1	**123**	11.61%	P4.2	**97**	12.04%
3.1	**110**	0.33%	P5.3	**106**	3.57%
4.1	**117**	6.78%	P5.1	**112**	1.37%
2.2	**144**	30.73%	P6.1	**114**	3.57%
3.2	**104**	5.79%	P4.1	**104**	5.14%
2.3	**144**	31.29%	P4.3	**124**	12.63%
3.3	**151**	37.57%	P3.3	**111**	1.04%
2.1	**69**	37.43%	P3.2	**116**	5.43%
3.11	**72**	34.26%	P4.11	**81**	26.76%
2.4	**84**	23.45%	P3.1	**81**	26.11%
4.2	**136**	23.48%	P3.4	**84**	24.02%
			P2.2	**82**	25.16%
			P2.5	**79**	28.07%
Average	**114**	4.06%		**100**	9.41%
Std Dev.	28			15	

Early in the planning stages of most projects, not all the information will be available, and in such a case the project manager will have to choose the prediction model from those in tables 3.11 and 3.12 that can be used with the available information. For example, a two-variable or three-variable model might be used. Once more data become available, then the other models should be checked, and then an average value can be obtained.

3.7 Summary and Conclusions

Through a literature review, this chapter explained the procedures states use to determine project duration. Next the chapter described the effort to analyze the time performance characteristics of WSDOT projects. Time growth percentage was used to measure performance. Through a statistical analysis of WSDOT historical records, time prediction characteristic tables (tables 3.2 to 3.4) were developed in which the duration of a project can be obtained for combinations of work that include contract value, ACP/HMA quantities, project length (miles), and a combination of of two categories at a time.

To improve the prediction ability of the characteristic tables, prediction models were developed to predict completion time (working days) by using general multiple regression models (GRM), Ridge regression models, and nonlinear partial least-square regression models (PLS). Six variables were used in building the models: ACP/HMA quantity (tons), grading quantity (tons), grading quantity (cy), surfacing quantity (tons), project length (miles), and contract value (paid-to-contractors, PTC). By using the first five variables, the best MAPE attained was 37.7 percent, and when the contract value was added, the best MAPE reached 30.7 percent. The MAPE is the mean absolute percentage error that measures the deviation of the predicted value from the actual value of completion times. Tables 3.11 and 3.12 show the parameters/coefficients of the models.

Tables 3.15 to 3.18 show time prediction models developed for two project groups, one with zero to 26,000 tons of ACP/HMA and the other for 26,000 to 160,000 tons of ACP/HMA. The models of the two groups showed a slight improvement in MAPE over the full sample models.

Given that only six variables were used in developing the time prediction models, the MAPE values attained would be considered reasonable for predicting completion time during the early stages of a project. Better models would be produced by doing the following:

- Increasing the number of variables in the model. However, this should be weighed against the ease of the model’s use and the (im)possibility of having more information available during the early stages of a project.
- Adding historical weather conditions into the model, e.g., through a categorical variable. The complexity with this would relate to the changes in weather during construction

time. An index might be developed to reflect a weighted average weather during construction.

- Developing a lane-mile equivalent and identifying every new project in terms of how many equivalent lane miles it has. A lane-mile equivalent would add more value to the prediction models than the project centerline miles used in this research.
- The prediction models are best developed on the basis of historical data. Completion time, as explained in the analysis, had high variability, which can affect the prediction ability of models. MAPE values are thus the best "average" value obtainable; MAPE can have a range as shown in Figure 3.29 for the model P5.2 (Table 3.12). In the figure, most values for MAPE are between zero and 40 percent, with average being 30.71 percent.

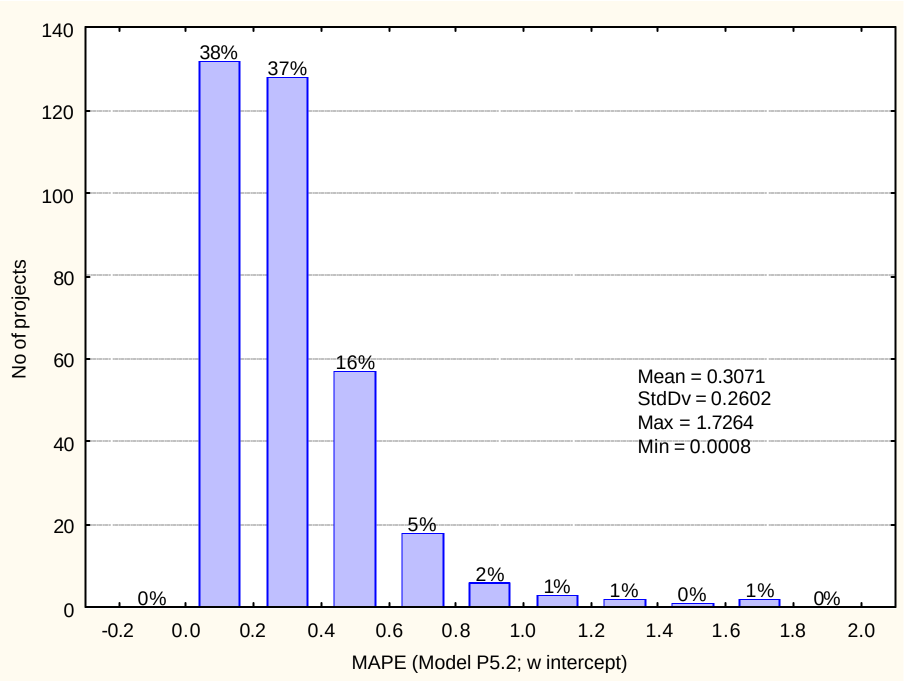


Figure 3.29: MAPE for model P5.2 of Table 3.12

3.8 Recommendations

WSDOT has a number of tools for estimating the duration of a project. The models described in this chapter would be excellent supplements to the existing tools. Time prediction through the characteristic tables should be valuable during the early stages of a project. Time prediction models were also developed to give WSDOT more tools for estimating project time.

It is recommended that

- WSDOT to use the characteristic tables and the prediction models to produce a good estimate of project duration before a fully detailed time estimate has been established

3.9 Implementation

It is suggested the characteristic prediction tables and the prediction models to be part of WSDOT's time and cost estimating efforts, e.g., for use by the Design Office and Construction Office. The developed models in this research were coded in a spreadsheet (Excel file) to facilitate the implementation and use of the prediction models, see Appendix C.

CHAPTER 4
COST PERFORMANCE AND PREDICTION

4.1 Introduction

The aim of predicting costs for a highway project is to forecast the most likely cost of a project before it reaches the bidding stage. Development of a project starts with the planning and programming stage and advances to the preliminary and final design stages, then proceeds to the bidding stage. In each of these stages, project estimates are prepared and updated to reflect the flow of information during the progress of design. A project budget is then prepared for funding purposes.

At contract award, the bid price will most likely deviate from the engineering estimate, which requires the agency to analyze and audit the actual bid prices and the engineering estimates in order to determine where the bid is high or low. Funding decisions that are based on the engineering estimate must be reviewed if more money will be required to accommodate the increased bid price; this may cause the project to differ from the way it was originally listed in order to compete with the other capital projects on the priority funding list.

Following contract award, the bid price becomes the benchmark for cost control purposes. Contractors are required to submit a cash flow schedule or payout schedule that the agency will use to assess project performance by comparing actual costs to the original bid price.

At project completion, the final cost is compared to the original bid price to assess any cost overruns sustained by the project. A comparison is also made with the engineering estimate to assess how far the estimate was off. This helps to improve the estimates of future projects.

Project performance, as explained, is assessed three times: at contract award to compare the bid price with the engineering estimate, during construction to compare the actual cost with the original bid price, and at construction completion to compare the final project cost with the original bid price. It is very common for highway projects to experience cost overruns. While the causes of cost overrun can be numerous, there is always a need to revisit how the estimate was originally established. An estimate is the best prediction that can be obtained at the time of bidding, and therefore, to improve future estimates, the estimating methods need to be reviewed, project conditions affecting the price need to be investigated and recorded, cost indexes need to be developed or improved, and historical project cost records need to be analyzed.

This chapter starts with a literature review on cost estimating methods. It then analyzes the cost performance of WSDOT projects at contract award and contract completion. Next, the methodology/approach and development of cost prediction models are explained. The models were developed by using a holistic approach that considered the total (final) project cost and the associated quantities of work (ACP/HMA, grading, and surfacing), project miles, and project duration in predicting the costs of new projects. This is different than the common method of using historical unit bid item costs.

The model results will support the current tools and methods WSDOT uses for estimating highway projects.

4.2 Current Practices Literature Review

A review of the literature indicated that a number of methods are used for estimating highway projects; the methods generally range between conceptual methods based on historical data and detailed methods based on actual/current data. The estimating methods include parametric methods, unit price methods, regression methods, and probabilistic risk analysis methods.

A comprehensive guidance book for cost estimation and management for highway projects was developed in a research study for the National Cooperative Highway Research Program (NCHRP) of the Transportation Research Board (TRB) (Anderson et. al 2007). The research identified 18 fundamental factors that cause cost escalation (overruns) in projects. Internal factors included, for example, schedule changes, construction complexity, scope changes, poor estimation, and ambiguous contract provisions. External factors included, for example, effects of inflation, market conditions, and unforeseen events. Following a comprehensive investigation into current and effective practices for cost estimation and management, the research provided strategies, methods, and tools for developing, tracking, and documenting more realistic cost estimates for the planning, programming and preliminary design, and final design phases. The research identified conceptual estimating methods for use in the planning phase at the project or regional levels (long-range planning). These methods included parametric techniques in which the cost per parameter could be obtained through past experience with similar projects or typical sections; e.g., cost per centerline mile of a highway. The parameter would then be used with an order-of-magnitude quantity, e.g., number of centerline miles, to obtain an approximate total cost. For the programming (project definition or scoping) and preliminary design phase, a baseline estimate must be established. A number of methods and tools were identified, including historical bid estimates and percentages, and parametric estimation. For the final design phase, the plans, specifications, and estimate (PS&E) are the focus. The recommended tools and methods for estimating included a detailed cost-based method and historical bid-based methods. The historical bid-based method relies on line items with quantities and good historical bid data for determining line-item cost.

Another comprehensive study was done by Schexnayder et al. (2003) on cost estimating for AASHTO and NCHRP. State DOTs were surveyed about the practice of cost estimating. As outlined in the report, for conceptual estimating, 31 DOTs reported using historic lane-mile cost averages or historic square-foot (square-meter) cost averages for bridges/structures. For detailed estimating, three methods were defined, including the use of historical data from recently awarded contracts, detailed estimating based on crews and production rates, and a combination of both. The report stated that most DOTs used the detailed estimating for major items of work, generally items that composed 65 to 80 percent of a project's cost. The report explained that state DOTs might review any bid for rejection or approval if it was above the DOT estimate by 5 to-25 percent, depending on the individual state's laws. The report also explained that most DOT's did not have a set of written estimating procedures to guide those charged with preparing the estimates. With so many variables that can affect the range of projected cost, the research suggested the use of probability assessment for cost estimating.

The availability of historical project records allows regression analysis to be used to develop cost prediction models. Sanders et. al (1992) described the development of a regression analysis model for predicting the cost of bridge widening projects for the Alabama Highway Department (AHD). The model produced estimates within ±20 percent of the low bid. Lowe et al. (2006) used forward and backward stepwise regression analysis models to predict the construction cost of buildings in the U.K.; the data for the models included 286 building construction projects. One of the significant conclusions of the research was that the best models used the log of the cost as the dependent variable instead of the raw cost, with a 0.661 coefficient of determination (R^2) and a 19.3 percent mean square percentage error (MAPE). Nassar et al. (2005) used regression analysis to predict the design cost of transportation projects for the Illinois Department of Transportation (IDOT). Shapanka and Allen (1984) conducted a study for the Virginia Department of Transportation to develop short-term forecasts of monthly cash flows by using regression analysis of historical project records. The study was done to improve budget forecasts for new projects. Similarly, Mills and Tasaico (2005) used regression analysis to predict monthly progress payments for the North Carolina DOT. In another study, Chou et al. (2005) assessed project data from the Texas Department of Transportation. The objective of the work was to improve the accuracy of budget estimates for projects by applying probabilistic estimating (via Monte Carlo simulation), in which project cost, or lane-mile cost, would be represented probabilistically in an average value, range of values, and probability of occurrence.

Along with regression analysis, neural networks have also been used to develop prediction models. For example, Hegazy and Ayed (1998) developed a neural network model to predict a parametric cost estimate of highway projects; the data for the model included information from 18 highway projects.

4.3 Cost Performance Analysis for WSDOT Projects

In the WSDOT, a number of methods have been used to estimate highway projects. One of WSDOT’s guidelines suggests three methods for preparing the engineer’s estimate (WSDOT 2004): (1) actual cost approach—an accurate detailed method that requires knowledge of quantities of work, resources, construction methods and equipment, and production rates, (2) historic data approach—an approximate method that makes use of the unit bid price of previous projects, and (3) combination approach—an approach that uses both of historic bid data and actual cost data. The guidelines recognize that the engineer's estimate should be within ±10 percent of the low bid for 50 percent of the projects in a year. WSDOT utilizes a number of tools and software packages for estimating, including spreadsheet templates, the *Estimating and Bid Analysis System package (EBASE), Planning Level Project Cost Estimation* (PLCE) using parametric techniques, *Transportation Cost Estimator* (TRACER) software, the *Cost Estimate Validation Process (CEVP)* for cost risk analysis, and commercial software such as *BidTabs Pro* (WSDOT 2007a). WSDOT is successfully using probabilistic risk analysis techniques for cost analysis of mega-projects (Molenaar 2005; WSDOT 2005, 2007b)

In a 1998 performance audit by the State of Washington Joint Legislative Audit and Review Committee (JLARC), the JLARC found that state highway construction costs increased beyond initial bid awards by about 10 percent and concluded that WSDOT was comparable to other states (JLARC 2005). The 1998 JLARC audit recommended that WSDOT begin tracking construction change orders that were avoidable (i.e., preventable through appropriate design or construction management) and that added no value (i.e., resulted in inefficiencies as opposed to merely correcting inaccurate bid estimates). At the time, the JLARC determined that of all the change orders, 38 percent were of the "avoidable/no-value added" kind. For its 2005 review, the JLARC analyzed data for fiscal years 2003 and 2004 and found that WSDOT had had construction cost increases between bid and close-out of only 6 percent during the last two years, and that only 29 percent of the change orders were avoidable/no-value added.

This current research was not a performance audit; rather, it investigated cost performance at the project level to determine whether there was a relationship between a change of performance and a change in major project variables such as contract value, ACP/HMA quantities, project miles, and project duration. This was done to understand the variables on which the development of cost prediction models would be based. However, interested readers may check annual performance, as measured by cost growth, estimate growth, award growth, and time growth, in Appendix B. These measures are illustrated in figures B.1 to B.4 for the data in the current research (964 pavement projects, Table 1.1) for the years 1990 to 2004. The measures show that WSDOT projects had a very good average of within 10 percent. However, the range of variation between the minimum and maximum values of the measures was between 25 percent, which means that better monitoring and control of projects are needed to reduce the gap. Time performance needs attention; however, the range of variation is narrowing.

The approaches for measuring project performance included the cost growth percentage, the award growth percentage, and the estimate growth percentage. These measures of WSDOT projects are briefly discussed in the following subsections.

4.3.1 Cost Growth Percentage Measure

The cost growth percentage measures the deviation of the final project cost against the original contract bid amount:

Cost Growth = 100 x (paid-to-contractors – prime bid amount) / prime bid amount

The cost growth percentage graph in Figure 4.1 shows that 96 percent of the projects had cost overruns of less than 30 percent; 91 percent of the projects had cost overruns of less than 20 percent; 78 percent of the projects had cost overruns of less than 10 percent; and 66 percent of the projects had cost overruns of less than 5 percent.

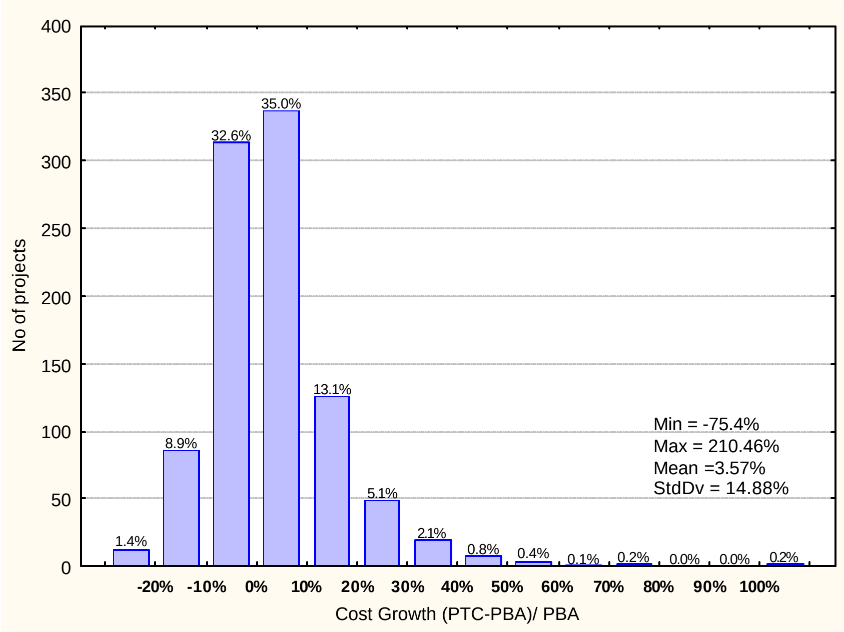


Figure 4.1: Distribution of projects with respect to the cost growth percentage

In examining the brackets (ranges) of the prime bid amount in Figure 4.2, the average cost growth was around 5 percent for all brackets except the last bracket of $10 million and above. While the average was reasonable, the range between the minimum and maximum cost growth for every bracket was quite significant. For example, the $2 million-$2.5 million bracket had a minimum of -15 percent and a maximum of 56 percent cost growth. The number of projects in this bracket was 87. The minimum and maximum figures represent the lowest and highest cost growth attained by projects; these limits could be considered the extreme cases, which, if used, would bias a decision about whether WSDOT projects have significant cost overruns. To obtain more representative cost growth ranges, the 5th and 95th percentiles could be used. In the $2 million-$2.5 million bracket, the 5th percentile was -11 percent and the 95th percentile was 27 percent. Thus, by excluding the lowest 5 percent of the projects (5th percentile) in the cost-growth scale, the lowest cost growth was -11 percent. Similarly, by removing the highest 5 percent of the projects (95th percentile), the highest cost growth was 27 percent. As shown in Figure 4.2, the 95th percentile had a consistent average value of 26 percent for all the brackets.

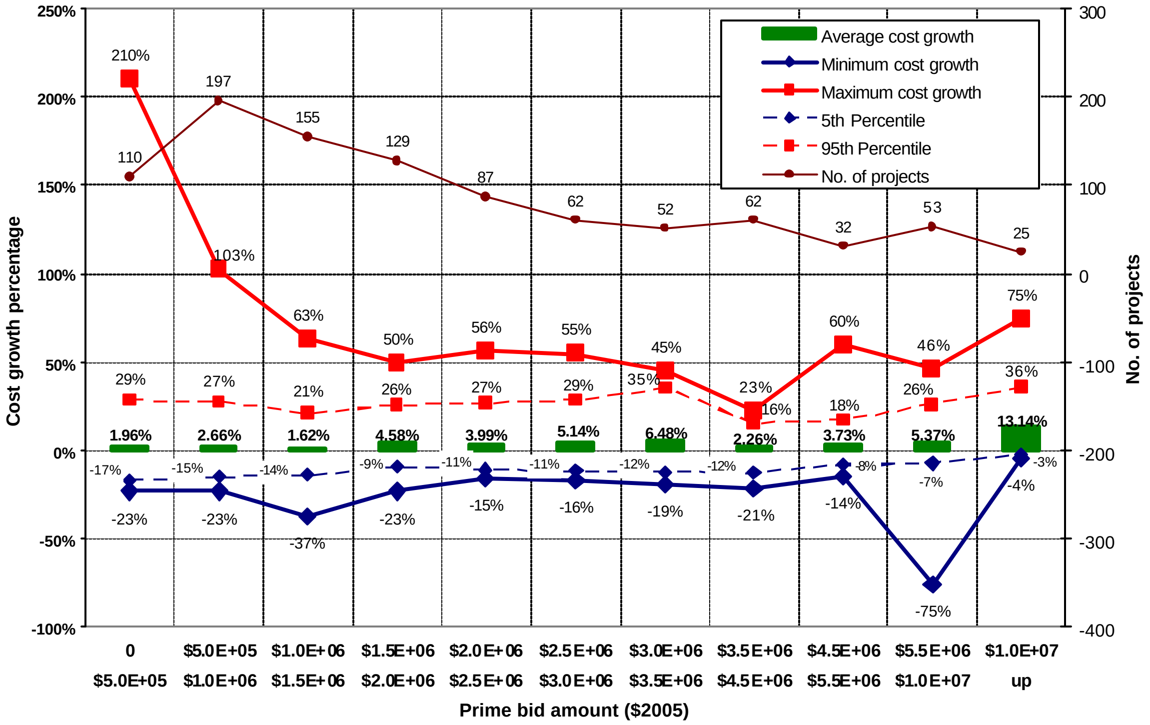


Figure 4.2: Cost growth percentages for specified prime bid amount (in $2005)

In assessing the relationship between the cost growth percentage and the main project parameters, e.g., ACP/HMA, project mile, and workable charged days, further information could be gleaned. For example, Figure 4.3 shows that projects in the range of 15,000 to 25,000 ACP/HMA tons had the highest cost growth percentage – 43 percent and 38 percent, respectively, while the average for the maximum cost overrun graph was at 26 percent (using the 95th percentile). In Figure 4.4, cost overruns tend to decrease with the increase of project miles; the average for the maximum cost overrun graph is 25.7 percent. In Figure 4.5, the average cost overrun tends to increase with an increase in workable charged days; the average for the maximum cost overrun is 25.9 percent for the different brackets of the workable charged days.

In conclusion, figures 4.2 to 4.5 represent tools that could be used by project managers at the planning stage. For example, for a given expected bid amount the likely range and average value of cost overrun could be predicted.

