Technical Report Documentation Page

1. Report No. FHWA/TX-05/0-4416-1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Development of Improved Information for Estimating Construction Time		5. Report Date October 2004 6. Performing Organization Code
7. Author(s) James T. O'Connor, Wai Kiong Chong, Youngki Huh, and Yao-chen Kuo		8. Performing Organization Report No. 0-4416-1
9. Performing Organization Name and Address Center for Transportation Research The University of Texas at Austin 3208 Red River, Suite 200 Austin, TX 78705-2650		10. Work Unit No. (TRAIS) 11. Contract or Grant No. 0-4416
12. Sponsoring Agency Name and Address Texas Department of Transportation Research and Technology Implementation Office P.O. Box 5080 Austin, TX 78763-5080		13. Type of Report and Period Covered Research Report September 2001 to September 2004 14. Sponsoring Agency Code
15. Supplementary Notes Project conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration, and the Texas Department of Transportation.		

16. Abstract

The primary objective of this research study was to develop an improved production rate information system for the Texas Department of Transportation (TxDOT). The improved production rate information is intended for determining construction contract time for highway construction projects carried out by TxDOT. A large number of work items that normally lie on the critical path were studied, and the production rates and "drivers" of the production rates were examined for statistically significant relationships. A user-friendly system, called the Highway Production Rate Information System (HyPRIS), was developed using Microsoft Excel and MS Visual Basic platforms.

17. Key Words Highway, Production Rates Estimation and Information System, Construction Time Estimation		18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161; www.ntis.gov	
19. Security Classif. (of report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of pages 202	22. Price

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

DEVELOPMENT OF IMPROVED INFORMATION FOR ESTIMATING CONSTRUCTION TIME

James T. O'Connor
Wai Kiong Chong
Youngki Huh
Yao-Chen Kuo

CTR Research Report:	0-4416-1
Report Date:	October 2004
Research Project:	0-4416
Research Project Title	Development of Improved Information for Estimating Construction Time

Center for Transportation Research
The University of Texas at Austin
3208 Red River
Austin, TX 78705

www.utexas.edu/research/ctr

Disclaimers

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

Patent Disclaimer: There was no invention or discovery conceived or first actually reduced to practice in the course of or under this contract, including any art, method, process, machine manufacture, design or composition of matter, or any new useful improvement thereof, or any variety of plant, which is or may be patentable under the patent laws of the United States of America or any foreign country.

Engineering Disclaimer

NOT INTENDED FOR CONSTRUCTION, BIDDING, OR PERMIT PURPOSES.

Project Engineer: James T. O'Connor
Professional Engineer License State and Number: Texas No. 64532
P. E. Designation: Research Supervisor

Acknowledgments

The authors express their deepest gratitude to the research committee, namely Dr. German J. Claros, Robert J. Hundley, Carlos F. Camacho, Douglas W. Eichorst, Mike P. Lehmann, Diane L. Venable, and Douglas F. Woodall. We also wish to thank the numerous TxDOT and contractor personnel from the sixty-three TxDOT projects around Texas, who have spent a tremendous amount of time and effort to make this project a success. The authors also gratefully acknowledge the sponsorship and assistance of the Texas Department of Transportation.

Products

This report also contains the following: (1) The Highway Production Rate Information System (HyPRIS) (0-4416-P2); (2) user manual for HyPRIS (Appendix H); (3) administrator manual for HyPRIS (Appendix I); and (4) formats and structures for updating of HyPRIS (Appendix I). This information is contained in a CD–ROM attached to the report.

Product P1 can be found in Chapters 3, 4, and 5 of the report, and Product P2 is contained in the attached CD-ROM.

Table of Contents

List of Figures

List of Tables

1. INTRODUCTION

1.1 Background of Study

A major requirement for preparing public highway construction contracts is the determination of the contract completion time for a project. Increased public inconvenience and safety hazards caused by highway construction projects have raised concerns about too much time being allowed for the construction. Contract time estimation depends heavily on the experience of senior staff even when reliable production rate support information exists. For example, many Texas Department of Transportation (TxDOT) planning engineers have relied upon TxDOT's Contract Time Determination System (CTDS; Hancher, et al. 1992) for such information. In every case, planning engineers seek durations that are achievable but not too long.

The information provided by CTDS includes production rates and associated factors for selected work activities. Planners can adjust the provided rates with the factors in order to obtain more realistic rates when certain project conditions apply. However, there has been concern about the reliability or accuracy of the CTDS production rates, and many planners have resorted to relying solely on their experience for determining activity durations. As a result, through this research project, TxDOT set out to improve the quality of information provided by CTDS.

As an initial step, researchers investigated the current level of usage of and satisfaction with the CTDS among TxDOT's various districts. The results of the multi-district survey are presented in Appendix K. A key conclusion of the survey was that TxDOT needed a new, more accurate alternative to CTDS.

In general, there is little reliable uniform information that can be used widely and easily for highway construction time estimation. Current highway construction time estimation is based primarily on construction experts' experiences and "best guesses," often with little formal and objective analysis.

Little research has been attempted to provide the industry with such reliable information. Many published papers in the field of productivity study focus on project performance evaluation or cost control rather than on time estimation. Furthermore, studies that deal with the aforementioned factors are often based on data from completed projects or surveys, and so their accuracy is questionable.

Thus, highway construction time estimation continues to be a challenge despite efforts by industry and academia. High production rate variance is one of the many barriers. It is widely recognized that production rates are affected by many factors such as weather, project type, site conditions and terrain, influence of the learning curve, and so forth. Such factors can either speed up or slow down the production of an activity. Thus, realistic production rates are needed in order to develop accurate construction time estimates, and thorough consideration of the factors affecting production rates is also important for accurate time estimation. As Herbsman and Ellis (1995) noted, "A scheduler has to consider a wide range of factors likely to affect highway project duration."

As a result, research was carried out to measure actual field production rates and to determine those factors that affect field production rates. The new information system resulting from this investigation, which is described in this report, includes production rates for many selected work items that normally lie on the critical path and quantified relationships with various production rate factors.

1.2 Research Objectives

The aim of this research was to develop improved information on field production rates to further advance the accuracy of construction contract time estimation for Texas highway projects. The most accurate production rate data and associated quantified effects of production rate factors is best acquired from consistent site observations at numerous projects. Thus, this research relied heavily on extensive data that were collected by researchers from ongoing Texas highway projects over the past thirty months.

The following objectives were accomplished.

- Field-based information on crew production rates was collected in order to improve existing information for estimating Texas highway bridge construction contract time.
- Many major factors driving field production rates were identified, and statistical techniques were used to formulate relationships between these factors and production rates.
- Prediction models for these factors were developed to improve the accuracy of production rate estimation.
- A user-friendly information system was developed to allow planners to readily access needed production rate information.

1.3 Scope Limitations

The scope of this study is limited to field production rates in Texas highway construction that will be used only for construction time estimation purposes. Cost aspects are not examined. The study of procedures and methods for determining overall construction contract time of a project (e.g., scheduling techniques and contract methods) is also beyond the scope of this investigation. In addition, owing to research time and budget constraints, the research focuses on twenty-six selected critical work items that the TxDOT 0-4416 research team identified as high priority. Finally, the issue of *how to improve* production rates and/or productivity is beyond the scope of this report.

1.4 Structure of Report

In the subsequent chapters, literature on relevant topics is reviewed and statistical techniques applied in this research are discussed. Chapter 3 includes discussions on research objectives, purposes, and methodologies, along with detailed analyses of the differences between CTDS production rates and units and those developed by this research. Chapter 4 presents in detail the relationships between work item production rates and significant drivers, along with formulas for modeling such relationships. Chapter 4 also presents the results from multiple regression analyses of some of the work items. Chapter

5 discusses the development of the Highway Production Rate Information System and how TxDOT planners can use the system to ascertain better production rates. Chapter 6 concludes the research and provides some recommendations for future research.

2. RESEARCH METHODOLGY

The research method adopted by this research was aimed at fulfilling the four research objectives discussed in Section 1.2. The chosen methodology included a series of plans, each aimed at fulfilling a portion of the research objectives.

The first plan was to develop a data collection technique so that field-based information on crew production rates could be collected accurately and efficiently. This information would be used to test the relevance of the Contract Time Determination System (CTDS) and to improve the existing structure and information in the CTDS (e.g., field production rates and factors driving these production rates). The data collection technique included the selection of a series of data collection tools that incorporated proven and new methods of field construction information collection. In addition, literature was reviewed to identify the common drivers of production rates that are most useful to designers. Information that the Texas Department of Transportation (TxDOT) found useful to the production rate estimation process were also identified and incorporated into these data collection tools.

The second plan involved selecting and visiting relevant projects located in the state of Texas and identifying data sources from the project sites that could provide data accurately and efficiently. The third plan involved selection of appropriate methods for analyzing these data. Linear and nonlinear regressions analysis, *t* tests, and regression modeling were preliminarily chosen. Using the analyses in this plan, production rates models could be developed for the twenty-six selected work items. The final plan in the series included the development of a user-friendly information system that TxDOT personnel could efficiently utilize to estimate production rates. This section contains the detailed execution plans of the adopted research methodology.

2.1 Literature Review

The Transportation Research Board conducted a series of studies in 1981 and 1995 to investigate and develop systems that could be used to estimate contract time for highway construction projects (NCHRP 1981; Herbsman et al. 1995). Conclusions indicated that "realistic production rates are the key in determining reasonable contract times" (Herbsman et al. 1995).

Developing scheduling networks is a complicated and time-consuming task. Hancher et al. (1992) highlighted several methods employed. A survey conducted in Hancher et al. (1992) surveyed participants from thirty-six departments of transportation (DOTs) highlighted the fact that personnel determining contract time relied heavily on personal experience. Figure 2.1 shows the results of the survey. Forty-four percent of the respondents relied on personal experience to estimate production rates, 30 percent used standard production rates that were usually provided by the DOTs, and 22 percent used production rates from historical records of previously completed projects.

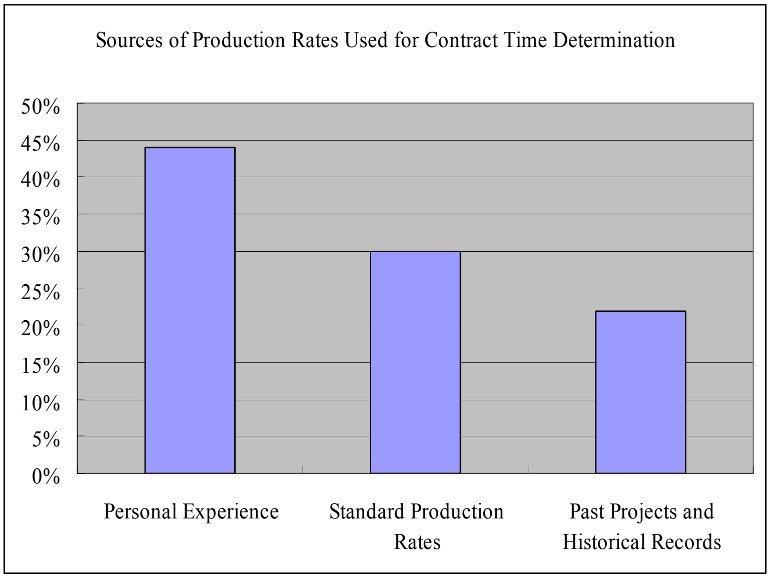


Figure 2.1 Sources of Production Rates Used for Contract Time Determination adopted from Hancher et al. (1992)

Production rates obtained from personal experience and historical records were usually not properly appraised and thus were often unreliable. Essential tools and information, such as consideration of production rate drivers, were often lacking. As a result, personnel who developed the project time estimation generally assumed a single representative production rate for all work items in the entire project. Once the production rate was established, inaccuracies would often be amplified when it was applied throughout the project. Rather than relying on experience or improperly appraised historical records, this research has attempted to quantify the impact of production drivers and to remove unreliable sources that would lead to inaccurate time estimates.

2.1.1 Contract Time Determination System

The CTDS is "a conceptual estimating system for predicting contract time for highway construction projects and is not to be used for the detailed planning of actual construction activities for a project" (Hancher et al. 1992). This system is a product from a research conducted by the Texas Transportation Institute and the TxDOT in 1992. Part of that project's objective was to explore production rates of different work items that are commonly used in highway construction. Survey forms were sent to participants in twenty-five TxDOT districts. The survey form was used to investigate the daily production rates of the forty-two most common work items found in the highway projects constructed by TxDOT. The participants were asked to evaluate the impact of the five production drivers, namely, *location*, *traffic conditions*, *complexity*, *soil conditions*, and *quantity of work* on each of the work items. Participants who completed the survey were required to estimate the low, average, and high production rates for each of the work items and to determine whether the drivers had any significant impact on the production rates. In addition, a request form was sent to all the transportation agencies in the forty-nine states to request similar production rate data. Twenty-four states responded. A production rate database was developed from the responses of the survey from these transportation agencies.

The CTDS database consists of three values of production rates (low, mean, and high) for forty-two work items, five production rate drivers, and production rate adjustment factors for the drivers.

2.1.2 Historical Records

Much research has relied on historical records to develop production rates. Such data come in the form of records kept by the contractors or the clients. Although some well-kept records may provide extremely accurate production rate information, there is insufficient information in these records to allow factors and the variability of these factors on production rates to be identified. Moreover, principal contractors do not keep detailed production rate information on some work items, such drilled shafts, that are carried out by subcontractors. For these reasons, historical records cannot be fully relied upon.

2.1.3 General Factors Affecting Productivity

Many studies have identified productivity factors and measured their effects on productivity. Most of these focused on the identification and quantification of factors that caused losses of construction productivity. Frequently cited factors from these studies include weather, scheduled overtime, disruption, congestion, and region (Halligan 1994; Koehn 2001). This section will review published studies associated with the identification and quantification of productivity factors related to this study.

Thomas and Yiakoumis (1987) employed the factor model to present relationships between labor productivity and productivity factors. The factor model displays the effects of the learning curve and other factors on labor productivity, as shown in Figure 2.2. In the factor model, the ideal productivity curve presents a correlation between the cumulative man-hour per unit of work and the cumulative unit of work in an ideal condition of no disruption. The ideal productivity curve is varied with different crews. Their study indicated that losses in productivity are caused by numerous factors such as environmental factors, site factors, management factors, and design factors.

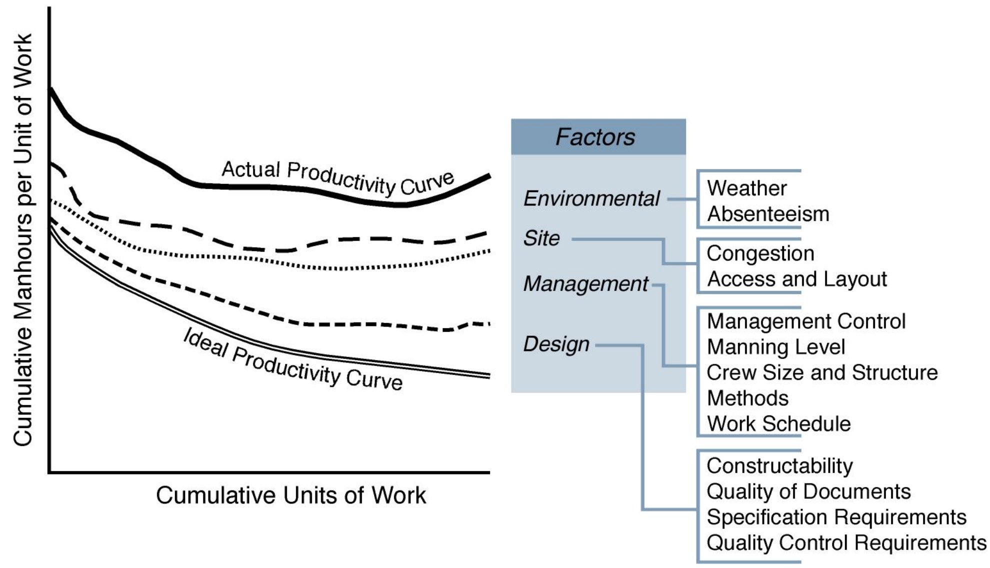


Figure 2.2 Factor Model (adopted from Thomas and Yiakoumis 1987)

2.1.4 Weather

Weather conditions at the construction site have a large impact on highway construction, and most construction operations are sensitive to weather conditions (Oglesby et al. 1989). Precipitation, extremes of temperature, and humidity cause productivity loss (Borcherding 1991; Halligan 1994) and may even cause activities to be delayed. Hot temperature may increase the frequency of workers' travel time as these workers may try to take shelter more frequently in order to avoid heat. As a result, productive time may be reduced (Borcherding 1991). Cold temperature may increase workers' idle time as the workers tend to warm themselves up around heat sources and stop their work (Borcherding 1991). Weather also affects work operations such as lime-treated subgrade, concrete placement, and hot mix asphalt, because many of these work operations have to be stopped to protect work quality (TxDOT 1993).

Several studies have been conducted to quantify the effects of adverse weather on labor productivity. Grimm and Wagner (1974) conducted a study to measure the effects of temperature and humidity on masonry productivity. It was reported that masonry productivity started to decrease beyond the temperature of 75 °F or above 60 percent relative humidity.

An experimental study (NECA 1974) conducted by the National Electrical Contractors Association found that productivity decreased when the temperature was above 80 °F or below 40 °F, or when relative humidity was above 80 percent. Another study carried out by Thomas et al. (1999) found that cold temperature caused a 32 percent drop in steel erection labor productivity.

Thus, weather should often be considered as an important driver of productivity.

2.1.5 Scheduled Overtime

Overtime work often affects productivity. Scheduled overtime is often considered as "a planned decision by project management to accelerate the progress of the work by scheduling more than forty work hours per week for an extended period of time for much of the craft work force" (Thomas and Raynar 1999). Scheduled overtime causes fatigue and reduces motivation among workers and indirectly contributes to losses in labor productivity. Many studies have attempted to quantify the effects of such overtime on labor productivity. The 1980 Business Roundtable republished the findings of weekly productive returns from working fifty or sixty hours a week for various numbers of weeks. In the late 1960s, Weldon McGlaun reported these findings to members of the National Constructors Association. It was found that productivity during the first week of scheduled overtime fell dramatically and that productivity continued to go down week by week. After working for fifty hours per week continuously for seven weeks, the weekly output became similar to that when the workers actually worked forty hours per week. For a sixty work-hour week, by the ninth week of scheduled overtime, the weekly output was similar to that of working for only forty hours a week. This is clearly shown in Figure 2.3.

However, conclusions from a study conducted by the Construction Industry Institute (1988) were inconsistent with previous findings. This study concluded that "productivity does not necessarily decrease with an overtime schedule" based on monitoring twenty-five crews on seven projects (three insulation crews, seven pipe crews, eleven electrical crews, one formwork crew, one rebar crew, and two concrete crews).

Thomas and Raynar (1997) quantified the effects of scheduled overtime on productivity by studying the productivity of electrical and piping craftsmen on four active construction projects. Their study reported a loss of 10–15 percent efficiency for both scheduled overtime scenarios of fifty working hours and sixty working hours per week.

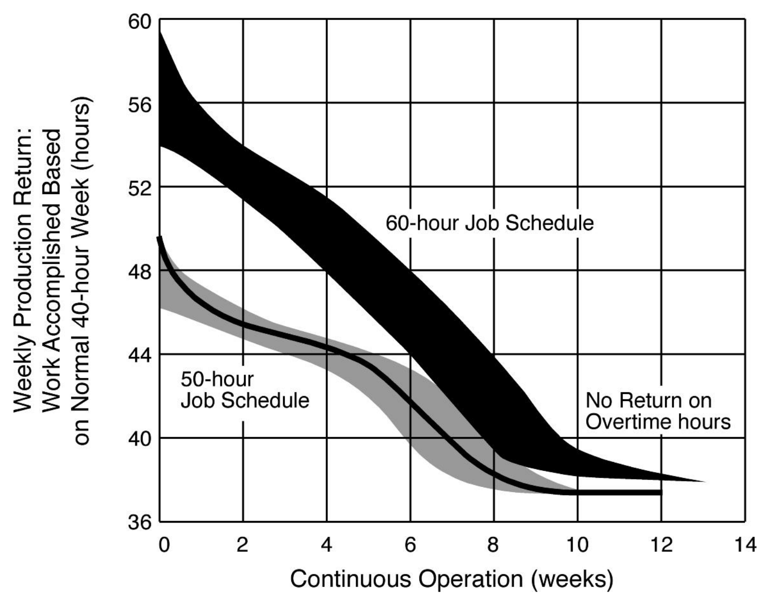


Figure 2.3 Effective Return from Working Fifty or Sixty Hours a Week for Various Numbers of Weeks (Source: Business Roundtable Cost Effectiveness Study Report C-3, November 1980.)

2.1.6 Disruptions

Disruptions can have a huge impact on construction productivity. Disruptions can be divided into two categories: short-term disruptions and long-term disruptions. A short-term disruption leads to productivity loss because extra work is needed to overcome the obstacles causing disruptions. A long-term disruption may even eradicate the productivity increases from learning curve effects (Halligan 1994).

Thomas and Raynar (1997) classified disruptions into 13 categories, which are listed as follows.

- Resources
- Material availability
- Tool availability
- Equipment availability
- Information availability
- Rework
- Change
- Rework
- Management
- Congestion
- Out-of-sequence work
- Supervisory
- Miscellaneous

In their study, each type of disruption was measured by the frequency of occurrence during a working week. It was found that more working days per week were required when there was a higher frequency of disruption. Rework, tool availability, material availability, equipment availability, and congestion were all found to have a significant impact on performance.

2.1.7 Congestion and Accessibility

Ovararin and Popescu (2001) conducted a study to quantify the effects of sixteen field factors on productivity loss in masonry construction. Fifty participants who were either owners or chief estimators of masonry contractors were randomly selected, and a survey package was distributed to them.

In their study, productivity losses caused by levels of congestion and accessibility were quantified. The definitions of levels of congestion and accessibility are shown in Table 2.1. The disruptions of an additional crew working in the same area were evaluated. The results reported that congestion caused 10–32 percent productivity loss. Levels of accessibility were evaluated by considering the convenience of accessing the work area and the distance between the work area and material storage. They found that disruptions associated with accessibility caused 13–35 percent productivity loss.

Table 2.1 Definition of Congestion and Accessibility (Ovararin and Popescu 2001)

Field Factors	**Standard Field Conditions**		
	Minor	**Moderate**	**High**
Congestion	An additional crew/contractor working in the same area 1 day/week	Additional crews/contractors working in the same area 2-3 days/week	Additional crews/contractors working in the same area everyday
Accessibility	4 days/week, <25 yards to material storage	2-3 days/week, 25-50 yards to material storage	Once/week, >50 yards to material storage

2.1.8 Region

The location of a construction project was found to be a factor influencing construction production rates. A productivity study was conducted by Koehn in 2001 to investigate the production rates in different regions in Bangladesh. Low production was found in rural areas. According to their investigation, lack of training and improper supervision was the major reason for low production. Most big construction companies in Bangladesh are located in urban areas, and only big construction companies provide training for the operation of sophisticated equipment.

Moreover, low productivity can be due to workers' fatigue from long-distance commuting (Borcherding and Alarcon 1991). The location of a project can affect both workers' motivation and the availability of advanced tools or equipment. Project location can also have an impact on the availability of skilled labor (AbouRizk et al. 2001). Worker motivation (Borcherding 1980; Borcherding and Garner 1981) and the availability of skilled labor (Koehn and Brown 1985) both have a huge impact on construction productivity.

2.1.9 Learning Curve

When performing repetitive tasks, productivity tends to increase as the number of cycles increase. This increased productivity is due to experience gained from previous tasks, improved resource allocation, better engineering support, better management and supervision, and development of more efficient methods (Thomas et al. 1986). Thomas et al. conducted a study to evaluate the efficiency of various learning curve models on productivity estimation and to investigate the learning rates from four field studies. The learning rate is the rate of change of the cumulative average man-hours when production doubles. It was found that the learning rate was not constant, and therefore a straight line model is not appropriate. Instead, the cubic power model was found to be the best learning curve model among five studied models.

2.1.10 Rainfall

Rainfall has a great impact on highway construction productivity. El-Rays (2001) presented a decision support system that could quantify the impact of rainfall on productive day losses and estimate the duration for certain types of construction operations in highway construction projects. A knowledge base of the effects of rainfall on productive day losses was acquired from interviews with experts in the highway construction industry. The experts indicated that three factors — namely the types of construction operation, the intensity of rainfall, and the drying conditions on site — are highly correlated to rainfall-related productivity losses. In addition, El-Rays and Moselhi (2001) indicated that earthmoving, construction of the base course, construction of drainage layers, and paving construction are the four tasks in highway construction that are most sensitive to rainfall.

2.1.11 Advancement in Technology

Technology advancements lead to improvement of construction productivity, which can be attributed to increased level of control, amplification of human energy, and information processing (Schexnayder and David 2002). Bhurisith and Touran (2002) conducted a case study with regard to obsolescence and equipment production rate. The ideal production rates of wheel-type loaders, track-type loaders, scrapers, and crawler dozers were collected from the 1983, 1992, and 1998 *Caterpillar Performance Handbooks*. Production rate changes according to change of technology were also examined. The results showed that production rates under ideal conditions have increased 1.58 percent on average per year because of technology advancements.

Jonason et al. (2002) studied the productivity of earthwork for different types of advanced positioning systems. In their study, the productivity of earthwork for each advanced positioning system was estimated based on site observation and interviews with field personnel. It was found that advanced positioning systems lead to improvements on schedule and cost performance of earthwork construction because of time savings and reductions in the cost of field surveying. However, there are still several shortcomings that inhibit the usage of these advanced positioning systems. The application of 2-D and 3-D guidance technologies is limited to work areas with direct line-of-sight between the control station and the receiver on the equipment. Furthermore, GPS-related signal noise can affect the accuracy of measurement.

Goodrum and Hass (2002) studied the change of productivity and technology according to productivity data published by RS Means, Richardson, and Dodge between 1976 and 1998. They found a substantial improvement in partial factor productivity among activities that have had significant improvements according to a technology index. The technology index was evaluated as a function of level of control, amplification of human energy, information processing, functional range, and ergonomics of equipment. It was found that site work has had the greatest improvement in mean partial factor productivity and technology index when compared with other work activities.

Allmon et al. (2000) examined changes in construction productivity and unit cost for twenty work items according to productivity data published by RS Means between 1974 and 1996. It was found that the productivity of soil compaction and concrete placement increased by 260 percent and 55 percent, respectively. It was reported that new technology was the main driver of this improvement.

2.1.12 Traffic

Jiang (2003) studied the effects of traffic flow on the construction productivity of hot mix asphalt pavement. He observed 24-hour traffic flow at a crossover work zone and used the queuing theory to compute the cycle time of transporting trucks in a hypothetical hot mix asphalt operation. According to the cycle time and an assumed number of transporting trucks, construction productivity of hot mix asphalt pavement was computed. It was found that traffic delays increased the cycle time of transporting trucks. As a result of increasing cycle time, the construction productivity, in terms of tonnage per hour, decreased. However, adding more transport trucks could balance the negative effects of congested traffic flow.

2.1.13 Construction Productivity Associated with Concrete Pavement

A constructability analysis tool was developed by Lee et al. (2000) to help the California Department of Transportation to examine the productivity performance and the traffic impacts of several strategies used on concrete pavement rehabilitation and construction in an urban area. A hypothetical concrete pavement construction (including the demolition of existing concrete pavement and base course, construction of cement treated base, and construction of concrete pavement) was used to examine the variability of productivity performance with the variability of design profile, required curing time, working methods, paving strategies, truck capacity, and loading/discharging time. This hypothetical project involved the replacement of two outer lanes of a four-lane roadway during weekend closures from 10:00 p.m. Friday to 5:00 a.m. Monday. The process of pavement rehabilitation, lead–lag relationships between activities, constraints that limit construction productivity, approximate process productivity, and capacities of equipment and facilities were gathered based on the previous urban freeway rehabilitation experience of a group of experienced California concrete paving contractors.

Table 2.2 presents their findings in terms of percent reduction in ideal productivity (lane-km/a weekend closure) for different factors. Slab thickness was found to have the greatest impact on the productivity of concrete pavement rehabilitation because thicker slabs increase the quantity of demolition. The curing time of poured concrete varied with the usage of various types of concrete material. Because the construction time was limited to fifty-five working hours in a weekend closure and the constructed lanes had to open for traffic at the end of closure, more curing time lead to less construction time and output. The work method (that reflects the relative sequence of base construction and paving construction) also had a great impact on output. In addition, the paving lane (which refers to the working sequence of the two replaced lanes) and the end dump truck capacity and load/discharge time also had impacts on output.

Table 2.2 Percent Reduction in Production Capacity under Optimistic Conditions (adopted from Lee et al. 2000)

Options		Comparison	Reduction
Design Profile		203 mm --> 254 mm	40%
		203 mm --> 305 mm	47%
		254 mm --> 305 mm	12%
Curing Time		4 hours --> 8 hours	10%
		8 hours --> 12 hours	11%
		4 hours --> 12 hours	19%
Working Method	203-mm slab	Concurrent --> Sequential	29%
	254- or 305-mm slab	Concurrent --> Sequential	21%
Paving Lane	203-mm slab	Double --> Single	17%
	254- or 305-mm slab	Double --> Single	7%
End Dump Truck Capacity		22 Ton --> 15 Ton	15%
Load/Discharge Time		3 minutes --> 4 minutes	24%

2.1.14 Methods of Productivity Analysis

Expert systems are another technique employed to deal with relationships between productivity and driving factors. Hendrickson et al. (1987) developed an expert system to predict the activity duration for masonry construction. The productivity estimation, as a part of the activity duration estimation, included two steps. The first step was to estimate the maximum expected productivity, and the subsequent step was to adjust the maximum rate to a reasonable rate according to the characteristics of the job or site. The information associated with productivity was established on the basis of interviews with an experienced mason and a supporting laborer. Another expert system was developed by Christian and Hachey (1995) to estimate the production rate of concrete pouring. After a simple question-and-answer routine, the expert system was able to estimate production rates of concrete pouring, depending on established decision rules.

In addition, neural networks have been used by many researchers (Karshenas and Feng 1992; Lu et al. 2000; AbouRizk et al. 2001) to predict construction productivity. A neural network has the capability of learning with an increase in data. The greatest advantage of using neural networks to predict construction productivity is that it can include interactive effects of multiple factors in the productivity estimation if the network is trained using an adequate and representative data set. In reality, the size and quality of the training data set usually limits the effectiveness of neural networks owing to lack of standards for collecting real productivity data.

2.1.15 Advancing to Present Research

Although many studies have addressed construction productivity, few studies have been undertaken to study production rates for highway construction time estimation. The purpose of this study is to examine and determine the production rate in two work areas — namely, earthwork, pipework, pavement construction and structures for highway projects. Such information will help TxDOT improve the accuracy of highway construction time estimation and should lead to better project time management.

2.1.16 Other Factors Affecting Production Rates

Herbsman and Ellis (1995) found seventeen factors affecting overall construction duration of a transportation facility project from a survey: weather and seasonal effects; location of a project; traffic impacts; relocation of construction utilities; type of project; letting time; special items; night and weekend work; dominant activities; environmental; material delivery time; conflicting construction operation; permits; waiting and delay time; budget and contract payment control; and legal aspects. These factors have been identified by other researchers as well.

2.1.17 Conclusion to Literature Review

There are so many factors that affect production rates that to consider the impact of all these factors would be a daunting task. It is impractical to collect a sufficient number of data points to make such analysis relevant.

The conclusion from the literature review is that the research needs to focus on the most important factors that drive production rates. If these factors are predictable at the design stage they will be of benefit. If they are not predictable, it is helpful for the designers to know this so that they may make an appropriate assumption. As a result, the factors were predetermined and will be discussed later in this chapter.

2.2 Scope Determination

2.2.1 Scope of Data Collection

The comprehensive literature review helped the research team better focus their scope of data collection through a better understanding of the respective factors that affect productivity and productivity measurement methods. A data collection process and associated tools that incorporated the selected factors and methods were developed to better achieve the objectives of this research.

First, work items that normally fall on the critical path were selected. Second, relevant factors that are generally considered meaningful were then selected. The researchers understood that certain factors may be detected only during the data collection process, and thus the data collection tools were flexible enough to adapt to new discoveries.

Third, representative projects were selected and data were collected from these projects. Fourth, to enhance data collection efficiency, projects that could yield outliers for the production rates were eliminated. The project selection process eliminated all unwanted projects. Fifth, data collected was verified and statistical techniques were used to further eliminate data that were considered outliers. Finally, the data analysis was expected to develop (1) a range of production rates for all the investigated work items, (2) an estimation formula for determining production rates caused by different factors, and (3) a range of production rates for different factors.

2.2.2 Work Items Selection

A highway construction project usually involves hundreds of work items. Some of them fall more frequently on the critical path; these items usually affect contract time, whereas other work items do not affect the overall time of construction. Through survey and rigorous discussion were carried out earlier in the research, the priorities of these work items were identified. Survey participants were selected by the Project Monitoring Committee (PMC) for TxDOT Research Project 0-4416. On the basis of the decisions made in the survey and discussions, twenty-six work items were selected for the study.

The selected work items addressed in this study are included in Table 2.3.

Table 2.3 Types of Work Items Selected

Item No.		Item Description(s)
110		Excavation
132		Embankment
247		Flexible base
260		Lime treatment (road mixed)
276		Cement treatment (plant mixed)
340		Dense graded hot mix asphalt (method)
360	360-1	Concrete pavement (slip form)
	360-2	Concrete pavement (conventional)
409		Prestressed concrete piling
416		Drilled shaft foundations
420	420-1	Concrete structures — footing
	420-2	Concrete structures — column — rectangle
	420-2	Concrete structures — column — round
	420-3	Concrete structures — cap
	420-4	Concrete structures — abutment (cast in place)
423		Retaining wall — MSE wall
425		Precast prestressed concrete structural members — beam erection
450		Railing — bridge railing
462	462-1	Concrete box culverts and storm drains (precast)
	462-2	Concrete box culverts and storm drains (cast in place)
464	464-1	Reinforced concrete pipe (18–42 in.)
	464-2	Reinforced concrete pipe (48–72 in.)
465		Manholes and inlets
466		Head walls and wing walls
529		Concrete curb, gutter, and combined curb and gutter
666/668		Pavement markings

2.3 Data Collection Methodology

A data collection process plan, shown in Figure 2.4, was developed to enhance the effectiveness of data collection. Three cycles were included in this plan. The first consists of the process flows of conducting a district meeting to select projects for data collection; the second involves conducting a project meeting to kick off the data collection in a project; the third, the regular collection of project data at the construction site.

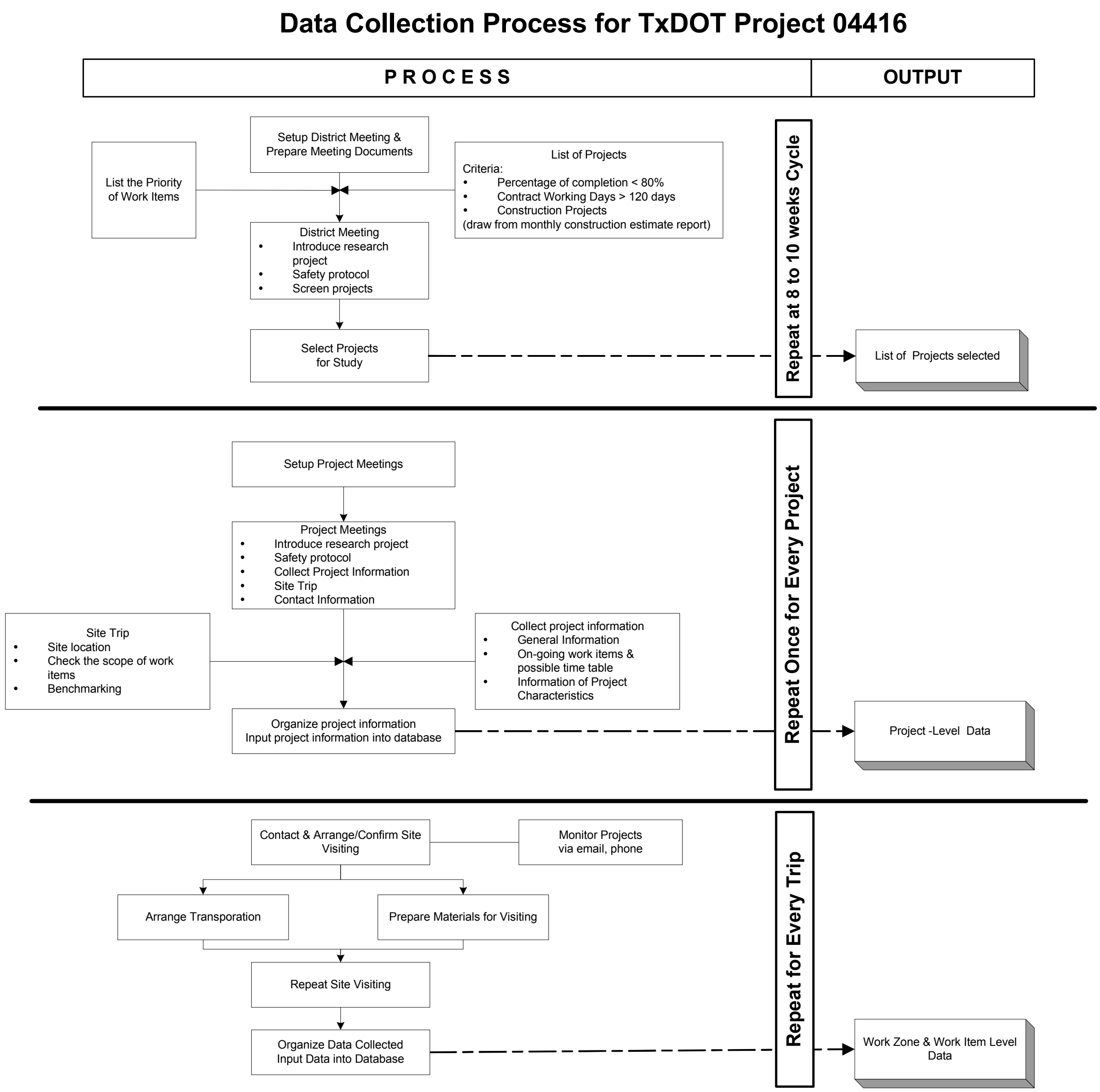


Figure 2.4 Data Collection Process

2.3.1 Data Collection Tools

Data collection tools were developed to facilitate the data collection process and to enhance the accuracy of data. These tools may be the first such comprehensive guide to measuring crew level production rates in highway construction. These tools consist primarily of data forms used to track production rates. Also contained in the tool is a Data Computation/Analysis Sheet, which is intended to process data for analysis. The tools helped to guide the data collection process and aimed to collect data such as time, quantities, factors affecting production rates, and other vital information that could help achieve the research objectives. These tools are documented in the Appendices. Data collected in these tools are divided into Project Level, Work Item Level, and Work Zone Level.

Project level data factors are generally considered to have an effect on productivity owing to the nature of the project. These drivers (also called candidate drivers) include the following: (1) project type, (2) location, (3) traffic flow, (4) traffic count, (5) weather (rain and winter length), (6) percentage of project completion, (7) contract amount, (8) technical complexity, (9) contract day, (10) accelerated construction provision, (11) liquidated damages, (12) soil types, (13) clay content of soil, (14) land slope, (15) depth of water table, (16) scheduling technique used, (17) work schedule (hours/day and days/week), (18) contract administration system, and (19) contractor's management system.

The form called "Production Rate Tracking; Project Level" was used to identify characteristics of a project and possible work items for which data related to production rates may be collected. The approximate total quantity of work for each work item was also noted in the data form, because it is generally considered an important factor in influencing production rates. The data form was completed for each project during the meeting with site personnel.

The "Production Rate Tracking; Work Zone and Work Item Levels" data form consists of four data sheets, including "Production Rate Tracking: Work Zone Level," "Work Item Sheet," "Production Rate Tracking: Work Item Level," and "Tracking Calendar." The "Work Zone Level" sheet was used to describe the work zone in which the work item was being performed and to document its characteristics, such as accessibility, congestion, and drainage effectiveness.

The "Work Item Sheet" form was used to specify the scope of each work item (what is "Included" and what is "Not-Included") for which data was collected. It provided guidance to ensure consistent observations and data collection. Work elements included in the scopes of the work items were those that most directly represented actual production of the work item.

The "Work Item Sheet" form also contains work item specific information and a list of possible work item specific factors that may affect the production rate of each work item. To accommodate for variability in the scope of work and work item level factors, a survey is completed for each work item.

The "Production Rate Tracking: Work Item Level" sheet was used to describe with sketches and notes the technical details of the work, such as dimensions, shapes, and sections as observed on site. Quantities of work completed were recorded as units completed. These measurement units are more time estimate friendly than those of the CTDS and most other cost control systems, thereby facilitating quick measurement of work quantities.

The "Tracking Calendar" sheet was used to classify each calendar day into normal working, half-day working, or non-working day, according to the level of operations for a work item in a given day. Possible factors affecting the operation were also indicated using notations as provided for on the sheet. These collection tools are documented in the Appendices.

2.3.2 Job Site Selection

The first cycle in Figure 2.6 displays tasks associated with the district kickoff meeting. District meetings were conducted every twelve to sixteen weeks after the completion of data collection in the previous district. Such meetings were arranged to ensure that the district construction engineer and engineers from the area offices fully understood the research and would facilitate project selection and data collection. Information on ongoing projects were obtained from the "Construction Report — Highways and Construction Monthly Estimate Report" on the TxDOT website (http://www. dot. state. tx. us/business/projectreports. htm). Projects that were less than 80 percent complete and had a contract duration greater than 120 working days were noted for further screening at the district meeting. Projects with production rates that could possibly be outliers, such as those with serious delays caused by legal problems or change orders, were eliminated. Visits to each district lasted three to five months, depending on the relevance and number of the projects selected.

2.3.3 Site Visitations and Data Validation

Once projects were selected, weekly visits were conducted on the job sites. Data were provided by TxDOT site personnel and further verified and standardized by the research assistants for this report. The data sheets were used to collect the data, which includes the following.

(1) The quantities of the work items that were completed
(2) Time expended to construct these work items
(3) The contractors' working and non-working days
(4) The reasons for non-productivity.
(5) Other information that could be candidate drivers affecting productivity
(6) Design drawings and other information that TxDOT personnel indicated as helpful

Benchmarking of a data point started at the first observation of a work item. Subsequent visits were conducted when necessary to complete the information for the form. The starting and ending nodes, as indicated in the data collection forms, were also used to guide the data collection process. The starting and ending nodes describe the scope of work operation that would be constituted in the measurement of production rates. Thus, data were only collected from work operations within the prescribed starting and ending nodes. These nodes can be found in the work item collection tools in the Appendices.

The observations for a data point ranged from a week to six weeks of work operations. Delays and variations of the work operations drove the range of observation periods.

To ensure accuracy, quantitative information, such as production quantities, working days, delay days, and non-working days, were collected from TxDOT's site personnel diaries and records, whereas qualitative information, such as work zone accessibility and congestion, were provided by the TxDOT site personnel and then visually verified by the researchers.

To further enhance the quality of the data, foremen were also interviewed to better characterize progress of the previous week. Generally, foremen recalled the work done in great detail.

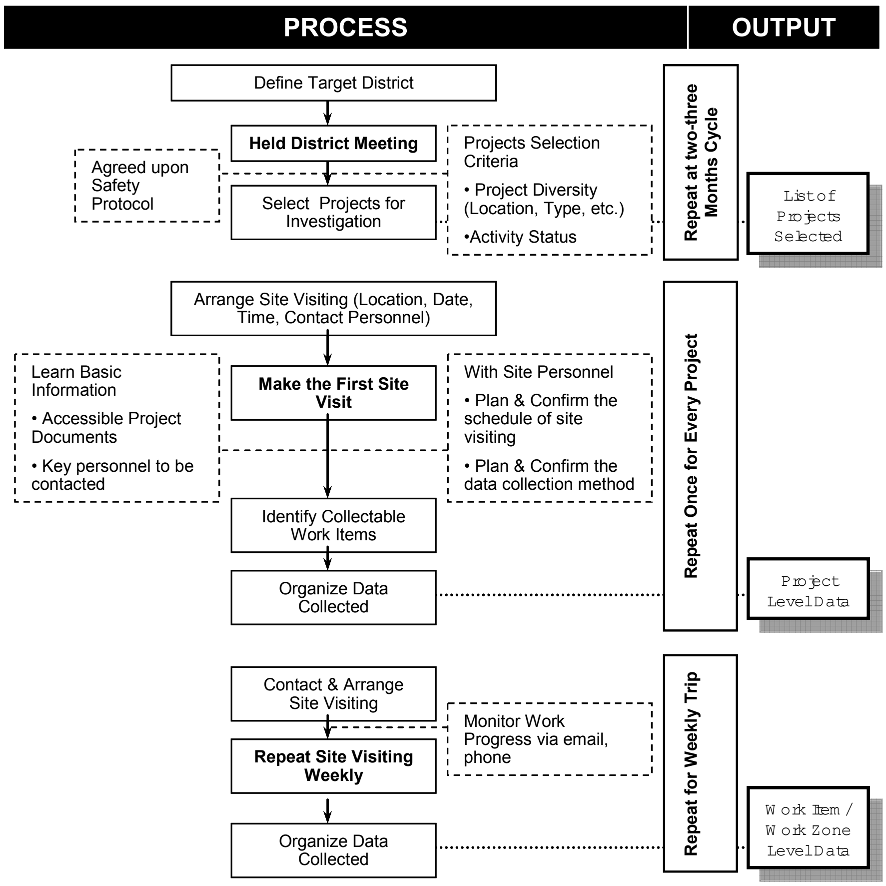


Figure 2.5 Structure of Factors Analyzed in Research

2.3.4 Summary of Data Collection Process

A total of sixty-three projects constructed by thirty-four contractors spread across seven TxDOT districts were selected. Projects were located across Texas and cost between $620,000 and $261 million. Projects were between 15 percent and 85 percent complete at the time of observation and had contract periods between 145 days to six years.

2.4 Rationale for Production Rate Computation

In all cases, production rates are defined in terms of output and crew work days, but by different formulae to accommodate differences in work items under observation.

The output value represents the quantity of work completed during a certain number of work days and is measured in units completed (i.e., each, span, or square feet). Although a minimal effort was needed to measure the output, clear guidelines were required to assess crew work days.

Production rates were calculated by dividing the total quantity by the time required to build that quantity. Thus, one data point represents a quantity being constructed in a period of time. For example, if 1,000 linear feet of pipe requires four days to construct, the production rate is 1,000 linear feet divided by four days, which is 250 linear feet per day (250 lf/day).

2.4.1 Correction for Delays and Crew Size

Delays are an inevitable part of any construction process, and thus simply calculating the total number of days and then dividing by the quantity yields unrealistic production rates that are not useful for TxDOT engineers. In order to eliminate such inconsistencies, the so-called the half-day rule was determined by the research team and TxDOT's PMC members. Crew work days were assessed as one whole work day if the delay effect caused by any of the factors amounted to less than two hours. When the delay was less than or equal to five hours but greater than two, the day was counted as a half-work day. Otherwise, it was counted as a non-work day. A work day having more than two hours of overtime was adjusted on the basis of actual overtime hours.

Table 2.4 Crew Work Day Computation — Half-Day Rule

Factors	**No Adjustment** *(Effect Embedded in the Production Rate)*	**Corrected** *(Effect isolated or adjusted)*
Weather (Rain, Too Wet, Snow, Wind etc) Unworkable Soil Condition Traffic Accident Construction Accident Equipment Down Time Material Unavailable Trade Problem Absenteeism	✓ **(IF Delay effect < ½ Day)**	✓ **(IF Delay effect ≥ ½ Day)**
Holidays, Non-Working Day, Non-Working Weekend, Day off		✓
Regional shortage(ROW, Unforeseen Condition, TxDOT Direction) Over-Time(>2 hours)		✓

Production rates were also adjusted according to crew size. Production rates that were gathered from larger crews were adjusted downward to fit the production rate of about one typical crew. Thus, production rates shown later reflect a standardized unit of crew day.

2.5 Statistical Methods of Data Analysis

The following sections discuss statistical techniques that were applied to analyze the data.

2.5.1 Descriptive Statistics and Box Plots

Descriptive statistics were often employed to summarize data such as mean, sum, count, and frequency of variables. In this research, data are shown on scatterplots to demonstrate relationships or associations between two variables. Nonrandom scatter in such plots suggest relationships in the data.

A box plot is a statistical summary that presents mean, median, quartile, outliers, and extreme values in a graphical format. Figure 2.6 is an annotated sketch of a box plot (SPSS Base 10.0 Applications Guide). The horizontal line in the shaded box represents the median or fiftieth percentile of the plotted sample. The dark circle highlights the mean of the targeted sample. The top and bottom ends of the box represent the third and first quartiles of the sample, respectively. The length of the box, from first quartile to third quartile, denotes the interquartile range (IQR). The horizontal line between third quartile and third quartile + 1.5 * IQR and between the first quartile and first quartile – 1.5 * IQR are the highest and lowest observed values, respectively, excluding outliers in the sample. Points beyond (third quartile + 1.5 * IQR) and under the (third quartile + 3 * IQR) as well as points under (first quartile – 1.5 * IQR) and beyond (first quartile – 3 * IQR) are outliers. Points beyond these outer limits are considered extreme values.

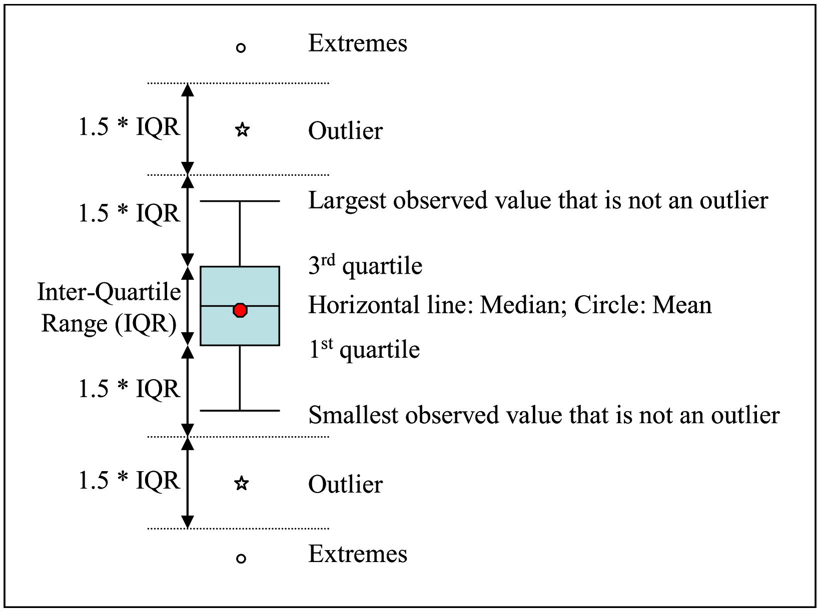


Figure 2.6 Annotated Sketch of the Box Plot

2.5.2 Test of the Difference of Mean Observed Production Rates and Average Contract Time Determination System Production Rates

Because few original data are available to determine the distribution of the production rate data in the CTDS study, the average CTDS production rates were compared with the mean observed production rate for the seven targeted work items. The one-sample *t* test was used for this comparison.

2.5.3 Driver Analysis

Procedures used for driver analysis are shown in Figure 2.8. Factors that were suspected to have significant effects on production rates and were known at the design stage were considered as candidate drivers. Once candidate drivers were identified, associated data were collected during regular job visits. Scatterplots were used to examine any relationships between observed production rates and each candidate driver. Drivers having no obvious relationship with observed production rates were excluded from further analysis. On the basis of the data attributes of the candidate drivers, two types of analysis approaches were used for further driver analysis. For those candidate drivers with continuous numerical data, regression analyses were conducted to identify drivers of production rates and to quantify their effects. For those candidate drivers with discrete numerical or categorical data, the analysis of variance (ANOVA) or *t* test was used to test the difference in mean production rate for the subsets in each candidate driver.

On the basis of the results of the statistical analyses, the drivers were identified. The quantitative effects of drivers on production rates were also investigated. In addition, the correlations between the identified drivers of each targeted item were computed to be used for reference when estimating effects of multiple drivers. If data were sufficient, multiple regression analysis was used to further investigate the interaction effects of multiple drivers.

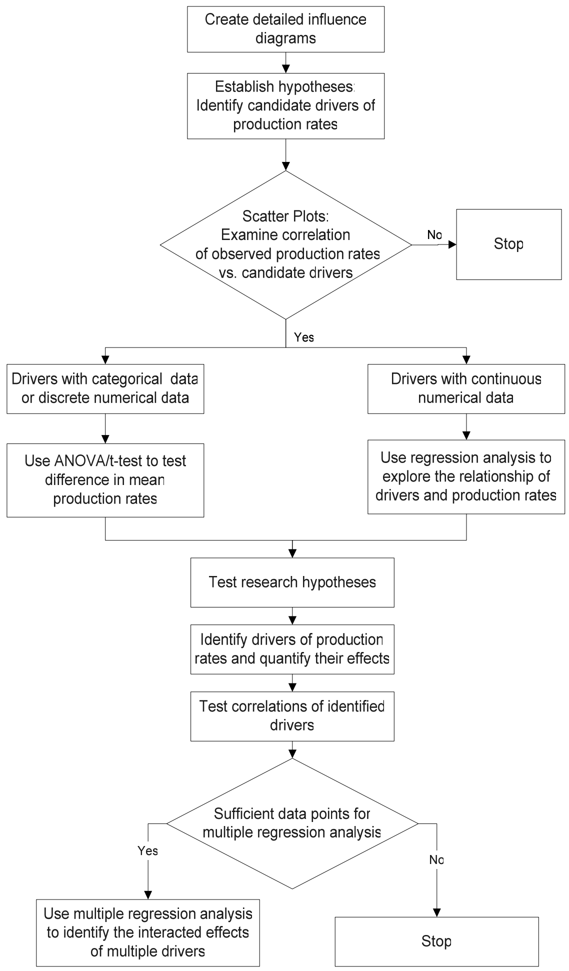


Figure 2.7 Flow Chart of Driver Analysis

2.5.3.1 Test of the Difference of Mean Observed Production Rates Between Subgroups of Candidate Drivers

The independent-samples *t* test is one of the most popular methods of testing the differences between two population means. Three basic assumptions should be examined before applying the *t* test. The three assumptions are as follows.

(1) The two samples are independent.
(2) Populations are normally distributed.
(3) There are equal standard deviations between the two populations.