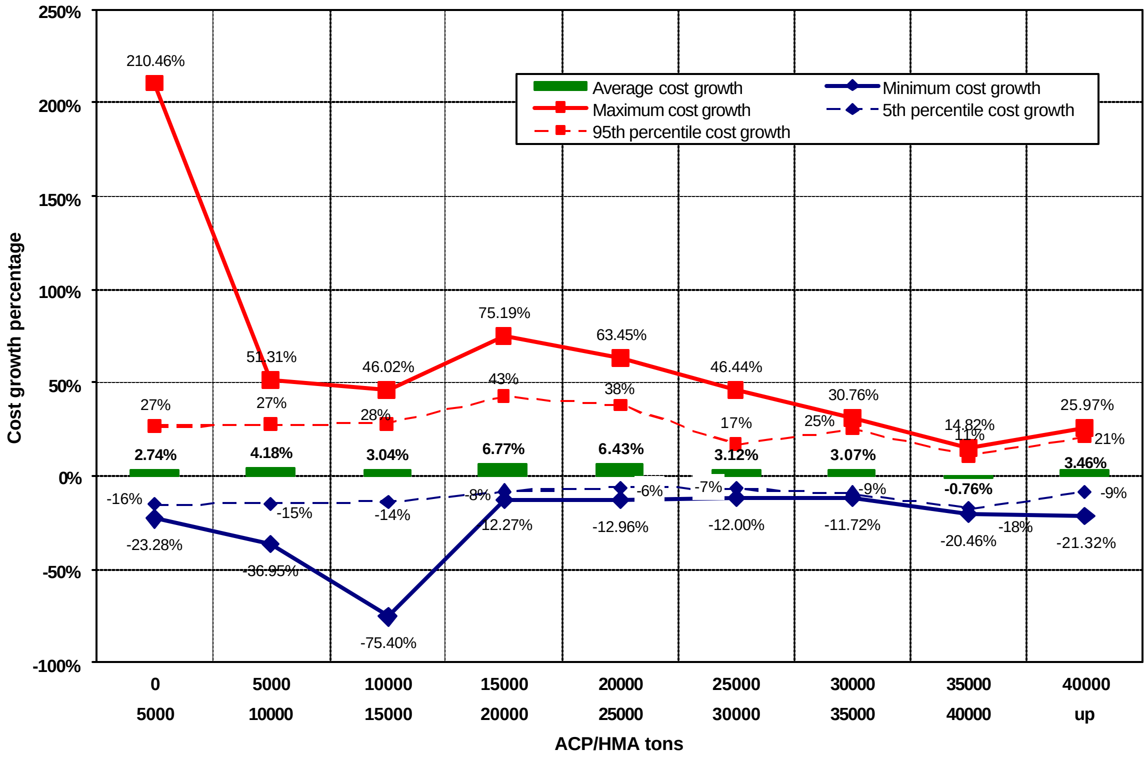


Figure 4.3: Cost growth percentages for specified quantities of ACP/HMA

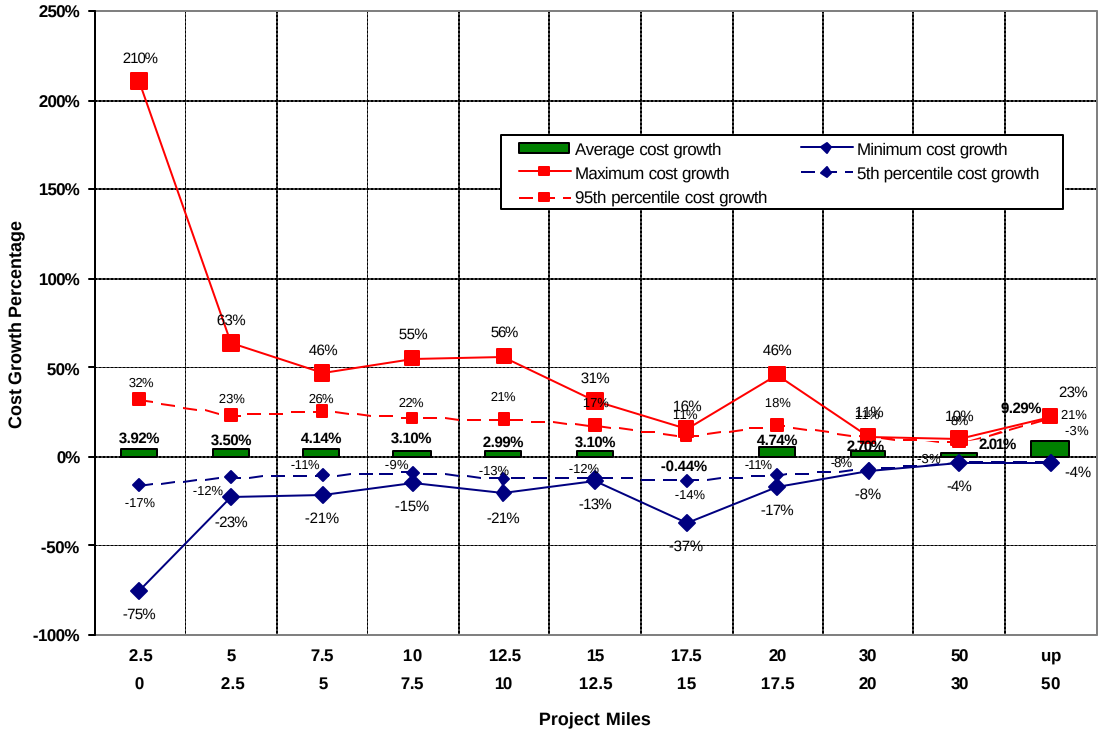


Figure 4.4: Cost growth percentages for specified project miles (in $2005)

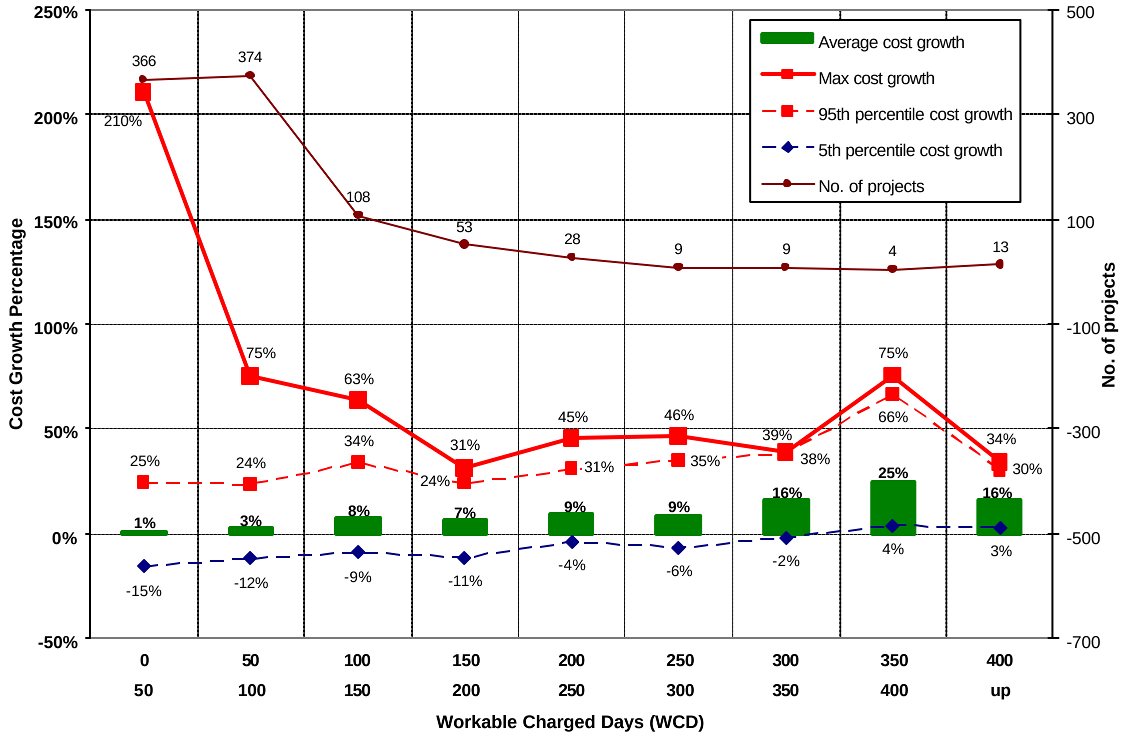


Figure 4.5: Cost growth percentages for specified workable charged days

4.3.2 Award Growth Percentage Measure

The award growth percentage measures the increase/decrease of the contract value against the engineering estimate for the project:

Award Growth = 100 x (prime bid amount – eng. estimate) / eng. estimate

Figure 4.6 shows that the majority of prime bid amounts had a range of variation of ± 40 percent in comparison to engineering estimates. A total of 72 percent of the projects had negative award growth percentages, mainly between 0 percent and -30 percent; i.e., the bid amounts were less than the engineering estimate. On the other side, around 20 percent of the projects had a 10 percent award growth; 6 percent of the projects had an award growth of between 10 percent and 20 percent; and only 2.5 percent of the projects had an award growth of between 20 percent and 100 percent.

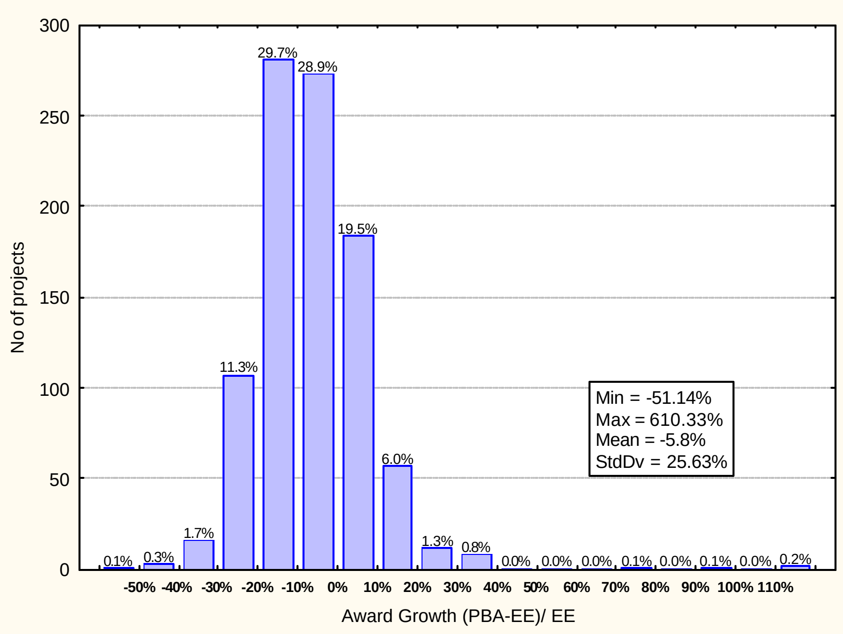


Figure 4.6: Distribution of projects with respect to award growth percentage

To explain the change of award growth with contract values, Figure 4.7 shows that the award growth had an average of -6 percent over the different prime bid brackets, with a range of variation of -25 percent to 13 percent, which represents the average 5th and 95th percentiles, respectively. A similar range of variation for award growth can also be discerned for the other project variables. For example, Figure 4.8 shows that for the different ACP/HMA brackets, the award growth had a range of variation of between -24.8 percent and 13.6 percent. Project miles, as shown in Figure 4.9, did not show a change in the range of variation with award growth; the range was -24.9 percent to 13.5 percent. The results were nearly the same for the change of award growth over different brackets of workable charged days; the range was -24.8 percent to 13.8 percent, as shown in Figure 4.10.

In conclusion, figures 4.7 to 4.10 can be used as tools to predict the likely range of variation in the prime bid amount in relation to engineering estimates.

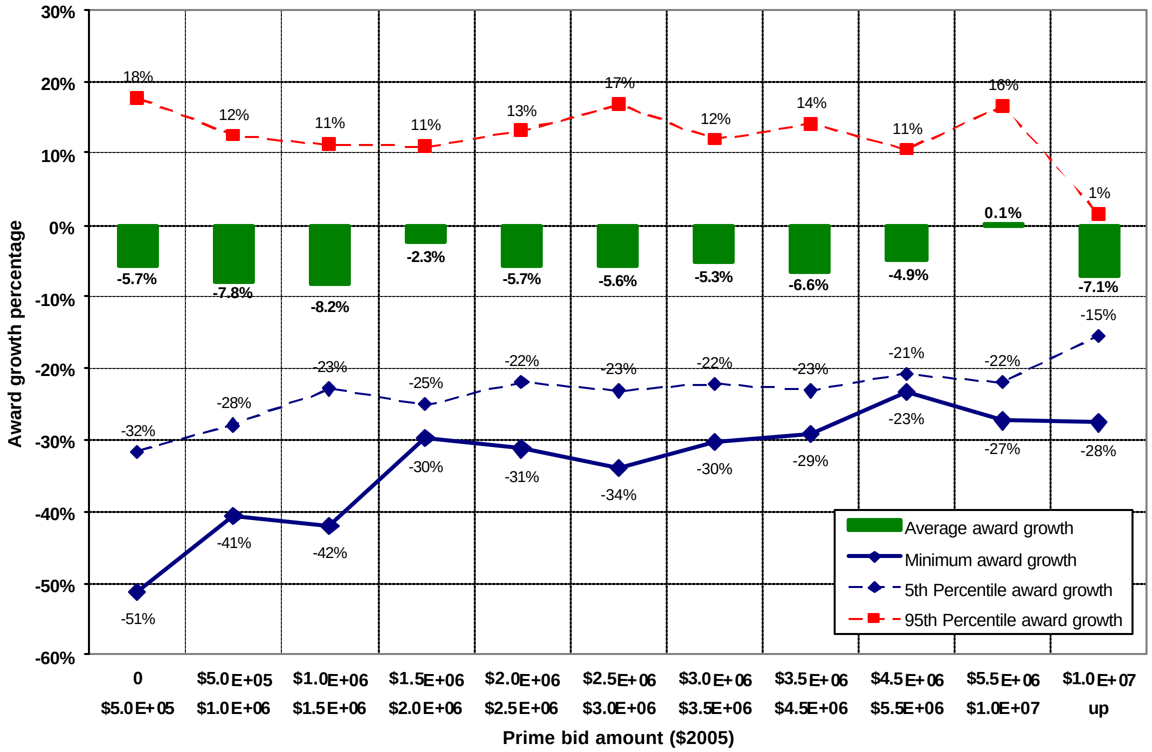


Figure 4.7: Award growth percentages for specified prime bid amount (in $2005)

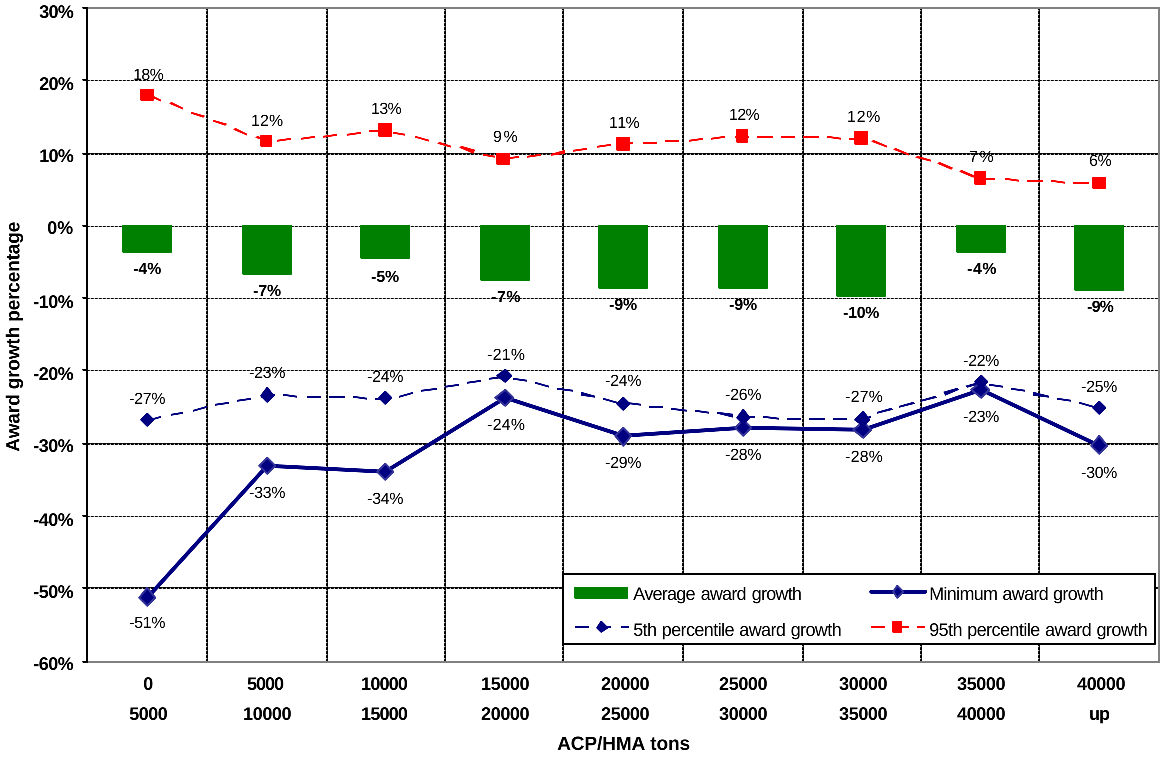


Figure 4.8: Award growth percentages for specified ACP/HMA quantities

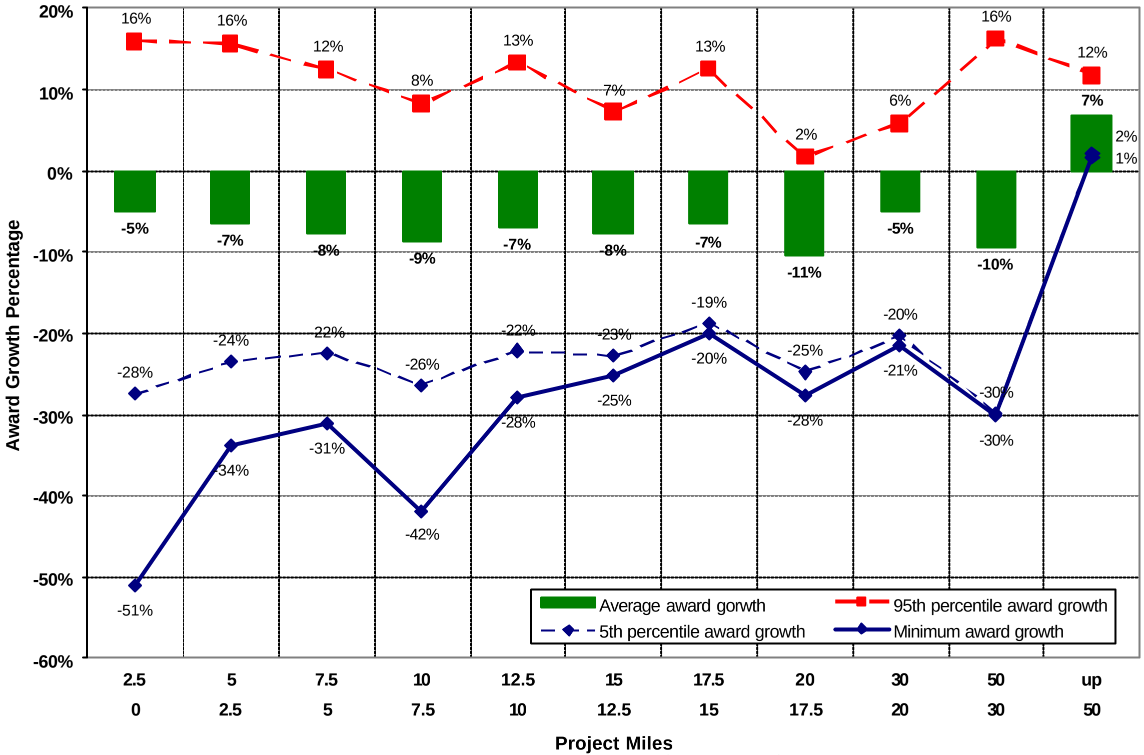


Figure 4.9: Award growth percentages for specified project miles

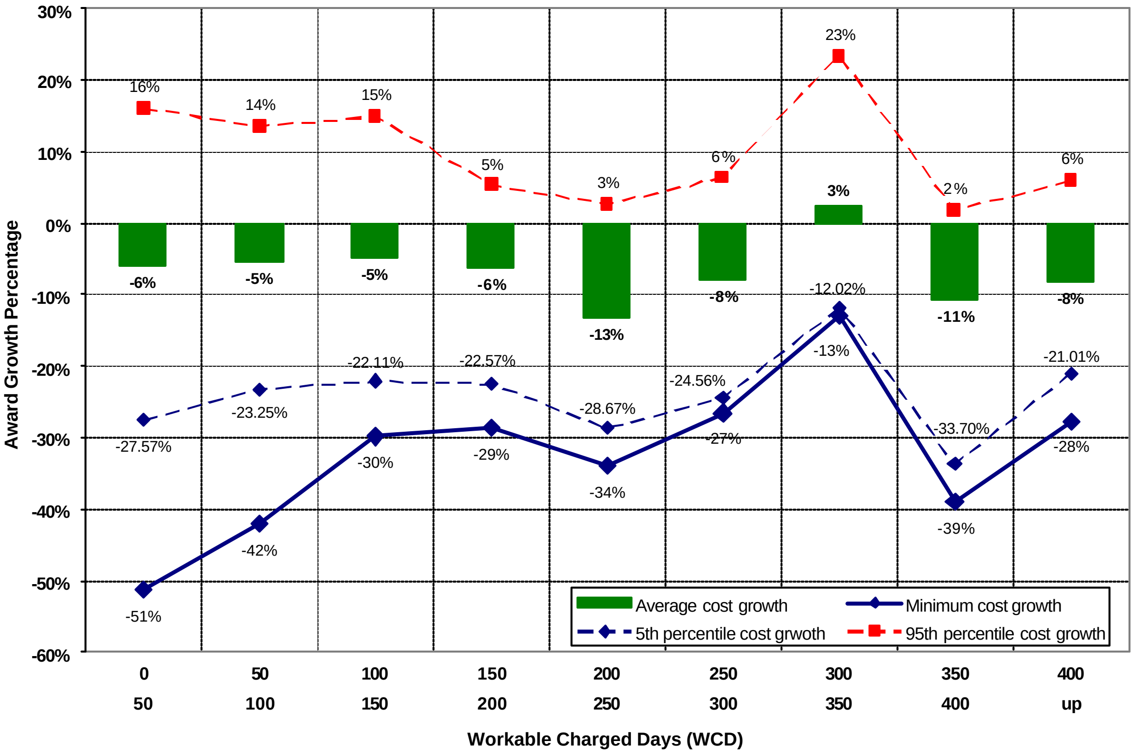


Figure 4.10: Award growth percentages for specified workable charged days

4.3.3 Estimate Growth Percentage Measure

The estimate growth percentage measures the difference between the final project cost and the engineering estimate:

Estimate Growth = 100 x (paid-to-contractor – eng. estimate) / eng. estimate

The estimate growth percentage is another measure of the quality of the engineering estimate. This measure, however, is more rigorous than the award growth percentage measure, as the engineering estimate is compared to the final project cost at completion. Figure 4.11 shows that the majority of the final project costs (paid-to-contractor dollars) had a ± 40 percent range of variation in comparison to the engineering estimates. A total of 64.5 percent of the projects had negative estimate growth percentages, mainly between 0 percent and -40 percent; i.e,. the final project costs were less than the engineering estimate. On the other side, 27.5 percent of the projects had estimate growth of between 0 percent and 20 percent, and 8 percent had estimate growth of between 20 percent and 100 percent.

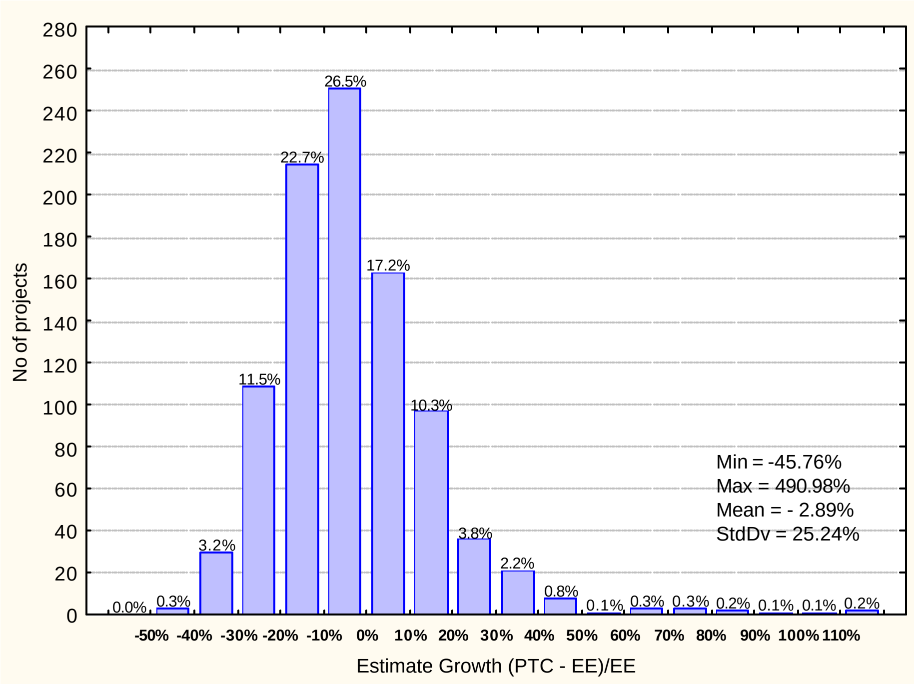


Figure 4.11: Distribution of projects with respect to the estimate growth percentage

Figure 4.12 shows that the estimate growth changes between positive and negative values, with an average of -3 percent over the different prime bid brackets and a range of variation of around ±27 percent (based on the 5^{th} and 95^{th} percentiles). A similar range of variation for estimate growth can be discerned for the other project variables, as shown in Figure 4.13 for ACP/HMA, Figure 4.14 for project miles, and Figure 4.15 for workable charged days.

In conclusion, figures 4.12 to 4.15 can be used as tools to predict the likely range of variation for the final project cost (estimate growth) based on the value of the engineering estimates.