If the two samples are not independent, other test methods such as the paired-sample *t* test may be used. The second assumption, that the populations are normally distributed, can be examined from Q–Q plots. If all data falls on a line with 45° of slope on the Q–Q plot, a typical normal distribution can be identified. If this assumption is violated, the results of the *t* test can be used only when the size of samples is reasonably large. The last assumption is that the standard deviations of the two tested populations should be equal. This assumption can be examined from the results of Levene's test in SPSS® v. 11.0 for Windows. The results of the *t* test may be incorrect if this assumption is violated, but the *t* test can have an accurate result if the sample sizes are equal under this circumstance. These methods were applied in this study to verify some of the research hypotheses and to identify some production rate drivers.

2.5.4 Regression Analysis

Once a linear or nonlinear relationship between two variables is observed from the scatterplot, a linear or nonlinear regression analysis should be performed to verify whether a relationship exists statistically. The form of estimating a regression model is $Y_i = b_0 + b_1 * X_{1i} + b_2 * X_{2i}$. Y_i is the dependent variable that a study is trying to predict. X_{1i} and X_{2i} are the independent variables. In advance of conducting a regression analysis, the sample size should be checked to verify whether data are sufficient to perform it.

According to a study conducted by Green (1991), the required sample size for a regression analysis can be determined by four values, which are α (the probability of making a Type I error), $1 - \beta$ (one minus the probability of making a Type II error), R^2, and number of predictors. Table 2.5 displays the required sample sizes to test the hypothesis that the population multiple correlation equals zero with a power of 0.8 and α of 0.05 based on power analysis (Green 1991). A regression model needs twenty-four data points for one predictor and thirty data points for two predictors when the α, $1 - \beta$, and R^2 values used to determine the statistical significance of a regression model are 0.05, 0.8, and 0.26, respectively. If the required R^2 used to determine the significance of a regression model increases, the number of data points can be reduced. In this study, the required R^2 is set as 0.34. Therefore, for this study a total of twenty data points are required to perform a simple regression analysis, and twenty-six data points are needed to perform a multiple regression analysis with two predictors. However, less than twenty data points may be also employed for a regression analysis if a higher R^2 is achieved.

Table 2.5 Sample Sizes Required to Test the Hypothesis that the Population Multiple Correlation Equals Zero with a Power of 0.80 and α of 0.05 (adopted from Green 1991)

Number of Predictors	**Sample Sizes Based on Power Analysis**		
	R^2 = 0.02	R^2 = 0.13	R^2 = 0.26
1	390	53	24
2	481	66	30
3	547	76	35
4	599	84	39
5	645	91	42
6	686	97	46
7	726	102	48
8	757	108	51
9	788	113	54
10	844	117	56
15	952	138	67
20	1066	156	77
30	1247	187	94
40	1407	213	110

In addition, the logarithmic model (Equation 2.1) and the power model (Equation 2.2) were employed to identify nonlinear relationships between selected cases with two variables. SPSS® v. 11.0 for Windows was used to perform the linear and nonlinear regression analyses.

$$\mathbf{Y_i = b_0 + b_1 * Log \;\; X_i} \quad (2.1)$$

$$\mathbf{Log \;\; Y_i = Log \;\; b_0 + b_1 * Log \;\; X_i} \quad (2.2)$$

Six steps are usually taken to perform a regression analysis. First, the dependent and independent variables should be checked to see whether they are approximately normally distributed. The normal distributions of independent variables and dependent variables are basic assumptions of a regression analysis. Violation of these assumptions would lead to a biased estimation caused by lack of information. Secondly, a scatterplot is developed to check for a plausible linear model, and a box plot is used to detect outliers. Outliers should be removed before performing a regression analysis because they impact the trend of the regression model. The third step is to fit the linear regression model and produce results of the regression analysis. In this step, the R^2, the adjusted R^2, and the p values are computed. The next step is to inspect the R^2 of the fitted model.

The coefficient of determination, or R^2, is also called the measurement of the goodness of fit of the regression line. The value of R^2 is always between 0 and 1, and indicates the proportion of variation of dependent variables that can be explained by the prediction model. The formula (Albright et al. 1999, p. 583) for calculating R^2 in a simple linear model is shown in Equation 2.3.

$$\mathbf{R^2 = 1 - \frac{\sum e_i}{\sum (Y_i - \overline{Y})^2}} \tag{2.3}$$

where $e_i = Y_i - \hat{Y}_i$ and $\hat{\mathrm{Y}}_\mathrm{i} = \mathrm{b}_0 + \mathrm{b}_1\mathrm{X}_\mathrm{i}$

Y_i : observed value; $\hat{Y}_i$: fitted value of Y_i

The fifth step is to inspect the results of testing coefficients for the fitted model. The *t* test is applied to test coefficients. The *p* values of the *t* tests should be used to check whether the coefficients of the fitted model are statistically different from 0. A *p* value less than 0.05 indicates that the null hypothesis of a coefficient being equivalent to zero can be rejected at the 95 percent confidence interval. In contrast, a *p* value not less than 0.05 represents that the tested coefficient is not statistically different from zero and, thus, there is no relationship between the dependent variable and the independent variable. The last step is to check for violations of model assumptions. Other than the approximate normal distribution of dependent and independent variables, three assumptions should be checked: (1) constant variance of errors, (2) normal distribution of errors, and (3) no high correlations between explanatory variables.

The constant variance of errors can be examined by plotting the scatterplot of the predicted value of the fitted model versus the residuals. Nonconstant variance of errors found in the regression model usually indicates the need for transformation of variables or adding another important variable. The normal distributions of variables and errors can be inspected by observing their Q–Q plots. If the data are perfectly normally distributed, the points in the Q–Q plot will "cluster around the 45° line. Any large deviations from a 45° line signal some type of non-normality" (Albright et al. 1999, p. 486).

2.5.5 Correlation Analysis

The Pearson product–moment correlation tests were used to check the correlations between the explanatory variables. The Pearson product–moment correlation, or γ, is a value between −1 and 1. A correlation equal to or near zero indicates no linear relationship existed between the two variables. On the other hand, a correlation with a magnitude close to 1 indicates a strong linear relationship.

2.6 Conclusion

The complete set of the finalized data collection tools are shown in the Appendices. Figure 2.8 summarizes the entire data collection, analysis, and conclusion process employed in this research.

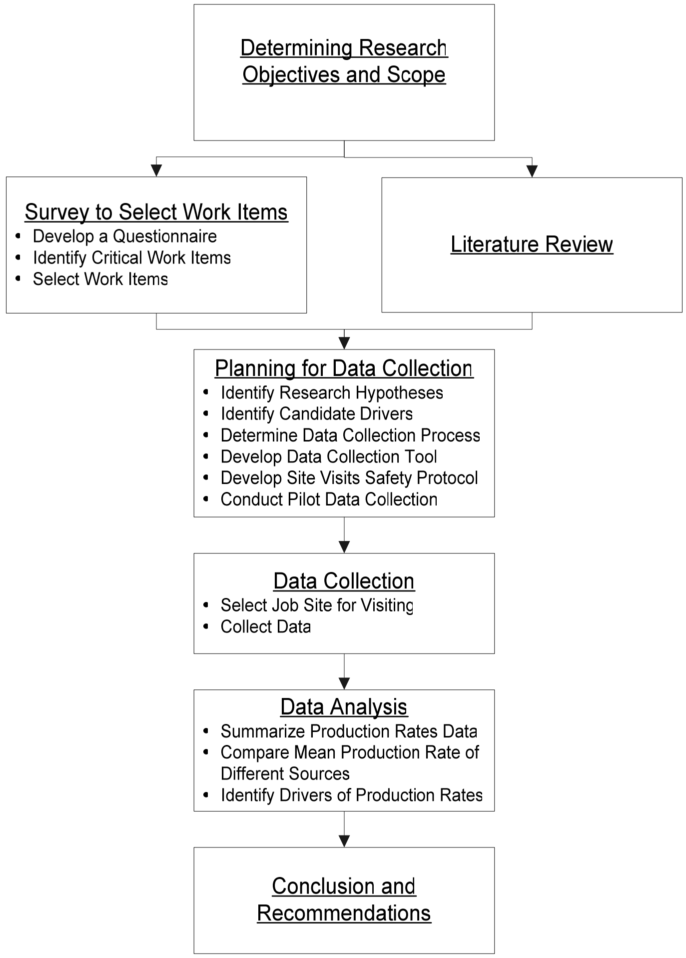


Figure 2.8 Research Methodology

3. DATA ANALYSIS: DESCRIPTIVE STATISTICS AND COMPARISON WITH CONTRACT TIME DETERMINATION SYSTEM

3.1 Data Point Information

Sixty-three projects in nine Texas Department of Transportation (TxDOT) districts were selected for the study. Weekly visits were scheduled for these projects over the time period indicated in Table 3.1. Ad hoc visits to some of these projects were also scheduled to collect more data on work items that had not reached the required number of data points. Table 3.1 summarizes the details of the scheduled visits, projects selected from each district, and the total number of data points.

Table 3.1 Details of Visits to Various Districts

Districts Visited	Dates of Scheduled Visits	Period of Ad Hoc Visits	Total Time Period of Visit (months)	Total Number of Projects	Total Number of Work Items Found	Total Number of Data Points
San Antonio	3/1/02 – 7/31/02	4/5/04 – 7/20/04	4	5	19	57
Yoakum	7/1/02 – 9/1/02	—	3	3	6	21
Austin	9/1/02 – 2/10/03	8/7/03 – 4/4/04	5	6	19	134
Dallas	11/7/02 – 2/25/03	5/5/04 – 7/12/04	5	8	18	105
Houston	3/20/03 – 10/16/03	1/5/04 – 5/5/04	7	16	24	192
Lubbock	9/16/03 – 11/06/03	—	2.5	3	10	24
Waco	11/13/03 – 02/07/04	—	4	11	17	98
Corpus Christi	4/13/03 – 10/1/03	4/4/04 – 6/20/04	5	6	8	54
Bryan	2/28/04 – 5/20/04	—	3.5	5	7	16

There were a minimum of three to a maximum of sixteen projects selected from each district. The total number of projects that were selected from each district varied. There are two main reasons for such variation. First, there were different numbers of projects under construction during the period of scheduled visits. For example, there were more than 200 highway projects underway in Houston at the period of scheduled visits, whereas there were only forty highway projects underway in Lubbock. Second, projects were selected only if the relevant work items were found in these projects. Fewer projects in a district meant that the chances of finding the twenty-six investigated work items from the district were much lower. Projects were not selected if none of the twenty-six work items were under construction during the period of scheduled visits.

The research team had also carefully selected relevant projects in each district so that there were sufficient data points to represent the production rates in the rural, urban, and metropolitan regions.

Table 3.2 documents the total number of data points for the twenty-six work items, the total quantity for all the data points, the units adopted by the research, the total working days for all data points, and the total number of districts and projects from which the data were collected from.

Table 3.2 Consolidated Data Points for Different Work Items

Item No.	Work item	Total No. of Data Points	Total Quantity	Units	Total No. of Work Days	Total No. of Districts	Total No. of Projects
110	Excavation	26	154,570	cy	113.5	5	12
132	Embankment	34	237,414	cy	213.5	5	16
247, 276	Aggregate base course	31	444,525	Lift–sy	135.5	7	16
260	Lime treatment subgrade	32	371,235	sy	229.5	6	18
340, 345	Hot mix asphaltic concrete	32	61,152	Ton	74	6	19
360-1	Concrete paving (slip form)	23	169,357	sy	118.5	3	10
360-2	Concrete paving (conventional form)	22	22,148	sy	68.5	5	9
409	Prestressed concrete piling	22	1,388	Piles	73.5	2	8
416	Drilled shaft foundation	38	19,733	lf	167	8	17
420-1	Footing	15	22	Footings	52	4	6
420-2	Column — rectangle	19	33	Columns	70.5	4	5
420-2	Column — round	19	126	Columns	56	4	8
420-3	Cap	40	59	Caps	258.5	5	13
420-4	Abutment (cast in place)	10	10	Abutments	44	2	5
422	Bridge deck (cast in place)	28	435,320	sf	542.5	6	17
423	MSE wall	50	107,604	sf	242	6	13
423-1	MSE wall — copings	11	7,084	lf	30	3	6
423-2	MSE wall — footings/leveling pads	11	13,163	lf	43.5	3	7
425	Beam erection	29	113	Spans	37	6	19
462-1	Precast concrete box culverts	49	34,226	lf	215	7	17
462-2	Cast in place concrete box culverts	12	3,310	lf	272	4	7
464-1	RCP 18–42 in.	50	30,013	lf	231	8	22
464-2	RCP 48–72 in.	21	11,187	lf	140	5	10
465	Inlets and manholes	37	278	Inlets/ manholes	129	7	21
466	Wing wall/head wall	28	6,397	sf	194	5	10
529	Concrete curb and gutter	12	23,307	lf	25	4	6
666/668	Pavement markings	0	Information gathered through interviews				

The total number of data points for each of the work items ranged from a minimum of ten to a maximum of fifty. The Total Quantity column highlights the total quantity of works that was recorded by this research. The Total Number of Work Days column records the total number of work days that were tracked by the research team for all the data points. The Total Number of Districts and the Total Number of Projects columns record the total number of districts and projects, respectively, from which the work items were found during the scheduled visits.

3.1.1 As-Built Data

Production rates calculated from historical records were also used for the data analyses. These historical records came from four selected projects. The contractors from these projects were found to have kept very reliable records of the quantities of work and the time spent to complete those quantities. These contractors were also very willing to share these data with the research team. The production rates were calculated by dividing the quantities of work by the total time for completing these work quantities. These projects were labeled as As-Built 1, As-Built 2, As-Built 3, and As-Built 4. Detailed descriptions of the as-built data are below.

- As-Built 1 and As-Built 2
    - Data came from contractors' historical records between March 2002 and August 2002. The projects were 55–80 percent complete during that time period.
    - Relevant documents, such as construction plans and workers' time cards, were also investigated to ensure consistency with the historical records.

- As-Built 3
    - Source of these data came from contractor's historical records between August 2001 and November 2002. The projects were 30–50 percent complete during that time period.
    - Relevant documents, such as construction plans and workers' time cards, were also investigated to ensure consistency with the historical records.

- As-Built 4
    - The data were accumulated from six completed projects.
    - The data came from the contractors' as-built schedules that were submitted to TxDOT in the format of Primavera™.
    - However, no documents were available to validate the accuracy of these data.

Because historical records from field operations rarely included records on production rate drivers, the production rates from these historical records were not used to analyze production rate drivers and to model the relationships between drivers and production rates.

3.2 Differences Between Contract Time Determination System and Observations

Various differences between the Contract Time Determination System (CTDS) and the observations are analyzed in this section. Three comparisons were made between CTDS and the observed data. First, an analysis was conducted to compare the differences between the units adopted by CTDS and those adopted by this research. Second, the differences between the work scope for the selected work items adopted by CTDS and the work scope adopted by this research were analyzed. Third, the differences between CTDS production rates, the observed production rates from this research, and the production rates calculated from the historical records were compared. The key differences are summarized at the end of this chapter.

3.2.1 Field Daily Production Rates: Units Applied and Definitions

Analysis of the adopted units of CTDS and this research highlighted two main differences.

- First, this research and CTDS adopted *crew day* and *day* for their time units, respectively. Crew day was adopted by this research to indicate that increasing crew size can increase production rates. The CTDS time unit of day does not clearly indicate whether the production rates are applicable to any of the crew sizes. Thus, production rates shown and analyzed in the following chapters of this research are for one crew size.
- Second, there are differences in the units adopted for flexible base, cement treatment base, concrete structures, precast prestressed concrete structural members, prestressed concrete pilings, reinforced concrete slab and concrete box culverts. The Research Management Committee for this research adopted different units for three reasons. First, the new units are able to improve the efficiency of the time estimation process. Second, these units can be more easily integrated into the production rate models that are developed by this research. Third, these units allow for better visualization of the work items during the production rate estimation process.

Table 3.3 summarizes the units adopted by CTDS and this research. Units that are different in both systems are highlighted in bold in the table.

Table 3.3 Units Adopted by Contract Time Determination System and This Research

WI#	Major Work Items	Production Rate Unit Adopted by CTDS	Production Rate Unit Adopted by Research
110	Excavation	cy/day	cy/crew day
132	Embankment	cy/day	cy/crew day
247	**Flexible base**	**sy/day**	**Lift-sy/crew day**
260	Lime treatment (road mixed)	sy/day	sy/crew day
276	**Cement treatment (plant mixed)**	**sy/day**	**Lift-sy/crew day**
340	Dense graded hot mix asphalt (method)	Ton/day	Ton/crew day
360	Concrete pavement (conventional and slip form)	sy/day	sy/crew day
409	**Prestressed concrete piling**	**lf/day**	**ea./crew day**
416	Drilled shaft foundations	lf/day	lf/crew day
420	**Concrete structures — footing, column, cap and abutment**	**cy/day**	**ea./crew day**
422	**Reinforced concrete slab — bridge deck**	**cy/day**	**sf/crew day**
423	Retaining wall — specifically MSE wall	sf/day	sf/crew day
425	**Precast prestressed concrete structural members — beam erection**	**lf/Day**	**Spans/crew day**
450	Railing — bridge railing	lf/day	lf/crew day
462	Concrete box culverts and storm drains (both cast in place and precast)	cy/day	lf/crew day
464	Reinforced concrete pipe	lf/day	lf/crew day
465	Manholes and inlets	ea./day	ea./crew day
466	Head walls and wing walls	sf/day	sf/crew day
529	Concrete curb, gutter and combined curb and gutter	lf/day	lf/crew day
666/668	Reflectorized pavement markings/prefabricated pavement markings	lf/day	lf/crew day

3.2.2 Field Daily Production Rates: Differences in Scopes of Work Items

Scope of work item describes the extent of the construction process that is included in the production rate measurement of the work items. Excluding or including any part of the process could result in significant differences in the measured production rates.

There are several differences between the scope of work items adopted by CTDS and that adopted by this research. The tables below summarize these differences. However, no adjustments were made to the affected CTDS production rates, because it is difficult to carry such an adjustment.

Table 3.4 Scope Differences Between Contract Time Determination System and the Research: 100 Items and 200 Items

WI #	Major Work Items	Scope Included in CTDS	Scope Determined as Useful by Research	Differences
110	Excavation	The removal and transporting of in situ soils on the construction site using mechanical equipment	From removing topsoil/starting the excavation of any work phase to completing subgrade/reaching the planned elevation of the working phase	None
132	Embankment	The placing and compaction of soil on the construction site using mechanical equipment	From placing the first load of embankment material to completing subgrade/ reaching the planned elevation of the working phase	None
247	Flexible base	The placement and compaction of flexible base material	From placing the first load of base material to finishing subgrade	None
260	Lime treatment (road mixed)	The placement, mixing, and compaction operations involved in the lime stabilization of highway subgrade soils.	From spreading lime/cutting and pulverizing subgrade to finishing subgrade	First curing is not included in the CTDS rate but it is in this research
276	Cement treatment (plant mixed)	The placement, mixing, and compaction of cement-treated base materials	From placing the first load of base material to finishing subgrade	None

Table 3.5 Scope Differences Between Contract Time Determination System and the Research: 300 to 420 Items

WI#	Major Work Items	Scope Included in CTDS	Scope Determined as Useful by Research	Differences
340	Dense graded hot mix asphalt (method)	The laydown and compaction of hot mix asphalt concrete base course material	From placing the first load of hot mix asphalt material to completing compaction	None
360	Concrete pavement (conventional and slip form)	The layout, reinforcing, placing, curing, and jointing of Portland cement concrete pavement	From setting string line to completing concrete placement	Curing is included in the CTDS rates but not in this research
409	Prestressed concrete piling	Includes installation of piling for bridge foundation but it is silent about whether the rate includes equipment setup time for piling	The rate is similar to that defined by CTDS because it is applicable to bridge foundation only. The rate also includes equipment setup time	The only unclear area is whether the rate in CTDS includes equipment setup
416	Drilled shaft foundations	No mention in CTDS	From equipment setup, drilling, casing, handling and placing of reinforcement, handling and placing of concrete and tub removal	Not sure
420	Concrete structures — footing	The layout, forming, reinforcing, placing, curing, and removing forms for reinforced concrete bridge footings	From starting excavation to placement of concrete	Layout/curing/ removing forms
420	Concrete structures — column/cap	The layout, forming, reinforcing, placing, curing and removing forms for reinforced concrete bridge columns, caps, and bents	From starting false work or form work to placement of concrete	Layout/curing/ removing forms

Table 3.6 Scope Differences Between Contract Time Determination System and the Research: 422 to 464 Items

WI#	Major Work Items	Scope Included in CTDS	Scope Determined as Useful by Research	Differences
422	Reinforced concrete slab — bridge deck	The layout, forming, reinforcing, placing, curing and removing forms for reinforced concrete bridge decks (The production rates have been set to include time for all components of the deck, including precast plank under slab; thus the full depth of the deck is used to calculate quantity)	From starting false work or forming system to placement of concrete	Layout/curing/ removing forms
423	Retaining wall — specifically MSE wall	The layout, forming, reinforcing, placing, curing and removing forms for cast in place reinforced concrete retaining walls	The grading and compacting of foundation to removal of placing tie strips on only precast MSE walls	The main difference is that CTDS rates are for cast in place walls whereas the research looks only at MSE walls
425	Precast prestressed concrete structural members — beam erection	Erection of premanufactured bridge beams by crane	From lifting the first beam to placing the last beam	None
450	Railing — bridge railing	For cast in place concrete bridge handrails	For slip form bridge rail	Totally different / not comparable
462	Concrete box culverts and storm drains (both cast in place and precast)	The excavation, installation, and backfilling of cast in place concrete box culverts on the construction site (If precast units are used, the units should be changed to lf and appropriate production rates should be substituted)	The excavation, installation, and backfilling of drainage or sewer pipe system on the construction site using precast or cast in place culverts	Cast in place in CTDS
464	Reinforced concrete pipe	The excavation, installation, and backfilling of drainage or sewer pipe system on the construction site using manufactured pipe	The excavation, installation, and backfilling of drainage or sewer pipe system on the construction site using manufactured pipe	None

Table 3.7 Scope Differences Between Contract Time Determination System and the Research: 465 to 668 Items

WI#	Major Work Items	Scope Included in CTDS	Scope Determined as Useful by Research	Differences
465	Manholes and inlets	The installation of premanufactured inlets and manholes for drainage and sewer systems on the construction	The research covers the installation of all cast in place and precast inlets and manholes and applicable only to sewerage pipe extension	Inclusion of cast in place inlets and manholes for this research and rates for the research includes only pipe extension
466	Head walls and wing walls	No mention in CTDS	Excavation, base preparation, forms and reinforcement installation, handling and placing of concrete and apron, curing, removal of forms and backfills	Not sure
529	Concrete curb, gutter and combined curb and gutter	The layout and construction of new roadway curb and gutter using automated equipment	From setting up string line/placing concrete to finishing	Not comparable
666/668	Reflectorized pavement markings/prefabricated pavement markings	The application of thermoplastic pavement marking materials to a highway pavement (If the markings are made using paint or reflectors, the production rates need to be adjusted accordingly)	None	Not comparable

3.2.3 Field Daily Production Rates: Contract Time Determination System and Research Rates

The production rates in the CTDS were represented in three values: low, mean, and high. These values were calculated from the survey inputs, but the calculation technique was not documented in the report.

Similarly, three such values were also taken from the observed production rates. The low and high values were the lowest and highest observed production rates, and the mean value was calculated by summing all the observed production rates and dividing the summed rates by the total number of data points. The following tables summarize these production rates.

Table 3.8 Contract Time Determination System Production Rates

WI#	Major Work Items	Unit	CTDS Production Rates		
			Low	**Mean**	**High**
110	Excavation	cy/day	1,200	3,400	7,000
132	Embankment	cy/day	1,200	3,500	7,000
247	Flexible base	sy/day	1,500	3,000	4,500
260	Lime treatment (road mixed)	sy/day	2,000	4,000	4,500
276	Cement treatment (plant mixed)	Ton/day	1,500	3,000	4,500
340	Dense graded hot mix asphalt (method)	Ton/day	500	1,200	4,500
360	Concrete pavement (conventional and slip form)	sy/day	1,000	3,000	5,000
409	Prestressed concrete piling	lf/day	200	300	400
416	Drilled shaft foundations	lf/day	200	300	400
420	Concrete structures — footing, column, cap, and abutment	cy/day	4	7	10
422	Reinforced concrete slab — bridge deck	cy/day	6	10	14
423	Retaining wall — specifically MSE wall	sf/day	100	150	200
425	Precast prestressed concrete structural members — beam erection	lf/day	150	200	250
450	Railing — bridge railing	lf/day	150	200	300
462	Concrete box culverts and storm drains (both cast in place and precast)	cy/day	10	15	20
464	Reinforced concrete pipe	lf/day	100	200	300
465	Manholes and inlets	ea./day	1	2	3
466	Head walls and wing walls	sf/day	100	150	200
529	Concrete curb, gutter and combined curb and gutter	lf/day	—	—	—
666/668	Reflectorized pavement markings/prefabricated pavement markings	lf/day	5,000	10,000	20,000

Table 3.9 Observed Production Rates

Item #	Work item	Units Adopted by Research	Observed Production Rates		
			Min	Mean	Max
110	Excavation	cy/crew day	199	1,163	3,558
132	Embankment	cy/crew day	249	1,097	3,000
247	Flexible base	Lift-sy/crew day	526	2,725	5,624
260	Lime treated subgrade	sy/crew day	82	1,563	3,722
276	Cement treated base	Lift-sy/crew day	1,416	4,050	6,500
340, 345	Hot mixed asphaltic concrete	Ton/crew day	158	817	1,460
360-1	Slip form concrete pavement (CRCP only)	sy/crew day	462	1,253	2,154
360-2	Conventional form concrete pavement	sy/crew day	30	283	582
409	Prestressed concrete piling	ea./crew day	1.75	6.40	10.67
416	Drilled shaft foundation	lf/crew day	40.00	111.60	278.75
420-1	Footing	ea./crew days	0.7	2.6	5
420-2	Column — rectangle	ea./crew days	0.7	2.9	6.5
420-2	Column — round	ea./crew days	0.2	0.5	1.3
420-3	Cap	ea./crew days	1.3	5	11.5
420-4	Abutment (cast in place)	ea./crew days	2	4.4	8.5
422-1	Bridge deck (cast in place)	sf/crew day	305	895	2,157
423	MSE wall	sf/crew day	225.00	453.50	1,164.25
423-1	MSE wall — copings	lf/crew day	150.50	284.10	352.94
423-2	MSE wall — footings/leveling pads	lf/crew day	67.73	178.09	300.00
425	Beam erection	Spans/crew day	1	3.2	6.5
450	Bridge railing	lf/crew day	89	1,366	2,676
462-1	Precast concrete box culverts	lf/crew day	14.40	141.98	322.40
462-2	Cast in place concrete box culverts	lf/crew day	1.83	10.36	16.28
464-1	RCP 18–42 in.	lf/crew day	36.00	138.67	189.37
464-2	RCP 48–72 in.	lf/crew day	9.00	94.92	193.80
465	Inlets and manholes	ea./crew day	0.20	1.84	3.00
466	Wing wall/head wall	sf/crew day	13.50	35.37	92.31
529	Concrete curb and gutter	lf/crew day	128	871	1,580
666/668	Pavement markings				

Significant differences could be observed by comparing the rates in both tables. For example, the CTDS low, mean, and high production rates for excavation are 1,200, 3,400, and 7,000 cy/day, respectively, but research observations found that the low, mean, and high production rates were 199, 1,163, and 3,558 cy/crew day, respectively. This example highlights that there are significant differences between production rates.

3.2.4 Field Daily Production Rates: Box-Whisker Plots of Contract Time Determination System, Observed, and As-Built Rates

Box-whisker plots were employed to allow for better visualization of the differences between the CTDS, the observed, and the as-built production rates. These plots are shown in Figures 3.1 to 3.21. The plots were prepared for work items only if similar units were found in the CTDS and observations. As-built information for some of the work items was also not available, and thus the as-built rates of these items were not plotted.

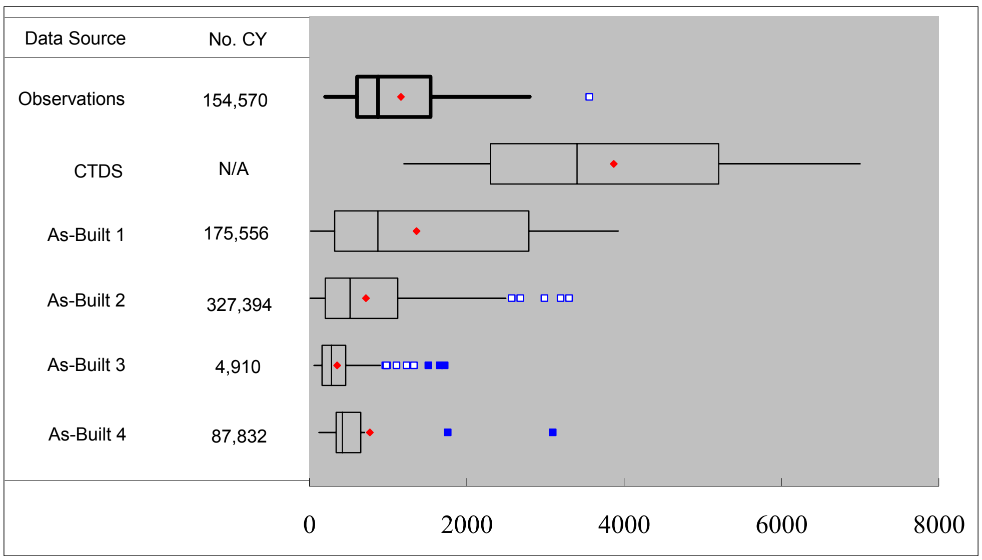


Figure 3.1 Production Rates Comparison — Excavation (cy/Crew Day)

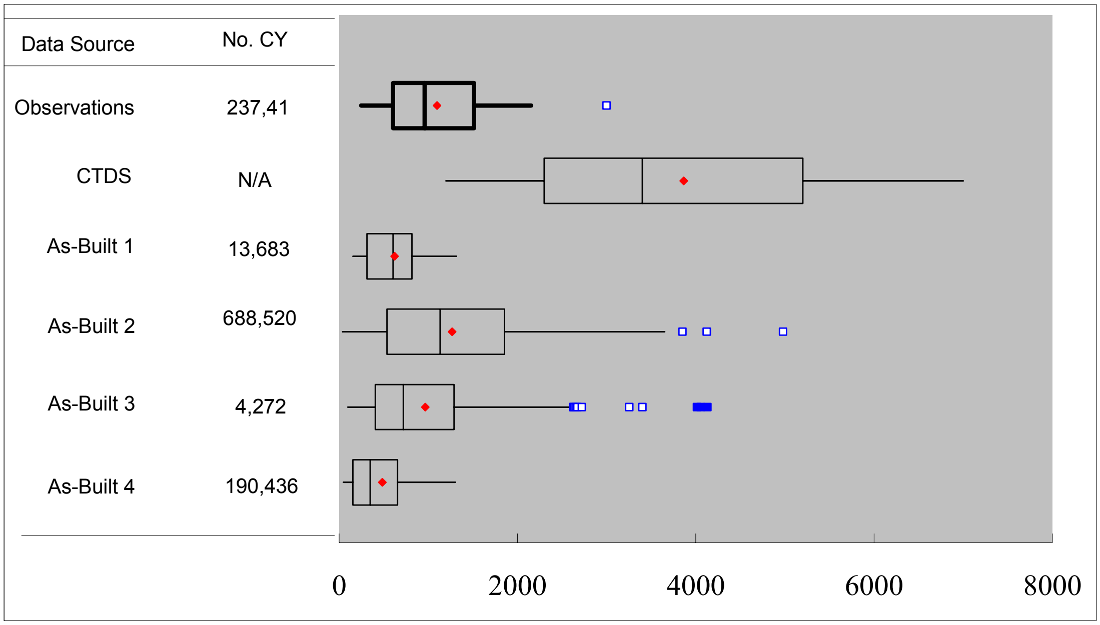


Figure 3.2 Production Rates Comparison — Embankment (cy/Crew Day)

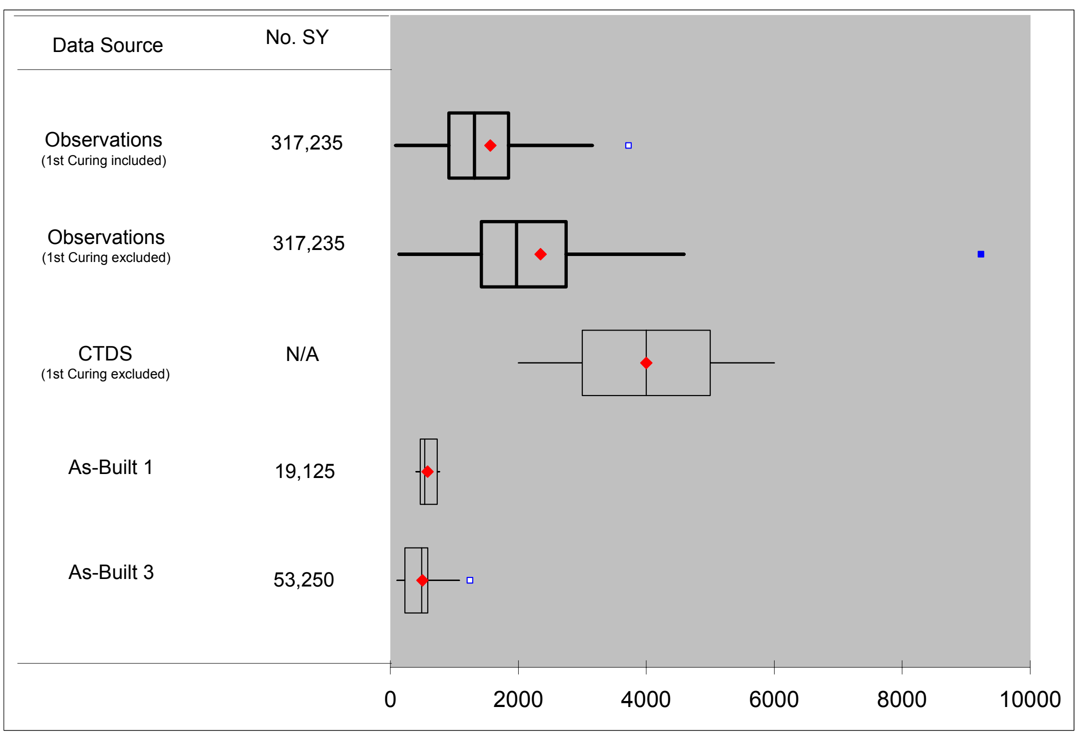


Figure 3.3 Production Rates Comparison — Lime Treated Subgrade (sy/Crew Day)

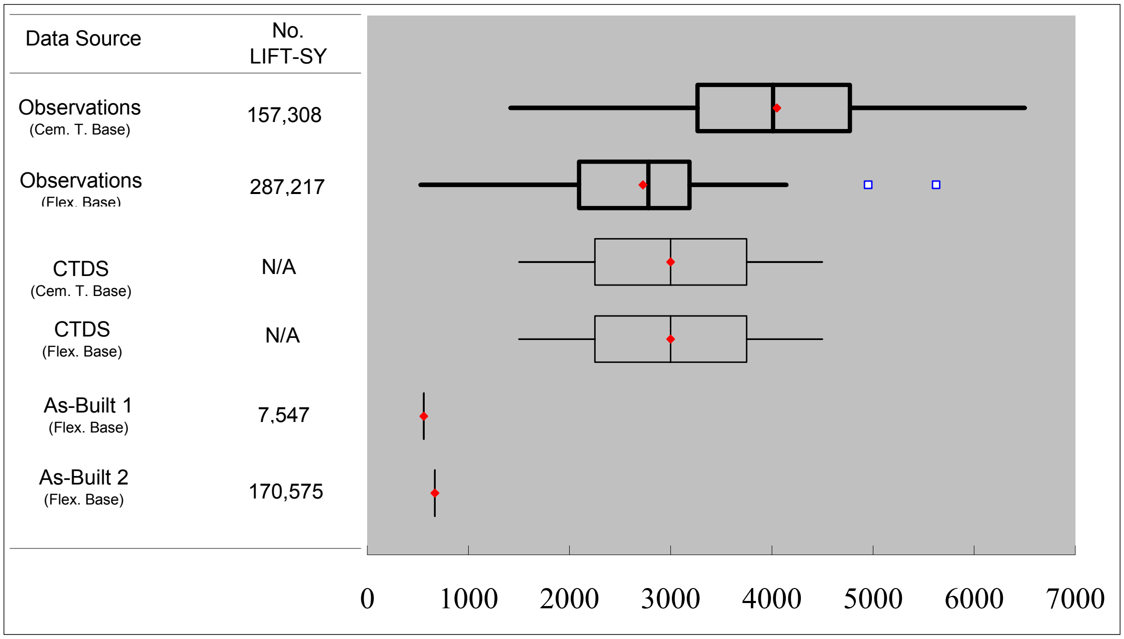


Figure 3.4 Production Rates Comparison — Aggregate Base (Lift-sy/Crew Day)

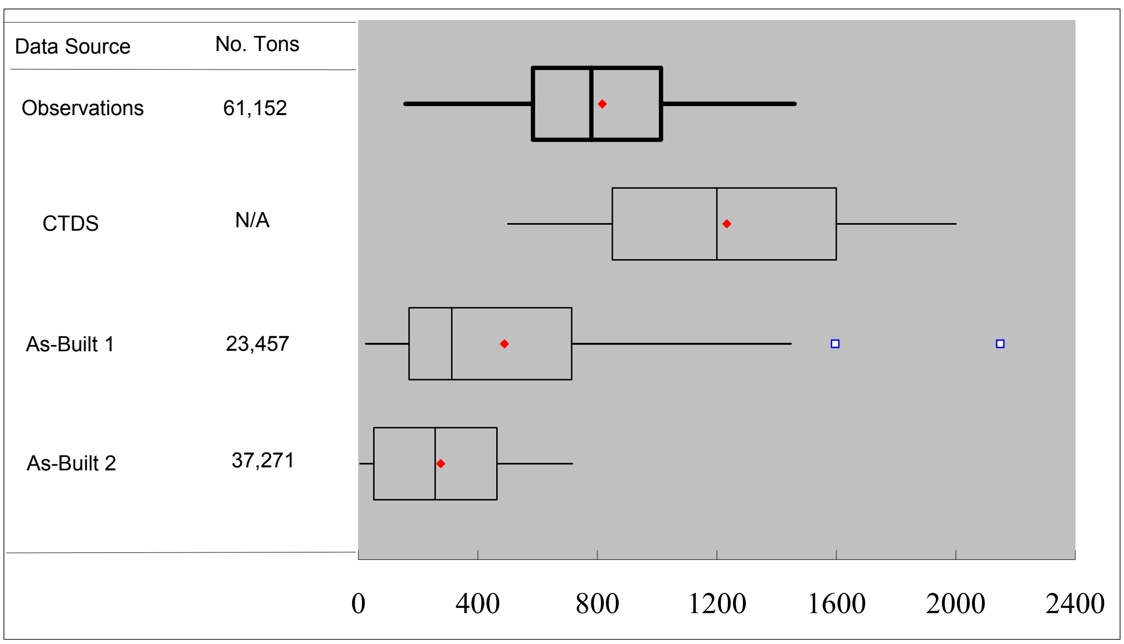


Figure 3.5 Production Rates Comparison — Hot Mix Asphalt (Ton/Crew Day)

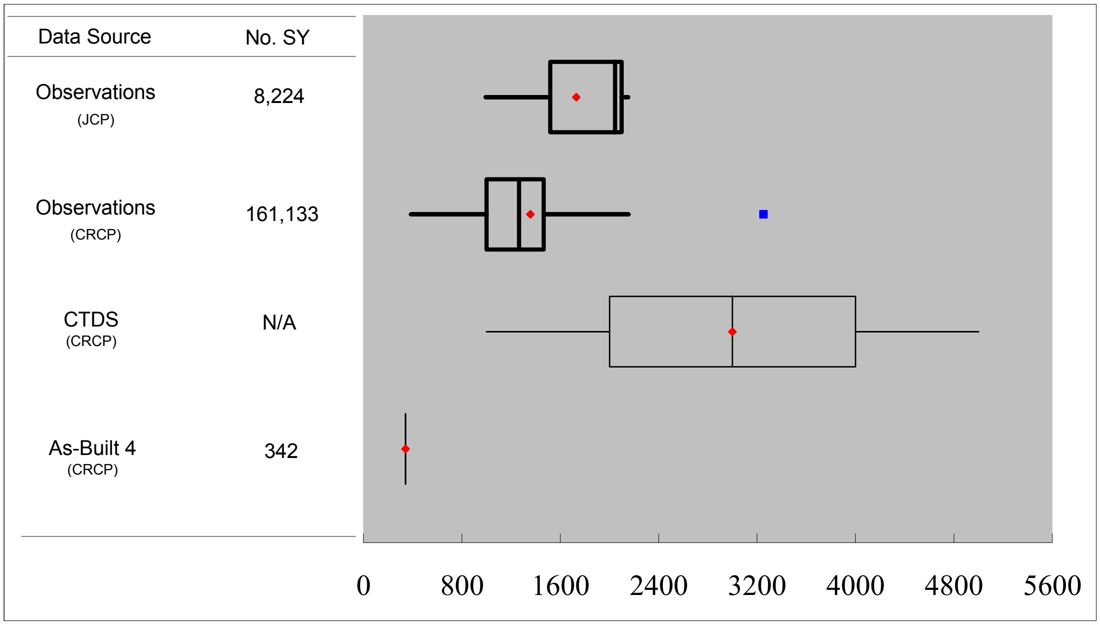


Figure 3.6 Production Rates Comparison — Slip Form Concrete Pavement (sy/Crew Day)

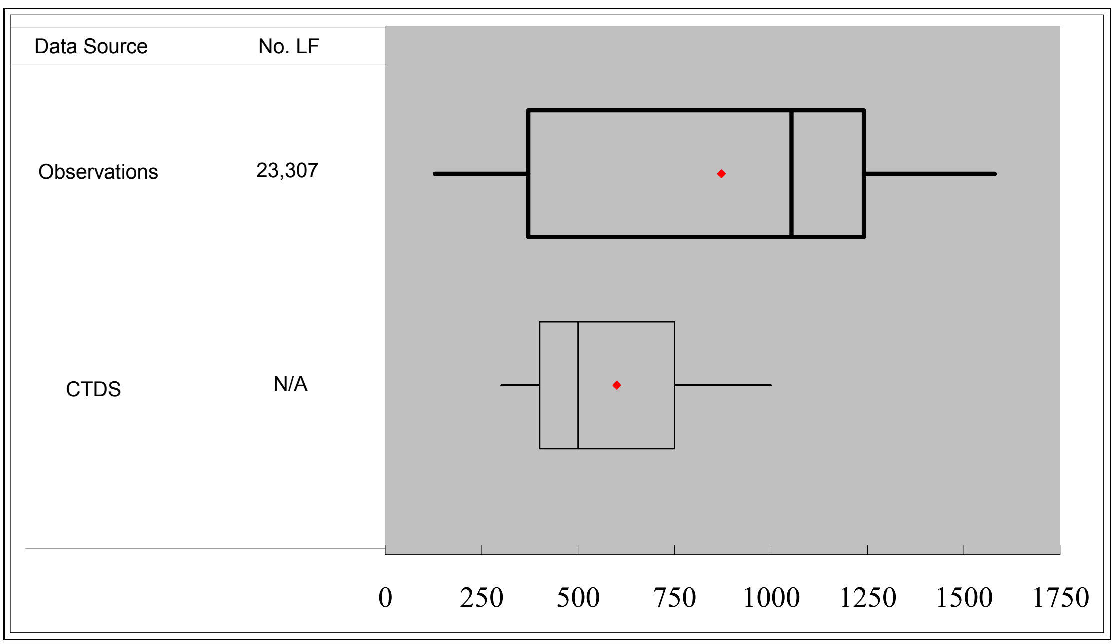


Figure 3.7 Production Rates Comparison — Concrete Curb and Gutter (cy/Crew Day)

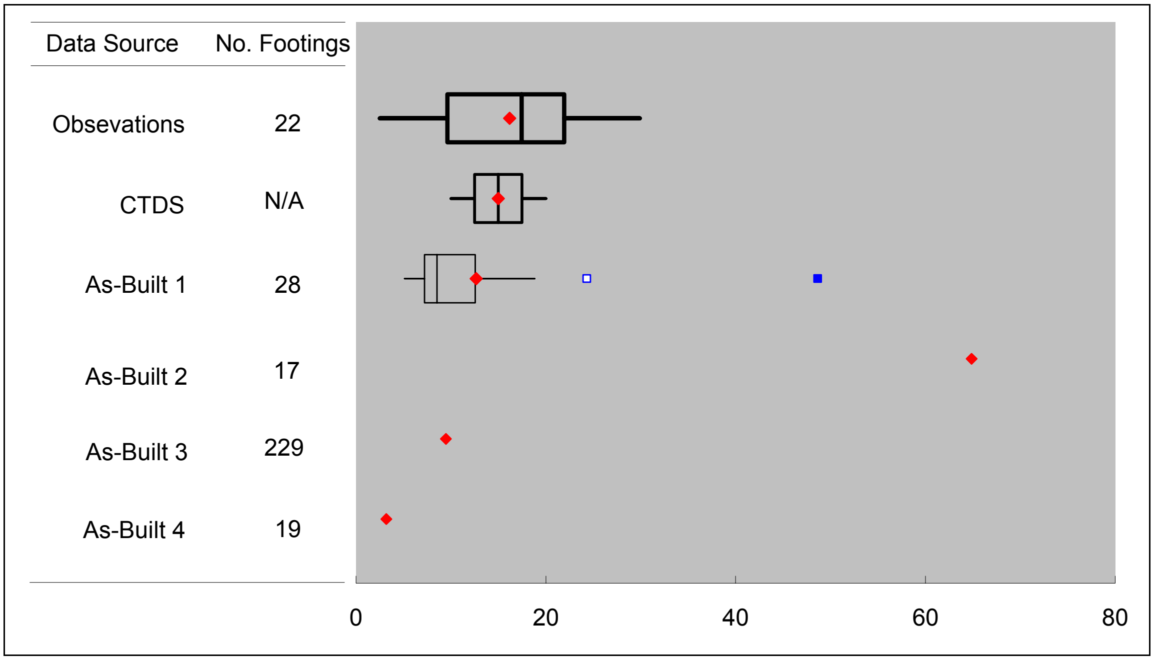


Figure 3.8 Production Rates Comparison — Footing (cy/Crew Day)

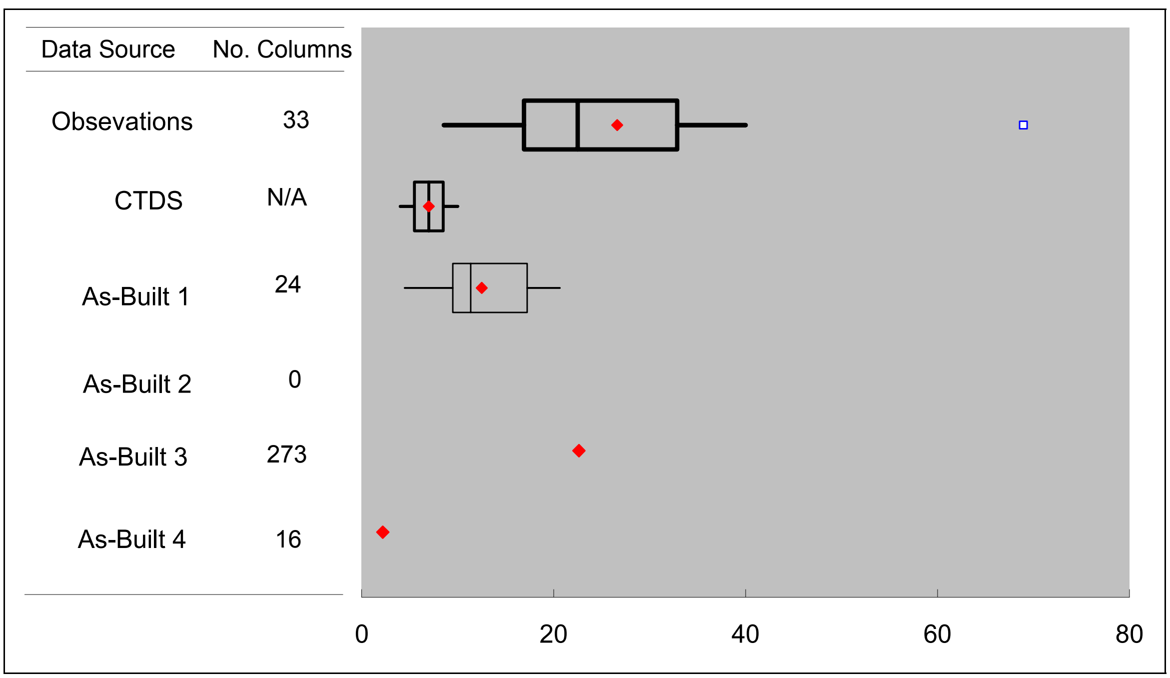


Figure 3.9 Production Rates Comparison — Column — Rectangle (cy/Crew Day)

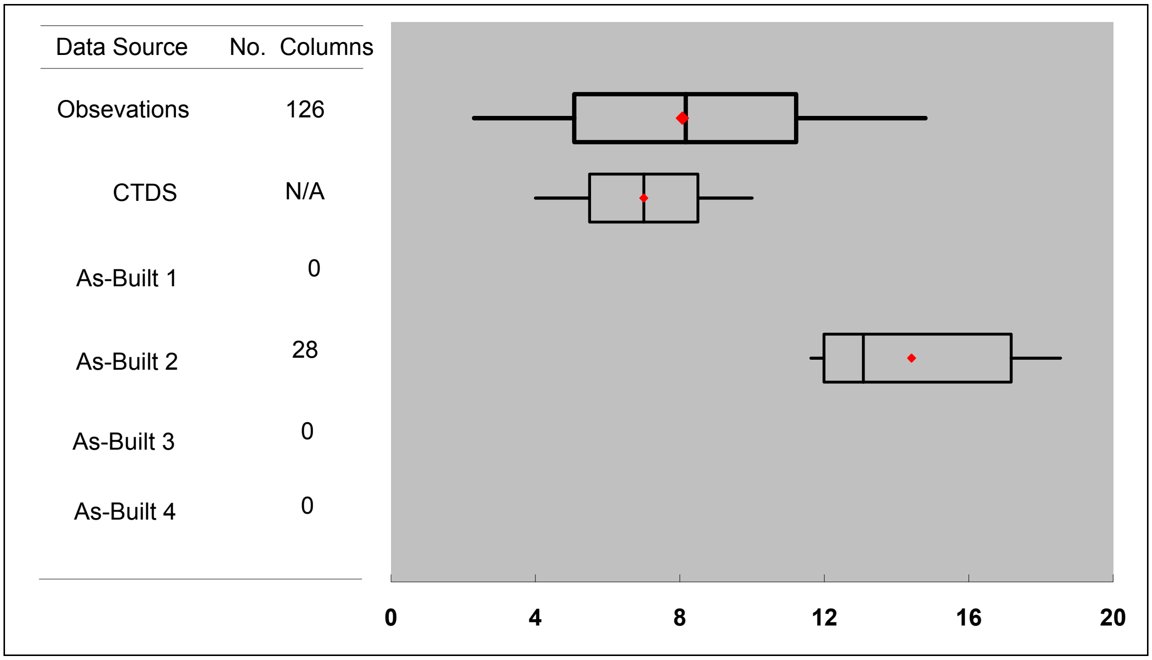


Figure 3.10 Production Rates Comparison — Column — Round (cy/Crew Day)

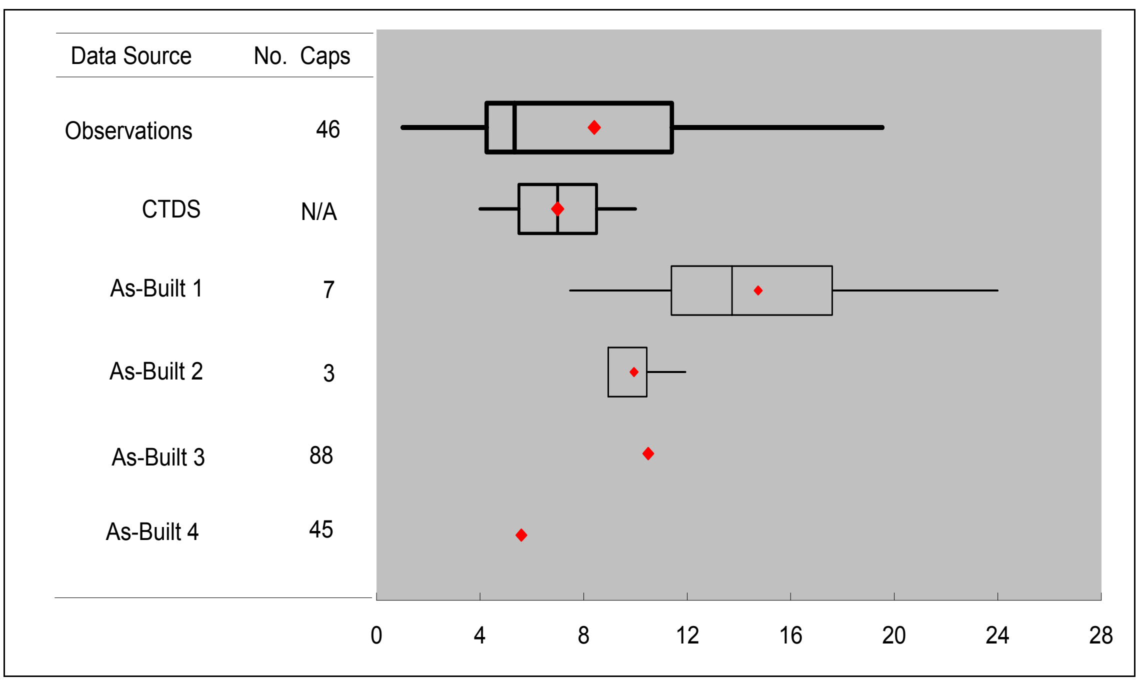


Figure 3.11 Production Rates Comparison — Cap (cy/Crew Day)