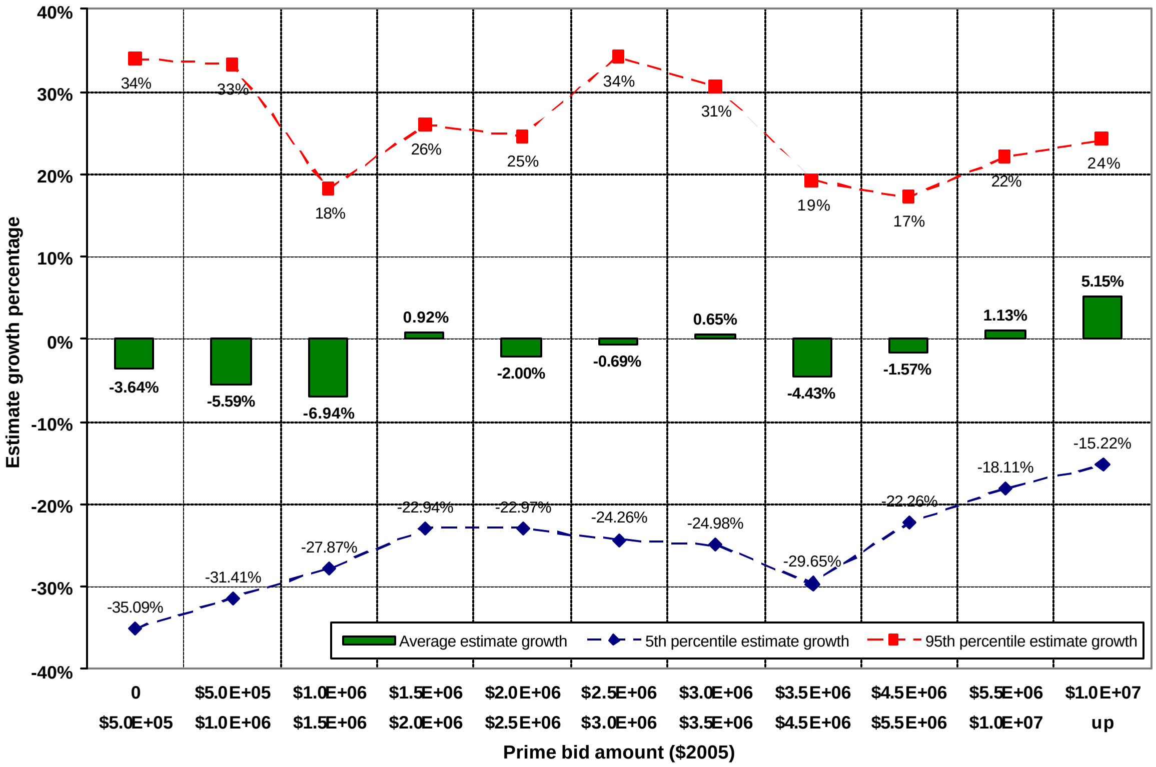


Figure 4.12: Estimate growth percentages for specified prime bid amount (in $2005)

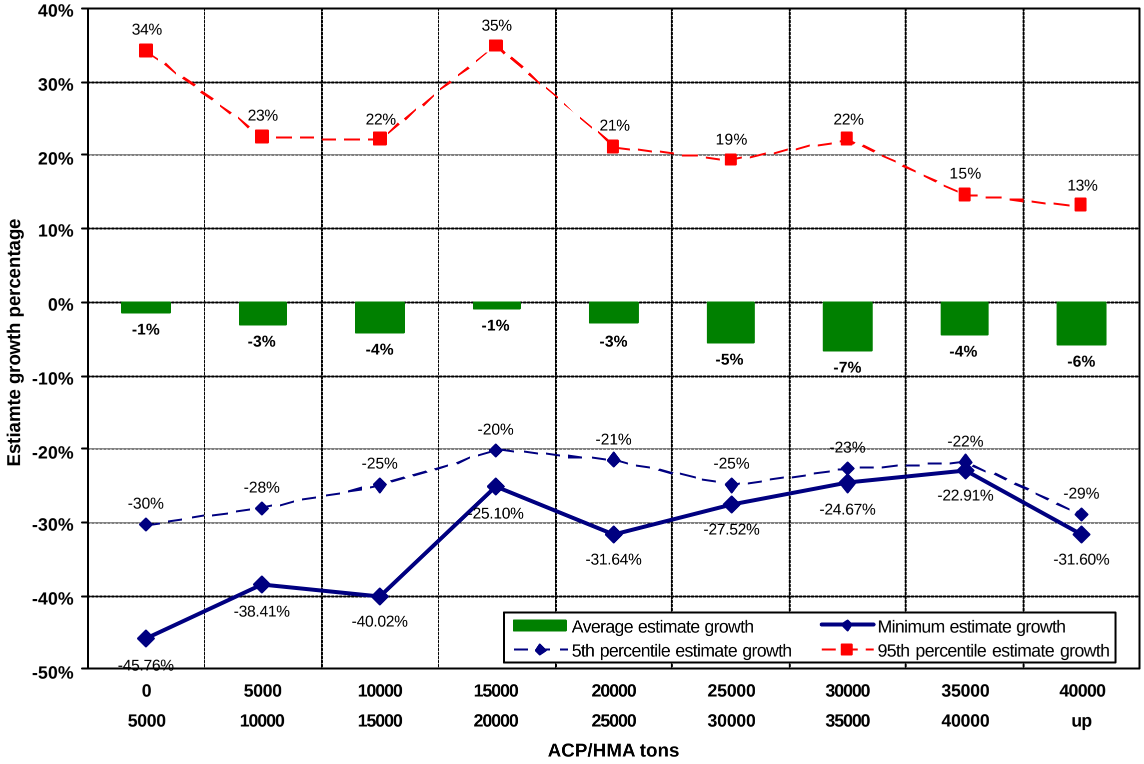


Figure 4.13 Estimate growth percentages for specified ACP/HMA quantities

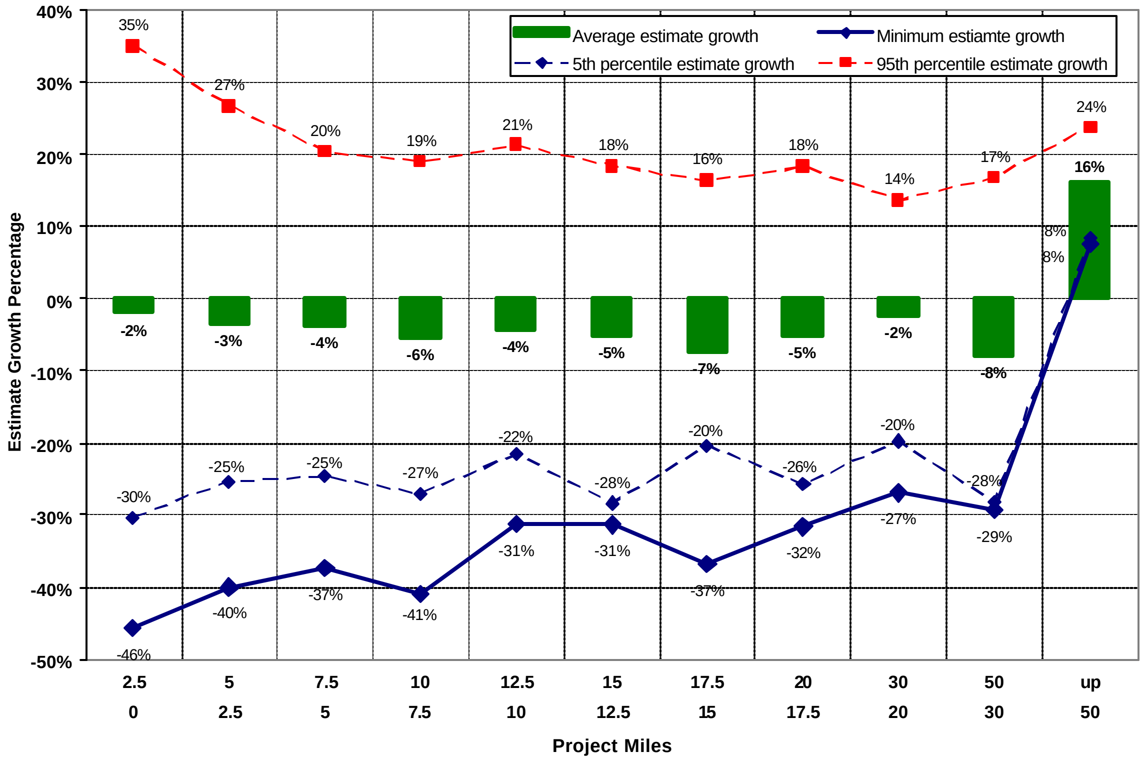


Figure 4.14 Estimate growth percentages for specified project miles

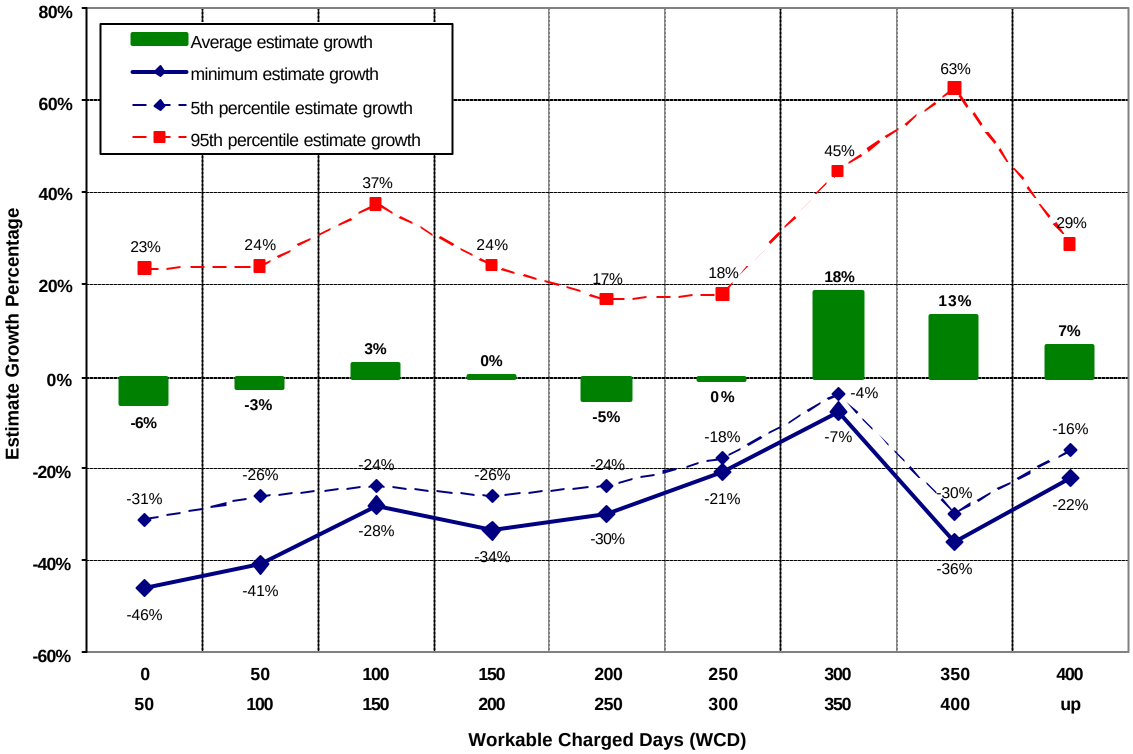


Figure 4.15 Estimate growth percentages for specified workable charged days

4.3.4 Summary of Cost Performance Measures

Table 4.1 summarizes the performance measures. While the average value for the cost growth measure shows very good performance, being within ±5 percent, the 95th percentile values and the high coefficients of variation require further control of project cost (unless extensions to the prime bid amounts were authorized for changes of scope or like reasons). Similarly, while the average value of the engineering estimate is satisfactory, the high coefficient of variation suggests a need for further attention. However, it is difficult to conclude that engineering estimates were underestimated or overestimated; the 5th and 95th percentile values do not firmly support that. Figure 4.16, illustrates the range of variation for each performance measure around the average value.

Table 4.1: Statistics of cost performance measures

Measure	**Average**	**Std. Dev.**	**Coeff. of Variation**	**Min.**	**Max.**	**Av of 5th Percentile**	**Av of 95th Percentile**
Cost Growth	3.57%	14.88%	416.81%	75.4%	210.46%	-12.60%	26.34%
Award Growth	-5.8%	25.63%	-441.90%	-51.14%	610.33%	-24.94%	13.47%
Estimate Growth	-2.89%	25.24%	-873.36%	-45.76%	490.98%	-27.14%	26.47%

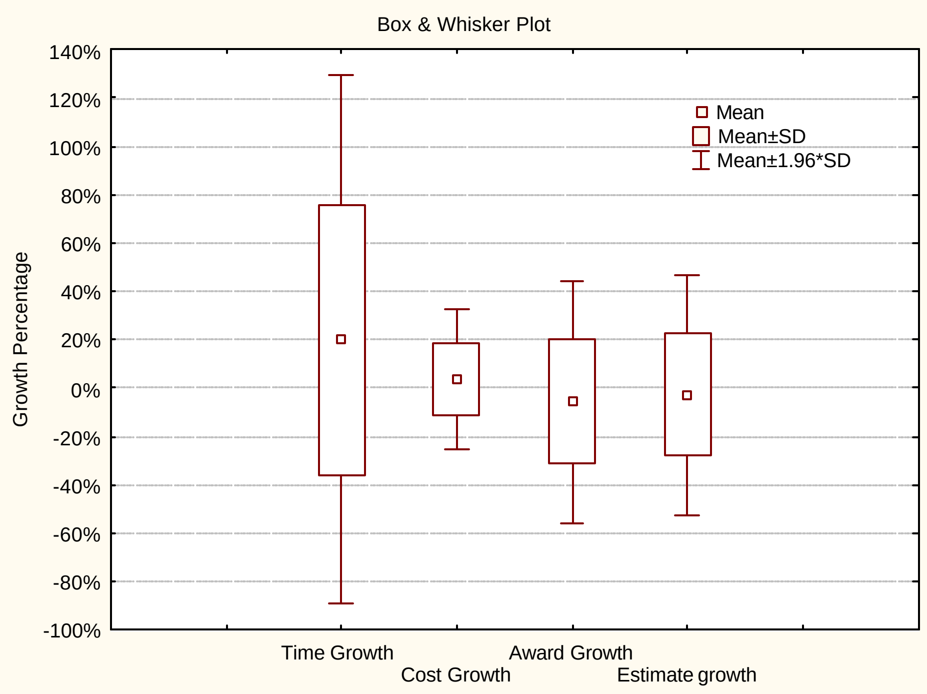


Figure 4.16: Box whisker plot for the performance measures

Figure 4.17 shows a summary of the "average" values of the performance measures plotted in relation to the prime bid amounts of the studied projects. An analysis of this graph suggests that better determination of project duration is generally needed, as well as better time and schedule control during project execution. On the basis of the average values, it could be concluded that contractors generally submit bids that are lower than the engineering estimates. However, by project completion, the final amount paid to contractor ends up higher than the prime bids. This could be interpreted –to mean that contractors submit lower bids to get the work, but finally end up getting more money than originally bid. This is further supported by Figure 4.18, which shows that the cost and estimate growth percentages coincide with an average value of around 26 percent, which is higher than the award estimate growth(average 13.5 percent.

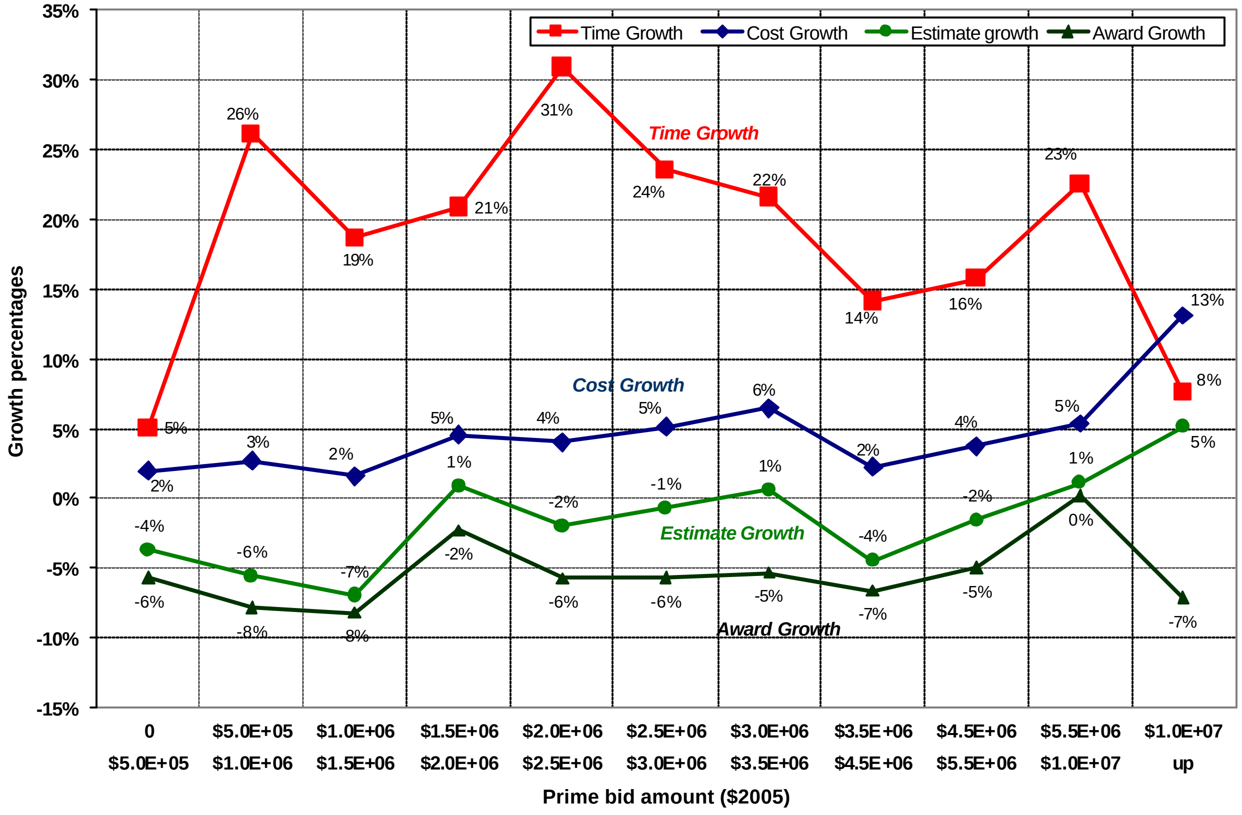


Figure 4.17 Average growth percentages for prime bid amount brackets

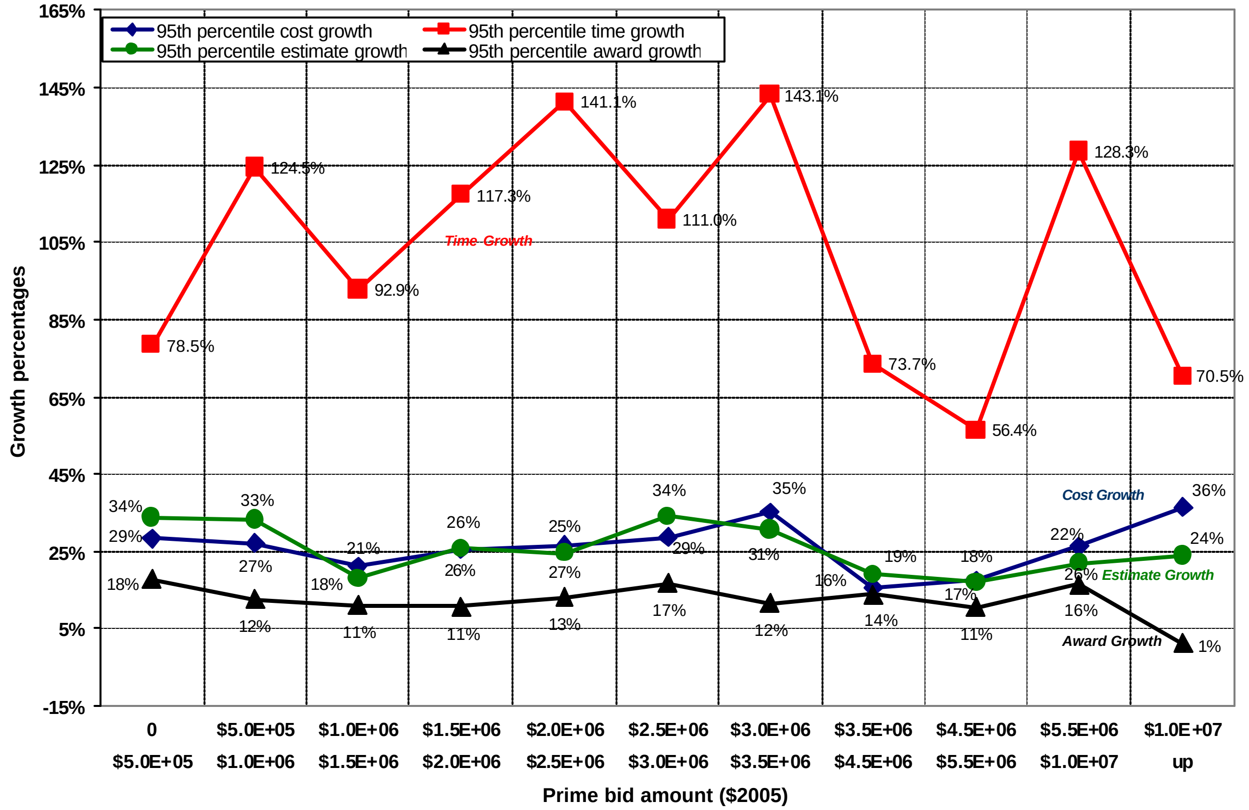


Figure 4.18: The 95th percentiles of cost performance measures for prime bid amount.

4.4 Research Approach for Cost Prediction

As explained in the performance analysis, WSDOT utilizes the unit bid items of recent projects to obtain an average, or a unit price, for use in estimating the costs of projects. This research also used historical data to predict project costs. However, unlike the WSDOT's current practice of using historical unit bid item costs, this research applied a holistic method that used the historical total (final) project costs and associated quantities of work, number of miles of highway, and duration of projects to estimate the costs of new projects. The work quantities utilized in the development of the prediction models were the quantities of asphalt concrete pavement (ACP)/hot mix asphalt (HMA), grading, and surfacing. The quantities of work were collected for each project (964 projects; Table 1.1) by using the WSDOT standard bid items (tables 1.2 –to 1.4). With projects awarded between 1990 and 2004, the total project costs were converted to 2005 dollars by using the WSDOT construction cost index.

The data were then subjected to regression analysis in order to develop prediction formulas for the time and cost of projects; this included the use of (1) ordinary general multiple regression analysis (GRM), (2) "Ridge" regression analysis, and (3) general partial least square regression analysis (PLS). With the WSDOT construction cost index, cost estimates for new projects had to be converted from the 2005 model output to the current year of the estimate.

4.5 Cost Prediction for WSDOT Projects – Characteristic Tables

As discussed in the above analysis of cost performance, WSDOT cost overrun and engineering estimate growth figures had a wide range around the average values. This section provides prediction tables that can supplement WSDOT's current tools for predicting project costs at the early planning stages.

Figures 4.19 to 4.21 illustrate the variation in the minimum, average, and maximum values of some of the major variables in relation to categories of the final project cost (paid-to-contractors dollars). The graphs show that good cost prediction could be achieved on the basis of the historical representation of costs, as explained by the positive increasing trend for the variables. However, note that the variation between the minimum and maximum increases the variance, which would affect the predictability of any model.

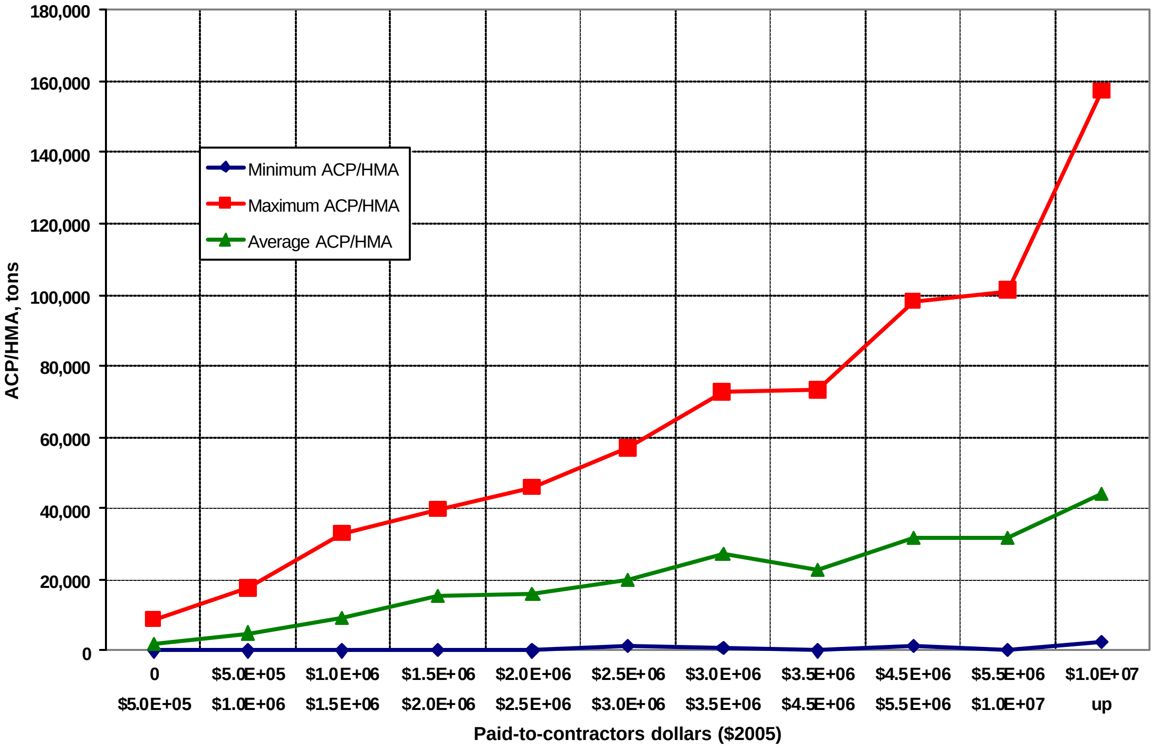


Figure 4.19: Variation of ACP/HMA quantities in relation to project costs ($2005)

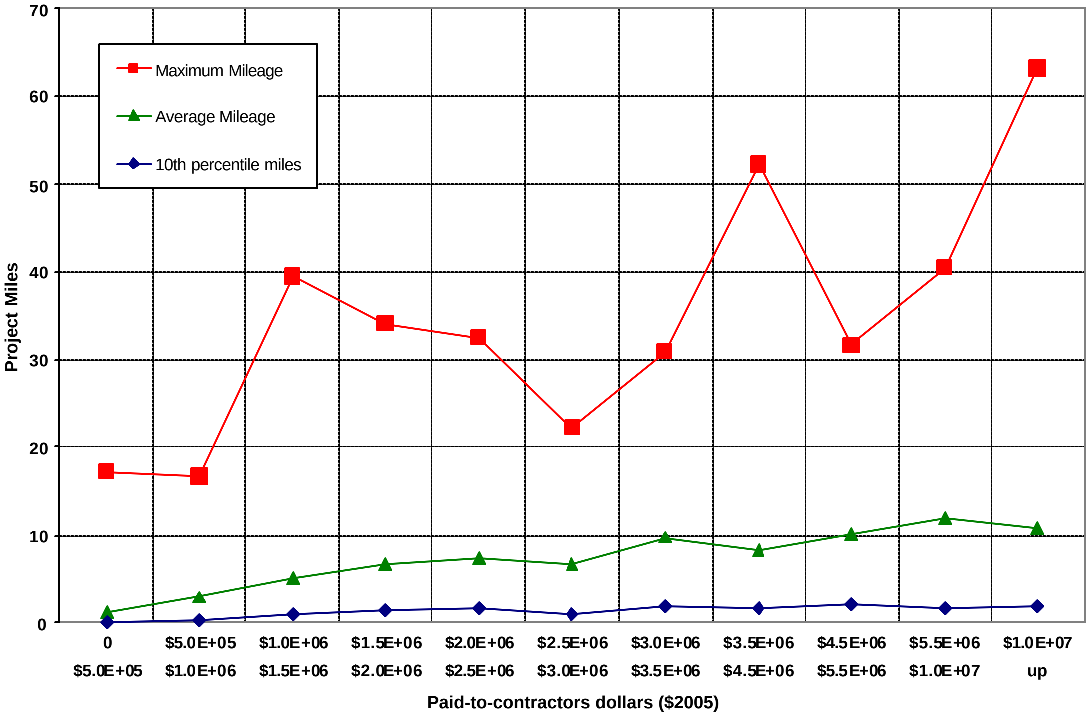


Figure 4.20: Variation of project miles in relation to project costs ($2005)