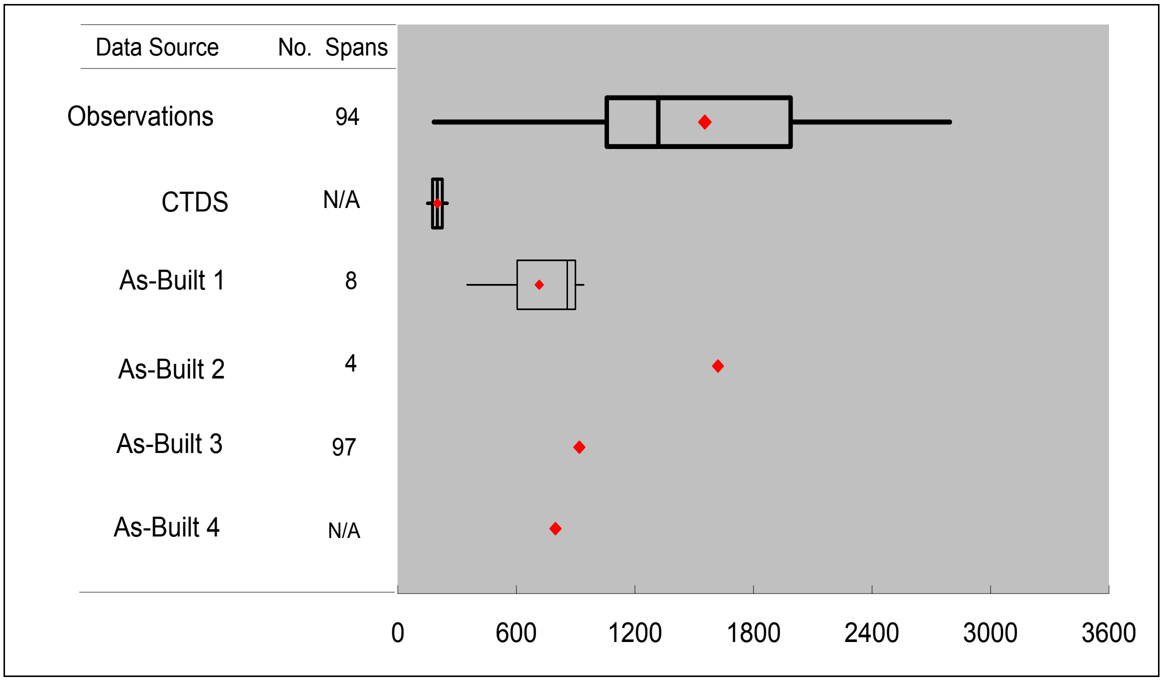


Figure 3.12 Production Rates Comparison — Beam Erection (lf/Crew Day)

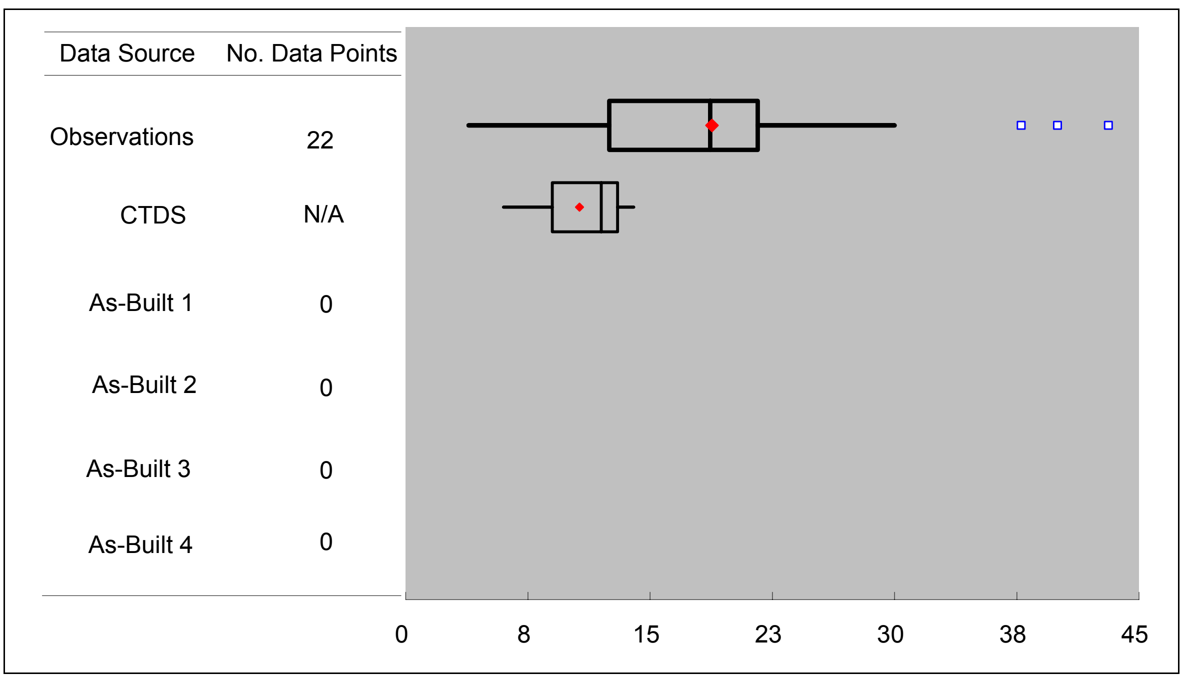


Figure 3.13 Production Rates Comparison — Bridge Deck (cy/Crew Day)

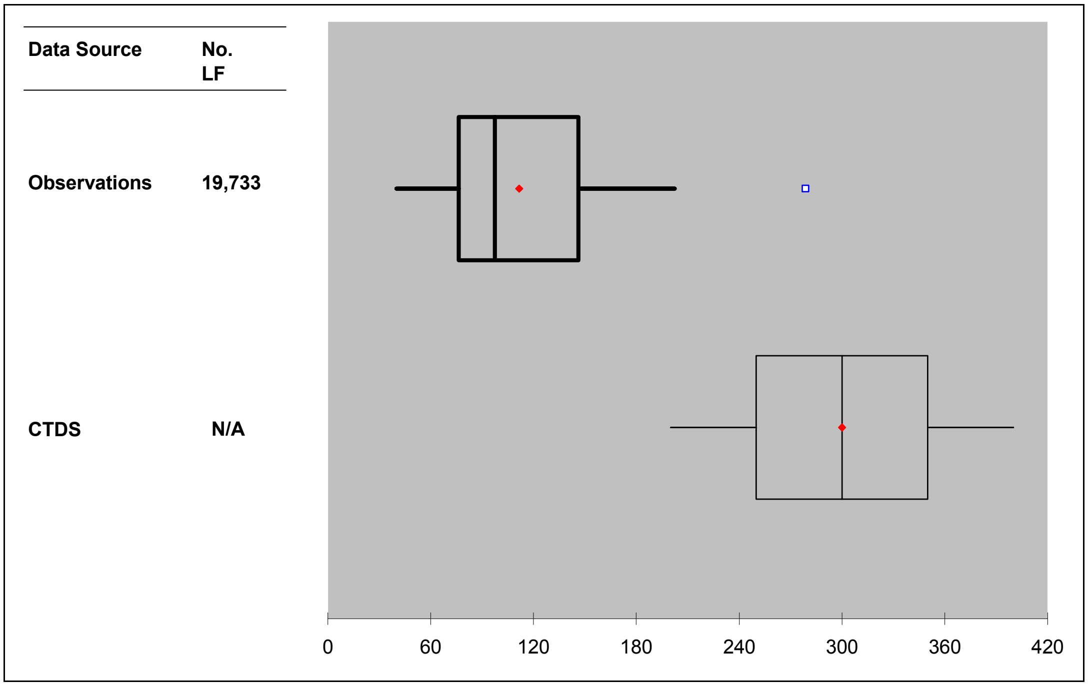


Figure 3.14 Production Rates Comparison — Drilled Shaft Foundation (lf/Crew Day)

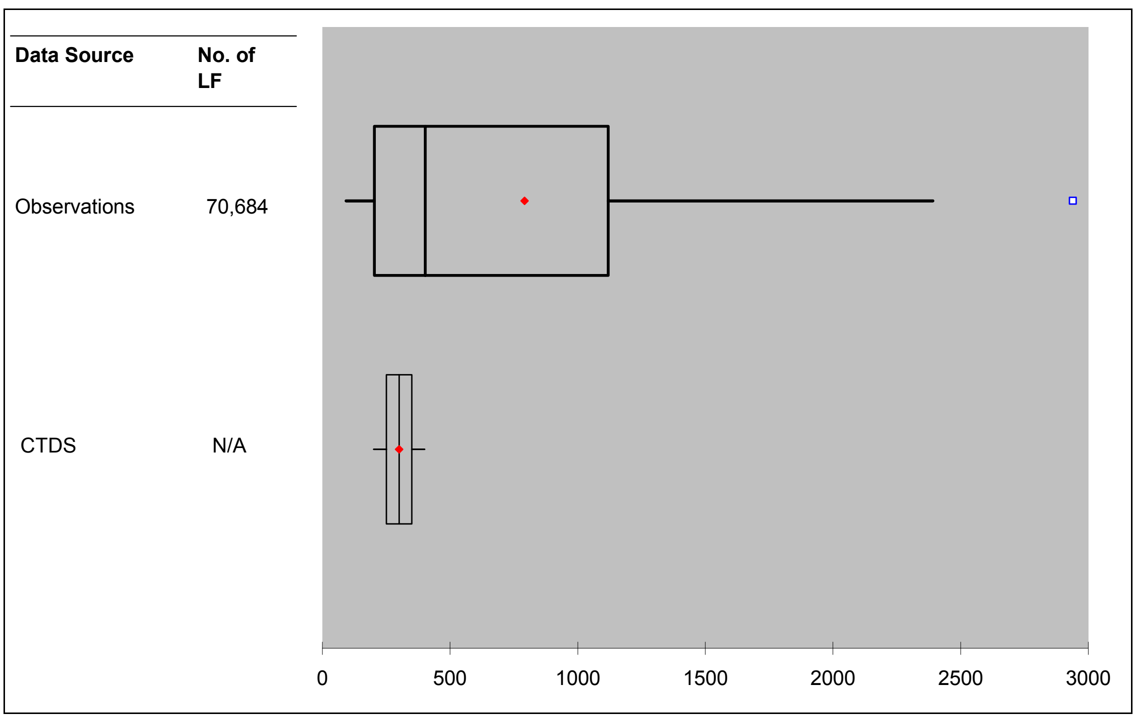


Figure 3.15 Production Rates Comparison — Piling Foundation (lf/Crew Day)

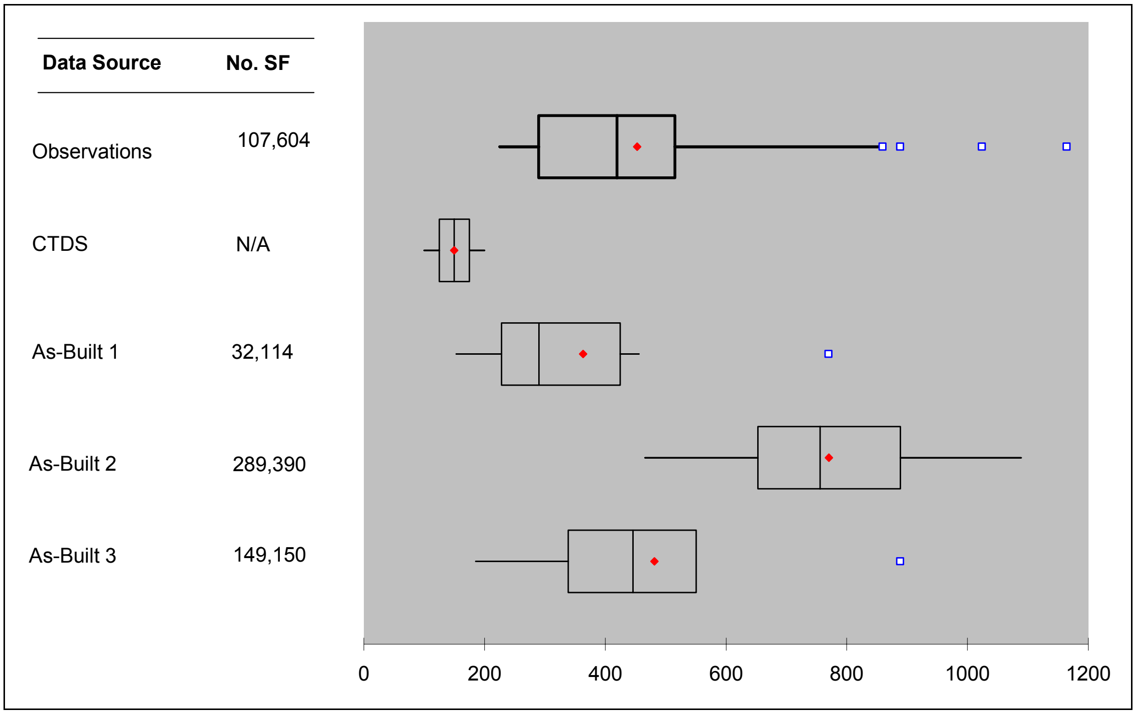


Figure 3.16 Production Rates Comparison — MSE Wall (sf/Crew Day)

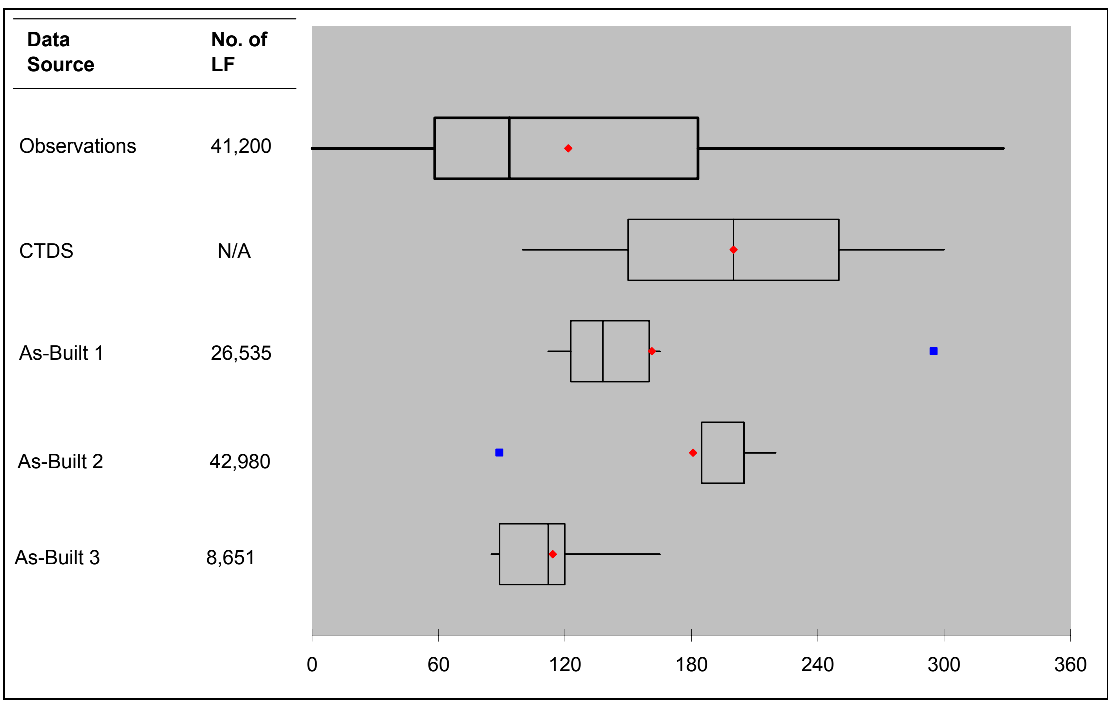


Figure 3.17 Production Rates Comparison — RCP (lf/Crew Day)

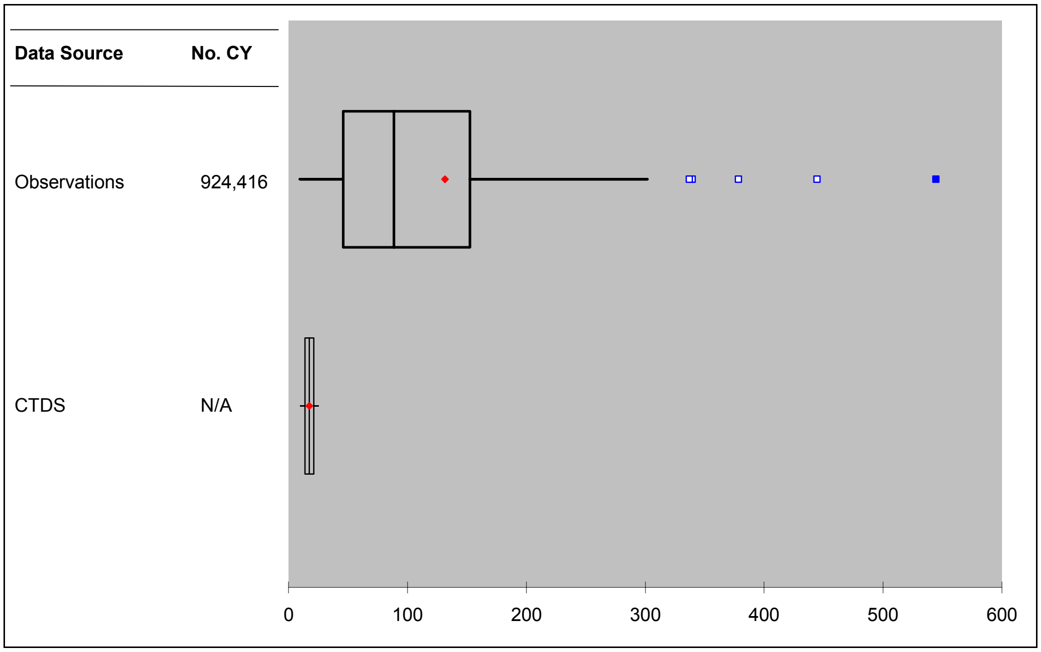


Figure 3.18 Production Rates Comparison — Precast Concrete Box Culverts (cy/Crew Day)

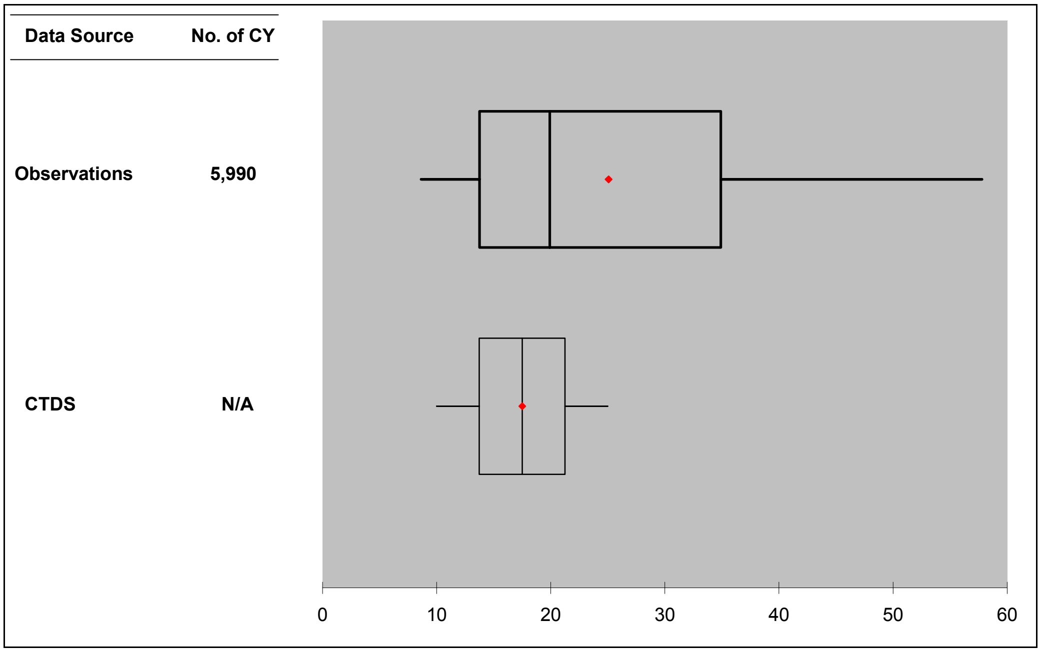


Figure 3.19 Production Rates Comparison — Cast in Place Concrete Box Culverts (cy/Crew Day)

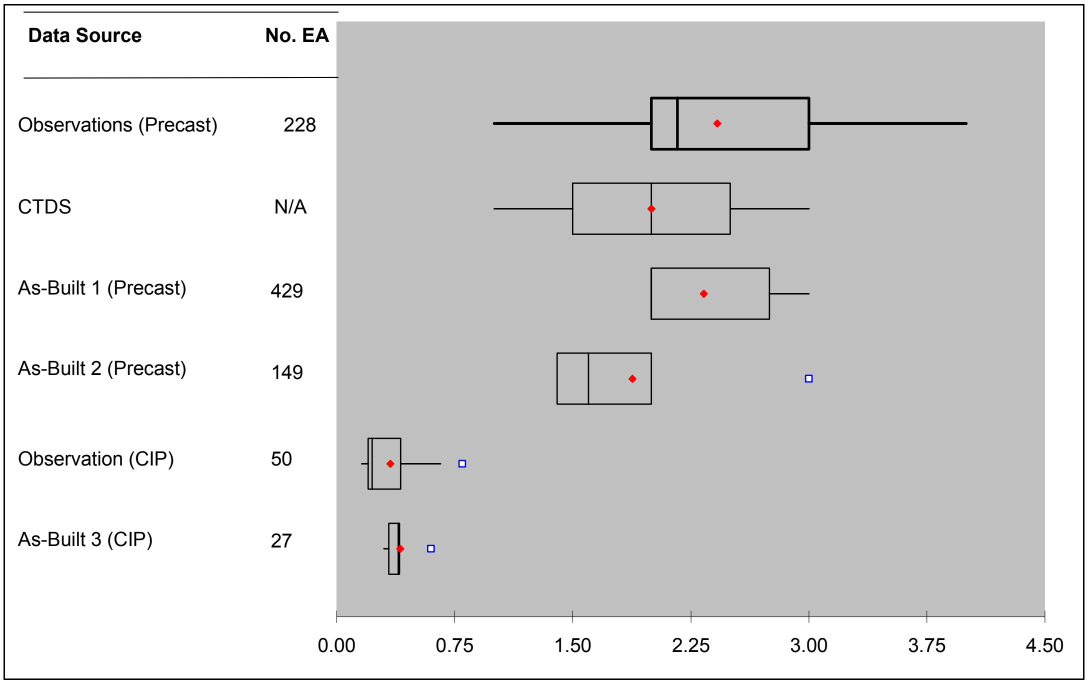


Figure 3.20 Production Rates Comparison — Inlets and Manholes (ea./Crew Day)

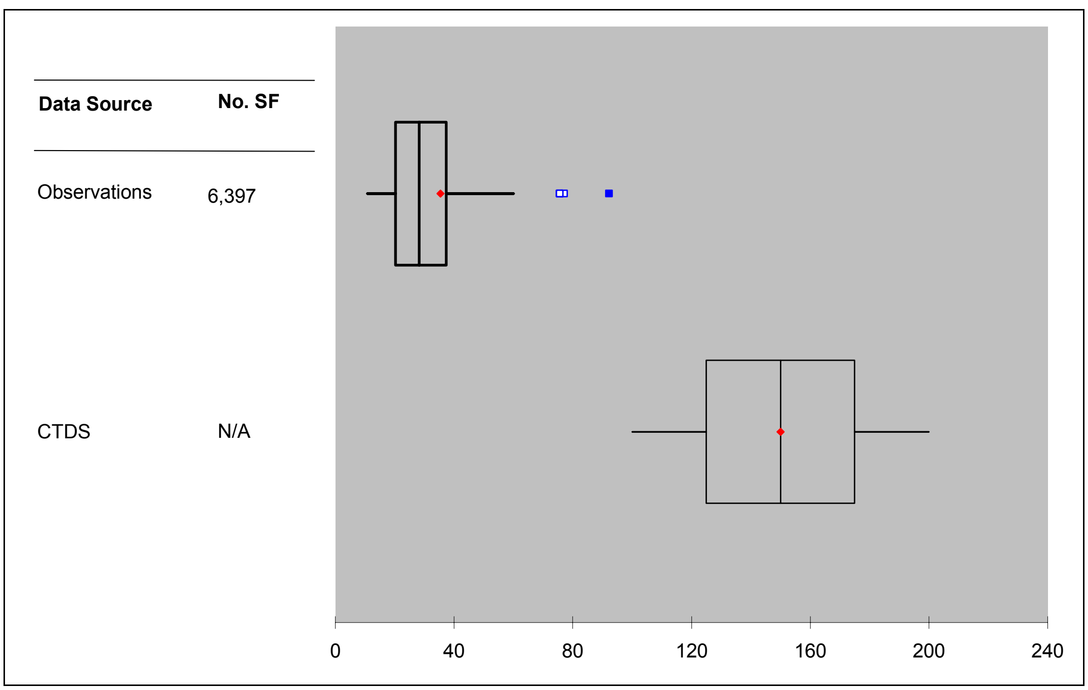


Figure 3.21 Production Rates Comparison — Head Wall/Wing Wall (sf/Crew Day)

Table 3.10 summarizes the findings shown in the box-whisker plots.

Table 3.10 Summary of Production Rates Comparisons with Contract Time Determination System

Item #	Work Item	Units Adopted by Research	Field Research Production Rates Compared with CTDS Rates				
			Much Lower	Lower	Similar	Higher	Much Higher
110	Excavation	cy/crew day	√				
132	Embankment	cy/crew day	√				
247	Flexible base	Lift-sy/crew day			√		
260	Lime treated subgrade	sy/crew day	√				
276	Cement treated base	Lift-sy/crew day				√	
340, 345	Hot mix asphaltic concrete	Ton/crew day		√			
360-1	Slip form concrete pavement (CRCP only)	sy/crew day	√				
360-2	Conventional form concrete pavement	sy/crew day			√		
409	Prestressed concrete piling	ea./crew day				√	
416	Drilled shaft foundation	lf/crew day	√				
420-1	Footing	ea./crew day			√		
420-2	Column — rectangle	ea./crew day					√
420-2	Column — round	ea./crew day			√		
420-3	Cap	ea./crew day			√		
422-1	Bridge deck — cast in place	sf/crew day				√	
423	MSE wall	sf/crew day					√
425	Beam erection	Spans/crew day					√
462-2	Cast in place concrete box culverts	lf/crew day				√	
464-1	RCP 18–42 in.	lf/crew day		√			
464-2	RCP 48–72 in.	lf/crew day		√			
465	Inlets and manholes	ea./crew day				√	
466	Wing wall/head wall	sf/crew day	√				
529	Concrete curb and gutter	lf/crew day				√	

Only five work items were found to have similar production rates in both CTDS and observations. Six items were found to have much lower rates, three had lower rates, six had higher rates, and three had much higher rates.

The analysis above shows that there are significant differences between the CTDS and observed production rates. Most of the as-built production rates were also found to be more similar to the observed rates. As a result, the observed rates were considered to be more reliable and would be used to develop production rate models for the twenty-six selected work items.

4. ANALYSIS OF DRIVERS

This chapter first discusses the methods used for production rate driver analysis. The analyses performed to identify significant production rate drivers and to establish and model the relationships between the production rates and the significant drivers are documented in the later part of this chapter.

4.1 Identifying Significant Drivers and Establishing Relationships

Several statistical techniques were employed to identify the relationship between the candidate drivers and the production rates.

The analysis of variance (ANOVA) *t* test was employed to test the difference in mean production rate within each group of the candidate drivers that contained categorical or discrete numerical data. The *p* value, which exhibits the significance of the differences between the means for each group, is set at 0.1.

Nonlinear or linear regression analysis was also employed to determine the relationships between production rates and drivers that contained continuous numerical data. The logarithmic model and the power model were then used to establish nonlinear relationships of production rates and the candidate drivers. For each factor analysis, the R^2 and the adjusted R^2 of the linear, logarithmic, and power models were used to determine whether significant relationships existed between the drivers and the production rates. All assumptions applicable to the respective applied models were strictly obeyed, and significant drivers that violated the assumptions were rejected.

Outlier analysis was also conducted, and all data points that were considered outliers were removed. The R^2 and *p* values of these models had to be significant to the established values before they were considered sufficiently useful to be used for production rate determination. On the basis of the suggestion provided by Green (1991), and as shown in Table 4.1, any model that had an R^2 value of 0.26 and a *p* value of 0.05 was accepted as a sufficiently good model that could be used to estimate production rates.

Table 4.1 Sample Sizes Required to Test the Hypothesis that the Population Multiple Correlation Equals Zero with a Power of 0.80 and α of 0.05 (Adopted from Green 1991)

Number of Predictors	Sample Sizes Based on Power Analysis		
	$R^2 = 0.02$	$R^2 = 0.13$	$R^2 = 0.26$
1	390	53	24
2	481	66	30
3	547	76	35
4	599	84	39
5	645	91	42
6	686	97	46
7	726	102	48
8	757	108	51
9	788	113	54
10	844	117	56
15	952	138	67
20	1066	156	77
30	1247	187	94
40	1407	213	110

Data that violated the assumptions for outlier, regression, and ANOVA analysis were rejected.

Other than the statistical methods and treatments mentioned above, production rates used for the analyses in this chapter have been adjusted to fit one crew size. Higher production rates were expected from operations that were carried out by more than one crew. Because the unit adopted by this research reflects the production rate from only one crew, affected data points were adjusted accordingly.

4.2 Analysis by Work Items

Detailed analyses were carried out according to the proposed statistical methods, and the results were arranged according to the work item number. The following sections discuss the results.

4.2.1 Item 110 — Excavation

Scatterplot and regression analysis initially identified several drivers that seemed to have some impact on excavation production rates. Detailed regression analysis was conducted on all these drivers, and only work area quantity (WAQ) was found to have affected the production rates. The analysis also showed that the logarithm model was the best model, and it was found to be statistically significant at 95 percent with an R^2 of 0.692. The coefficients of this model were statistically different from zero at the 95 percent confidence interval because the *p* values were less than 0.05. Figure 4.1 displays the results of a regression analysis using the logarithmic model. The natural log applies to the formula.

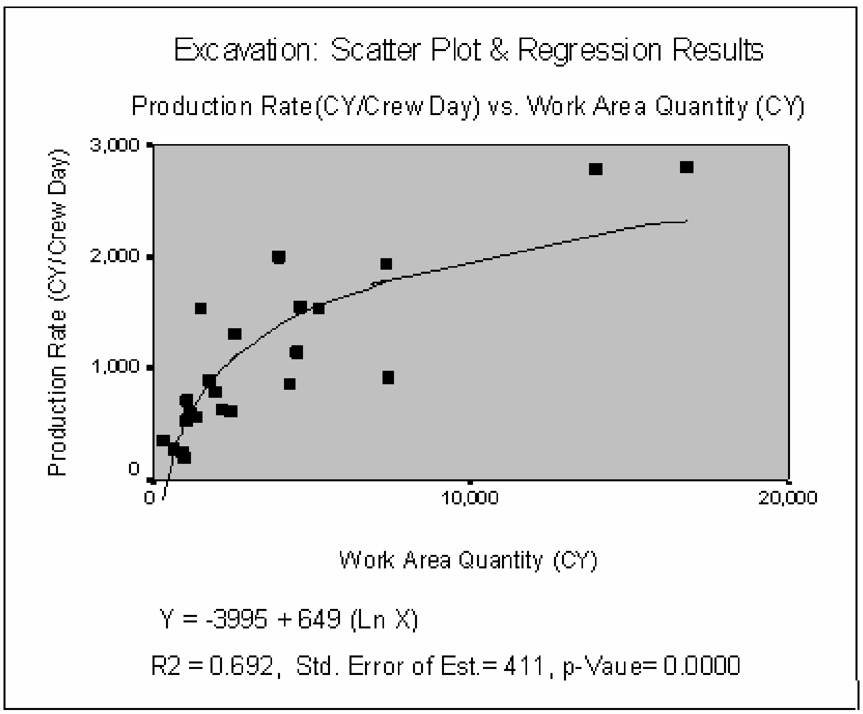


Figure 4.1 Excavation: Scatterplot and Regression Results [vs. Work Area Quantity (cy)]

This model is applicable only to a WAQ of more than 820 cy and less than 16,789 cy, because this model was developed on the basis of data collected within this range. Any predicted production rate below a WAQ of 820 cy will yield a negative production rate value, and any WAQ above 16,798 cy will yield an unrealistic production rate. Thus, the production rate ranges from 382.66 to 2,318 cy/crew day.

4.2.2 Item 132: Embankment

Using the two statistical methods mentioned, two factors were found to be significant drivers for embankment.

Work Area Quantity

The logarithmic model was found to be the most efficient model to model the production rates from the relationships between the observed embankment production rates and the WAQ. With one outlier removed, the fitted logarithmic model was statistically significant at the 95 percent confidence interval. Figure 4.2 displays the results of the regression analysis using the logarithmic model. The model had an R^2 of 0.343, the coefficient of this model was statistically different from zero at the 95 percent confidence interval, and the *p* value was less than 0.05.

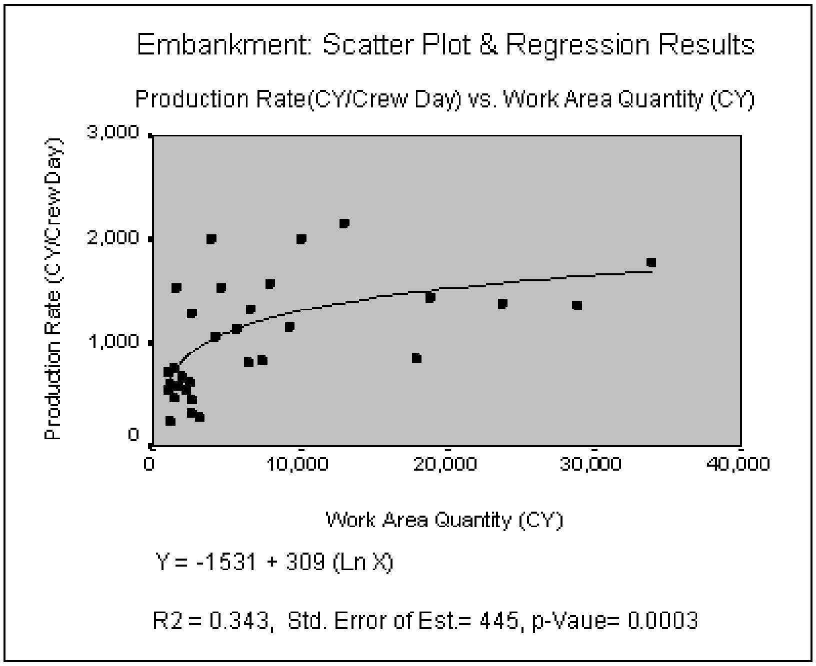


Figure 4.2 Embankment: Scatterplot and Regression Results [vs. Work Area Quantity (cy)]

This model is applicable only to WAQs between the range of 1,064 and 33,938 cy, because this model was developed from data collected within this range. On the basis of this model, the estimated production rates can range from 621 to 1,691 cy/crew day.

Work Zone Congestion

Embankment usually involves three tasks: dumping, spreading, and compacting. When the work zone allows for only one of the three tasks to be carried out at a time, work zone congestion is considered severe. When the work zone allows for two different tasks to be performed simultaneously, it is considered moderate, and when three tasks can be carried out simultaneously, it is considered minor. Severe work zone congestion was dropped from the analysis, because only one data point was available.

The results from the *t* test yielded a *p* value of 0.34 for the group variances test, indicating that the two levels had equal variances at the 95 percent confidence interval. The homogeneity testing of variance yielded a *p* value of 0.09, thus indicating that the two groups have an equal variance at the 90 percent confidence interval. On the basis of the equal variances, the *p* value of the *t* test was less than 0.05. Therefore, the mean production rate in work zones with minor congestion is significantly different from the mean production rate in work zones with moderate congestion.

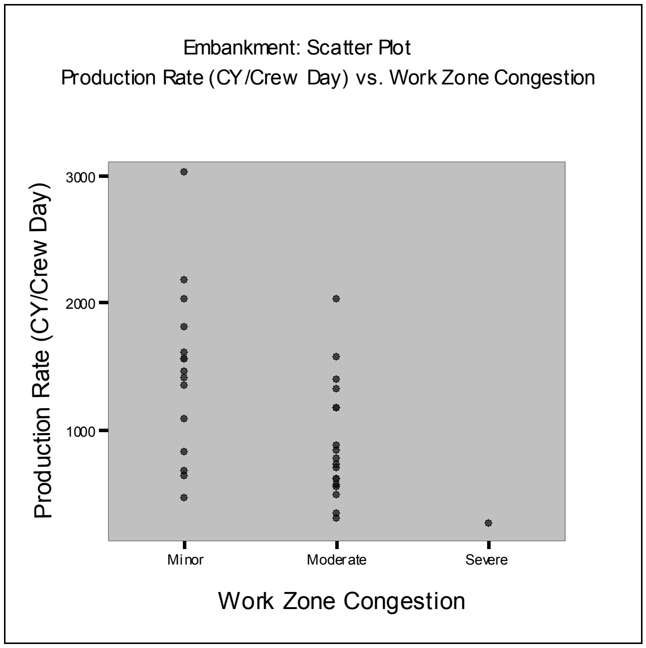


Figure 4.3 Embankment: Scatterplot (vs. Work Zone Congestion)

The mean production rate is 1,424 cy/crew day for a work zone with minor congestion and 872 cy/crew day for a work zone with moderate congestion. The difference between the two is 552 cy/crew day.

4.2.3 Item 260: Lime Treatment Subgrade

Two factors, WAQ and length of work area, were found to be significant drivers for lime treatment subgrade.

Work Area Quantity

Again, the logarithmic model was found to be the most efficient model for lime treatment subgrade WAQ. Four data points were found to be outliers and were removed from further analysis.

This model was found to be statistically significant at the 95 percent confidence interval with an R^2 of 0.714. The coefficient of this model was statistically different from zero at the 95 percent confidence interval.

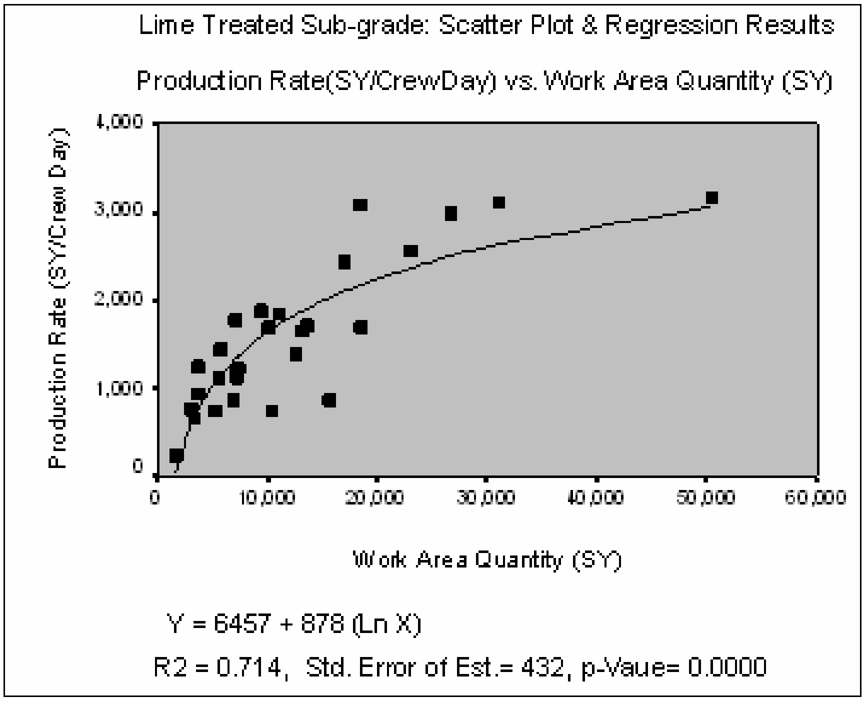


Figure 4.4 Lime Treated Subgrade: Scatterplot and Regression Results [vs. Work Area Quantity (sy)]

This model is applicable only to WAQs within the range of 1,332 to 50,010 sy, because this model was developed on the basis of observed data in this range. The estimated production rates of this model can range from 122 to 3,022 sy/crew day.

Length of Work Area

The logarithmic model was also found to be the most efficient for modeling the effects of length of work area. Two data points were found to be outliers and were removed from further analysis. The fitted logarithmic model showing the relationship between the observed production rates and the length of work area for lime treated subgrade construction can be found in Figure 4.5.

This model was statistically significant at the 95 percent confidence interval with an R^2 of 0.631, and the coefficient was statistically different from zero at the 95 percent confidence interval.

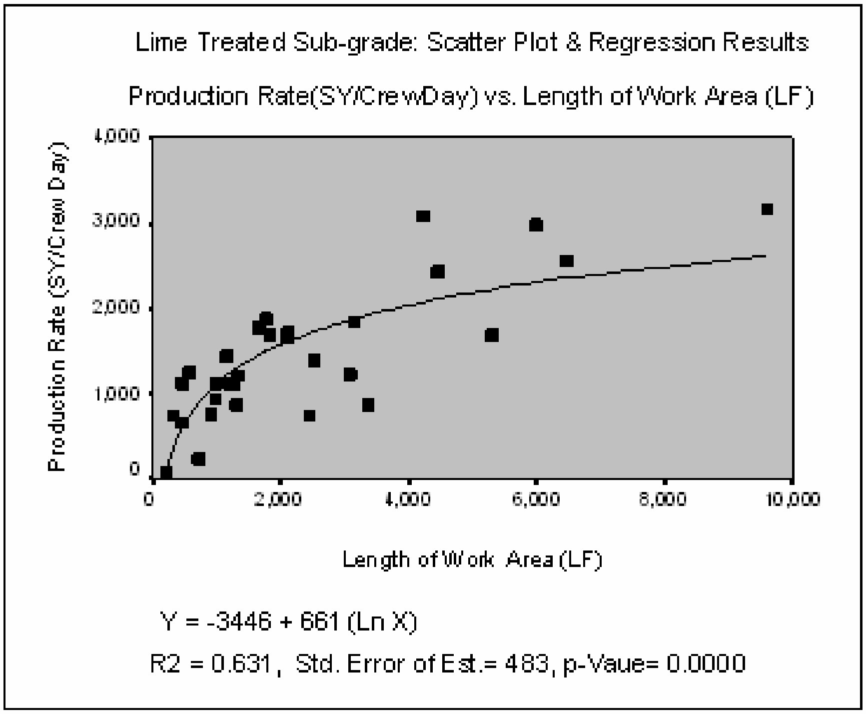


Figure 4.5 Lime Treated Subgrade: Scatterplot and Regression Results [vs. Length of Work Area (lf)]

This model is applicable only to work area length within the range of 1,632 to 50,490 lf. The estimated production rates of this model can range from 1,444 to 3,712 sy/crew day.

4.2.4 Items 247 and 276: Aggregate Base Course

Two types of aggregate operations were observed for this study: flexible base and cement treated base (CTB) operations. Because there are differences in the operation requirements for these types of base course, these two operations were found to yield different production rates although the drivers were similar. Thus, these base courses were separately analyzed.

4.2.4.1 Flexible Base

WAQ and lift length of work area were found to be statistically significant drivers for the flexible base operations.

Work Area Quantity

The logarithmic model was found to be the best model, and the fitted logarithmic model is shown in Figure 4.6. This model was statistically significant at the 95 percent confidence interval with an R^2 of 0.594.

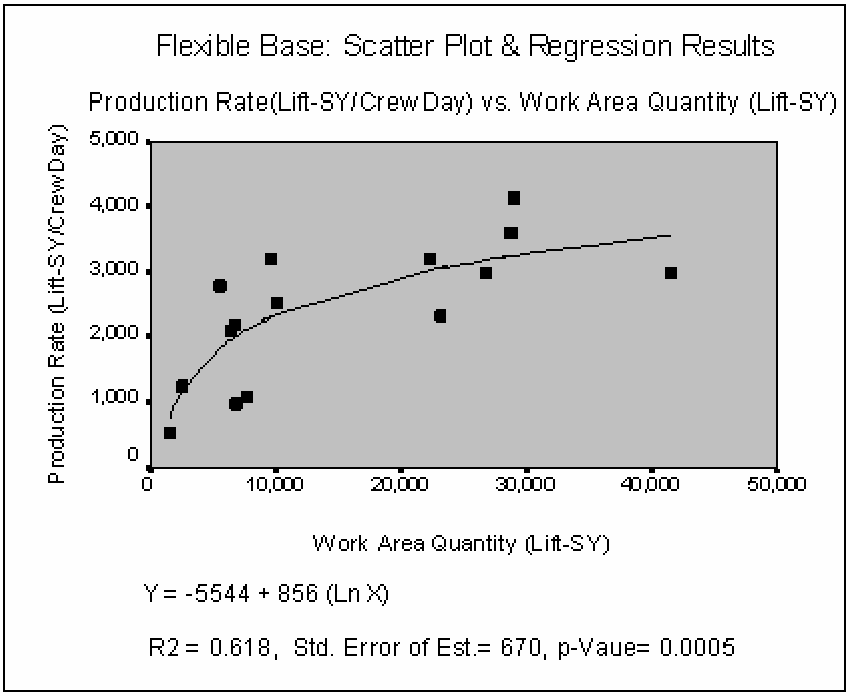


Figure 4.6 Flexible Base: Scatterplot and Regression Results [vs. Work Area Quantity (Lift-sy)]

This model is applicable only within the range of 1,579 to 41,607 Lift-sy, with estimated production rates of the fitted logarithmic model ranging from 531 to 4,215 Lift-sy/crew day.

Lift-Length of Work Area

The logarithmic model was found to be most suitable to model the relationship between observed production rates and lift-length of work area. No outliers were observed in the data set. The fitted logarithmic model is shown in Figure 4.7. This model was statistically significant at the 95percent confidence interval with an R^2 of 0.67.

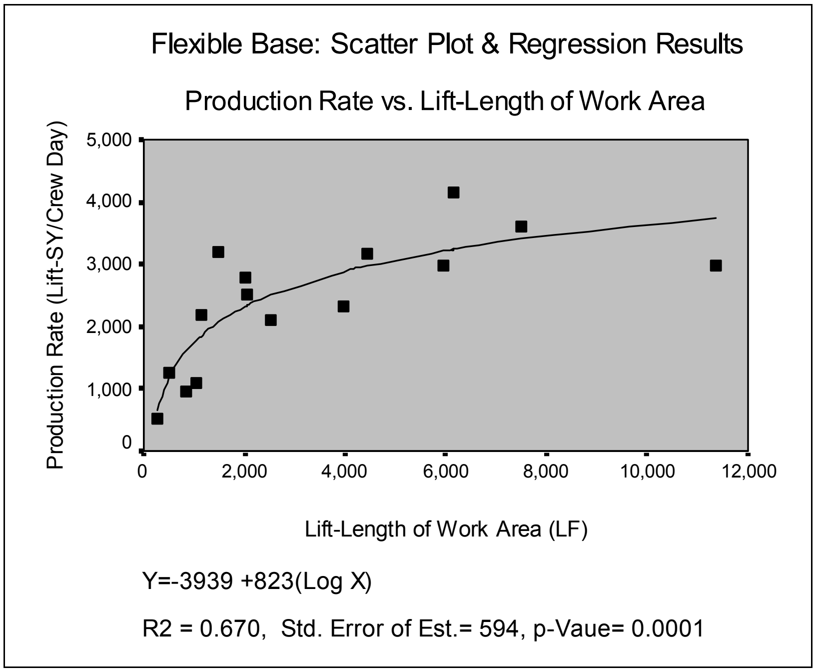


Figure 4.7 Flexible Base: Scatterplot and Regression Results [vs. Lift-Length of Work Area (lf)]

This model is applicable only within the range of 263 to 11,371 lf because this model was developed on the basis of observed data in this range. The estimated production rates of the fitted logarithmic model can range from 565 to 4,321 Lift-sy/crew day.

4.2.4.2 Cement Treated Base

As with cement treated base, WAQ and lift-length of work area were found to be significant drivers for cement treated base production rates.

Work Area Quantity (Lift-sy)

The logarithmic model was found to best fit the relationship between observed production rates and WAQ. No outlier was found in the data. The fitted logarithmic model is shown in Figure 4.8. This model was statistically significant at the 95 percent confidence interval with an R^2 of 0.627; the coefficients of this model were statistically different from zero at the 95 percent confidence interval. This model is applicable only for WAQs between 1,416 and 35,956 Lift-sy. The estimated production rates of this fitted logarithmic model can range from 1,941 to 5,922 sy/crew day.

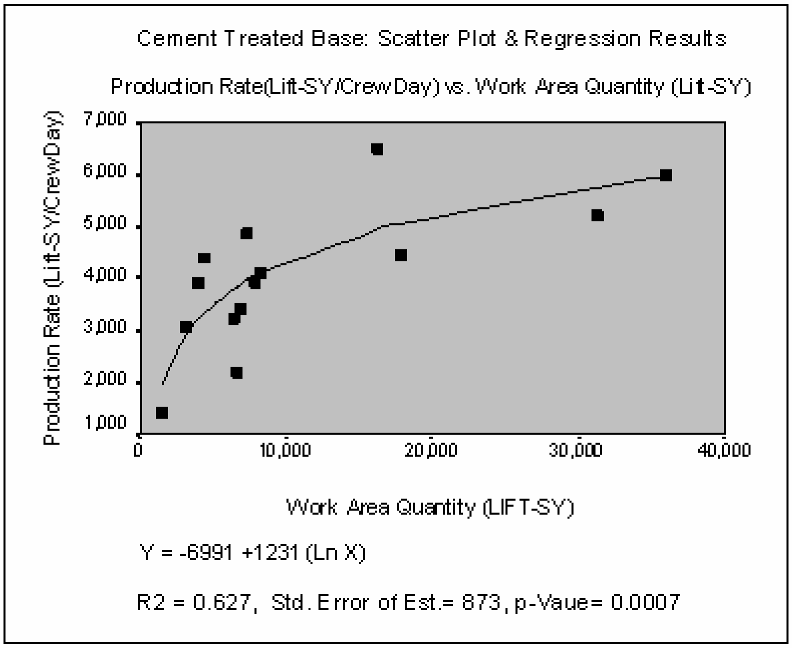


Figure 4.8 Cement Treated Base: Scatterplot and Regression Results [vs. Work Area Quantity (Lift-sy)]

Y = -6991 +1231 (Ln X)

Lift-Length of Work Area

The linear model was found to be the best-fitting model to explain the relationship between observed production rates and lift-length of work area. Two outlying data points were removed from the data set before running the regression analysis. The fitted linear model is shown in Figure 4.9.

The results of a regression analysis on the model demonstrated significance at the 95 percent confidence interval with an R^2 of 0.393. The coefficients of this fitted model were statistically different from zero at the 95 percent confidence interval, because the *p* values of testing coefficients for WAQ and constant were less than 0.05.

This model is applicable only to WAQs within the range of 250 to 3,250 lf. The estimated production rates of the fitted linear model can range from 2,621 to 5,681 lift-sy/crew day.

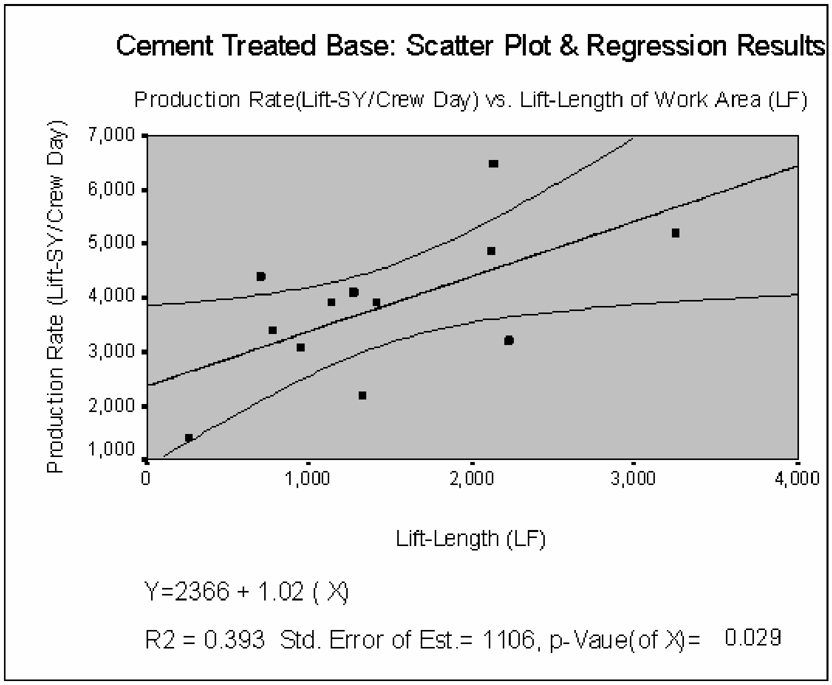


Figure 4.9 Cement Treated Base: Scatterplot and Regression Results [vs. Lift-Length of Work Area (lf)]

4.2.5 Items 340/345: Hot Mix Asphalt

WAQ and type of course were found to be significant drivers for hot mix asphalt operations.

Work Area Quantity

The logarithmic model was found to be the best fitted model to explain the relationship between observed production rates and WAQ for hot mix asphalt pavement. No outlier was observed from the data. The fitted logarithmic model is shown in Figure 4.10.

The fitted model was statistically significant at the 95 percent confidence interval with an R^2 of 0.432. This model is applicable only to WAQs within the range of 227 to 5,840 tons. The estimated production rates of the fitted logarithmic model can range from 310 to 1,213 tons/crew day.

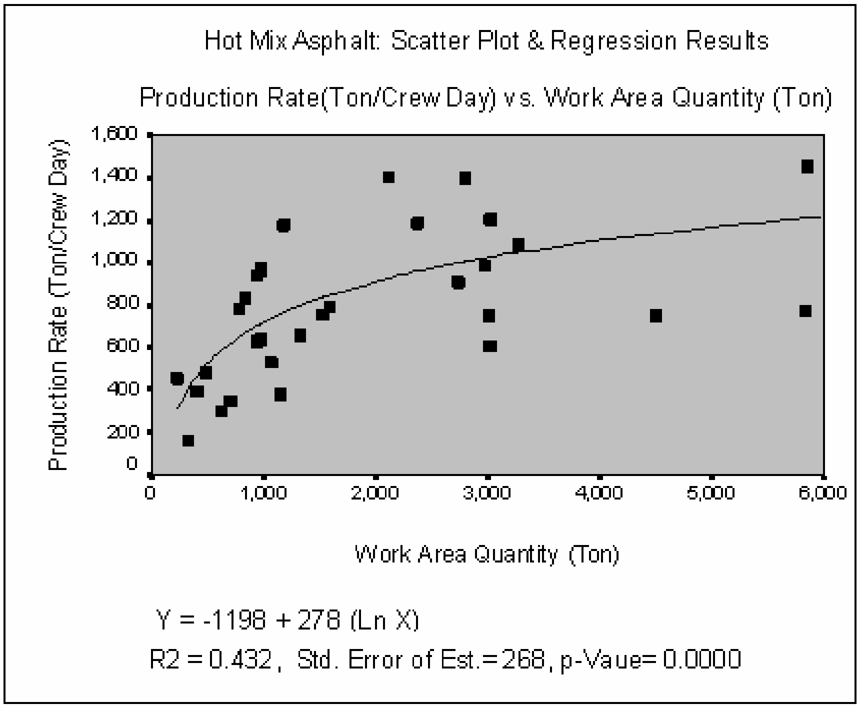


Figure 4.10 Hot Mix Asphalt: Scatterplot and Regression Results [vs. Work Area Quantity (Ton)]

Course Type

A total of thirty-two hot mix asphalt data points were observed in this portion of the study. Twenty-two pertained to base course construction, and nine pertained to surface course. One observation included both surface and base course construction. In order to investigate any production rate difference between the base and surface course, the data point observed with both surface and base course construction was removed. The *t* test was employed to test the difference in mean production rate between surface and base course construction, because the two groups are independent and normally distributed. The homogeneity testing of variance yielded a *p* value of 0.10, thus indicating that the two groups had equal variance at a 90 percent confidence interval. On the basis of the assumption of equal variance between the two groups, the *p* value of the *t* test was less than 0.1. Therefore, it can be concluded that the average production rate between surface and base course construction is different at the 90 percent confidence interval.