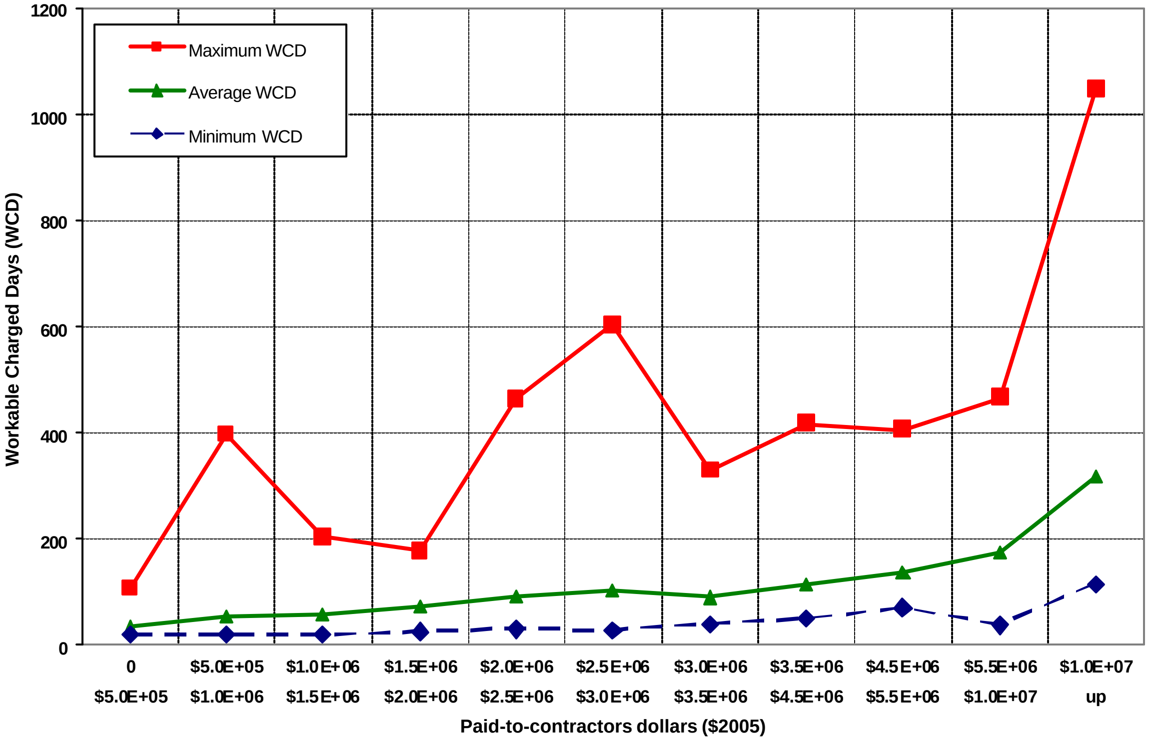


Figure 4.21: Variation of workable days in relation to project costs ($2005)

Figures 4.19 to 4.21 illustrate the relationship between the contract value (paid-to-contrator) and quantities of ACP/HMA, project miles, and the duration of projects. These figures, while useful, explain the relationship in a two-dimensional medium, the chart. With so many variables affecting the cost of a project, a better method would be to explain the contract value in terms of more than one variable. Characteristics tables are three-dimensional matrixes that can give project costs when two variables change at a time. The tables are based on statistical measures of the historical contract values for categorized/classified project variables. The statistical measures include the minimum, the average, the maximum, and the standard deviation. As explained earlier, the minimum and maximum may not be best represented by the absolute zero and 100th percentiles, and the 5th and 95th percentile are better. Table 4.2 lists statistical information for contract values in relation to different categories of project length (miles) and number of working days. The sequential order of the information for each cell in the table is (1) average value, (2) minimum value, (3) maximum value, (4) standard deviation, and (5) the number of projects in the relevant categories. For example, for a project of 6.5 miles and 75 working days, $2.17 million would be the average project cost, $1.037 million and $3.529 million the minimum and maximum values, and $0.782 million the standard deviation; 60 projects were used in obtaining this information for the two categories. Table 4.3 gives the contract values for a combination of ACP/HMA quantity and miles. Table 4.4 gives the contract values for a combination of ACP/HMA and project duration. The contract values are in 2005 dollars, and new projects would have to be adjusted with the WSDOT construction cost index.

Table 4.2: Contract value information for specific project miles and duration categories ($2005) (continued on next page)

Miles	Days	0	50	100	150	200	250	300	350	>400	Cont. Val for Miles
		50	100	150	200	250	300	350	400		
0	**2.5**	623370, 172595, 1457984, 444284, 180	1454248, 391946, 3953080, 1045898, 114	2677315, 500405, 6757230, 1884804, 33	4044195, 887139, 8244334, 3276767, 20	4525702, 865872, 10889160, 3887985, 7	3480321, 1236316, 5764571, 2516190, 3	7970899, 2519808, 18770344, 7558105, 6	15667109, 2314205, 29020013, 20982064, 2	7686545, 7686545, 7686545, N/A , 1	1577728, 228035, 4556590, 2563864, 366
2.5	**5**	1049317, 573273, 1816861, 425151, 76	2040816, 840671, 4287260, 1103868, 73	3287691, 789843, 8133369, 2077750, 29	3616023, 1284957, 9191015, 3730504, 6	7501039, 3836319, 12344830, 3482895, 7	18715550, 18715550, 18715550, N/A, 1	N/A	6958166, 6958166, 6958166, N/A, 1	21201188, 6777769, 31834589, 12657803, 4	2599608, 660609, 7827494, 3844950, 197
5	**7.5**	1281889, 556148, 2136003, 667609, 52	2171162, 1037819, 3529475, 782139, 60	2889641, 1096955, 6500585, 2269303, 14	6585568, 2566543, 10418582, 3377939, 5	12064694, 2340977, 27643882, 15814026, 3	7558127, 3616396, 12193257, 4841530, 3	9625847, 9625847, 9625847, N/A, 1	20097434, 20097434, 20097434, N/A, 1	29734472, 3185237, 55297718, 27836431, 4	3354493, 686521, 9625448, 6912662, 143
7.5	**10**	1755768, 777568, 3127255, 715272, 28	2375318, 1196865, 4369245, 1168433, 49	3964012, 1694736, 8318242, 2827720, 7	5848307, 1806500, 9406950, 3117106, 6	5091600, 4553765, 5861527, 781218, 3	10372497, 10372497, 10372497, N/A, 1	17557065, 9436873, 25677257, 12759651, 2	N/A	3510577, 2719573, 4301580, 1242942, 2	3052177, 1100472, 8099955, 3142592, 98
10	**12.5**	1895500, 676975, 3689266, 1152724, 11	3074013, 845208, 5157314, 1512620, 21	5175478, 3925614, 8187890, 1698978, 10	3738146, 1726973, 7315757, 2525849, 6	8019119, 3732401, 11396208, 3710819, 4	N/A	N/A	N/A	49787911, 49787911, 49787911, N/A , 1	4555713, 806885, 9232683, 6770935, 53
12.5	**15**	1870244, 1158503, 2648359, 831761, 3	2604970, 1023129, 4359859, 1024388, 21	5893159, 4394903, 7379003, 1657905, 2	1995216, 991094, 2999338, 1577825, 2	6397329, 6397329, 6397329, N/A, 1	N/A	N/A	N/A	N/A	2957841, 942893, 6202754, 1635315, 29
15	**17.5**	1590339, 497424, 2534595, 957969, 5	3031058, 1731838, 4733824, 1135083, 10	3970170, 1818247, 6327734, 2139674, 4	8583949, 8583949, 8583949, N/A, 1	N/A	N/A	N/A	N/A	N/A	3136345, 694037, 6786492, 1967099, 20
17.5	**20**	1231453, 1231453, 1231453, N/A, 1	3212135, 1416232, 5131491, 1413486, 8	5630844, 5122478, 6240453, 633601, 3	5420014, 4783410, 6056618, 1000326, 2	10290945, 9280677, 11371061, 1164535, 3	10820065, 10820065, 10820065, N/A, 1	N/A	N/A	25826872, 25826872, 25826872, N/A, 1	6430572, 1359073, 12934633, 5639896, 19

(Sequential values in each cell: average, minimum, maximum, standard deviation, and number of projects)

Table 4.2: Contract value information for specific project miles and duration categories ($2005) (continued)

Days **Miles**		**0**	**50**	**100**	**150**	**200**	**250**	**300**	**350**		**Cont. Val for Miles**
		50	**100**	**150**	**200**	**250**	**300**	**350**	**400**	**>400**	
20	**30**	2627345, 1293112, 5208742, 1884282, 5	3468192, 1783225, 5879706, 1444235, 13	3168605, 2206568, 4736929, 1593355, 3	14008419, 14008419, 14008419, N/A, 1	N/A	N/A	N/A	N/A	N/A	3612053, 1433871, 6118382, 2722721, 22
30	**50**	3846979, 1327041, 6834672, 2439807, 5	3143129, 1280255, 5991862, 2145707, 4	4682717, 2181493, 6535739, 2548489, 3	8341682, 5987440, 11339362, 3078010, 3	N/A	N/A	N/A	N/A	N/A	4861482, 1590938, 8728111, 2883059, 15
>50		N/A	4274996, 4274996, 4274996, 4274996, 1	N/A	15663213, 15663213, 15663213, 15663213, 1	N/A	N/A	N/A	N/A	N/A	9969104, 4844407, 15093802, 8052685, 2
Cont Value for Working days		**1022981, 227846, 2403353, 832263, 366**	**2151291, 601001, 4407703, 1237366, 374**	**3437805, 691189, 7629545, 2181760, 108**	**5157829, 1047724, 12891495, 3777291, 53**	**7325552, 1477798, 13363763, 5786024, 28**	**8113717, 1911418, 16356664, 5586811, 9**	**10285041, 2559687, 23998946, 8564200, 9**	**14597455, 1749692, 28942733, 13305936, 4**	**22620394, 2398755, 53157797, 19830633, 13**	

(Sequential values in each cell: average, minimum, maximum, standard deviation, and number of projects)

Table 4.3: Contract value information for specific project miles and ACP/HMA quantities categories ($2005) (continued on next page)

ACP / **Miles**		**0**	**2.5**	**5**	**7.5**	**10**	**12.5**	**15**	**17.5**	**20**	**30**	**>50**	**Cont Val for ACP**
		2.5	**5**	**7.5**	**10**	**12.5**	**15**	**17.5**	**20**	**30**	**50**		
0	**5.0k**	1004625, 187335, 2672653, 1865071, 231	1826302, 666141, 4531323, 1647683, 50	2083060, 553812, 5203881, 1911533, 33	2901958, 838227, 9283625, 2586429, 27	2857362, 723008, 6943450, 2467720, 12	2284241, 830521, 5071906, 1796400, 7	N/A	3737156, 1685561, 6030948, 2432628, 3	2656655, 1422111, 3593599, 1261316, 3	3506403, 1190886, 6879758, 3420739, 3	15663213, 15663213, 15663213, N/A, 1	1530052, 222202, 5029211, 2167001 370
5.0k	**10k**	1714932, 411431, 4445144, 1833971, 74	1441193, 587247, 3610337, 1059308, 45	2674010, 960127, 7483847, 2407798, 15	4887334, 1023410, 16588446, 7721329, 10	1668061, 830856, 2389197, 877573, 3	2291156, 2291156, 2291156, N/A, 1	2346563, 484316, 5919439, 2934421, 4	1231453, 1231453, 1231453, N/A, 1	4842782, 1589689, 12040883, 4785151, 6	5281789, 5281789, 5281789, N/A, 1	N/A	2081210, 483038, 5806359, 2775044, 160
10k	**15k**	2563825, 880707, 4971890, 1668106, 27	1591562, 742544, 3783560, 1022021, 44	1194552, 705630, 1668314, 326175, 18	3626653, 619948, 7533684, 2952869, 6	3900681, 1373149, 7469596, 2761482, 5	1089956, 1089956, 1089956, N/A, 1	2024142, 2024142, 2024142, N/A, 1	10820065, 10820065, 10820065, N/A, 1	1514753, 1514753, 1514753, N/A, 1	1800690, 1800690, 1800690, N/A, 1	N/A	2088256, 713695, 4912708, 1788828, 105
15k	**20k**	4832655, 1265003, 15487369, 6741141, 20	2489219, 1191767, 5584189, 2208327, 17	1578083, 888784, 3110061, 684898, 21	1998274, 1213495, 3646158, 1036687, 8	5068926, 1962152, 10678402, 4613021, 4	2708447, 1062417, 4354476, 2586485, 2	2465315, 2465315, 2465315, N/A, 1	1373253, 1373253, 1373253, N/A, 1	N/A	N/A	N/A	2940904, 915550, 7546584, 4005028, 74
20k	**25k**	3954113, 2247215, 6309134, 1648862, 7	2885236, 1255579, 5965806, 2374565, 15	2519587, 1183718, 4323108, 1780914, 21	2411198, 1203828, 5128760, 1416937, 12	2186139, 1263789, 3429510, 1058141, 4	4038936, 1977659, 6967988, 2472435, 4	N/A	4712676, 4712676, 4712676, N/A, 1	4168025, 2836941, 5572717, 1522601, 3	2229137, 2229137, 2229137, N/A, 1	N/A	2899253, 1188226, 6610085, 1879102, 68
25k	**30k**	4428008, 2662866, 6703145, 2331595, 3	3350715, 1850911, 6396706, 1798895, 11	2528835, 1417496, 4593541, 1150991, 15	2155981, 1424277, 3480996, 812165, 9	3585538, 1960800, 6499111, 1934643, 7	2026116, 2026116, 2026116, N/A, 1	N/A	25826872, 25826872, 25826872, N/A, 1	2044888, 1625385, 2358676, 427864, 3	N/A	N/A	3331293, 1494643, 7341975, 3582142, 50
30k	**35k**	1880861, 1803059, 1958663, 122254, 2	3360922, 2752666, 3785116, 617133, 3	3359157, 1427038, 7014960, 2479532, 6	2232258, 1463789, 3864899, 773279, 16	3380469, 2583878, 4177060, 1251722, 2	3843711, 3499237, 4188185, 541289, 2	3557910, 1751845, 7512284, 2630397, 6	N/A	N/A	11774570, 11774570, 11774570, N/A, 1	N/A	3086472, 1505708, 8231428, 2145589, 38

(Sequential values in each cell: average, minimum, maximum, standard deviation, and number of projects)

Table 4.3: Contract value information for specific project miles and ACP/HMA quantities categories ($2005) (continued)

ACP	**Miles**	**0**	**2.5**	**5**	**7.5**	**10**	**12.5**	**15**	**17.5**	**20**	**30**	**>50**	**Cont Val for ACP**
		2.5	**5**	**7.5**	**10**	**12.5**	**15**	**17.5**	**20**	**30**	**50**		
35k	**40k**	N/A	6587322, 4378880, 8611683, 2228327, 4	3053865, 1912872, 4581667, 1557981, 3	4713951, 2856719, 7552177, 2877101, 3	3358569, 2840457, 4002327, 663937, 3	2539203, 1943996, 2955843, 437988, 6	2596938, 1890040, 3303836, 1110783, 2	N/A	1973631, 1973631, 1973631, N/A, 1	2145091, 2145091, 2145091, N/A, 1	N/A	3664185, 1851564, 8281937, 2059355, 23
>40k		3937168, 3724098, 4150238, 334807, 2	15879991, 3805237, 31460142, 10995860, 8	17821759, 2661636, 53633335, 19800520, 11	5134976, 3048065, 8974648, 2474369, 7	8592400, 3310167, 25550335, 12523528, 13	3977037, 2921735, 5987967, 1470025,	3718310, 2695289, 4884289, 894007, 6	6091371, 2841441, 10846662, 2943546, 11	4062278, 3146556, 5380547, 1093845, 5	5595962, 3573294, 7047647, 1416372, 7	4274996, 4274996, 4274996, N/A, 1	8573130, 2869093, 30757113, 10827618, 76
Cont Val for Miles		1577728, 228035, 4556590, 2563864, 366	2599608, 660609, 7827494, 3844950, 197	3354493, 686521, 9625448, 6912662, 143	3052177, 1100472, 8099955, 3142592, 98	4555713, 806885, 9232683, 6770935, 53	2957841, 942893, 6202754, 1635315, 29	3136345, 694037, 6786492, 1967099, 20	6430572, 1359073, 12934633, 5639896, 19	3612053, 1433871, 6118382, 2722721, 22	4861482, 1590938, 8728111, 2883059, 15	9969104, 4844407, 15093802, 8052685, 2	

(Sequential values in each cell: average, minimum, maximum, standard deviation, and number of projects)

Table 4.4: Contract value information for specific duration and ACP/HMA quantities categories ($2005) (continued on next page)

Days	**ACP**	**0**	**5,000**	**10,000**	**15,000**	**20,000**	**25,000**	**30,000**	**35,000**	**>40,000**	**Cont Val for Miles**
		5,000	**10,000**	**15,000**	**20,000**	**25,000**	**30,000**	**35,000**	**40,000**		
0	50	692898, 172240, 1718562, 535190, 192	998655, 407662, 2291968, 781045, 64	1065236, 706904, 1612007, 289010, 39	1372505, 892645, 2088704, 378858, 26	2022779, 1168739, 4677450, 1258852, 16	1952565, 1506070, 2465837, 376480, 13	2041053, 1386663, 2820632, 512190, 9	2895548, 1937279, 3958955, 1130660, 3	4201706, 2957402, 6649393, 2025441, 4	1026750, 228035, 2409039, 834244, 366
50	100	1605636, 404771, 3708753, 1186700, 125	1957845, 829472, 4244552, 1152918, 60	1754780, 804661, 3658458, 926591, 35	2228680, 1254799, 4448472, 989847, 31	2516197, 1697939, 3950817, 736026, 30	2774484, 1375637, 4951057, 1414250, 25	2434716, 1617893, 3925506, 825898, 19	2826379, 1865189, 4510890, 904216, 15	3777504, 2577112, 5510951, 971535, 34	2167433, 601390, 4450835, 1254754, 374
100	150	3468543, 488875, 9548782, 2856646, 30	2438247, 635782, 6395285, 1802432, 16	2691401, 920487, 5111591, 1735076, 17	3452654, 2884749, 4373262, 671154, 7	3181063, 1348736, 6188983, 1839681, 10	3019328, 2260401, 3539309, 619749, 5	3387684, 1867300, 4255793, 1044065, 6	5620001, 3525424, 8279603, 2732150, 3	5299924, 3732347, 7652753, 1539995, 14	3437805, 691189, 7629545, 2181760, 108
150	200	5693069, 787924, 15628835, 5374681, 11	3991414, 1346907, 10720608, 3991363, 9	4349677, 1944703, 7215519, 2078394, 7	3057824, 1086900, 5067339, 1773959, 5	4476489, 1331832, 9775083, 3473232, 7	4403359, 3724498, 5399574, 1010033, 3	8082692, 4457960, 11295977, 3276390, 4	8023248, 8023248, 8023248, N/A, 1	7134181, 3790178, 10702738, 2871882, 6	5131848, 1071337, 12668110, 3709380, 53
200	250	3344563, 767565, 8041152, 3432073, 5	9212314, 5391791, 13032837, 6003373, 2	4089917, 3658152, 4502050, 418383, 4	11084781, 10444014, 11725547, 1006868, 2	3902253, 2324287, 5738807, 1923743, 3	5895204, 3351511, 7639717, 2579363, 3	N/A	8310680, 8310680, 8310680, N/A, 1	11716966, 5333090, 24314315, 7977298, 8	7325552, 1477798, 13363763, 5786024, 28
250	300	10372497, 10372497, 10372497, N/A, 1	3568061, 1337638, 6095848, 2289488, 4	10820065, 10820065, 10820065, N/A, 1	6024765, 6024765, 6024765, N/A, 1	N/A	N/A	N/A	N/A	15766942, 13113196, 18420689, 4169960, 2	8113717, 1911418, 16356664, 5586811, 9
300	350	11290728, 3337082, 19244375, 12497950, 2	10768737, 2748033, 24222302, 13693282, 3	8534630, 8534630, 8534630, N/A, 1	14697037, 14697037, 14697037, N/A, 1	7223018, 5060472, 9385564, 3398113, 2	N/A	N/A	N/A	N/A	10285041, 2559687, 23998946, 8564200, 9
350	400	830549, 830549, 830549, N/A, 1	N/A	N/A	30503669, 30503669, 30503669, N/A, 1	N/A	N/A	N/A	N/A	13527800, 7615130, 19440471, 9290866, 2	14597455, 1749692, 28942733, 13305936, 4

(Sequential values in each cell: average, minimum, maximum, standard deviation, and number of projects)

Table 4.4: Contract value information for specific duration and ACP/HMA quantities categories ($2005) (continued)

ACP Days		0	5,000	10,000	15,000	20,000	25,000	30,000	35,000	>40,000	Cont Val for Miles
		5,000	10,000	15,000	20,000	25,000	30,000	35,000	40,000		
>400		5063623, 2855780, 7405155, 2532837, 3	5835609, 2427987, 9243231, 5354561, 2	4389470, 4389470, 4389470, N/A, 1	N/A	N/A	25826872, 25826872, 25826872, 25826872, 1	N/A	N/A	39497782, 20740921, 54822180, 39497782, 6	22620394, 2398755, 53157797, 19830633, 13
Cont Value for ACP/HMA		1530052, 222202, 5029211, 2167001, 370	2081210, 483038, 5806359, 2775044, 160	2088256, 713695, 4912708, 1788828, 105	2940904, 915550, 7546584, 4005028, 74	2899253, 1188226, 6610085, 1879102, 68	3331293, 1494643, 7341975, 3582142, 50	3086472, 1505708, 8231428, 2145589, 38	3664185, 1851564, 8281937, 2059355, 23	8573130, 2869093, 30757113, 10827618, 76	

(Sequential values in each cell: average, minimum, maximum, standard deviation, and number of projects)

4.6 Cost Prediction for WSDOT Projects – Prediction Models

4.6.1 Introduction

The analysis of project cost performance showed that the average values for the performance measures were within a range of 10 percent. While this average was reasonable, the range of variation between the minimum and maximum values was large. Sources of variation and cost overrun are numerous, as explained in the literature. The more that project managers are able to control the sources of cost overrun, the narrower the gap will be between the minimum and maximum values of the performance measures. As with the time prediction models, cost prediction models would have to be used with the understanding that prediction errors would occur because of the several factors that contribute to the determination of the final project cost. The prediction quality of a cost model depends on several factors, including, for example, the number of variables in the model, the quality of the data used to build the model, and the correlation between the model's independent variables and dependent variable. As with the time prediction model, the variables considered in this research included quantities of ACP/HMA (tons), grading (tons), grading (cy), surfacing (tons), project length (centerline miles), and contract value (paid –to contractor, dollars). These variables constituted a significant percentage of the cost of pavement projects.

The following subsections explain the phases of development for the cost prediction models. In phase one, the statistical characteristics of the variables were investigated, and a preliminary regression analysis was conducted. In the subsequent phases, a number of regression analysis techniques were used to develop prediction equations that would attain reasonable *mean absolute percentage error* (MAPE) values. The MAPE was used to check prediction error by comparing predicted cost to actual cost.

4.6.2 Phase I Development

The development of the prediction model included a number of phases. The objective was to develop cost prediction models with reasonable *mean absolute percentage error* (MAPE) values. The models would preferably have no intercept values and no negative parameter values. In phase one, the statistical characteristics of the variables were obtained, and a preliminary regression analysis was conducted. The relationship between the final contract value (PTC) and the independent variables were checked. For example, the scatterplot between the paid-to-contractors dollars (PTC05) and working days (WCD), shown in Figure 4.22, shows the data clumped together at the lower left side of the diagram. This suggested that the relationship was nonlinear and that a log transformation would be a good choice, which was substantiated by the results of the scatterplot for the log of variables, shown in Figure 4.23.

The correlation between PTC05 and WCD in both the non-log and log cases, as shown in the figures, suggested a good correlation between the two variables, which is generally needed for good model design. A similar analysis was done for PTC and the other independent variables, as well as between the dependent variables.

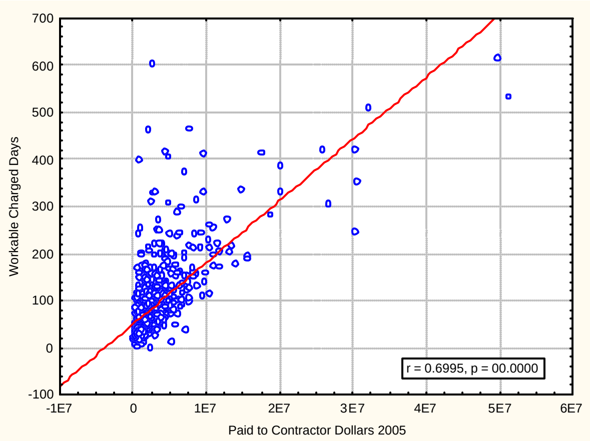


Figure 4.22: Scatterplot of PTC vs. WCD

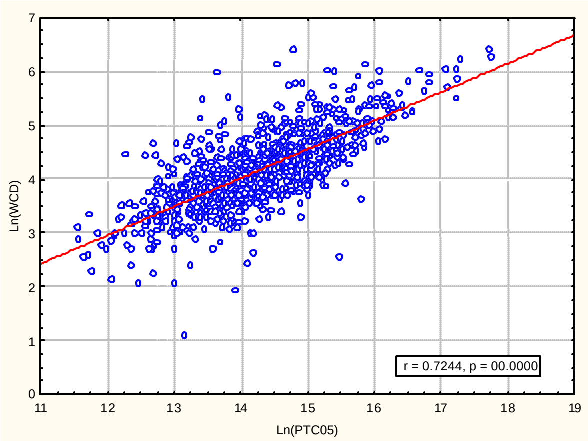


Figure 4.23: Scatterplot of Ln PTC & WCD

A first attempt was made to design the prediction models by using the original variables. However, with six variables, the number of models to be tested was considerable, and therefore the *best subset* regression was used to assist in selecting the most significant models and variables. The best subset regression runs all possible regressions between the dependent variable and all possible subsets of the independent explanatory variables. Subset models are then ranked in terms of the best fit by using the coefficient of determination R^2, adjusted R^2, or *Mallows* C_p statistic. Table 4.5 shows a sample of results for the first ten best subset models. Table 4.6 shows the parameters of the six-variable model. The analysis was performed on a test sample of 80 percent of the projects, while 20 percent was left for a validation sample.