The average production rate of surface course construction is 646 tons/crew day, and the average production rate of the base course is 882 tons/crew day. The difference of average production rate between the two types of course construction is 236 tons/crew day.

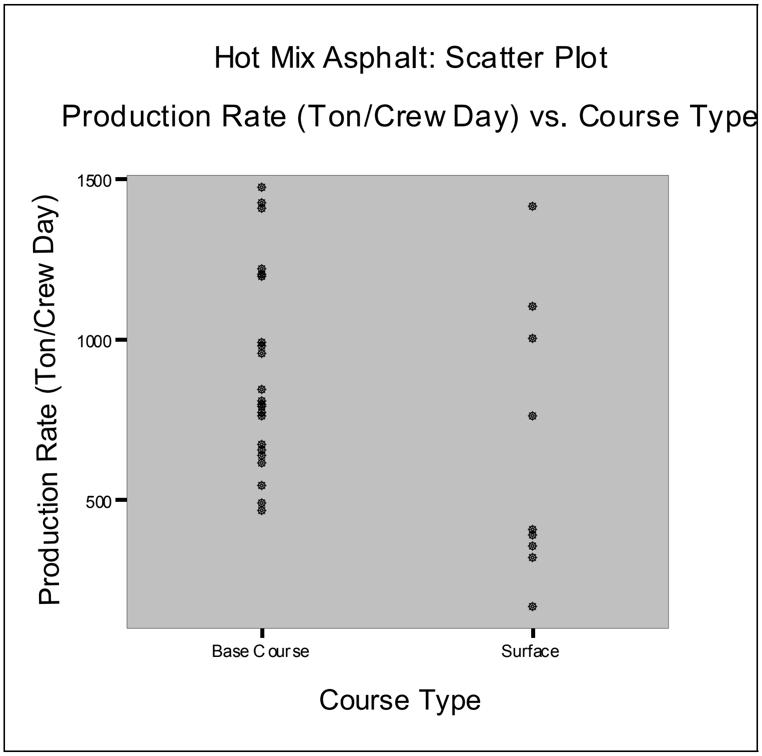


Figure 4.11 Hot Mix Asphalt: Scatterplot (vs. Course Type)

4.2.6 Item 360: Concrete Paving

Slip form concrete paving and conventional form concrete paving are the two types of concrete paving methods commonly used by TxDOT.

4.2.5.1 Slip Form Concrete Paving

Two factors, WAQ and length of work area, were found to be significant drivers of slip form concrete paving production rates.

Work Area Quantity

The logarithmic model was found to have the best-fitted relationship between observed production rates and WAQ. One data point was found to be an outlier and was removed from the regression analysis. The fitted logarithmic model for slip form concrete pavement construction is shown in Figure 4.12. The model fell within the 99.9 percent confidence interval with an R^2 of 0.653. The coefficients of this model were statistically different from zero at the 95 percent confidence interval, because the *p* values of testing coefficients for WAQ and the constant term were less than 0.05.

This model is only applicable to WAQs within the range of 1,156 to 18,592 sy, because the data collected falls within this range. The estimated production rates of the fitted logarithmic model can range from 591 to 1,752 sy/crew day.

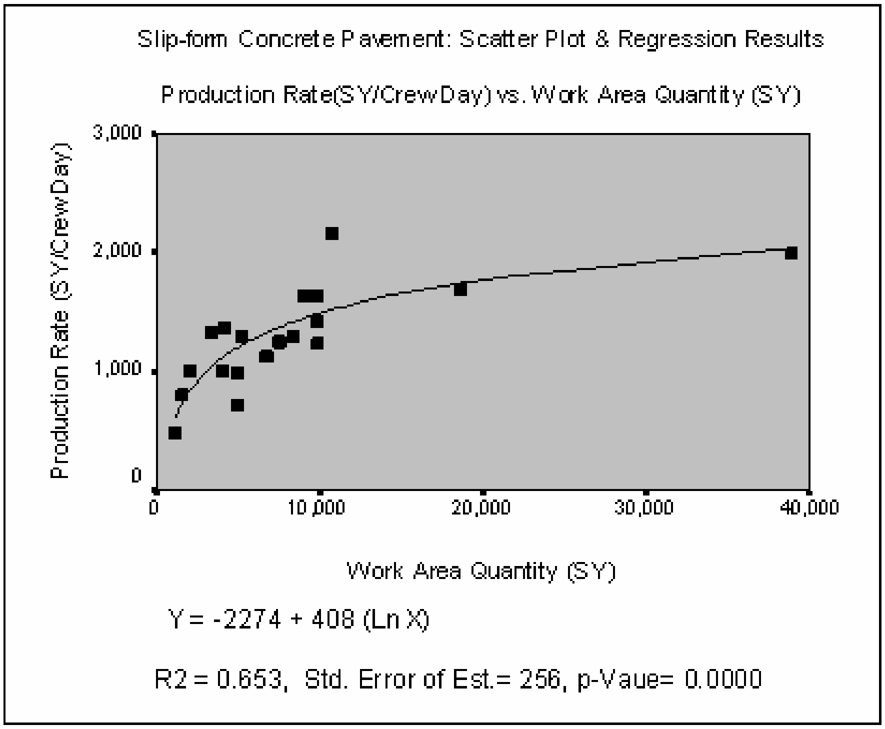


Figure 4.12 Slip Form Concrete Pavement: Scatterplot and Regression Results [vs. Work Area Quantity (sy)]

Length of Work Area

The logarithmic model was found to best fit the relationship between observed production rates and the length of work area. Two data points were found to be outliers and were removed from the regression analysis. The fitted logarithmic model for slip form concrete pavement construction is shown in Figure 4.13.

The fitted model was statistically significant at the 95 percent confidence interval with an R^2 of 0.356. The coefficient for the length of work area of the fitted model was statistically different from zero at the 95 percent confidence interval. Although the constant term was not statistically different from zero in the fitted model at the 95 percent confidence interval, the fitted model can still be used to quantify the relationship between WAQ and observed production rates.

This model is applicable only to lengths of work area within the range of 473 to 7,783 lf. The estimated production rates of the fitted logarithmic model can range from 692 to 1,549 sy/crew day.

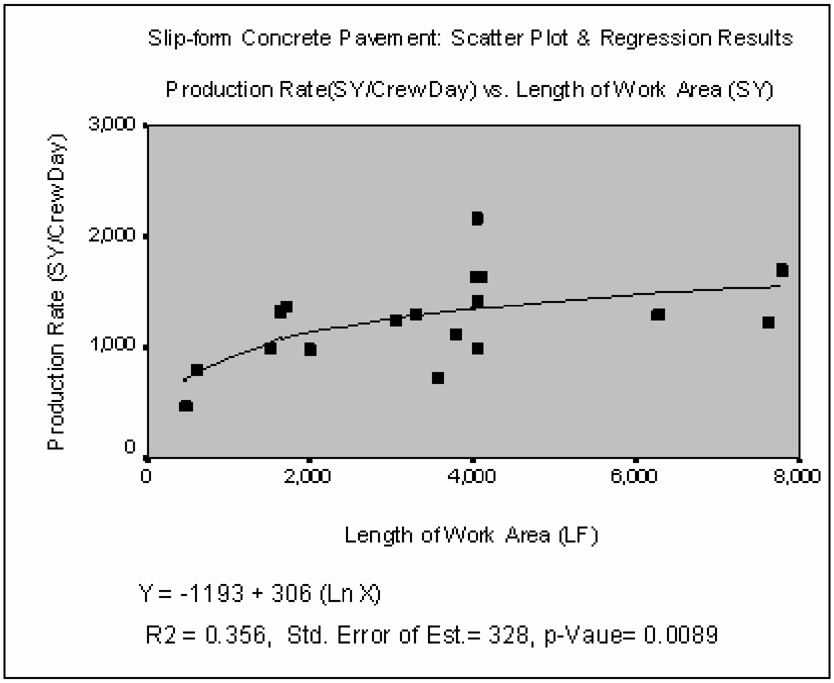


Figure 4.13 Slip Form Concrete Pavement: Scatterplot and Regression Results [vs. Length of Work Area (lf)]

4.2.5.2 Conventional Form Concrete Paving

Conventional form concrete paving operations were found to be significantly impacted by WAQ and configuration.

Work Area Quantity

The logarithmic model was found to be the model of best fit to describe the relationship between observed production rates and WAQ. Two data points were found to be outliers and were removed from the regression analysis. The fitted logarithmic model for conventional form concrete pavement construction is shown in Figure 4.14.

The fitted model was statistically significant at 95 percent confidence interval with an R^2 of 0.511. The coefficients of the fitted model were statistically different from zero at the 95 percent confidence interval.

This model applies only to WAQs within the range of 211 to 4,320 sy. The estimated production rates of the fitted logarithmic model can range from 140 to 547 sy/crew day.

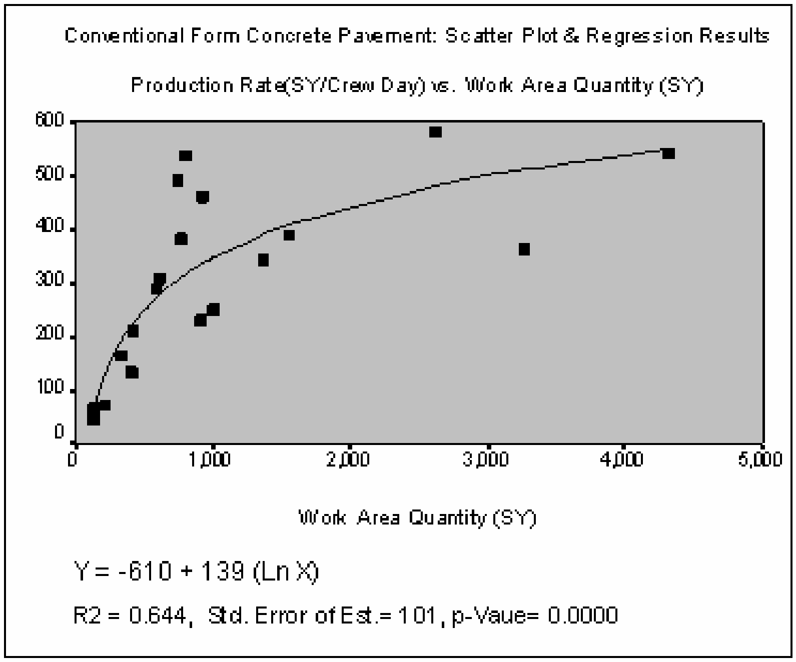


Figure 4.14 Conventional Form Concrete Pavement: Scatterplot and Regression Results [vs. Work Area Quantity (sy)]

Configuration

Conventional form concrete pavement observations were divided into two configuration categories. The first category includes sharp angle(s) or curve(s), and the second includes configurations without any curve or sharp angle. Each category had ten observed data points. The *t* test was employed to test the difference in mean production rate between the two categories, because the two groups are independent and both groups are normally distributed. A *p* value of 0.6 of homogeneity of variances test indicated that the two groups have equal variances at the 95 percent confidence interval. On the basis of the assumption of equal variances between two groups, the *p* value of the *t* test was less than 0.05. Therefore, it can be concluded that the average production rates of the conventional form concrete pavement construction are different between the two categories at the 95 percent confidence interval.

The average production rate for conventional form concrete pavement construction is 420 sy/crew day without any curves or sharp angles and 192 sy/crew day for the curved or sharp angled configurations. The difference of average production rates between the two categories is 228 sy/crew day.

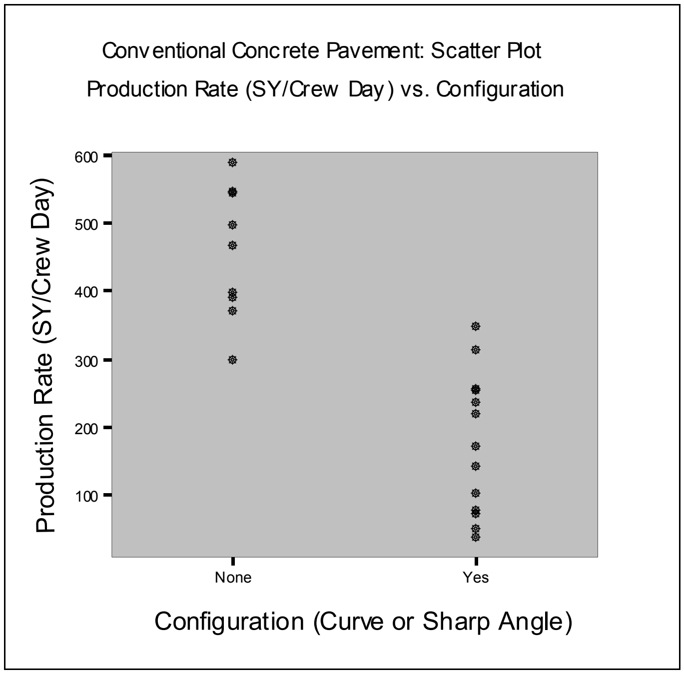


Figure 4.15 Conventional Form Concrete Pavement: Scatterplot (vs. Configuration)

4.2.7 Item 409: Prestressed Concrete Piling Foundations

The total number of piles where piles can be continuously installed is found to be the only significant driver of piling production rates. In short, this driver is described as total quantity (ea.) of piles in a cluster.

The linear model was found to have the best-fitted relationship between the observed production rates and the total number of piles in a cluster. One data point was found to be an outlier and was removed from the regression analysis. The fitted linear model for piling installation is shown in Figure 4.16. The model fell within the 99.9 percent confidence interval with an R^2 of 0.593. The coefficients of this model were statistically different from zero at the 99 percent confidence interval because the p values of testing coefficients for the driver and constant term were less than 0.01.

This model is applicable only to pile cluster size between 13 and 152 ea. The estimated production rates of the fitted linear model can range from 4.268 to 10.358 ea./crew day.

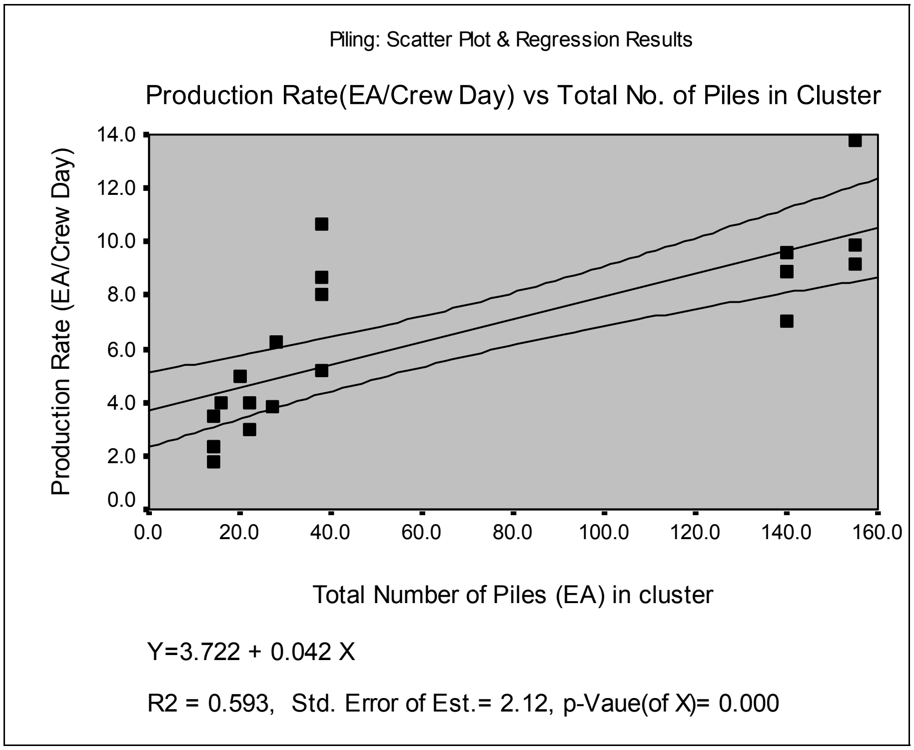


Figure 4.16 Prestressed Concrete Piling Foundations: Scatterplot [vs. Total Number of Piles (ea.) in Cluster]

As observed in the linear model in Figure 4.16, two different groups were found to cluster at opposite ends. The first group involves a smaller number of piles within a cluster (between fifteen and forty), whereas the second group involves a much higher number of piles within a cluster (between 140 and 158). A second regression analysis was conducted to analyze the relationship between the total number of piles in the smaller cluster, but the second regression analysis was not done on the larger cluster because there was insufficient data points.

Smaller Cluster

Another model was developed for estimating the production rate of the smaller cluster. The linear model was found to have the best-fitted relationship between the observed production rates and the total number of piles in a cluster. One data point was found to be an outlier and was removed from the linear regression analysis. The fitted linear model for piling installation is shown in Figure 4.17. The model falls within the 95 percent confidence interval with an R^2 of 0.72. The coefficients of this model were statistically different from zero at the 99 percent confidence interval, because the p values of testing coefficients for WAQ and constant term were less than 0.01.

This model is applicable only to cluster sizes within the range of 13 to 38 ea., because the data collected falls within this range. The estimated production rates of the fitted linear model can range from 2.413 to 7.988 ea./crew day.

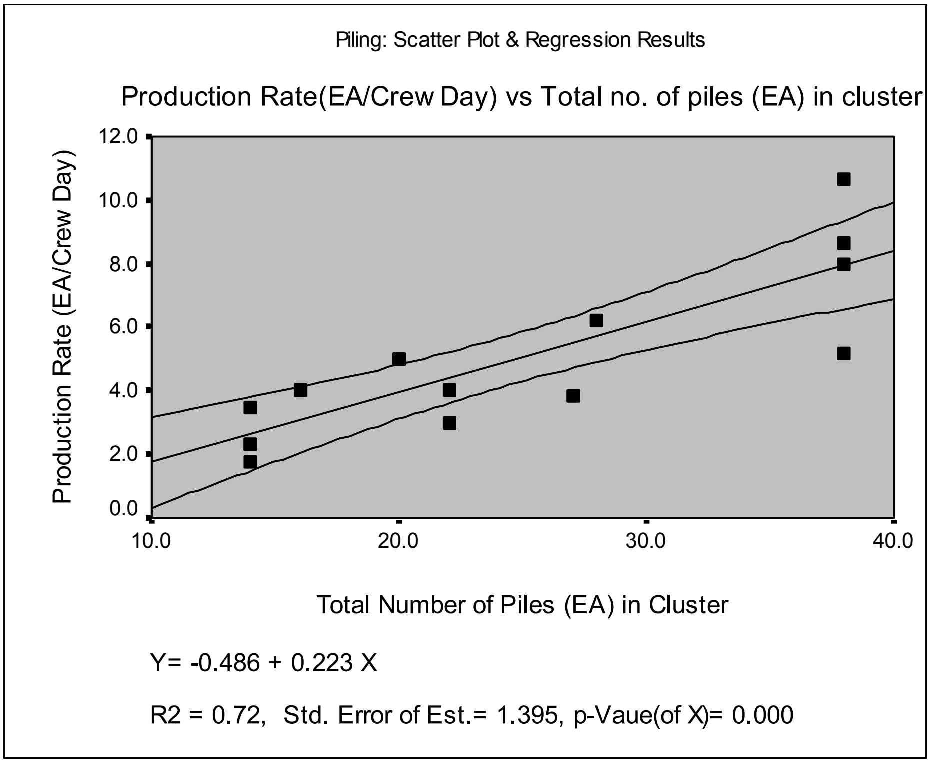


Figure 4.17 Prestressed Concrete Piling Foundations: Scatterplot [vs. Total Number of Piles (ea.) in Cluster] for Small Pile Cluster

The higher R^2 value in the smaller pile cluster model suggests that it is a better model. Thus, it is suggested that this model be used to predict production rates for smaller pile clusters, whereas the former should be used to predict production rates of larger clusters.

4.2.8 Item 416: Drilled Shaft Foundations

Two production rate units were employed for drilled shaft foundations because both units appear to be useful for the time estimation process.

4.2.7.1 Production Unit: lf/Crew Day

Using the production unit of lf/crew day, two significant drivers, total length (ft) in a cluster where drilled shafts can be continuously installed and location of operation, were found.

Total Length (lf) in a cluster

The linear model was found to best describe the relationship between the observed production rates and the total length of drilled shaft in a cluster. Two data points were found to be outliers and were removed from the regression analysis. The fitted linear model for drilled shaft foundations is shown in Figure 4.18. The model fell within the 99.9 percent confidence interval with an R^2 of 0.593. The coefficients of this model were statistically different from zero at the 95 percent confidence interval because the *p* values of testing coefficients for the driver and constant term were less than 0.01.

This model is applicable only to drill shafts with a total length in cluster between 50 and 1,800 lf. The estimated production rates of the fitted linear model can range from 67.46 to 231.96 lf/crew day.

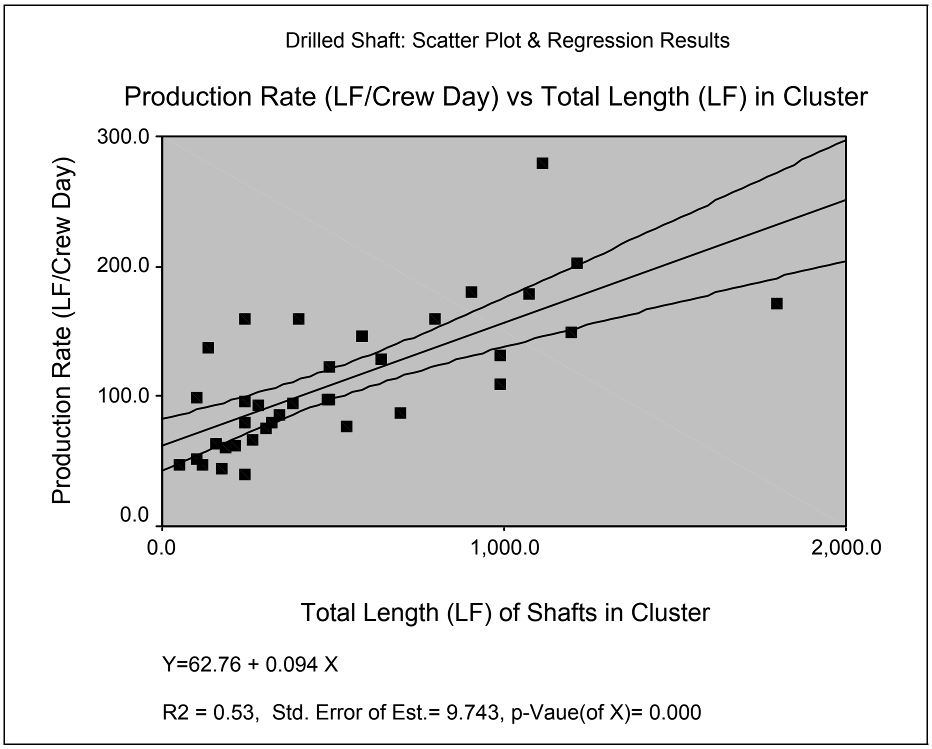


Figure 4.18 Drilled Shaft Foundations: Scatterplot [vs. Total Length of Shafts (lf) in Cluster]

Location of Operation

Drilled shaft production rates were found to be driven by the location in which the operation took place. There are two categories in this driver: ample space and next to an operating road. If the adjacent road next to the drilled shaft operations remained open during installation and the operations took place less than 20 ft. from that road, the data points were considered to be in the next to an operating road category. Otherwise, data points were considered to be in the ample space category.

The *t* test was employed to test the difference in mean production rate between the two categories, because the two groups are independent and both groups are normally distributed. On the basis of the assumption of equal variances between two groups, the *p* values of the *t* test were less than 0.1. Therefore, it can be concluded that the average production rates of the drilled shaft construction are different between the two categories at the 90 percent confidence interval. The average production rate for drilled shafts built beside an operating road is 100.34 lf/crew day, and the mean production rate for drilled shafts built with ample space is 133.26 lf/crew day. The difference between the two categories is 33.08 lf/crew day.

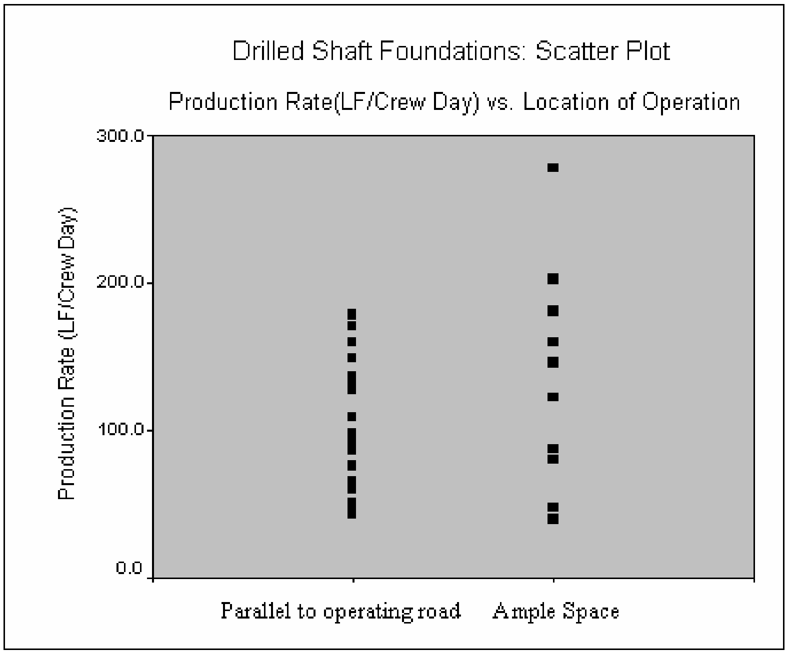


Figure 4.19 Drilled Shaft Foundations: Scatterplot (vs. Location of Operation)

4.2.7.2 Production Unit: ea./Crew Day

Utilizing the alternate unit, only one significant driver, the total number of shafts in a cluster, was found.

Total Number of Shafts in Cluster

The linear model was found to have the best-fitted relationship between the observed production rates and the total number of drilled shafts in a cluster. Two data points were found to be outliers and were removed from the regression analysis. The fitted linear model for drilled shaft foundations is shown in Figure 4.20. The model falls within the 99.9 percent confidence interval with an R^2 of 0.41. The coefficients of this model were statistically different from zero at the 95 percent confidence interval. This model is applicable only for installing a drill shafts cluster that has two to thirty shafts. The estimated production rate of the fitted linear model can range from 1.75 to 2.57 ea./crew day.