Table 4.5: Best subset models with standardized coefficients

Subset #	**Adj. R^2**	**# of Vars**	**WCD**	**Mileage**	**ACP ton**	**Grading ton**	**Grading cy**	**Surfacing ton**
1	0.73438	5	0.50626		0.23930	-0.31556	0.33924	0.191570
2	0.73427	6	0.50219	0.01784	0.22911	-0.32063	0.34386	0.192664
3	0.72446	4	0.54463		0.27051	-0.26336	0.42462	
4	0.72424	5	0.54214	0.01153	0.26404	-0.26645	0.42791	
5	0.71839	4	0.52982		0.26534		0.08018	0.141038
6	0.71815	5	0.53192	-0.01016	0.27091		0.07993	0.140878
7	0.71806	4	0.52183		0.24068	-0.06964		0.270030
8	0.71779	5	0.52323	-0.00644	0.24435	-0.06902		0.269250
9	0.71640	3	0.52819		0.25430			0.209828
10	0.71617	4	0.53058	-0.01151	0.26065			0.209399

Table 4.6: Parameter estimates

Effect	**parameter**	**Std. Err**	**t**	**p-value**	**Tolerance**	**VIF**
WCD	21188.64	1014.19	20.89208	0.000000	0.478043	2.091861
Mileage	9351.88	12117.84	0.77174	0.440456	0.516883	1.934675
ACP	47.10	5.34	8.81994	0.000000	0.409351	2.442889
Grading ton	-3.69	0.48	-7.68423	0.000000	0.158646	6.303333
Grading cy	7.13	0.92	7.76980	0.000000	0.141030	7.090704
Surfacing ton	40.46	6.64	6.09277	0.000000	0.276240	3.620044

A closer look at tables 4.5 and 4.6 reveal that (1) through the t statistic and p-value, the centerline mileage variable did not add much in explaining the variation of the contract value, and (2) negative coefficient values were experienced, suggesting the contradictory conclusion that an increase in the quantities of these variables would reduce the cost of the project. Therefore, multicolinearity between the variables was suspected. Table 4.5 shows the tolerance of the “Grading (ton)” and “Grading (cy)” approaching zero, and a variance inflation factor of greater than 6. Multicolinearity was also expected because the number of working days in a project should normally be dependent on the quantities of the ACP and grading operations. Multicolinearity affects the stability of the model coefficients; however, Dielman (2005) explained that it does not affect the quality of forecasts or predictions, as long as the pattern of multicolinearity continues for those observations for which forecasts are desired. In the six-variable model the mean absolute percentage error (MAPE) was 70.9 percent.

Figure 4.24 shows the normal probability plot of the six-variable model with a violation of the normality assumption. Also, Figure 4.25 shows a cone-shaped standardized residual plot, suggesting another violation of the constant variance assumption of the regression model. In conclusion, the preliminary model was deemed not appropriate for prediction because of the violations of assumptions and the use of the original variables.

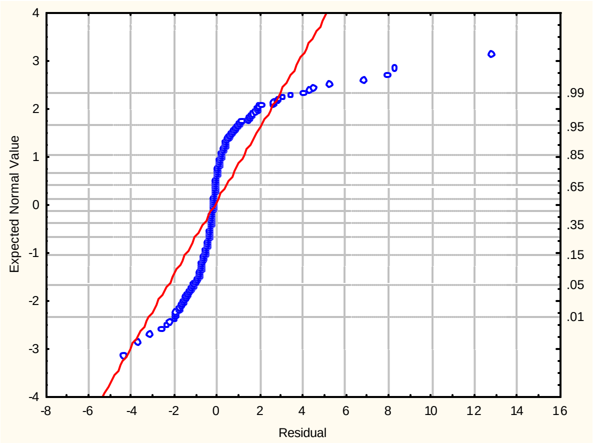


Figure 4.24: Normal probability plot

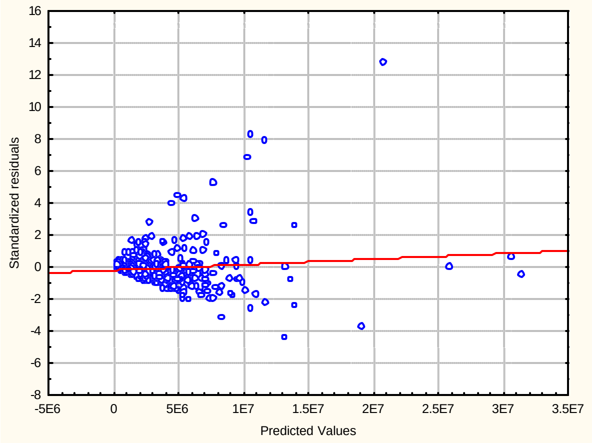


Figure 4.25: Standardized residuals

4.6.3 Phase II Development

In Phase II, both the dependent and explanatory variables were transformed by using the natural logarithm. Table 4.7 shows the first ten best subset models. Note that around 99 percent of the variations of the dependent variable, contract value, were explained by the models, i.e., a better R^2 was obtained than those shown in Table 4.5. While transformation helped meet the normality and linearity assumptions, the negative values of the mileage and grading variables still suggested the existence of multicollinearity. As shown in Table 4.8, correlations between the variables were generally greater than 0.5.

Table 4.7: Best subset models (transformed variables) with standardized coefficients

Subset #	**Adj. R^2**	**# of Vars**	**Ln (WCD)**	**Ln (Mileage)**	**Ln (ACP)**	**Ln (Grading ton)**	**Ln (Grading Cy)**	**Ln(Surfacing Ton)**
1	0.993387	6	0.454197	-0.029436	0.417384	-0.081123	0.074937	0.154458
2	0.993347	5	0.457394	-0.030630	0.414170	-0.028739		0.177593
3	0.993340	4	0.446023	-0.030094	0.418743			0.155753
4	0.993322	5	0.444281	-0.029935	0.419584		0.005458	0.151168
5	0.993070	5	0.486856	-0.028905	0.467181	-0.074158	0.139899	
6	0.993019	4	0.477137	-0.029372	0.468225		0.075002	
7	0.992936	5	0.469871		0.370399	-0.088881	0.099528	0.150559
8	0.992860	3	0.467347		0.367100			0.167074
9	0.992857	4	0.504210	-0.031295	0.476289	0.040467		
10	0.992855	4	0.459281		0.371939		0.023739	0.146876

Table 4.8: Correlations between variables

	Ln (PTC05)	**Ln (WCD)**	**Ln (Mileage)**	**Ln (ACP)**	**Ln (Grading ton)**	**Ln (Grading cy)**	**Ln (Surfacing ton)**
Ln(PTC05)	1.00	0.73	0.59	0.64	0.48	0.50	0.60
Ln(WCD)		1.00	0.30	0.38	0.53	0.51	0.53
Ln(Mileage)			1.00	0.60	0.12	0.10	0.30
Ln(ACP)				1.00	0.24	0.22	0.43
Ln(Grad. ton)					1.00	0.89	0.67
Ln(Grad. cy)						1.00	0.71
Ln(Surf. ton)							1.00

Ridge regression was tried in order to deal with the multicolinearity effects in the regression models (Dielman 2005; Kutner et al. 2005; Sen and Srivastava 1990). Ridge regression uses a procedure to artificially decrease the correlations between the variables so that more stable beta coefficients can be obtained. A constant (lambda) is added to the diagonal of the correlation matrix, which is then re-standardized, and the off-diagonal elements are divided by the constant. The use of Ridge regression in the current cost prediction models proved to be helpful. In a test sample, the analysis was performed on models in which six, five, four, three, and two log variables were used in the design. Validation was performed with the validation sample.

With Ridge regression, none of the variables experienced negative coefficients and the multicollinearity was substantially reduced with acceptable tolerance and VIF values. By using the mean absolute percentage error (MAPE) of the validation sample to test the quality of fit, the best Ridge models were ranked, as shown in Table 4.9. While the MAPE values of the validation and full sample were very acceptable, note that the values were for the transformed log variables. Calculating MAPE after transforming the predicted and observed values of the dependent variable, PTC, allowed the right MAPE to judge the quality of fit of the models. Unfortunately, as shown in column 6 or Table 4.9, the MAPE values did not suggest good prediction quality.

The use of the log transformation in the Ridge regression models reduced the violations of the normality and constant variance assumptions, as shown in figures 4.26 and 4.27 for the six-variable model. However, while the transformation and Ridge regression improved the model design, good predictions were not attained.

Table 4.9: Ridge regression model ranked on the basis of MSD and MAPE

Model	**Variables (Ln)**	**Adj R^2**	**MAPE Ln** (Val. Sample)	**MAPE Ln** (Full sample)	**MAPE Orig.** (Full Sample)	**Adj R^2 Full Sample**
(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**
3.1	WCD, ACP, ST	0.9582	0.0546	**0.08027**	**0.90071**	0.9577
2.1	WCD, ACP	0.9433	0.0592	**0.08270**	**0.72009**	0.9425
4.1	WCD, ACP, GT, ST	0.9643	0.0629	**0.07929**	**1.03843**	0.9648
5.1	WCD, ACP, GT, GC, ST	0.9670	0.0643	**0.08314**	**1.22998**	0.9677
6.1	All including mileage	0.9669	0.0650	**0.08460**	**1.29144**	0.9677
3.2	WCD, ACP, GC	0.9557	0.0657	**0.08366**	**0.93953**	0.9562
1.2	WCD	0.8945	0.0944	**0.13381**	**1.37117**	0.8943
1.1	ACP	0.8898	0.1047	**0.12341**	**0.64304**	0.8879

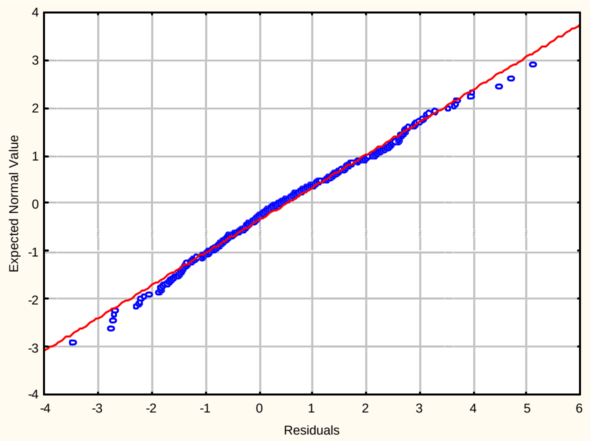


Figure 4.26: Normal probability plot

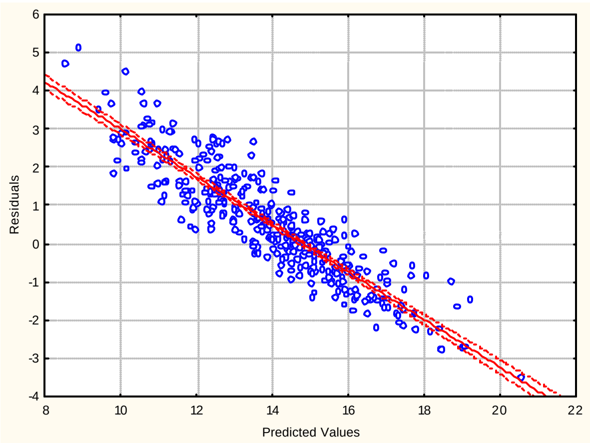


Figure 4.27: Standardized residuals

4.6.4 Phase III Development

In an attempt to improve the prediction quality of the models, some of the required assumptions/conditions, e.g. no intercept or no negative parameters, had to be relaxed. In this phase of model development, *general multiple regression* (GRM), Ridge regression, and *nonlinear partial least-squares regression* (PLS) were performed on the log transformed variables while allowing for an intercept. Tables 4.10 to 4.12 show a significant improvement in the models' prediction through better MAPE values. The parameters were generally positive except for "Grading (ton)," which had negative values in the GRM and Ridge regression models; however, in both models this variable was not significant (p-value 0.44 and 0.22).

Table 4.10: GRM regression for models with intercept values

Model	Adj R2	MAPE Orig.	Inter-cept	Ln WCD	Ln Mileage	Ln ACP	Ln Grad. ton	Ln Grad. cy	Ln Grad. cy
6.1	0.8269	**0.3364**	8.6654	0.7217	0.1901	0.1995	-0.0509	0.0912	0.0329
4.1	0.8087	**0.3456**	7.6303	0.7535		0.3234	-0.0020		0.0719
5.2	0.8022	**0.3552**	9.1046	0.7022	0.2214	0.1280		0.0369	0.0705
5.1	0.7986	**0.3604**	7.6386	0.7471		0.3150	-0.0679	0.0872	0.0613
3.3	0.7730	**0.3683**	9.4597	0.8533	0.2301	0.1131			
3.2	0.7714	**0.3747**	7.9769	0.7698		0.3171	0.0251		
4.2	0.7772	**0.3760**	9.4254	0.7086	0.2374	0.1301		0.0608	
2.2	0.7435	**0.3931**	10.1793	0.9017	0.2897				
3.1	0.7458	**0.4053**	8.4778	0.8057		0.2095			0.0732
2.1	0.7317	**0.4122**	8.5825	0.8836		0.2263			

Table 4.11: Ridge regression for models with intercept values

Model	Adj R2	MAPE Orig.	Inter-cept	Ln WCD	Ln Mileage	Ln ACP	Ln Grad. ton	Ln Grad. cy	Ln Grad. cy
6.1	0.7624	**0.3555**	9.1018	0.5840	0.1809	0.1914	-0.0138	0.0614	0.0542
4.1	0.7272	**0.3882**	8.2542	0.6481		0.2803	0.0105		0.0866
5.1	0.7280	**0.3904**	8.2128	0.6345		0.2753	-0.0222	0.0534	0.0826
3.2	0.7046	**0.4016**	8.5390	0.6820		0.2850	0.0382		
2.2	0.6697	**0.4097**	10.5685	0.8129	0.2713				
3.1	0.7008	**0.4140**	8.7405	0.6579		0.2251			0.0985
2.1	0.6444	**0.4431**	9.2187	0.7722		0.2066			

Table 4.12: PLS regression for models with intercept values

Model	Adj R2	MAPE Orig.	Inter-cept	Ln WCD	Ln Mileage	Ln ACP	Ln Grad. ton	Ln Grad. cy	Ln Grad. cy
6.1	0.8185	**0.3446**	8.9795	0.5163	0.2228	0.2178	0.0151	0.0247	0.0811
4.1	0.7736	**0.3791**	7.7222	0.7040		0.3255	0.0035		0.0775
5.1	0.7486	**0.4060**	7.8908	0.5743		0.3220	0.0040	0.0197	0.1116
5.2	0.7439	**0.4187**	9.2803	0.6602	0.2372	0.1094		0.0407	0.0871
4.2	0.7404	**0.4201**	9.5255	0.6863	0.2507	0.1190		0.0708	
2.1	0.7146	**0.4279**	8.6080	0.8712		0.2281			
2.2	0.7105	**0.4391**	10.1282	0.9158	0.2876				
3.1	0.6909	**0.4576**	8.6399	0.7298		0.2091			0.0947

4.6.5 Phase IV Development

While the models in tables 4.10 to 4.12 would be sufficient for prediction, the researchers decided to investigate further avenues for enhancing the prediction ability of the models. Cluster analysis was considered. Cluster analysis allows a number of classification algorithms to organize observed data into meaningful structures. The *k-means* clustering algorithm produces *k* different clusters of greatest distinction by moving cases/projects in and out of groups (clusters) to get the most significant ANOVA results that (1) minimize the variability within the clusters and (2) maximize the variability between the clusters. Table 4.10 shows the results of cluster analysis. The table shows the number of projects in each cluster. Working with two clusters, GRM, Ridge, and PLS regression analyses were performed, and prediction models were developed for each cluster. Increasing the number clusters, e.g., to three or four, would add better quality to the prediction; however, the number of projects (observations) would be problematic in obtaining good results.

Table 4.13: Clustering based on ACP variance

ACP Clusters	Between SS	Within SS	# in C1	# in C2	# in C3	# in C4	# in C5	# in C6
2	1.893448E+11	1.151274E+11	173	789				
3	2.528505E+11	5.162170E+10	43	258	661			
4	2.729557E+11	3.151647E+10	24	124	267	547		
5	2.832719E+11	2.120033E+10	20	61	157	229	495	
6	2.898917E+11	1.458051E+10	14	33	103	162	230	420

4.6.6 Summary on Project Cost Prediction

The above section discusses the cost models built on the basis of general multiple regression models (GRM), Ridge regression models, and nonlinear partial least-square regression (PLS). Six variables were used in building the models: ACP/HMA quantity (tons), grading quantity (tons), grading quantity (cy), surfacing quantity (tons), project length (miles), and project duration (working days). Tables 4.14 to 4.16 present the best models developed in the analysis. The smaller the MAPE value, the better the prediction. Given that only six variables were used, the MAPE values should be considered reasonable.

Table 4.14: Best regression models with intercept values – full sample

Model	**Adj R2**	**MAPE Orig.**	**Inter-cept**	**Ln WCD**	**Ln Mileage**	**Ln ACP**	**Ln Grad. ton**	**Ln Grad. cy**	**Ln Grad. cy**
6.1	0.8185	**0.3446**	8.9795	0.5163	0.2228	0.2178	0.0151	0.0247	0.0811
5.2	0.8022	**0.3552**	9.1046	0.7022	0.2214	0.1280		0.0369	0.0705
3.3	0.7730	**0.3683**	9.4597	0.8533	0.2301	0.1131			
3.2	0.7714	**0.3747**	7.9769	0.7698		0.3171	0.0251		
4.2	0.7772	**0.3760**	9.4254	0.7086	0.2374	0.1301		0.0608	
4.1	0.7736	**0.3791**	7.7222	0.7040		0.3255	0.0035		0.0775
2.2	0.7435	**0.3931**	10.1793	0.9017	0.2897				
3.1	0.7458	**0.4053**	8.4778	0.8057		0.2095			0.0732
5.1	0.7486	**0.4060**	7.8908	0.5743		0.3220	0.0040	0.0197	0.1116
2.1	0.7317	**0.4122**	8.5825	0.8836		0.2263			

Table 4.15: Best regression models for cluster #1/2

Model	**Adj R2**	**MAPE Orig.**	**Inter-cept**	**Ln WCD**	**Ln Mileage**	**Ln ACP**	**Ln Grad. ton**	**Ln Grad. cy**	**Ln Grad. cy**
5.1	0.7696	**0.2322**	4.9065	0.5616		0.6662	0.0054	0.0282	0.0415
4.1	0.7844	**0.2530**	3.9779	0.6317		0.7457	0.0063		0.0476
6.1	0.7965	**0.2550**	5.8858	0.7564	-0.0092	0.5088	-0.0652	0.0697	0.0557
3.2	0.7642	**0.2567**	5.2735	0.8148		0.5751	0.0152		
3.1	0.7670	**0.2729**	4.5693	0.7120		0.6563			0.0441
2.1	0.7449	**0.2769**	4.7516	0.7869		0.6439			
4.2	0.7701	**0.2955**	5.3822	0.7622	-0.0009	0.5698		0.0368	
5.2	0.7728	**0.3000**	5.4199	0.7353	-0.0203	0.5559		0.0168	0.0517
3.3	0.7625	**0.3046**	5.3923	0.8521	0.0086	0.5590			
2.2	0.6573	**0.3383**	10.4916	0.9715	0.1177				

Table 4.16: Best regression models for cluster #2/2

Model	**Adj R2**	**MAPE Orig.**	**Inter-cept**	**Ln WCD**	**Ln Mileage**	**Ln ACP**	**Ln Grad. ton**	**Ln Grad. cy**	**Ln Grad. cy**
4.1	0.7077	**0.4009**	8.3279	0.7043		0.2359	0.0095		0.0880
2.2	0.6980	**0.4025**	10.3580	0.8500	0.2637				
5.1	0.6931	**0.4043**	8.2871	0.5785		0.2788	0.0088	0.0211	0.0934
6.1	0.7027	**0.4194**	9.5477	0.5909	0.2165	0.1083	0.0126	0.0475	0.0646
3.1	0.6598	**0.4389**	9.0146	0.7620		0.1539			0.0821
2.1	0.6296	**0.4468**	9.2892	0.8418		0.1578			
3.2	0.5588	**0.4934**	9.3793	0.6441		0.1889	0.0510		

4.6.7 Examples for Using Cost Prediction Models

Tables 4.14 to 4.16 show the best cost prediction models. The following examples illustrate applications of the models. The first example is contract #6545 in 2003. The project work quantities are in Table 4.17, and the work was originally accomplished in 104 working days with a contract value of $2,469,162.80 (2003 dollars). The final amount paid –to contractor was $3,178,849.82 ($2003), which equals the value of **$3,858,465.99** in 2005 dollars.

Given the miles and working days in Table 4.17, the expected contract would be **$3.96 million** by using the miles-days "characteristic table", Table 4.2. With the ACP/Miles characteristic table, Table 4.3, the expected value is **$2.23 million** (maximum is $3.86 million). With the days/ACP characteristics table, Table 4.4, the expected value is **$3.38 million.** The characteristic tables could establish a minimum and maximum range for the contract value, as well.

By taking the natural logarithm of the project miles and quantities and multiplying the logarithmic values by the corresponding model coefficients, the results for the different models can be obtained as shown in Table 4.18. For each model, the percentage of error (deviation of the predicated value from the original value) is shown next to the model results. The average value obtained by the models was **$3,316,633.49,** which is within 14 percent of the final amount paid to the contractor ($3,858,465.99 in 2005 dollars). Given that only six variables were used in building the models, the predicted value should be reasonable for planning purposes. The characteristic tables and the prediction models can both supplement WSDOT's methods for predicting project costs.

Table 4.17: Contract #6545 in 2003

year	Contract #	Days	Miles	ACP/HMA Tons	Grad. ton	Grad. cy	Surfacing Ton	PTC05 $
2004	6545	104	8.43	34297.59	384.06	579.64	3306.5	3,858,465.98

Table 4.18: Predicted contract values for contract #6545 in 2003

Model #	Predicted Cont value	MAPE
6.1	**$3,373,481.26**	12.57%
5.2	**$3,208,667.81**	16.84%
3.3	**$3,591,020.36**	6.93%
3.2	**$3,311,845.14**	14.17%
4.2	**$3,164,994.34**	17.97%
4.1	**$3,404,745.39**	11.76%
2.2	**$3,219,587.04**	16.56%
3.1	**$3,272,007.04**	15.20%
5.1	**$3,185,618.30**	17.44%
2.1	**$3,434,368.21**	10.99%
Average	$3,316,633.49	**14.04%**
Std Dev.	**$134,739.85**	

Another example is contract #6708 in 2004. The information for this contract is listed in Table 4.19. The project was completed in 110 working days, and the final amount paid –to –the contractor was 3,382,380.43 (2005 dollars) .

Given the miles and working days in Table 4.19, the expected contract would be **$3.97 million** by using the miles-days characteristic table, Table 4.2. With the ACP/Miles characteristic table, Table 4.3, the expected value is **$3.557 million**. With the days/ACP characteristics table, Table 4.4, the expected value is **$3.38 million.**

Taking the natural logarithms of the values and multiplying them by the relevant model coefficients produced the predicted contract values shown in Table 4.20. The average value obtained by the models was $4,037,560.71, which is within 19 percent of the final amount paid to the contractor. Again, for planning purposes, this would be a good estimate.

Table 4.19: Contract #6708 in 2004

year	Contract #	WCD	Miles	ACP/HMA	Grad. ton	Grad. cy	Surfacing Ton	PTC 05
2004	6708	110	15.92	37618.30	91823.00	91823.00	1031.30	3,382,380.43

Table 4.20: Predicted contract values for contract #6708

Model #	**Predicted Cont Value**	**MAPE**
6.1	**$4,572,146.38**	35.18%
5.2	**$4,316,438.86**	27.62%
3.3	**$4,406,344.72**	30.27%
3.2	**$4,085,948.10**	**20.80%**
4.2	**$5,273,127.93**	55.90%
4.1	**$3,399,518.62**	**0.51%**
2.2	**$4,071,571.25**	20.38%
3.1	**$3,204,820.47**	**5.25%**
5.1	**$3,360,561.01**	**0.65%**
2.1	**$3,685,129.76**	**8.95%**
Average	**$4,037,560.71**	**19.37%**
Std Dev.	**$642,285.08**	

Unlike the first example, the results from the prediction model in the current example were on the high side in comparison to the results of the characteristic tables. However, a closer look at the data tables 4.17 and 4.19 shows that the miles for the second example were almost twice those of the first example. Furthermore, most of the results in Table 4.20 had a high MAPE, including the mileage variables in the model (models 6.1, 5.2, 3.3, 4.2, and 2.2; check the models in Table 4.14]). Whenever there is doubt about the effect of one variable on the final results, the models that do not include this variable could be used for prediction. In that case, these models would be 3.2, 4.1, 3.1, 5.1, and 2.1. As shown in the results of Table 4.17, these models produced the smallest MAPE values, i.e., had better prediction; the average of these five models was **$3.55 million**, a prediction that is in line with the actual value of the contract (**$3,382,380.43**), with an average MAPE value of 7.23 percent

4.7 Conclusions

This chapter reviewed the literature for cost estimating, and reviewed the cost performance of WSDOT projects. A number of characteristic prediction tables were statistically derived in this research to assist in predicting the costs of projects early in a project's life. Furthermore, a number of cost prediction models were also developed by using different types of regression analysis. Both the characteristic tables and the prediction models can be used at the early stages of a project to predict project costs.

The prediction models were developed on the basis of six variables. The variables represent common items in projects, such as quantities of ACP/HMA, length of projects, and duration of a project. The models produced reasonable MAPE values and could be used by the WSDOT Design Office and/or Construction Office.

4.8 Recommendations

WSDOT has a number of tools for estimating the costs of projects. The models discussed in this chapter would be good supplements to WSDOT's existing tools. Cost prediction through the characteristic tables should be valuable during the early stages of a project. Cost prediction models were also developed to add more tools to WSDOT's cost estimating effort. It is recommended that WSDOT use the characteristic tables and the prediction models to establish good estimates of project costs before a fully detailed cost estimate is undertaken.

4.9 Implementation

It is suggested the characteristic prediction tables and the prediction models be part of WSDOT's time and cost estimating efforts, e.g., for the use by the Design Office and the Construction Office. The developed models in this research were coded in a spreadsheet (Excel file) to facilitate the implementation and use of the prediction models, see Appendix C.

ACKNOWLEDGMENTS

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APPENDIX A
Online Survey Questionnaire

Forecasting Contractor's Performance (Progress Curves) in Highway Projects

Background,
The construction office of the Washington State Department of Transportation (WSDOT) is conducting a research toward improving the performance evaluation process of projects and contractors. One of the main sources of information for this research is a survey of State DOTs. The survey aims at soliciting the current practice of highway agencies in measuring the performance of highway projects and in using construction progress charts (or curves) in evaluating the performance of contractors. The scope is limited to design-bid-build or traditional procurement of projects.

Your agency's response will maximize the value of the research results. The survey will take approximately 10 minutes to complete and you will have the opportunity to review and modify your answers prior to the final submission.

Thank you very much.

Sincerely,

Ahmed M. Abdel Aziz
Principal Investigator and Assistant Professor
The University of Washington

Performance Analysis during Construction and at Project Completion

1. During construction, for measuring the progress of work the agency analyzes the following:
   a. Schedule – Comparing the actual project schedule to the original/revised schedules
   b. Cash Flow – Comparing the actual project cash flow to the planned cash requirements
   c. Both (a) and (b)
   d. Quantities – Comparing the actual project quantities to the planned quantities of work
   e. Labor Hours – Comparing the actual labor hours to the planned labor requirements
   f. All of the above (a), (b), (d), and (e)
   g. Other, please specify
   ……………………………………………………………………………..

2. During construction, the agency uses the following tools for measuring the progress of work:
   a. Progress reports
   b. Progress charts (curves)
   c. Both progress reports and progress curves (charts)
   d. Other, please specify
   ……………………………………………………………………………..

3. During construction, the frequency for measuring the progress of work is:
   a. With every progress payment, pay request, or voucher
   b. daily
   c. weekly
   d. Monthly
   e. Quarterly
   f. Semi-annually
   g. Annually
   h. On-demand for special events (e.g. analysis of claims)
   i. Other, please specify
      ……………………………………………………………………………..

4. During construction, an unsatisfactory progress with project schedule, e.g. not meeting intermediate milestones, may trigger the agency to:
   a. Charge performance penalties to the contractor
   b. Increase the retainage percentage of progress payments
   c. Do nothing
   d. Other, please specify
      ……………………………………………………………………………..

5. During construction, an unsatisfactory progress with cash flow, e.g. not meeting planned cash expenditure, may trigger the agency to:
   a. Charge performance penalties to the contractor
   b. Increase the retainage percentage of the progress payment
   c. Do nothing
   d. Other, please specify
      ……………………………………………………………………………..

6. During construction, does the agency uses specific software for recording project progress:
   a. No; paper work is used instead
   b. Yes, please specify if possible
      ……………………………………………………………………………..

7. At project completion, the agency uses the following for measuring the performance of a project (choose all that apply):
   a. Deviation from engineer's estimate (Award Growth), i.e. (Original Contract Amount – Engineers' Estimate) / Engineers' Estimate
   b. Deviation from original contract amount (Cost Growth), i.e. (Final Contract Amount – Original Contract Amount) / Original Contract Amount
   c. Deviation from original contract days (Time Growth), i.e. (Final Contract Days – Original Contract Days) / Original Contract Days
   d. Construction Placement = Final Construction Contract Cost / Final Construction Contract Days
   e. Other, Please Specify
      ……………………………………………………………………………..

8. At project completion, a project would be successful or satisfactory if it was completed:
  a. At the award bid price (or authorized adjustments)
  b. At the required completion date (or authorized working days)
  c. At both the award bid price and completion time
  d. Within a reasonable percentage of the bid price
  e. Within a reasonable percentage of the completion time
  f. Within a reasonable percentage of both the bid price and completion time

9. If a reasonable percentage of bid price is selected for a project to be successful (in previous question), the percentage would be:
  a. Less than 5%
  b. Between 5% - 10%
  c. Between 10% - 20 %
  d. Other, please specify

10. If a reasonable percentage of completion time is selected for a project to be successful (as in previous question), the percentage would be:
  a. Less than 5%
  b. Between 5% - 10%
  c. Between 10% - 20 %
  d. Other, please specify

11. Does the agency have an official document, or part of document that describe the progress evaluation process?
  a. No.
  b. Yes, (Please specify the document title and where it could be located)

Construction Progress Charts (Curves) – Development and Use

A progress chart (curve): a plotting of the percent of project completion against the percent of time.

12. Does the agency use progress charts (or curves) for measuring project progress during construction?
  c. Yes. (Please proceed to the next questions.)
  d. No. (Please proceed to question # 26)

13. Does the agency has a document, or part of document, that describe the progress charts (or curves)?
  a. No.
  b. Yes. (Please specify the document title and where it could be located)

14. As used by the agency, the construction progress chart (curve) reflects:
    a. Progress with project cash flow: the percentage of time elapsed against the percentage of money spent (dollars-paid-to-contractor)
    b. Progress with project time: the percentage of time elapsed against the percentage of time/schedule completion
    c. Progress with project quantities: the percentage of time elapsed against the percentage of quantities put in place
    d. Progress with project labor hours: the percentage of time elapsed against the percentage of labor hours used
    e. Other, please specify
    ………………………………………………………………………………..

15. As used by the agency, the construction progress curve/chart(s) represents:
    a. A curve/chart statistically driven from records of progress on several past projects
    b. A standard cumulative chart in the form of an S-curve
    c. A progress chart (curve) submitted by the contractor after contract award
    d. A specific progress profile, e.g. 0.5% work during the 1st month, 1% during the 2nd month, 5% during the 3rd month, etc.
    e. Other, please specify

16. The construction progress curves/charts were developed based on:
    a. Average progress of past projects
    b. Lower limit of progress of past projects
    c. Upper limit of progress of past projects
    d. Other, please specify
    ………………………………………………………………………………..

17. The construction progress curves/charts were developed based on projects that were
    a. Satisfactorily completed projects
    b. All satisfactorily and less-than satisfactorily completed projects
    c. Other, please specify

18. The agency uses for measuring progress:
    a. One construction progress curve for all projects
    b. A number of classified progress curves based on project type and other criteria
    c. Other, please specify

19. The project progress chart (curve) is used if the project value:
    a. No price limit
    b. Projects over $10,000
    c. Projects over $100,000
    d. Projects over $500,000
    e. Other, please specify
    ………………………………………………………………………………..

Construction Progress Charts (Curves) – Consequences

20. A progress is considered unsatisfactory if the actual progress is continued to be less than the expected progress for:

  a. Two sequential/successive periods on the progress chart
  b. Three sequential/successive periods on the progress chart
  c. Other, please specify
  ……………………………………………………………………………..

21. A temporary (e.g. for one or two periods) unsatisfactory progress would trigger:

  a. A warning to the contractor
  b. Other, please specify
  ……………………………………………………………………………..

22. A "continued" unsatisfactory progress may trigger the agency to:

  c. Charge performance penalties to the contractor
  d. Retain a higher percentage of the progress payment
  e. Inform the surety company of the contractor
  f. Declare the contractor in default
  g. Rank the contractor at a lower prequalification level for future bids
  h. Other, please specify
  ……………………………………………………………………………..

23. For a more-than-satisfactory progress, the agency may:

  a. May provide bonus payment
  b. Do nothing
  c. Other, please specify
  ……………………………………………………………………………..

Construction Progress Charts (Curves) – Effectiveness

24. The progress curves were useful tools for measuring overall progress of projects:

  a. Agree
  b. Neutral
  c. Disagree
  d. Other, please specify

25. Progress charts (or curves) were useful tools, however as a suggestion they should be improved to include/reflect the following

  Please, specify
  ……………………………………………………………………………..
  ……………………………………………………………………………..
  ……………………………………………………………………………..

26. Are there other information for measuring the progress of projects and the performance of contractors that you would like to mention, please

APPENDIX B
Annual Time and Cost Performance Measures

Figure B.1 show the change in the cost growth percentage (completion cost compared to the original bid price) of WSDOT projects between 1990 and 2005 for the data set of the current research (964 projects; Table 1.1). The number of projects for each year is listed in the graph along with the minimum, average, and maximum cost growth for the projects of the relevant year. While the average is very reasonable, with an average value of 3.5 percent over the 1990-2005 years, the range of variation between the minimum and the maximum values in a year moves between -12 percent and 25 percent over the same period.

Figure B.2 show the variation of the estimate growth percentage (final project completion cost compared to the engineer's estimate), which, for the study period, had an average of -3.57 percent. However, the range of variation was between -25 percent and 24 percent. The award growth (bid amount compared to the engineer's estimate) in Figure B.3 had an average of -5.52 percent with a range of variation of between -23 percent and 13 percent.

The average values of the cost performance measures are much reasonable. However, the range of variation needs to be narrowed to reduce the variability of the measures. This means that more monitoring and control are needed.

The time performance shown in Figure B.4 was not as good as cost performance. Time percentage growth had an average of 15 percent over the years, with a wide range of variation that had an average minimum of -22 percent and an average maximum growth of 84 percent. However, the variation has narrowed from 2000 to 2004.

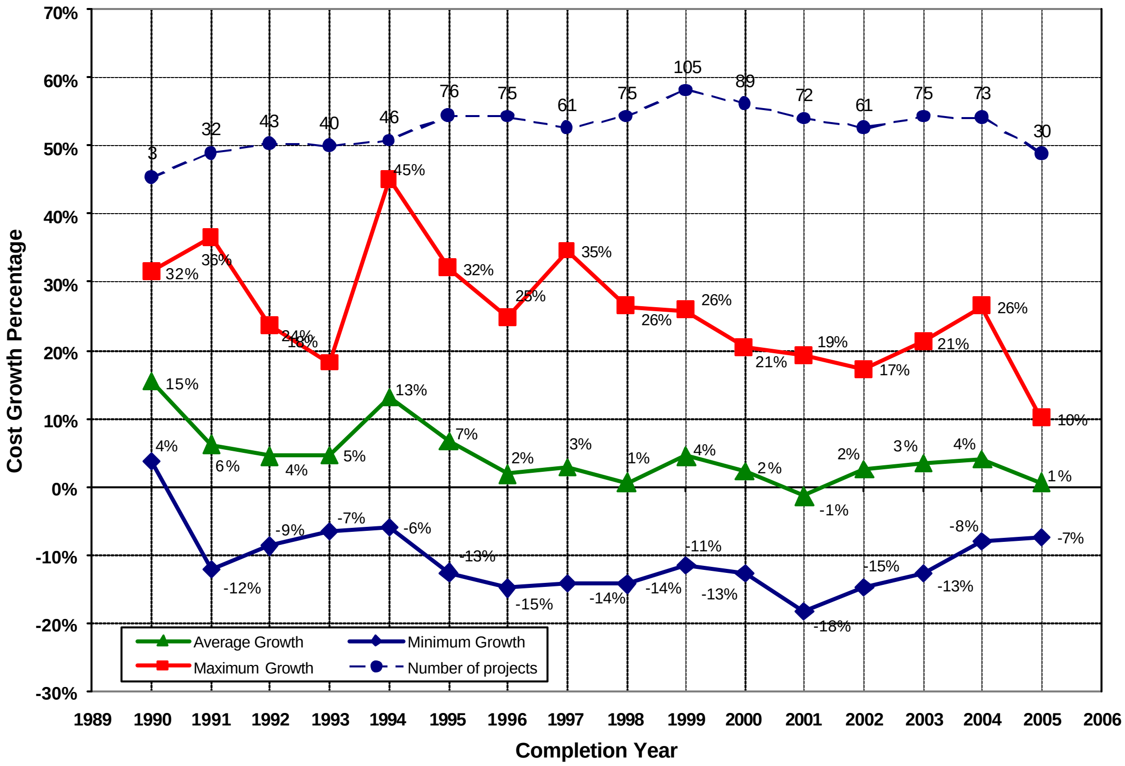


Figure B.1: Performance of the cost growth of WSDOT projects between 1990 and 2005

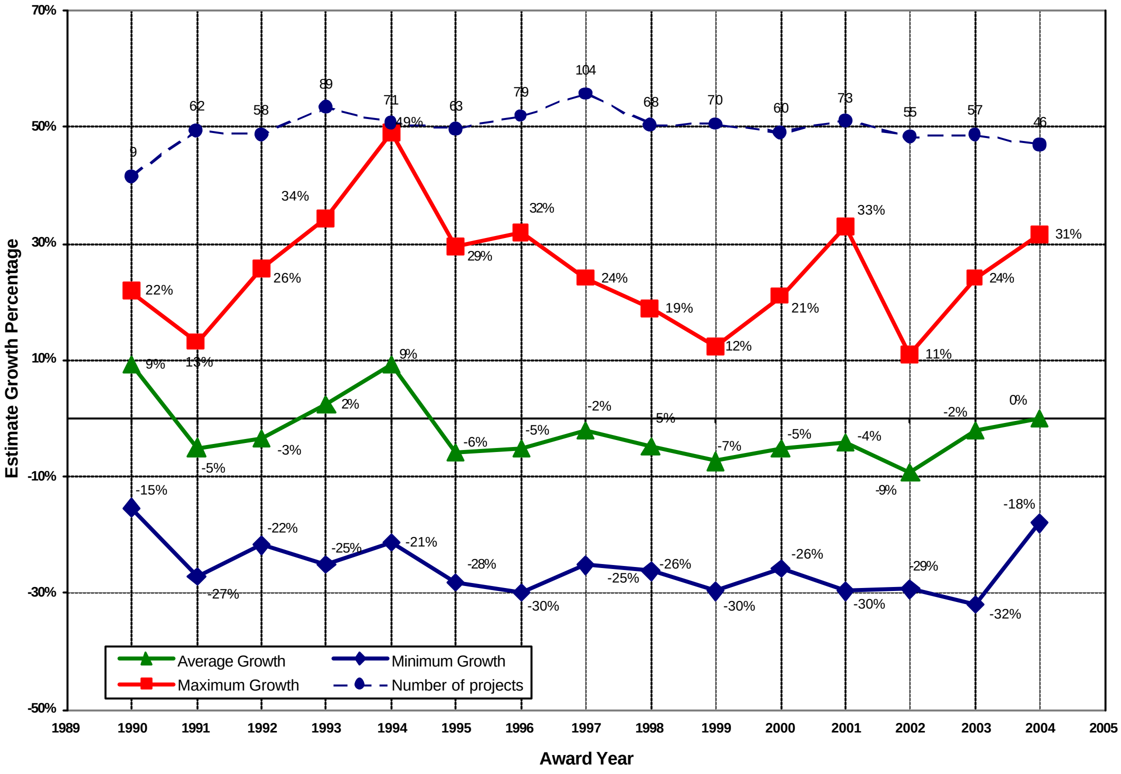


Figure B.2: Performance of the estimate growth of WSDOT projects between 1990 and 2005

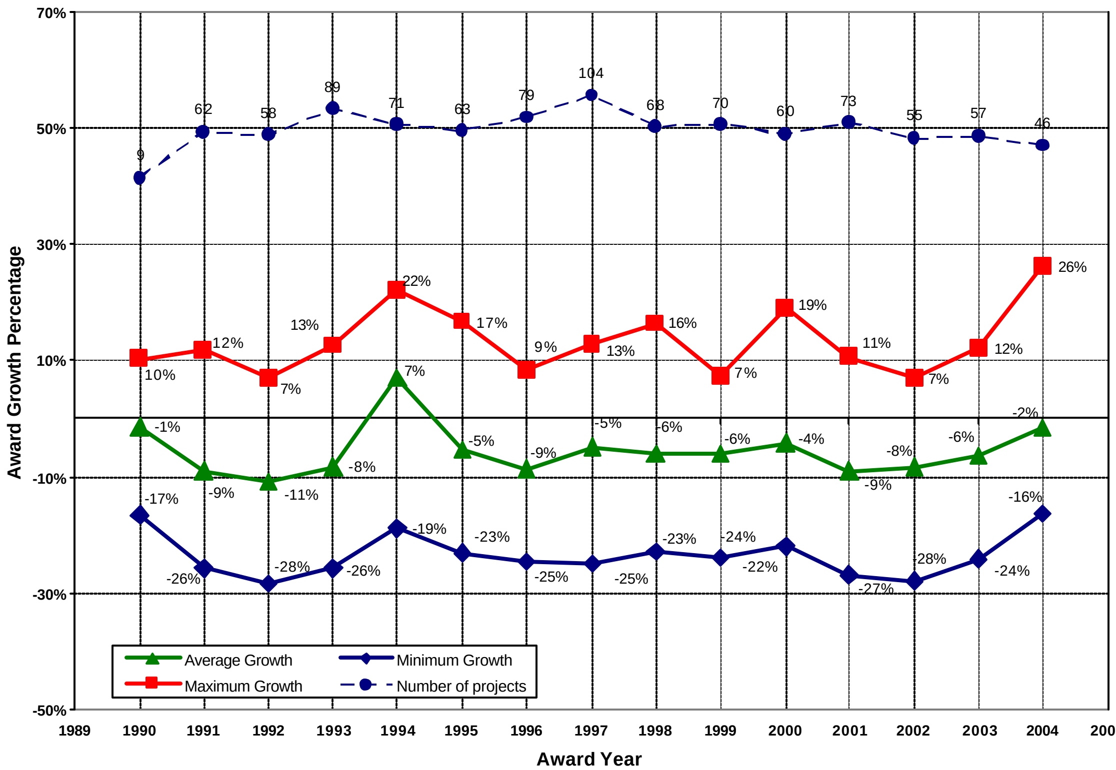


Figure B.3: Performance of the award growth of WSDOT projects between 1990 and 2005

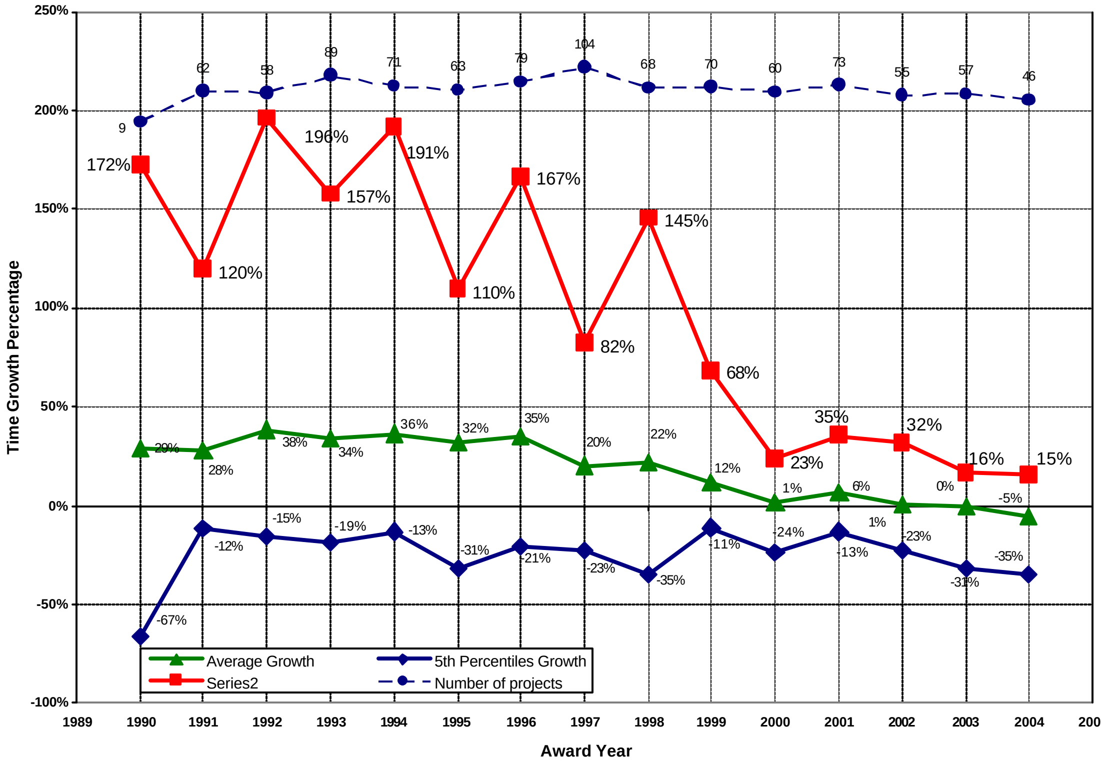
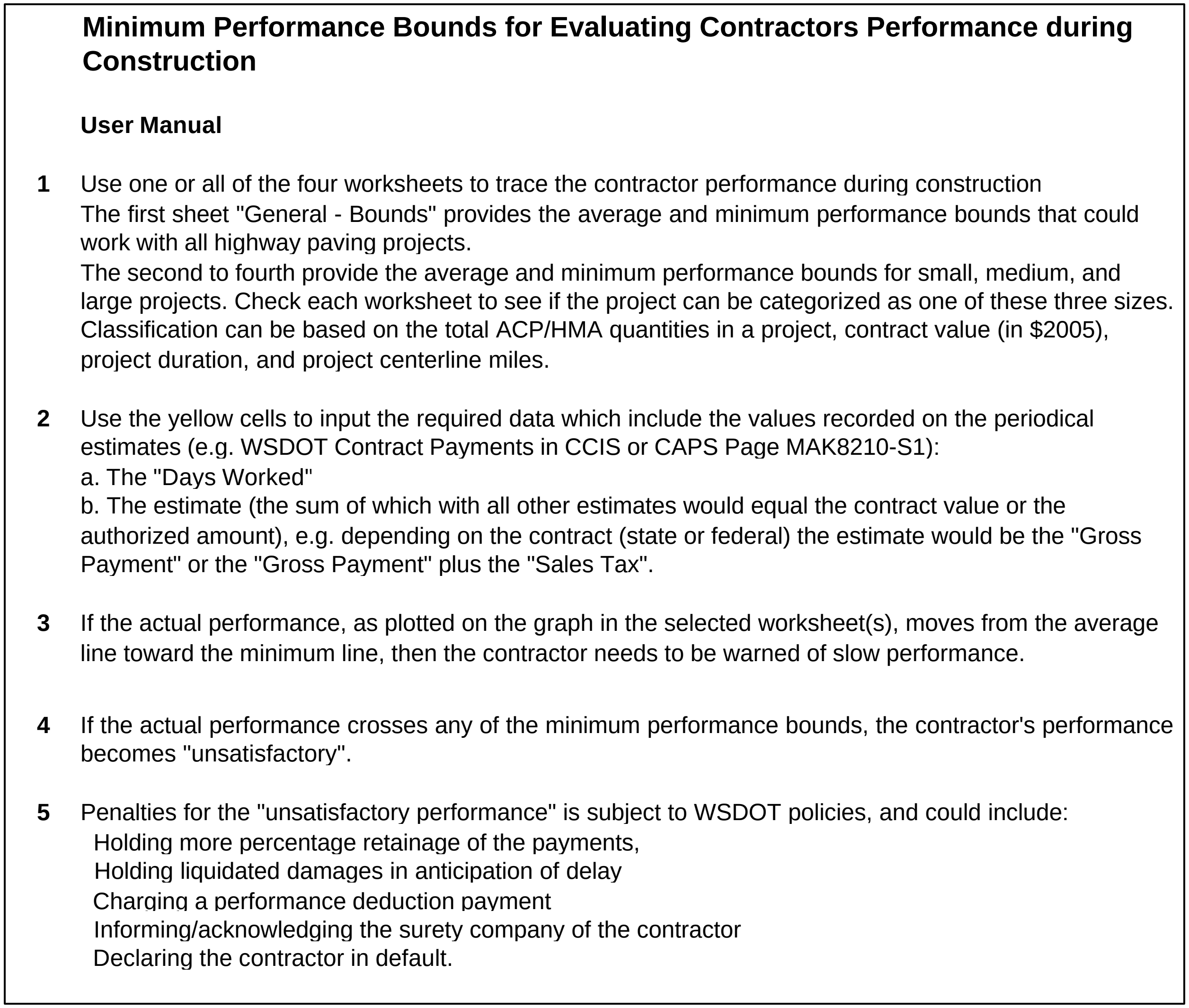


Figure B.4: Performance of the time growth of WSDOT projects between 1990 and 2005

APPENDIX C

Spreadsheets for the Performance and Prediction Models

C.1 Minimum and Average Performance Models



Minimum Performance Bounds for Evaluating Contractors Performance during Construction

User Manual

1 Use one or all of the four worksheets to trace the contractor performance during construction
The first sheet "General - Bounds" provides the average and minimum performance bounds that could work with all highway paving projects.
The second to fourth provide the average and minimum performance bounds for small, medium, and large projects. Check each worksheet to see if the project can be categorized as one of these three sizes. Classification can be based on the total ACP/HMA quantities in a project, contract value (in $2005), project duration, and project centerline miles.

2 Use the yellow cells to input the required data which include the values recorded on the periodical estimates (e.g. WSDOT Contract Payments in CCIS or CAPS Page MAK8210-S1):
a. The "Days Worked"
b. The estimate (the sum of which with all other estimates would equal the contract value or the authorized amount), e.g. depending on the contract (state or federal) the estimate would be the "Gross Payment" or the "Gross Payment" plus the "Sales Tax".

3 If the actual performance, as plotted on the graph in the selected worksheet(s), moves from the average line toward the minimum line, then the contractor needs to be warned of slow performance.

4 If the actual performance crosses any of the minimum performance bounds, the contractor's performance becomes "unsatisfactory".

5 Penalties for the "unsatisfactory performance" is subject to WSDOT policies, and could include:
Holding more percentage retainage of the payments,
Holding liquidated damages in anticipation of delay
Charging a performance deduction payment
Informing/acknowledging the surety company of the contractor
Declaring the contractor in default.

Average and minimum bounds for general projects

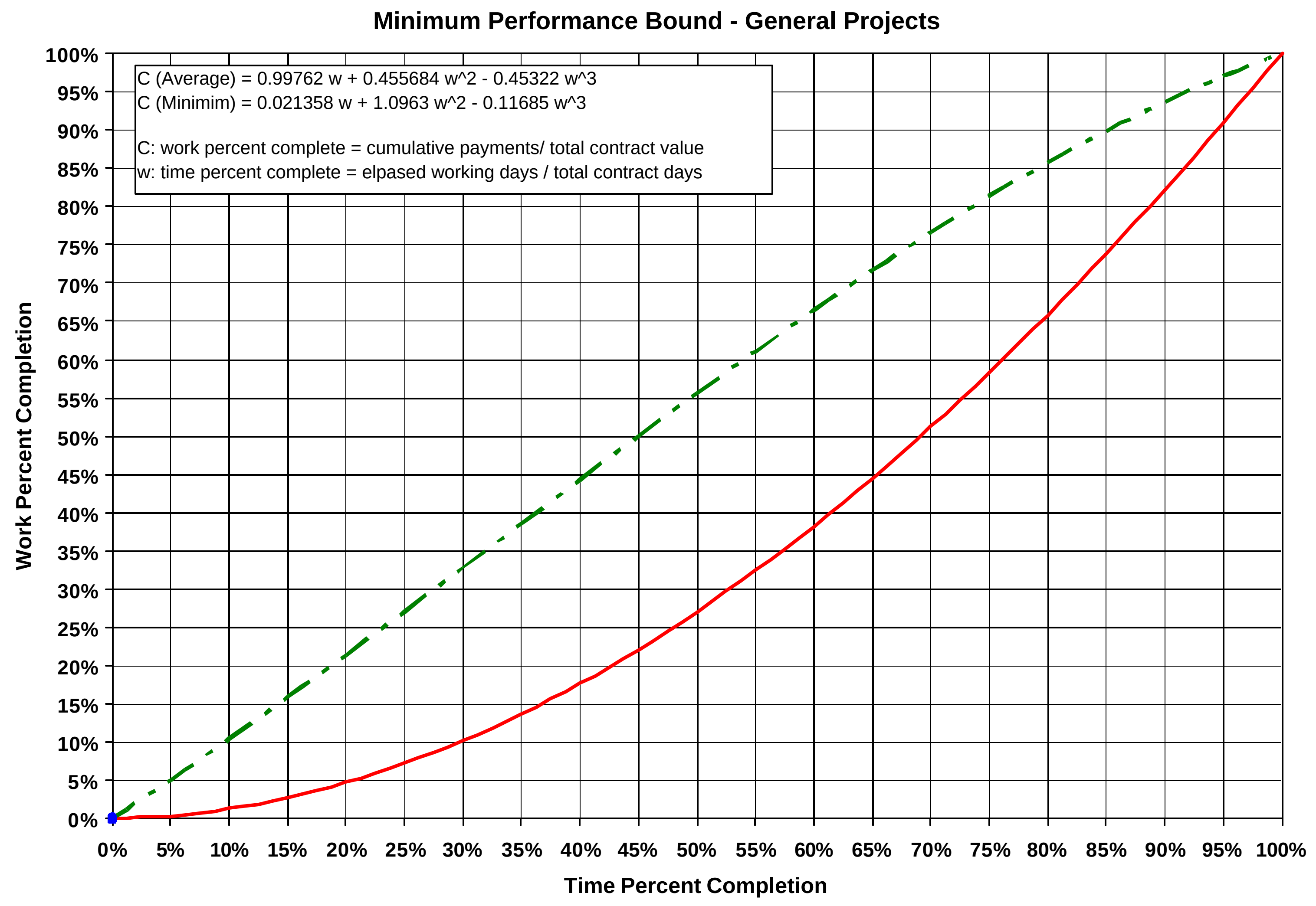
Contract # ______________________ **Date:** ______________
Contractor: ______________________
Total or authorized working days **Total days to date** 0
Total or authorized contract value **Total value to date** $0

Estimate #	Working Days	Payments $	% Time Completed	% Work Completed		Estimate #	Working Days	Payments $	% Time Completed	% Work Completed
1			0%	0%		26			0%	0%
2			0%	0%		27			0%	0%
3			0%	0%		28			0%	0%
4			0%	0%		29			0%	0%
5			0%	0%		30			0%	0%
6			0%	0%		31			0%	0%
7			0%	0%		32			0%	0%
8			0%	0%		33			0%	0%
9			0%	0%		34			0%	0%
10			0%	0%		35			0%	0%
11			0%	0%		36			0%	0%
12			0%	0%		37			0%	0%
13			0%	0%		38			0%	0%
14			0%	0%		39			0%	0%
15			0%	0%		40			0%	0%
16			0%	0%		41			0%	0%
17			0%	0%		42			0%	0%
18			0%	0%		43			0%	0%
19			0%	0%		44			0%	0%
20			0%	0%		45			0%	0%
21			0%	0%		46			0%	0%
22			0%	0%		47			0%	0%
23			0%	0%		48			0%	0%
24			0%	0%		49			0%	0%
25			0%	0%		50			0%	0%

Notes:
% Time Completed = cumulative working days to the estimate date / Total or authorized working days
% Work Completed = cumulative payments to the estimate date / Total or authorized contract value
The "yellow" cells are the only INPUT cells, other cells may have been blocked for protection

Contract # ______________________________ **Date**:____________________

Contractor: ______________________________



Average and minimum bounds for *small projects*

Contract #		**Date:**	________________________
Contractor:			
Total or authorized working days		**Total days to date**	0
Total or authorized contract value		**Total value to date**	$0

Estimate #	**Working Days**	**Payments $**	**% Time Completed**	**% Work Completed**		**Estimate #**	**Working Days**	**Payments $**	**% Time Completed**	**% Work Completed**
1			0%	0%		**26**			0%	0%
2			0%	0%		**27**			0%	0%
3			0%	0%		**28**			0%	0%
4			0%	0%		**29**			0%	0%
5			0%	0%		**30**			0%	0%
6			0%	0%		**31**			0%	0%
7			0%	0%		**32**			0%	0%
8			0%	0%		**33**			0%	0%
9			0%	0%		**34**			0%	0%
10			0%	0%		**35**			0%	0%
11			0%	0%		**36**			0%	0%
12			0%	0%		**37**			0%	0%
13			0%	0%		**38**			0%	0%
14			0%	0%		**39**			0%	0%
15			0%	0%		**40**			0%	0%
16			0%	0%		**41**			0%	0%
17			0%	0%		**42**			0%	0%
18			0%	0%		**43**			0%	0%
19			0%	0%		**44**			0%	0%
20			0%	0%		**45**			0%	0%
21			0%	0%		**46**			0%	0%
22			0%	0%		**47**			0%	0%
23			0%	0%		**48**			0%	0%
24			0%	0%		**49**			0%	0%
25			0%	0%		**50**			0%	0%

Notes:
% Time Completed = cumulative working days to the estimate date / Total or authorized working days
% Work Completed = cumulative payments to the estimate date / Total or authorized contract value
The "yellow" cells are the only INPUT cells, other cells may have been blocked for protection

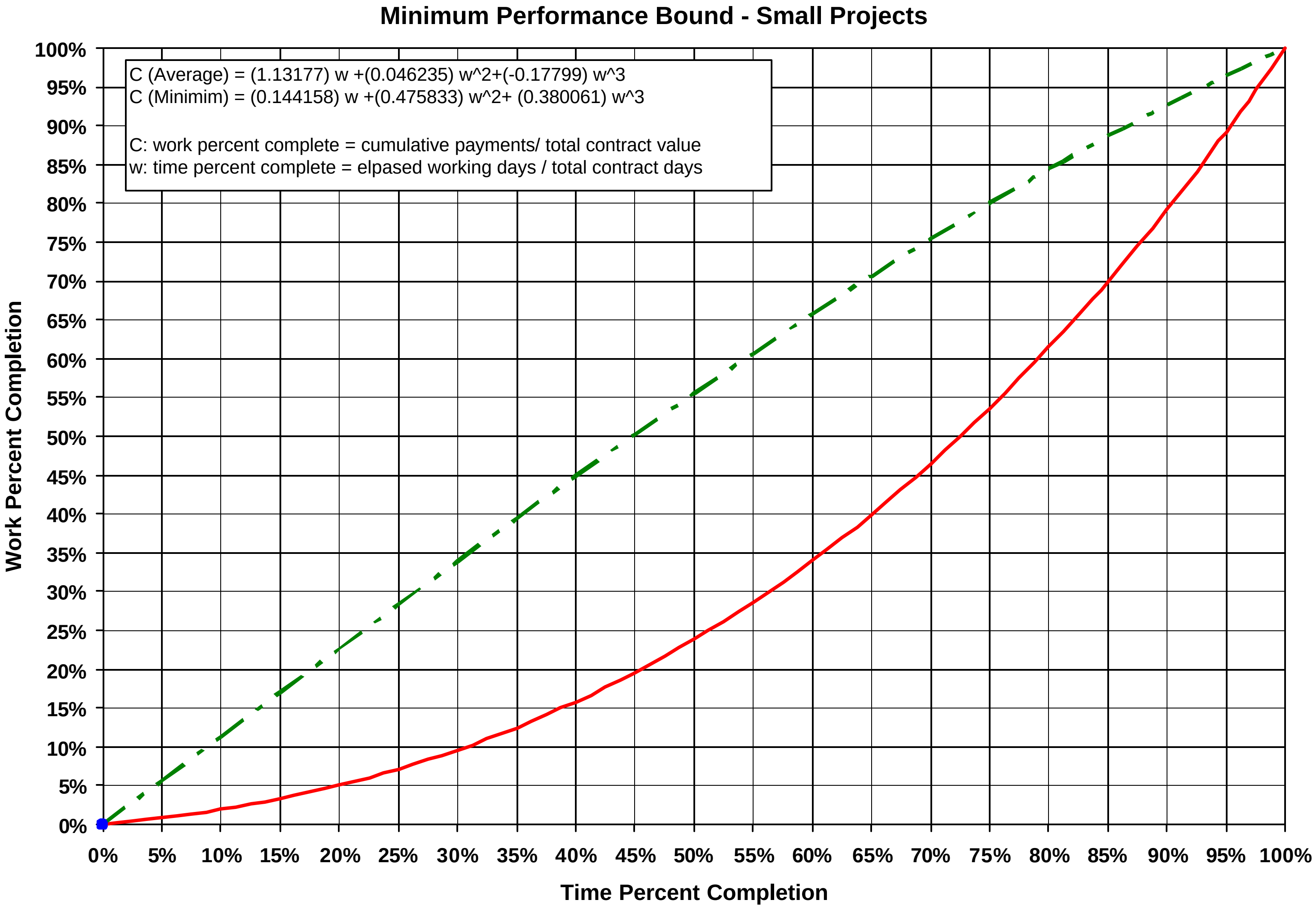
A project is categorized as ***small project*** if it is mainly within the following classifications:

Category	# of projects	Min value	Max Value	Mean	Standard Deviation	Variance
Miles	326	**0.01**	**6.27999973**	**2.380509**	1.737348	3.018379
Days	331	**3**	**64**	**39.81873**	13.75843	189.2943
Value	348	**$105,018.58**	**$2,321,238.82**	**$1,073,383**	$600,158	3.60E+11
HMA	342	**0**	**16,753.74**	**4,978.59**	4,986.13	24,861,530

Manager Note:

Contract # ______________________________ **Date:** ______________

Contractor: ______________________________



Minimum Performance Bound - Small Projects

C (Average) = (1.13177) w +(0.046235) w^2+(-0.17799) w^3
C (Minimim) = (0.144158) w +(0.475833) w^2+ (0.380061) w^3

C: work percent complete = cumulative payments/ total contract value
w: time percent complete = elpased working days / total contract days

Average and minimum bounds for *medium projects*

Contract #
Contractor:
Total or authorized working days
Total or authorized contract value

Date: ____________________
Total days to date 0
Total value to date $0

Estimate #	Working Days	Payments $	% Time Completed	% Work Completed		Estimate #	Working Days	Payments $	% Time Completed	% Work Completed
1			0%	0%		26			0%	0%
2			0%	0%		27			0%	0%
3			0%	0%		28			0%	0%
4			0%	0%		29			0%	0%
5			0%	0%		30			0%	0%
6			0%	0%		31			0%	0%
7			0%	0%		32			0%	0%
8			0%	0%		33			0%	0%
9			0%	0%		34			0%	0%
10			0%	0%		35			0%	0%
11			0%	0%		36			0%	0%
12			0%	0%		37			0%	0%
13			0%	0%		38			0%	0%
14			0%	0%		39			0%	0%
15			0%	0%		40			0%	0%
16			0%	0%		41			0%	0%
17			0%	0%		42			0%	0%
18			0%	0%		43			0%	0%
19			0%	0%		44			0%	0%
20			0%	0%		45			0%	0%
21			0%	0%		46			0%	0%
22			0%	0%		47			0%	0%
23			0%	0%		48			0%	0%
24			0%	0%		49			0%	0%
25			0%	0%		50			0%	0%

Notes:
% Time Completed = cumulative working days to the estimate date / Total or authorized working days
% Work Completed = cumulative payments to the estimate date / Total or authorized contract value
The "yellow" cells are the only INPUT cells, other cells may have been blocked for protection

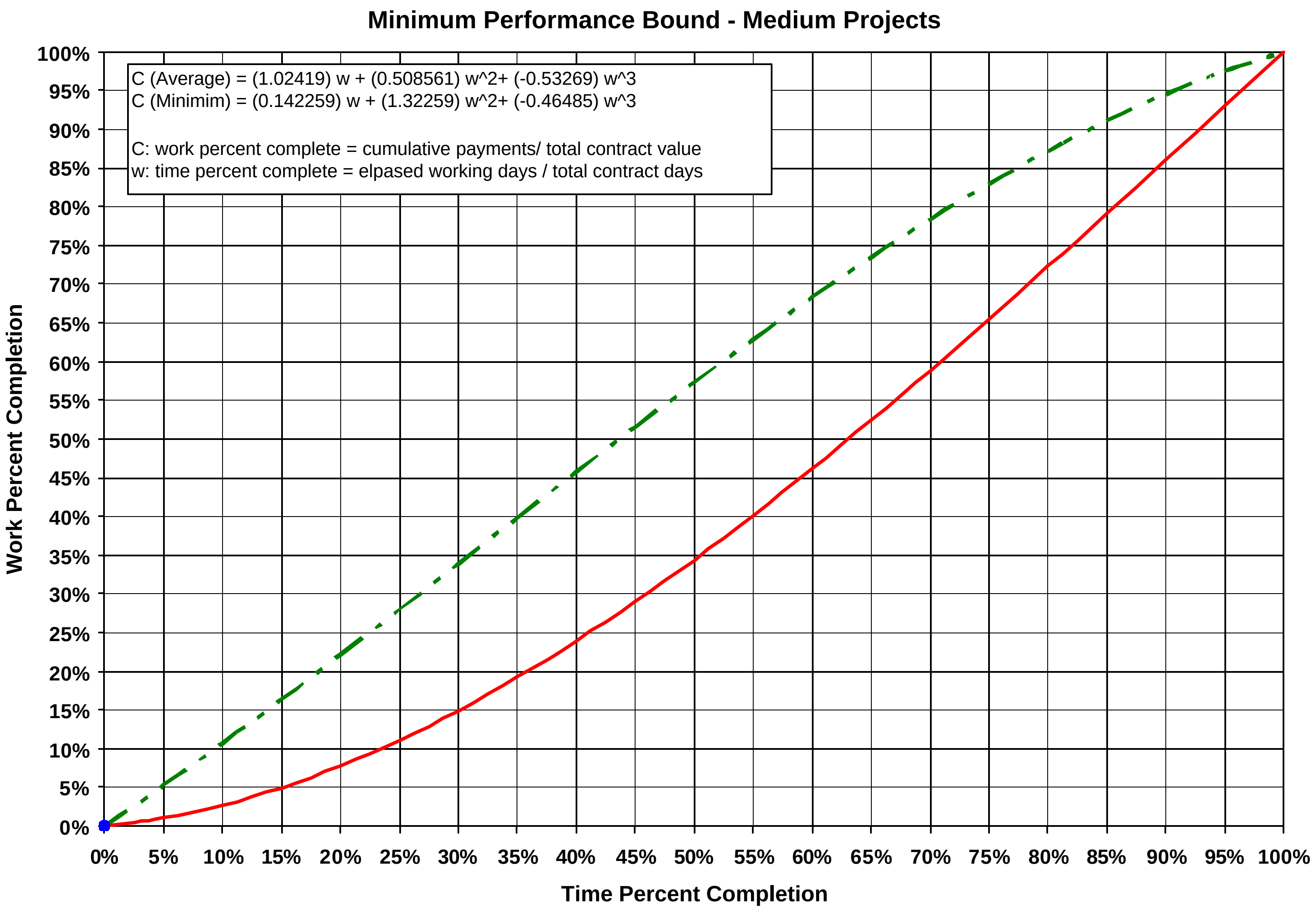
A project is categorized as ***medium project*** if it is mainly within the following classifications:

Category	# of projects	Min value	Max Value	Mean	Standard Deviation	Variance
Miles	145	**6.4**	**18.9500008**	**10.37874**	3.238595	10.48849
Days	143	**65**	**146.5**	**89.01748**	20.44104	417.836
Value	128	**$2,357,167.46**	**$6,495,159.59**	**$3,612,667**	$1,031,118	1.06E+12
HMA	129	**16,927.26**	**48,767.96**	**28,764.12**	8,153.35	66,477,130

Manger Notes:

Contract # ______________________________ **Date:**______________

Contractor: ______________________________



Minimum Performance Bound - Medium Projects

C (Average) = (1.02419) w + (0.508561) w^2+ (-0.53269) w^3
C (Minimim) = (0.142259) w + (1.32259) w^2+ (-0.46485) w^3

C: work percent complete = cumulative payments/ total contract value
w: time percent complete = elpased working days / total contract days

Average and minimum bounds for *large projects*

Contract #			**Date:**	______________________
Contractor:				
Total or authorized working days			**Total days to date**	0
Total or authorized contract value			**Total value to date**	$0

Estimate #	Working Days	Payments $	% Time Completed	% Work Completed		Estimate #	Working Days	Payments $	% Time Completed	% Work Completed
1			0%	0%		**26**			0%	0%
2			0%	0%		**27**			0%	0%
3			0%	0%		**28**			0%	0%
4			0%	0%		**29**			0%	0%
5			0%	0%		**30**			0%	0%
6			0%	0%		**31**			0%	0%
7			0%	0%		**32**			0%	0%
8			0%	0%		**33**			0%	0%
9			0%	0%		**34**			0%	0%
10			0%	0%		**35**			0%	0%
11			0%	0%		**36**			0%	0%
12			0%	0%		**37**			0%	0%
13			0%	0%		**38**			0%	0%
14			0%	0%		**39**			0%	0%
15			0%	0%		**40**			0%	0%
16			0%	0%		**41**			0%	0%
17			0%	0%		**42**			0%	0%
18			0%	0%		**43**			0%	0%
19			0%	0%		**44**			0%	0%
20			0%	0%		**45**			0%	0%
21			0%	0%		**46**			0%	0%
22			0%	0%		**47**			0%	0%
23			0%	0%		**48**			0%	0%
24			0%	0%		**49**			0%	0%
25			0%	0%		**50**			0%	0%

Notes:
% Time Completed = cumulative working days to the estimate date / Total or authorized working days
% Work Completed = cumulative payments to the estimate date / Total or authorized contract value
The "yellow" cells are the only INPUT cells, other cells may have been blocked for protection

A project is categorized as ***large project*** if it is mainly within the following classifications:

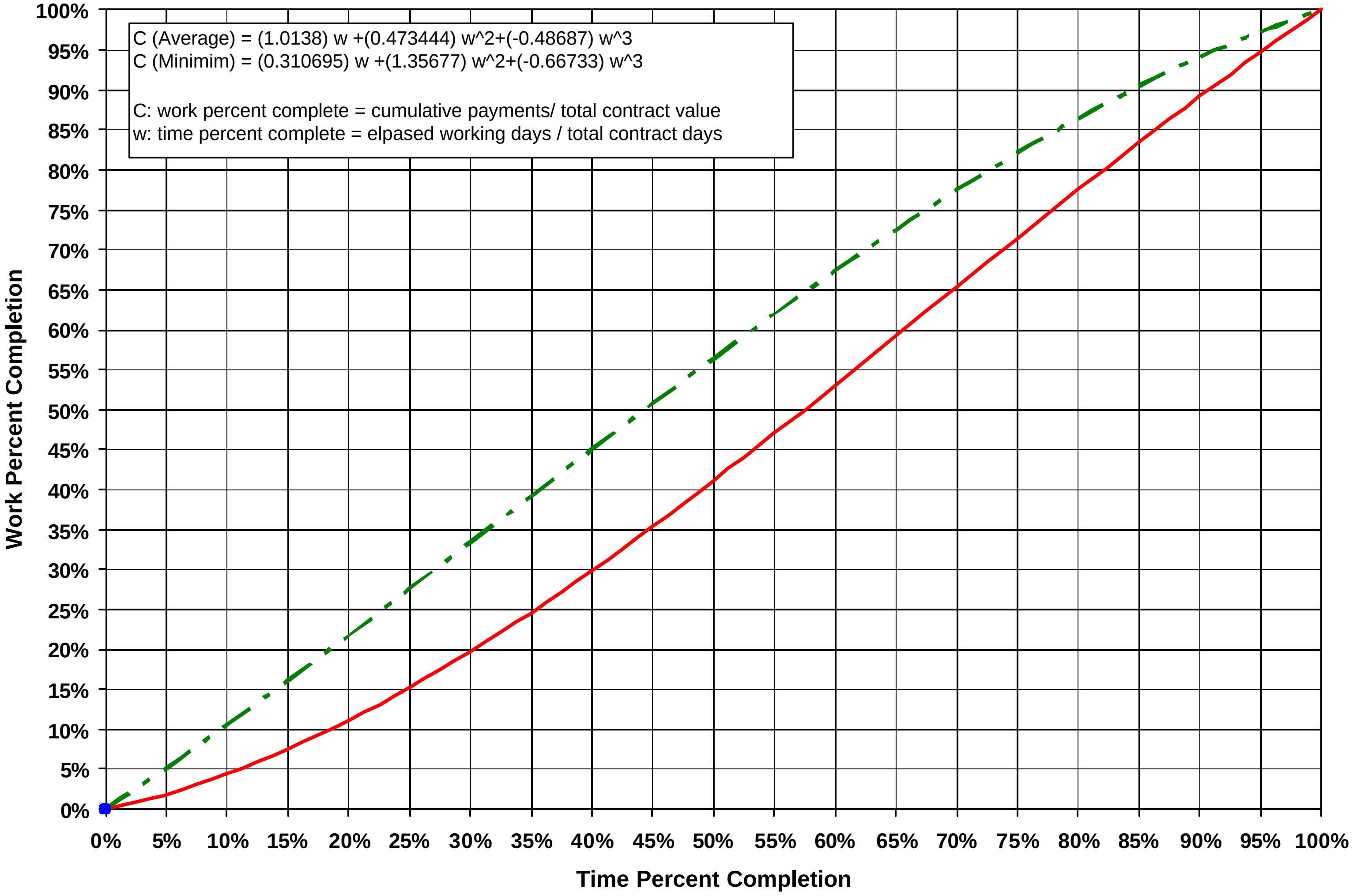
Category	# of projects	Min value	Max Value	Mean	Standard Deviation	Variance
Miles	26	**20.113**	**52.1700011**	**28.10381**	7.845677	61.55465
Days	23	**154**	**615.5**	**212.0217**	96.55574	9323.011
Value	19	**$6,638,740.47**	**$18,715,549.56**	**$9,484,181**	$3,368,837	1.14E+13
HMA	26	**51,338.70**	**99,426.20**	**69,997.30**	16,447.71	270,527,300

Manger Notes:

Contract # ______________________________ **Date:** ______________

Contractor: ______________________________

Minimum Performance Bound - Large Projects


C (Average) = (1.0138) w +(0.473444) w^2+(-0.48687) w^3
C (Minimim) = (0.310695) w +(1.35677) w^2+(-0.66733) w^3

C: work percent complete = cumulative payments/ total contract value
w: time percent complete = elpased working days / total contract days

C.2 Time and Cost Prediction Models

Time and Cost Prediction for highway projects

1 Use the worksheets of "**Time Prediction Models**" and "**Cost Prediction Models**" to predict time and cost of a highway paving project. (Use the "**Time Tables**" and "**Cost Tables**" to have preliminary predictions.

In the two prediction sheets, the predicted values of the individual models or the average values could be used to support the prediction of WSDOT time and cost models. Prediction could be done using the "general" models or those classified based on the total quantity of ACP/HMA in a project.

2 Prediction is based on small number of variables and therefore should be reasonable only for the early stages of a project, i.e. planning stage. Not all of the six variables are needed for the prediction. The availability of all variables should produce better prediction.

The total quantities of ACP/HMA used in a project represent one of the prediction variables. Quantities that may be used in any of the current WSDOT Standard Bid Items, or their future equivalents, should be added to get the total ACP/HMA quantity. The "preparation" worksheet has the SBIs used for aggregating the ACP/HMA.

Quantities of grading in tons and in cubic yards, as well as quantities of surfacing (tons) represent three other variables. SBIs used for these quantities are also listed in the "preparation" worksheet.

3 Use the yellow cells to input the required data. All other cells are blocked for protection.

Review the reference below for solved examples on how to use the time and cost prediction models.

Preparation Sheet

Skip this preparation sheet if the quantities for ACP/HMA, grading (ton and cy), or surfacing (ton) are already known.

The two prediction models uses the following variables. Not all of them are needed to use the models:

1 ACP/HMA, tons (SBIs for ACP/HMA, pre-leveling, approaches and repair)
2 Grading, cy
3 Grading, tons
4 Surfacing, ton
5 Project duration (working days; used in cost prediction models only)
6 Contract value (used in time prediction models only)
7 Project miles (centerline miles including auxiliary lanes)

ACP/HMA English ton

ACP/HMA Classes	Q	Pre-leveling	Q	Approaches	Q	Repair	Q
5751		5716		5854		5737	
5752		5717		5872		5738	
5753		5718		5873		5739	
5754		5726		5874		5740	
5756		5729		5875			
5757		5731					
5758		5732					
5760		5733					
5761		5734					
5762		5741					
5764		5742					
5765		5743					
5766		5744					
5767							
5768							
5769							
5775							
5780							
5787							
5790							
5797							
5799							
Sub Total	0		0		0		0

ACP/HMA Metric ton

ACP/HMA Classes	Q	Pre-leveling	Q	Approaches	Q	Repair	Q
8822		8851		8888		8865	
8823		8852		8881		8866	
8824		8853		8882		8867	
8825		8855		8883		8868	
8826		8856		8884			
8827		8857					
8828		8858					
8876		8859					
8877		8860					
8878		8861					
8870		8862					
8871		8863					
8841		8864					
8842							
8843							
-							
8872							
8873							
8874							
8875							
8880							
8885							
	0		0		0		0

Total ACP/HMA ton	0

Grading

Grading, cy

English	Q	Metric (m3)	Q
300		2940	
310		2945	
320		2950	
330		2955	
360			
405		2972	
409		2975	
421		2977	
460		2987	
470		2990	
Subtotal	0		0
Total Grading cy	0		

Grading

Grading, ton

English		Metric	
408		2974	
431		2979	
Subtotal	0		0
Total Grading ton	0		

Surfacing

Surfacing, ton

English		Metric	
5047		8665	
5090		8671	
5100		8673	
5110		8675	
5120		8677	
Subtotal	0		0
Total Surfacing ton	0		

Time Prediction:

Input the values in the yellow cells. Check the predicted duration (working days) in the darkened cells

Descriptions	Project year	Contract #	Project Miles	Contract Value in project-year $	ACP/HMA tons	Grading tons	Grading cy	Surfacing tons	WSDOT Cost Index in 2005	Current WSDOT Cost Index of the project year
Input Values	**2004**	**6708**	**15.92**	**3267072.01**	**37618.30**	**91823.00**	**91823.00**	**1031.30**	**176**	**170**

1. General Determination

1 (a) : Population - Best in Non-Cost Models

	Data	Log NonLog	Intercept ?	Cost ?	Reg Type	Notes	Model #	Adj R2	MAPE	Intercept	Miles	Contract Value	ACP/HMA tons	Grading tons	Grading cy	Surfacing tons		Predicted value (logarithmic)	Predicted Duration	
1	Population	Log	Yes	No Cost	GRM			0.46399	**0.37709**	2.09200	0.06149		0.06855	0.10264		0.09002		4.781990582	**119**	
2	Population	Log	Yes	No Cost	GRM			0.45602	**0.38111**	2.06996	0.06165		0.07143	0.07527	0.03186	0.08547		4.810365555	**123**	
3	Population	Log	Yes	No Cost	RIDGE			0.43001	**0.38122**	1.92910			0.10522	0.08838		0.09362		4.697149366	**110**	
4	Population	Log	Yes	No Cost	GRM			0.45456	**0.38691**	1.72118			0.12223	0.07597	0.02500	0.08696		4.76611101	**117**	
5	Population	Log	Yes	No Cost	GRM			0.45011	**0.38704**	1.98808			0.13220	0.13893				4.9684506	**144**	
6	Population	Log	Yes	No Cost	RIDGE			0.42121	**0.38728**	1.85634			0.10951		0.08285	0.09857		4.640829613	**104**	
7	Population	Log	Yes	No Cost	GRM			0.44389	**0.39153**	1.93251			0.12884		0.14727			4.972755974	**144**	
8	Population	Log	Yes	No Cost	GRM			0.44542	**0.39666**	1.85635			0.13926	0.07386	0.07455			5.019464305	**151**	
9	Population	Log	Yes	No Cost	GRM			0.41440	**0.40213**	1.88716			0.09476			0.19402		4.231651678	**69**	
10	Population	Log	Yes	No Cost	GRM			0.42645	**0.40345**	1.97274	0.05779		0.07522			0.19540		4.280964204	**72**	
11	Population	Log	Yes	No Cost	GRM			0.13941	**0.49191**	3.05272	0.05967		0.11536					4.433193995	**84**	
12	Population	Log	No	No Cost	RIDGE			0.92545	**0.51837**		0.16850			0.13723	0.14096	0.18246		4.911417831	**136**	
																		Average	**114**	
																		Std Deviation	**28**	24.42%

1 (b) : Population - Best in Cost Models

	Data	Log NonLog	Intercept ?	Cost ?	Reg Type	Notes	Model #	Adj R2	MAPE	Intercept	Miles	Contract Value	ACP/HMA tons	Grading tons	Grading cy	Surfacing tons		Predicted value (logarithmic)	Predicted Duration	
1	Population	Log	Yes	Cost	RIDGE		**P5.2**	0.49931	**0.30707**	0.39454	0.03301	0.20628		0.03501	0.02802	0.04935		4.649949443	**105**	
2	Population	Log	Yes	Cost	RIDGE		**P4.2**	0.44748	**0.33015**	0.22879		0.20399	0.04015		0.04309	0.05204		4.572151801	**97**	
3	Population	Log	Yes	Cost	RIDGE		**P5.3**	0.47518	**0.33897**	0.06827	0.01128	0.21762	0.02922	0.04933		0.06072		4.664151812	**106**	
4	Population	Log	Yes	Cost	RIDGE		**P5.1**	0.48088	**0.33955**	0.06851		0.21102	0.03394	0.03682	0.03104	0.04903		4.714081667	**112**	
5	Population	Log	Yes	Cost	RIDGE		**P6.1**	0.48067	**0.34052**	0.15763	0.01464	0.20585	0.03064	0.03704	0.03164	0.04829		4.73559739	**114**	
6	Population	Log	Yes	Cost	RIDGE		**P4.1**	0.46171	**0.34294**	0.11409		0.21471	0.03246	0.04793		0.05994		4.647730118	**104**	
7	Population	Log	Yes	Cost	RIDGE		**P4.3**	0.46454	**0.34412**	0.06953		0.22788	0.03526	0.04270	0.04065			4.819453169	**124**	
8	Population	Log	Yes	Cost	RIDGE		**P3.3**	0.42825	**0.35089**	0.05581		0.23845	0.03663		0.05988			4.71083745	**111**	
9	Population	Log	Yes	Cost	RIDGE		**P3.2**	0.42453	**0.35211**	0.19493		0.23326	0.03597	0.05886				4.753347875	**116**	
10	Population	Log	Yes	Cost	RIDGE		**P4.11**	0.41689	**0.35453**	0.18487	0.01506	0.21959	0.03401			0.07248		4.389066811	**81**	
11	Population	Log	Yes	Cost	RIDGE		**P3.1**	0.41202	**0.36614**	0.04268		0.23185	0.03227			0.07632		4.397925671	**81**	
12	Population	Log	Yes	Cost	RIDGE		**P3.4**	0.32583	**0.39868**	0.05997	0.00556	0.26806	0.03041					4.425755629	**84**	
13	Population	Log	Yes	Cost	RIDGE		**P2.2**	0.30940	**0.40168**	0.25521		0.25400	0.03196					4.410658143	**82**	
14	Population	Log	Yes	Cost	PLS		**P2.5**	**0.98635**	**0.43158**	0.01343	0.00984	0.28804						4.371071678	**79**	
																		Average	**100**	
																		Std Deviation	**15**	15.52%

2. Classified Determination using Clusters of ACP/HMA Quantities

2.1 : Cluster 1 : ACP/HMA > 26,000 tons

2.1 (a) : Cluster 1 /2 Best in Non-Cost Models

	Data	Log NonLog	Intercept ?	Cost ?	Reg Type	Notes	Model #	Adj R2	MAPE	Intercept	Miles	Contract Value	ACP/HMA tons	Grading tons	Grading cy	Surfacing tons		Predicted value (logarithmic)	Predicted Duration	
1	Cluster 1/2	Log	No	No Cost	RIDGE	L 0.15	**3.1**	0.93701	**0.35754**				0.16323	0.13981		0.16192		4.440836886	**85**	
2	Cluster 1/2	Log	No	No Cost	RIDGE	L 0.2	**2.1**	0.89629	**0.37680**				0.20377			0.23134		3.751924739	**43**	
3	Cluster 1/2	Log	No	No Cost	RIDGE	L 0.2	**4.1**	0.93311	**0.37765**				0.13227	0.10279	0.10249	0.12746		4.623714085	**102**	
4	Cluster 1/2	Log	No	No Cost	RIDGE	L 0.2	**3.2**	0.92152	**0.37823**				0.15482		0.14009	0.16033		4.344479236	**77**	
5	Cluster 1/2	Log	No	No Cost	RIDGE	L 0.1	**2.3**	0.93662	**0.37948**				0.24323		0.20148			4.864951969	**130**	
6	Cluster 1/2	Log	No	No Cost	RIDGE	L 0.2	**2.2**	0.89320	**0.37974**				0.21870	0.20883				4.690440983	**109**	
7	Cluster 1/2	Log	No	No Cost	RIDGE	L 0.2	**3.3**	0.91719	**0.39112**				0.16984	0.13806	0.13842			4.948778909	**141**	
8	Cluster 1/2	Log	No	No Cost	RIDGE	L 0.15	**4.3**	0.94199	**0.39375**		0.29430		0.13745	0.12587		0.14037		4.675038007	**107**	
9	Cluster 1/2	Log	No	No Cost	RIDGE	L 0.2	**5.1**	0.93874	**0.41505**		0.28178		0.11197	0.09215	0.09307	0.10987		4.838443163	**126**	
10	Cluster 1/2	Log	No	No Cost	RIDGE	L 0.2	**3.11**	0.91275	**0.42100**		0.42869		0.15976			0.18647		4.163322838	**64**	
11	Cluster 1/2	Log	No	No Cost	RIDGE	L 0.2	**2.4**	0.87150	**0.48239**		0.67014		0.23649					4.346168587	**77**	
12	Cluster 1/2	Log	No	No Cost	RIDGE	L 0.15	**4.2**	0.93430	**0.50054**		0.41021			0.11919	0.11914	0.15143		4.909555925	**136**	
																		Average	**100**	
																		Std Deviation	**31**	30.98%

FALSE

2.1 (b) Cluster 1/2 Best in Cost Models

	Data	Log NonLog	Intercept ?	Cost ?	Reg Type	Notes	Model #	Adj R2	MAPE	Intercept	Miles	Contract Value	ACP/HMA tons	Grading tons	Grading cy	Surfacing tons		Predicted value (logarithmic)	Predicted Duration	
1	Cluster 1/2	Log	No	Cost	RIDGE	L 0.15	**P3.2**	0.94113	**0.30233**			0.10392	0.14543	0.14541				4.756057343	**116**	
2	Cluster 1/2	Log	No	Cost	RIDGE	L 0.15	**P4.1**	0.95165	**0.32405**			0.08265	0.11555	0.10641		0.12013		4.509375511	**91**	
3	Cluster 1/2	Log	No	Cost	RIDGE	L 0.15	**P3.3**	0.94084	**0.33054**			0.10441	0.14566		0.14176			4.724264735	**113**	
4	Cluster 1/2	Log	No	Cost	RIDGE	L 0.15	**P3.1**	0.94180	**0.33119**			0.10001	0.13775			0.16178		4.077345856	**59**	
5	Cluster 1/2	Log	No	Cost	RIDGE	L 0.15	**P4.3**	0.95020	**0.33453**			0.08749	0.12350	0.10098	0.10141			4.929206311	**138**	
6	Cluster 1/2	Log	No	Cost	RIDGE	L 0.15	**P2.2**	0.91850	**0.33670**			0.14162	0.19485					4.181943628	**65**	
7	Cluster 1/2	Log	No	Cost	RIDGE	L 0.15	**P5.1**	0.95658	**0.34155**			0.07332	0.10317	0.07922	0.07924	0.09865		4.684661008	**108**	
8	Cluster 1/2	Log	No	Cost	RIDGE	L 0.15	**P5.2**	0.95006	**0.40774**		0.26606	0.08515		0.08970	0.09009	0.11086		4.840408862	**127**	
9	Cluster 1/2	Log	No	Cost	RIDGE	L 0.15	**P5.3**	0.95370	**0.35643**		0.20184	0.07467	0.10233	0.10052		0.10921		4.665730161	**106**	
10	Cluster 1/2	Log	No	Cost	RIDGE	L 0.15	**P6.1**	0.95810	**0.37402**		0.17927	0.06685	0.09228	0.07487	0.07586	0.08973		4.818482899	**124**	
11	Cluster 1/2	Log	No	Cost	RIDGE	L 0.15	**P4.11**	0.94611	**0.38380**		0.25812	0.08789	0.11885			0.14366		4.28451128	**73**	
12	Cluster 1/2	Log	No	Cost	RIDGE	L 0.15	**P3.4**	0.92935	**0.40672**		0.37585	0.11627	0.15692					4.441385898	**85**	
13	Cluster 1/2	Log	No	Cost	RIDGE	L 0.15	**P2.5**	0.89795	**0.46153**		0.63246	0.17875						4.437739091	**85**	
																		Average	**99**	
																		Std Deviation	**25**	25.09%

2.2 Cluster 2 : ACP/HMA <= 26,000 tons

2.2 (a) Cluster 2/2 Best in non-cost models

	Data	Log NonLog	Intercept ?	Cost ?	Reg Type	Notes	Model #	Adj R2	MAPE	Intercept	Miles	Contract Value	ACP/HMA tons	Grading tons	Grading cy	Surfacing tons		Predicted value (logarithmic)	Predicted Duration
1	Cluster 2/2	Log	Yes	No Cost	RIDGE	L 0.05	**5.1**	0.47248	**0.34230**	2.18549	0.07907		0.07153	0.08476	0.01657	0.06971			
2	Cluster 2/2	Log	Yes	No Cost	GRM		**4.3**	0.48445	**0.34342**	2.14943	0.07957		0.07328	0.10105		0.07247			
3	Cluster 2/2	Log	Yes	No Cost	GRM		**3.1**	0.46089	**0.35032**	1.85084			0.11236	0.09519		0.08102			
4	Cluster 2/2	Log	Yes	No Cost	RIDGE	L 0.15	**4.1**	0.42638	**0.35185**	2.00006			0.10105	0.06771	0.02541	0.07695			
5	Cluster 2/2	Log	Yes	No Cost	RIDGE	L 0.15	**4.2**	0.42647	**0.35248**	2.72655	0.10363			0.06912	0.02805	0.08018			
6	Cluster 2/2	Log	Yes	No Cost	GRM		**2.2**	0.41552	**0.36390**	2.07506			0.13195	0.12455					
7	Cluster 2/2	Log	Yes	No Cost	GRM		**3.3**	0.41142	**0.36924**	2.03202			0.12856	0.08615	0.04823				
8	Cluster 2/2	Log	Yes	No Cost	GRM		**3.2**	0.38178	**0.39630**	1.78965			0.11413		0.09159	0.08959			
9	Cluster 2/2	Log	Yes	No Cost	GRM		**2.3**	0.35481	**0.39874**	2.10343			0.12533		0.12844				
10	Cluster 2/2	Log	Yes	No Cost	GRM		**2.1**	0.37489	**0.40104**	1.90239			0.09044			0.19353			
11	Cluster 2/2	Log	Yes	No Cost	GRM		**3.11**	0.34276	**0.43286**	2.08449	0.06890		0.07398			0.17943			
12	Cluster 2/2	Log	Yes	No Cost	GRM		**2.4**	0.08935	**0.50293**	3.21619	0.06569		0.09326						
																		Average	**No**
																		Std Deviation	**No**

2.2 (b) Cluster 2/2 Best in Cost Models

	Data	Log NonLog	Intercept ?	Cost ?	Reg Type	Notes	Model #	Adj R2	MAPE	Intercept	Miles	Contract Value	ACP/HMA tons	Grading tons	Grading cy	Surfacing tons		Predicted value (logarithmic)	Predicted Duration
1	Cluster 2/2	Log	Yes	Cost	RIDGE	L 0.75	**P5.2**	0.44442	**0.31228**	0.61920	0.02945	0.19465		0.03681	0.02645	0.04280			
2	Cluster 2/2	Log	Yes	Cost	RIDGE	L 0.8	**P6.1**	0.42859	**0.32225**	0.46193	0.01544	0.18574	0.03272	0.03766	0.02604	0.04604			
3	Cluster 2/2	Log	Yes	Cost	RIDGE	L 0.8	**P5.3**	0.42300	**0.34998**	0.16399	0.02067	0.21438	0.02676	0.04634		0.05957			
4	Cluster 2/2	Log	Yes	Cost	RIDGE	L 0.85	**P3.2**	0.38932	**0.35209**	0.24315		0.22503	0.04737	0.05213					
5	Cluster 2/2	Log	Yes	Cost	RIDGE	L 0.9	**P4.1**	0.37760	**0.36102**	0.27109		0.21381	0.02507	0.04544		0.05298			
6	Cluster 2/2	Log	Yes	Cost	RIDGE	L 0.85	**P4.3**	0.40053	**0.36187**	0.21235		0.21154	0.05033	0.03756	0.03793				
7	Cluster 2/2	Log	Yes	Cost	RIDGE	L 0.8	**P3.3**	0.37704	**0.36907**	0.18835		0.22382	0.04362		0.05937				
8	Cluster 2/2	Log	Yes	Cost	RIDGE	L 0.9	**P2.5**	0.28680	**0.37749**	0.48620	0.01454	0.25251							
9	Cluster 2/2	Log	Yes	Cost	RIDGE	L 0.9	**P4.11**	0.35780	**0.38065**	0.19329	0.01489	0.22247	0.03066			0.07265			
10	Cluster 2/2	Log	Yes	Cost	RIDGE	L 0.95	**P2.2**	0.28173	**0.39965**	0.27909		0.24847	0.03219						
11	Cluster 2/2	Log	Yes	Cost	RIDGE	L 0.95	**P3.1**	0.34189	**0.40293**	0.20678		0.21735	0.03792			0.07187			
12	Cluster 2/2	Log	Yes	Cost	RIDGE	L 0.85	**P5.1**	0.36141	**0.41209**	0.00614		0.22338	0.02405	0.04087	0.03014	0.04567			
13	Cluster 2/2	Log	No	Cost	RIDGE	L 0.1	**P3.4**	0.93494	**0.43754**		0.09033	0.14914	0.19538						
																		Average	**No**
																		Std Deviation	**No**

Cost Prediction:
Input the values in the yellow cells. Check the predicted total cost in the darkened cells

Descriptions	Project year	Contract #	Original WCD	Project Miles	ACP/HMA tons	Grading tons	Grading cy	Surfacing tons
Input Values	2007	6545	104.00	8.43	34297.59	384.06	579.64	3306.5

WSDOT Cost Index in 2005	WSDOT Cost Index of the project year
176	245

1. General Determination

Population Best

	Data	Log NonLog	Intercept ?	Cost ?	Reg Type	Notes	Model #	Adj R2	MAPE	Intercept	Original WCD	Project Miles	ACP/HMA	Grading tons	Grading cy	Surfacing tons		Predicted (logarithmic)	Predicted Cost (project-year $)
1	Population	Log			PLS		6.1	0.81847	**0.34464**	8.9795	0.5163	0.2228	0.2178	0.0151	0.0247	0.0811		15.03145578	$4,696,039.25
2	Population	Log			GRM		5.2	0.80218	**0.35517**	9.1046	0.7022	0.2214	0.1280		0.0369	0.0705		14.9813664	$4,466,611.44
3	Population	Log			GRM		3.3	0.77301	**0.36829**	9.4597	0.8533	0.2301	0.1131					15.09394694	$4,998,863.56
4	Population	Log			GRM		3.2	0.77144	**0.37468**	7.9769	0.7698		0.3171	0.0251				15.01301604	$4,610,238.98
5	Population	Log			GRM		4.2	0.77717	**0.37596**	9.4254	0.7086	0.2374	0.1301		0.0608			14.96766183	$4,405,815.99
6	Population	Log			PLS		4.1	0.77360	**0.37910**	7.7222	0.7040		0.3255	0.0035		0.0775		15.04068072	$4,739,560.35
7	Population	Log			GRM		2.2	0.74354	**0.39313**	10.1793	0.9017	0.2897						14.98476366	$4,481,811.51
8	Population	Log			GRM		3.1	0.74581	**0.40527**	8.4778	0.8057		0.2095			0.0732		15.00091413	$4,554,782.53
9	Population	Log			PLS		5.1	0.74863	**0.40600**	7.8908	0.5743		0.3220	0.0040	0.0197	0.1116		14.97415696	$4,434,525.48
10	Population	Log			GRM		2.1	0.73169	**0.41222**	8.5825	0.8836		0.2263					15.04934354	$4,780,796.65
																		Average	**$4,616,904.57**
																		Std Deviation	**$187,564**

2. Classified Determination using Clusters of ACP/HMA Quantities

(a) Cluster 1 : ACP/HMA > 26,000 tons

Cluster 1 /2 Best in Non-Cost Models

	Data	Log NonLog	Intercept ?	Cost ?	Reg Type	Notes	Model #	Adj R2	MAPE	Intercept	Original WCD	Project Miles	ACP/HMA	Grading tons	Grading cy	Surfacing tons		Predicted (logarithmic)	Predicted Cost (project-year $)
1	Cluster 1/2	Log					5.1	0.7696	**0.2322**	4.9065	0.5616		0.6662	0.0054	0.0282	0.0415		15.01994534	$4,642,295.67
2	Cluster 1/2	Log					4.1	0.7844	**0.2530**	3.9779	0.6317		0.7457	0.0063		0.0476		15.12242363	$5,143,260.84
3	Cluster 1/2	Log					6.1	0.7965	**0.2550**	5.8858	0.7564	-0.0092	0.5088	-0.0652	0.0697	0.0557		15.19856609	$5,550,176.63
4	Cluster 1/2	Log					3.2	0.7642	**0.2567**	5.2735	0.8148		0.5751	0.0152				15.15363978	$5,306,345.87
5	Cluster 1/2	Log					3.1	0.7670	**0.2729**	4.5693	0.7120		0.6563			0.0441		15.08722771	$4,965,387.64
6	Cluster 1/2	Log					2.1	0.7449	**0.2769**	4.7516	0.7869		0.6439					15.13062944	$5,185,639.12
7	Cluster 1/2	Log					4.2	0.7701	**0.2955**	5.3822	0.7622	-0.0009	0.5698		0.0368			15.10425308	$5,050,648.94
8	Cluster 1/2	Log					5.2	0.7728	**0.3000**	5.4199	0.7353	-0.0203	0.5559		0.0168	0.0517		15.12334996	$5,148,027.41
9	Cluster 1/2	Log					3.3	0.7625	**0.3046**	5.3923	0.8521	0.0086	0.5590					15.20575029	$5,590,193.77
10	Cluster 1/2	Log					2.2	0.6573	**0.3383**	10.4916	0.9715	0.1177						15.2545395	$5,869,697.86
																		Average	**$5,245,167.37**
																		Std Deviation	**$350,997**

(b) Cluster 2 : ACP/HMA <= 26,000 tons

Cluster 2/2 Best in non-cost models

	Data	Log NonLog	Intercept ?	Cost ?	Reg Type	Notes	Model #	Adj R2	MAPE	Intercept	Original WCD	Project Miles	ACP/HMA	Grading tons	Grading cy	Surfacing tons		Predicted (logarithmic)	Predicted Cost (project-year $)
1	Cluster 1/2	Log					4.1	0.707681	**0.40090**	8.327902	0.704252		0.235890	0.009475		0.087957			
2	Cluster 1/2	Log					2.2	0.698021	**0.40250**	10.357993	0.849976	0.263656							
3	Cluster 1/2	Log					5.1	0.6931349	**0.40430**	8.287091	0.578469		0.278837	0.008809039	0.021055585	0.093448			
4	Cluster 1/2	Log					6.1	0.7027005	**0.41938**	9.547663	0.590878	0.216508646	0.108255	0.012621	0.047533168	0.064601775			
5	Cluster 1/2	Log					3.1	0.6597947	**0.43889**	9.014593	0.762014		0.153886			0.082092			
6	Cluster 1/2	Log					2.1	0.6296115	**0.44677**	9.289241	0.841835		0.157824						
7	Cluster 1/2	Log					3.2	0.558805	**0.49338**	9.379348	0.644110		0.188885	0.051040741					
																		Average	**No**
																		Std Deviation	**No**