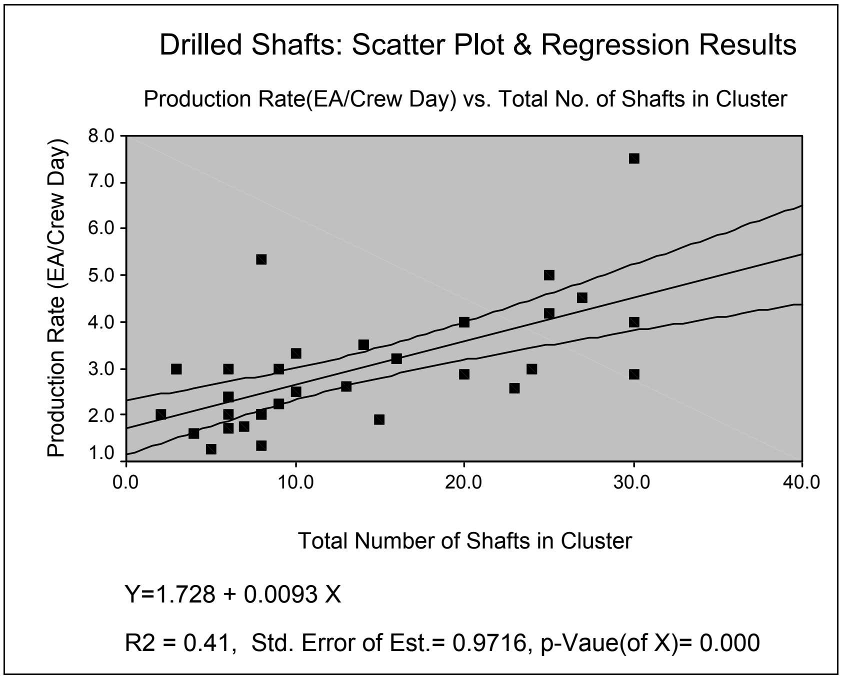


Figure 4.20 Drilled Shaft Foundations: Scatterplot (vs. Total Number of Shafts in Cluster)

4.2.9 Item 420: Concrete Structures

TxDOT specifications do not divide concrete structures into types. However, this research breaks concrete structures into four categories: 420-1 for footing, 420-2 for rectangular and round columns, 420-3 for cap, and 420-4 for cast in place abutment.

4.2.8.1 Item 420-1: Footing

Three candidate drivers, size, excavation depth (ft), and number of footings per bent, were found to have significant effects on production rates of footings.

Size of Footing (cy/ea.)

Different sizes of footings was found to be a significant driver for the footing production rate. The *t* test was employed to test the difference in mean production rate between footing sizes of less than 20 cy/ea. and more than 60 cy/ea., because the two groups are independent and both groups are normally distributed.

On the basis of the assumption of equal variances between two groups, the *p* value of the *t* test was less than 0.1. Therefore, it can be concluded that the average production rates of footings construction are different between the two categories at the 90 percent confidence interval. The average production rate for footings smaller than 20 cy/ea. is 1.714 ea./crew day, whereas the mean production rate for footings larger than 60 cy/ea. is 3.143 ea./crew day. The difference between the two categories is 1.429 ea./crew day.

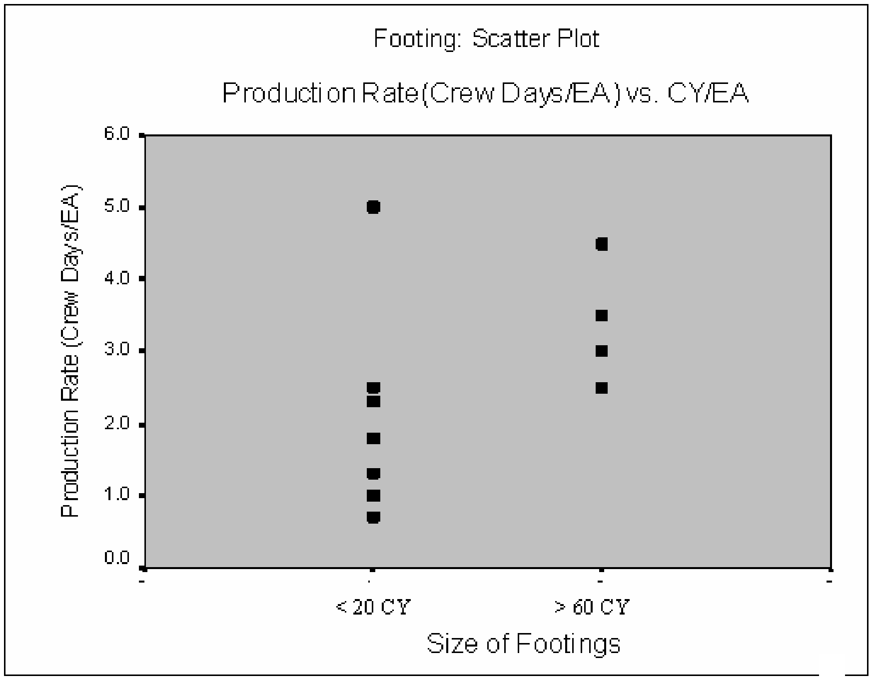


Figure 4.21 Footing: Scatterplot (vs. cy/ea.)

Excavation Depth

The linear model was found to have the best-fitted relationship between the observed production rates and excavation depth. The fitted linear model is shown in Figure 4.22. The model falls within the 95 percent confidence interval with an R^2 of 0.445. The coefficients of this model were statistically different from zero at the 95 percent confidence interval because the p values were less than 0.01. This model is applicable only to an excavation depth range of 5 to 15 ft. The estimated production rates of the fitted linear model can range from 1.75 to 3.65 ea./crew day.

.

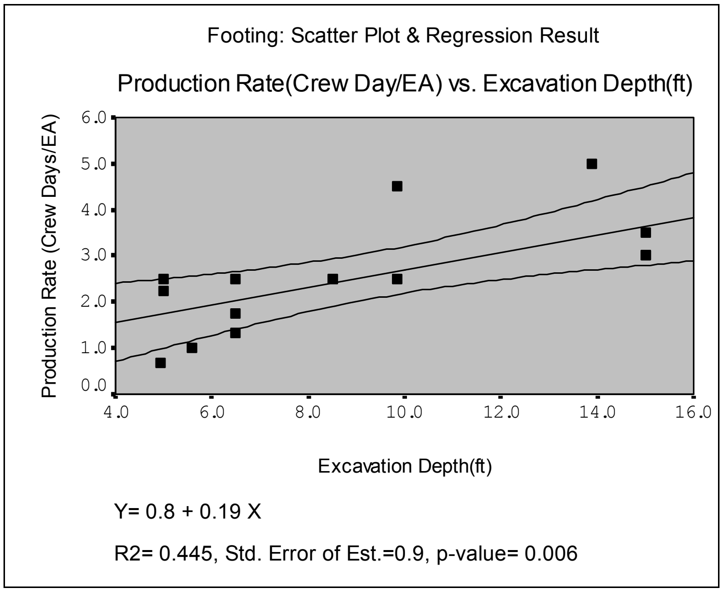


Figure 4.22 Footing: Scatterplot and Regression Results [vs. Excavation Depth (ft)]

Number of Footings per Bent

The *t* test was employed to test the difference in mean production rate between one, two, and three footings per bent.

The *p* value of the *t* test was 0.011, so the average production rates of footings are different between the three categories at the 90 percent confidence interval. Because there was only one data point for the category of three footings per bent, it was excluded from the analysis.

The average production rate for one footing per bent is 3.18 ea./crew day, and the mean production rate for two footings per bent is 1.65 ea./crew day. The difference between the two categories is 1.53 ea./crew day.

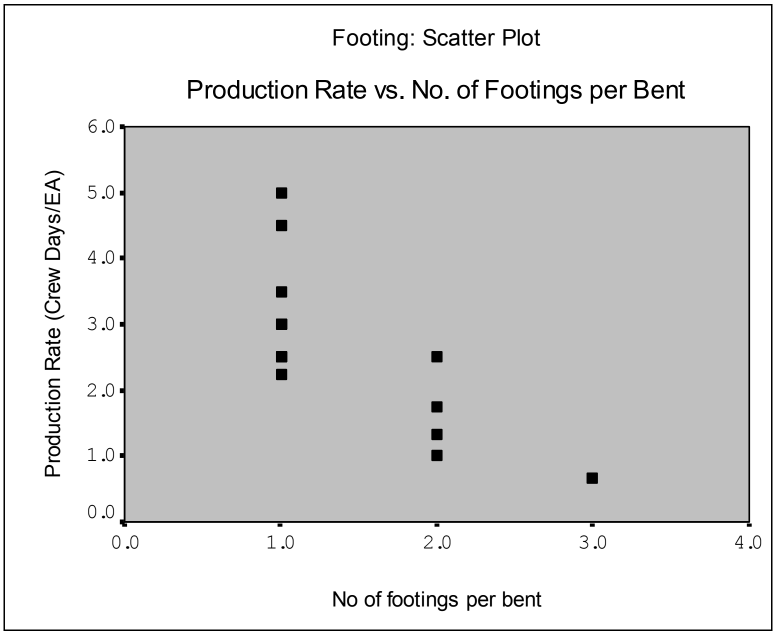


Figure 4.23 Footing: Scatterplot (vs. Number of Footings per Bent)

4.2.8.2 Column — Rectangle

Three candidate drivers were found to influence production rates of columns, including size (cy/ea.), column height (ft), and number of columns per bent.

Size (cy/ea.)

The *t* test was employed to test the difference in mean production rate between column size of less than 100 cy/ea. and column size of more than 100 cy/ea.

The average production rates of column construction are different between the two categories at the 90 percent confidence interval because the *p* value was less than 0.1.

The average production rate for column size that is smaller than 100 cy/ea. is 1.45 ea./crew day, and the mean production rate for column size larger than 100 cy/ea. is 4.44 ea./crew day. The difference between the two categories is 2.99 ea./crew day.

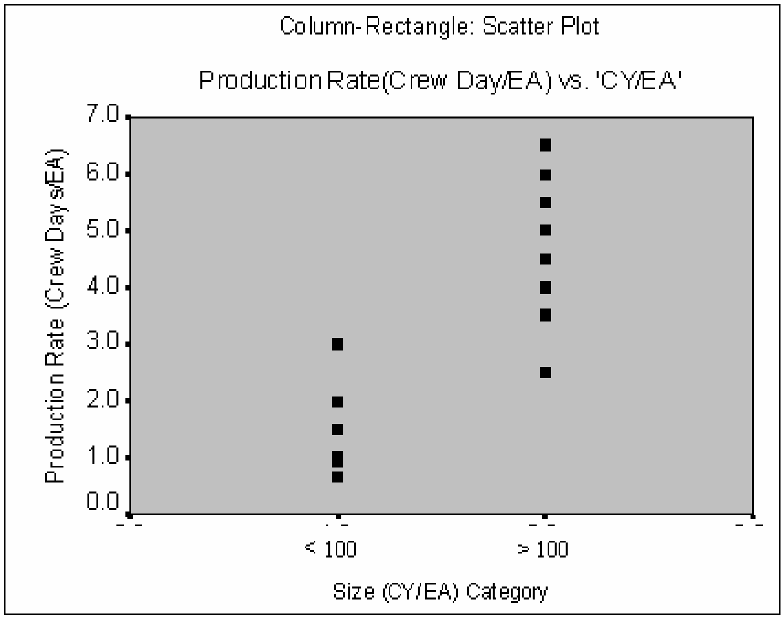


Figure 4.24 Column — Rectangle: Scatterplot [vs. Size (CY/EA) Category]

Height

The *t* test was employed to test the difference in mean production rate between columns with height of less than 30 ft. and more than 30 ft.

Because the *p* value of the *t* test was less than 0.1, it can be concluded that the average production rates of column construction are different between the two categories at the 90 percent confidence interval.

The average production rate for column height of less than 30 ft. is 1.23 ea./crew day, and the mean production rate for column height of more than 30 ft. is 3.92 ea./crew day with a difference of 2.69 ea./crew day.

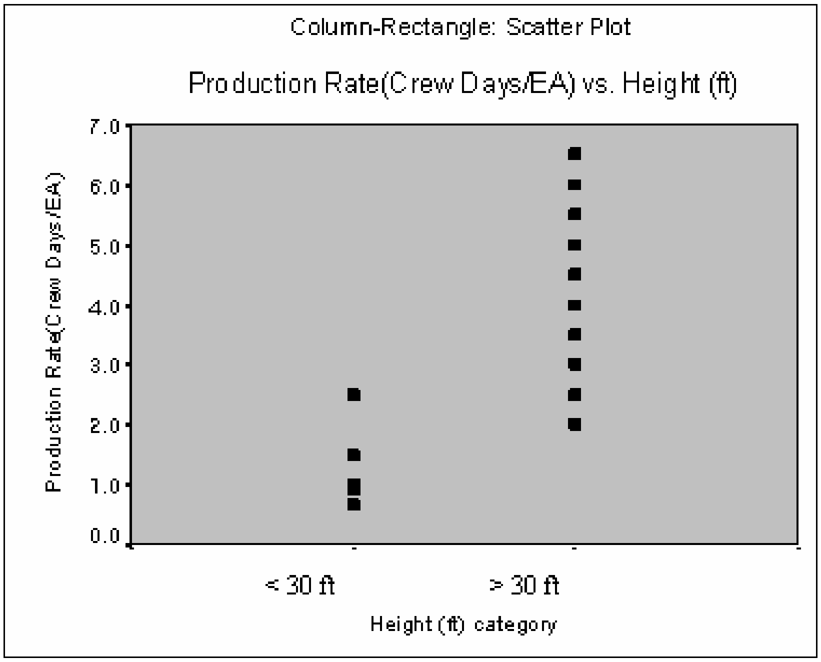


Figure 4.25 Column — Rectangle: Scatterplot (vs. Height Category)

Number of Columns per Bent

The *t* test was employed to test the differences in mean production rate among one, two, and three column(s) per bent.

The average production rates of column construction were found to be different between the three categories at the 90 percent confidence interval.

The mean production rate for one column per bent is 4.05 ea./crew day, for two columns per bent it is 2.00 ea./crew day, and for three columns per bent it is 1.02 ea./crew day.

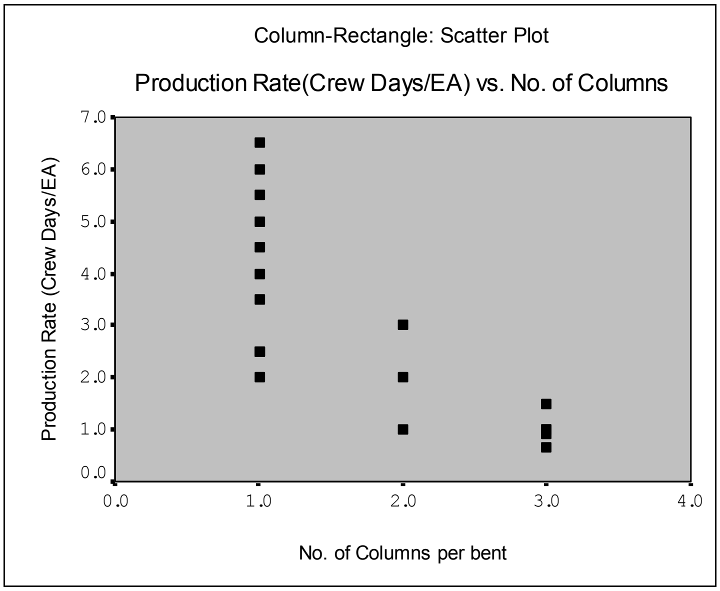


Figure 4.26 Column — Rectangle: Scatterplot (vs. Number of Columns per Bent)

4.2.8.3 Column — Round

Three candidate drivers were found to have significant effects on round column production rates. These included column height (ft), column diameter (ft), and number of columns per bent.

Column Height (ft)

The linear model was found to have the best-fitted relationship between the observed production rates and excavation depth. The fitted linear model for this driver is shown in Figure 4.27. The model fell within the 95 percent confidence interval with an R^2 of 0.49. The coefficients of this model were statistically different from zero at the 95 percent confidence interval.

This model is applicable only to column height within the range of 5 to 40 ft., because the data collected falls within this range. The estimated production rates can range from 0.16 to 1.07 ea./crew day.

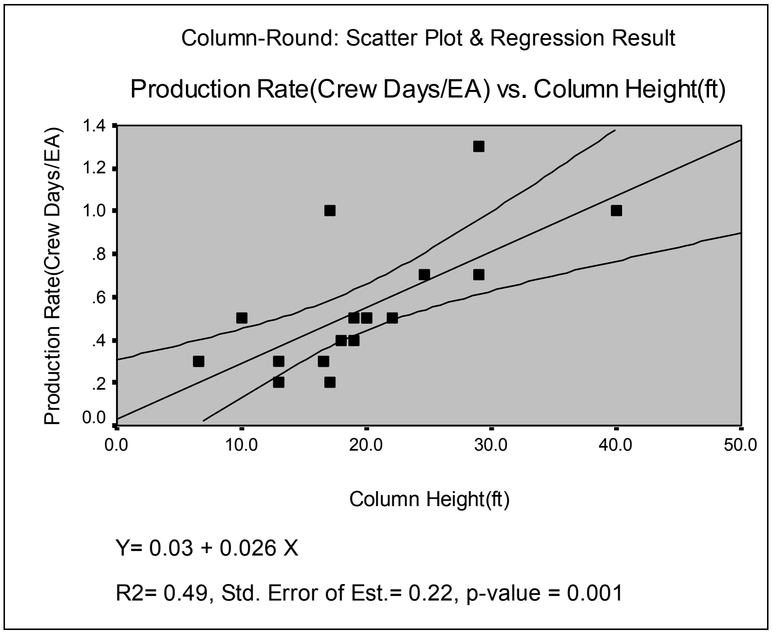


Figure 4.27 Column — Round: Scatterplot and Regression Results [vs. Column Height (ft)]

Column Diameter (ft)

The *t* test was employed to test the differences in mean production rate among the three categories — namely, 2.0, 2.5, and 3.0 ft. in diameter. Because there was only one data point for column diameter of 2.0 ft., this category was not included in the analysis.

On the basis of the assumption of equal variances between the two groups, the *p* value of the *t* test was 0.001, which is less than 0.1. Therefore, it can be concluded that the average production rates of column construction are different among the three categories at the 90 percent confidence interval.

The mean production rate for columns of diameter of 2.5 ft. is 0.36 ea./crew day, and the mean production rate for columns of diameter of 3.0 ft. is 0.814 ea./crew day. The difference of mean production rate between 2.5 and 3.0 ft. diameter is 0.454 ea./crew day.

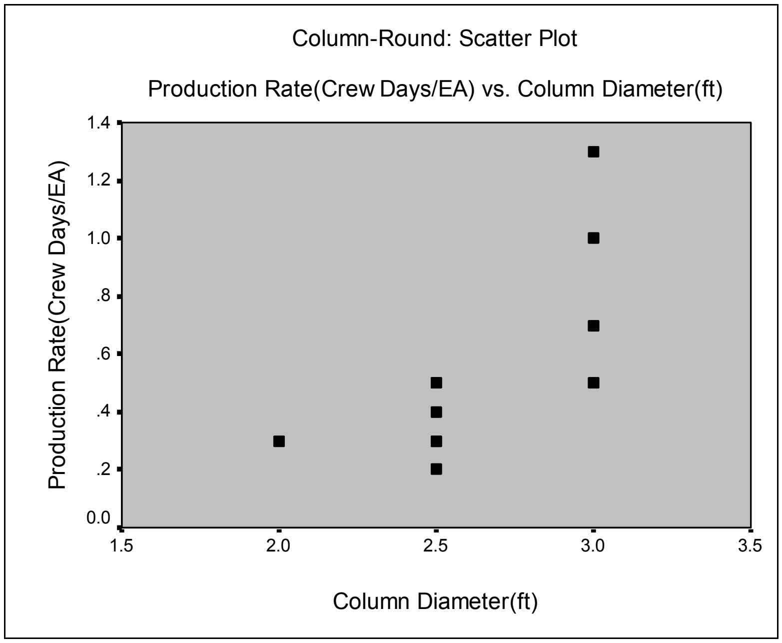


Figure 4.28 Column — Round: Scatterplot [vs. Column Diameter (ft)]

Number of Columns per Bent

The *t* test was employed to test the difference in mean production rate between three or fewer columns per bent and four or more columns per bent. On the basis of the assumption of equal variances between the two groups, the *p* value of the *t* test was less than 0.1. Therefore, the average production rates of column construction are different between the two categories at the 90 percent confidence interval.

The mean production rate for three or fewer columns per bent is 0.68 ea./crew day, and that for four or more columns per bent is 0.344 ea./crew day. The difference of mean production rate between the two categories is 0.335 ea./crew day.

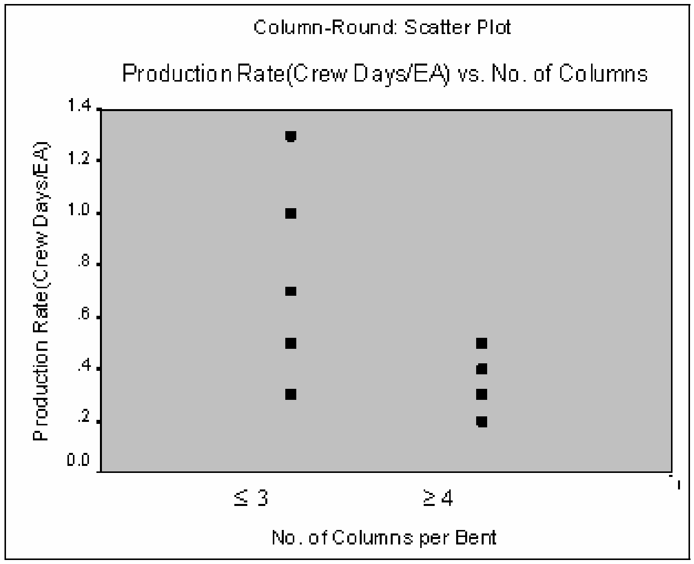


Figure 4.29 Column — Round: Scatterplot (vs. Number of Columns per Bent Category)

4.2.8.4 Cap

Three candidate drivers were found to have significant relationships with production rates of caps. These are size (cy/ea.), cap length (ft), and shape of cap (rectangle or inverted T).

Size (cy/ea.)

Production rates were found to be linearly related to the sizes of caps, as shown in Figure 4.30. The model fell within the 95 percent confidence interval with an R^2 of 0.51, and the coefficients of this model were statistically different from zero at the 95 percent confidence interval with a p value of less than 0.01.

This model is applicable only to cap sizes within the range of 1 to 125 cy/ea., because data collected falls within this range. The estimated production rates of the fitted linear model can range from 3.21 to 8.2 ea./crew day.

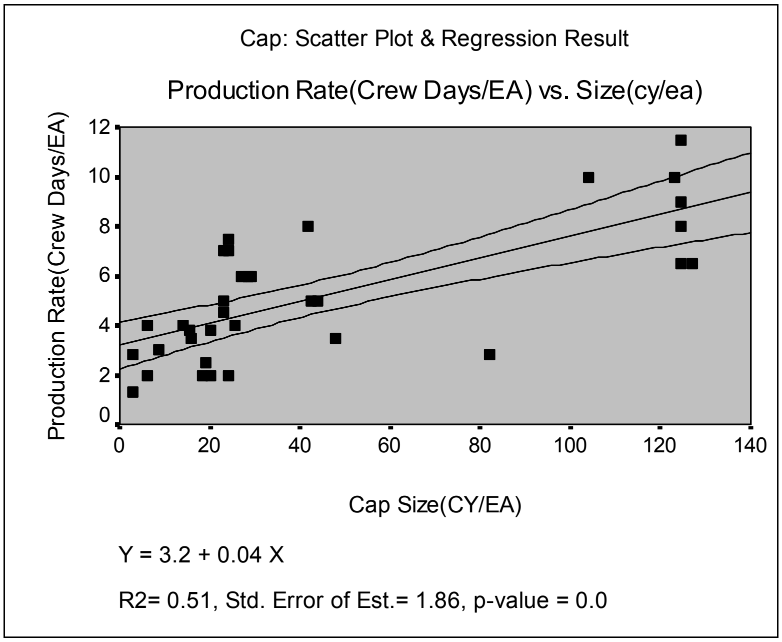


Figure 4.30 Cap: Scatterplot and Regression Results [vs. Size (cy/ea.)]

Cap Length (ft)

The production rate of caps exhibited a linear relationship with the length of cap. The fitted linear model for this driver is shown in Figure 4.31. The model fell within the 95 percent confidence interval with an R^2 of 0.50. The coefficients of this model were statistically different from zero at the 95 percent confidence interval because the *p* values of testing coefficients for the driver and constant term were less than 0.01.

This model is applicable only to cap lengths from 8 to 105 ft. because the data collected falls within this range. The estimated production rates of the fitted linear model range from 2.16 to 8.95 ea./crew day.

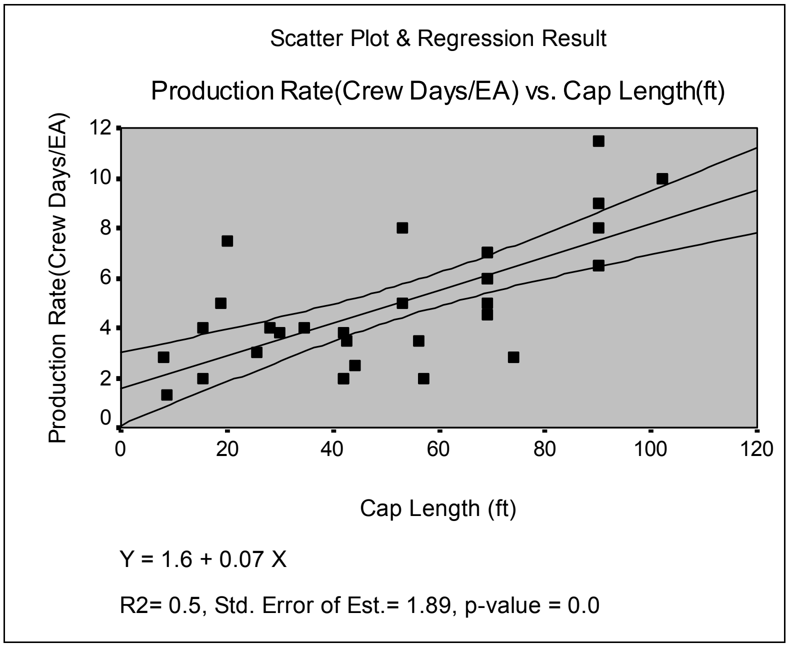


Figure 4.31 Cap: Scatterplot and Regression Results [vs. Cap Length (ft)]

Shape of Cap (Rectangle or Inverted T)

The *t* test was employed to test the difference in mean production rate among three types of cap shapes — namely, rectangle, inverted, and aesthetic. However, only one data point was available for an aesthetic cap, and countryspecialist@eatonconsultinggroup.com this type was not included in further analysis. On the basis of the assumption of equal variances between the two groups, the *p* value of the *t* test was less than 0.1.

The mean production rate for rectangular caps is 4.26 ea./crew day, and that for inverted T caps is 6.04 ea./crew day. The difference in mean production rate between the two categories is 1.78 ea./crew day.

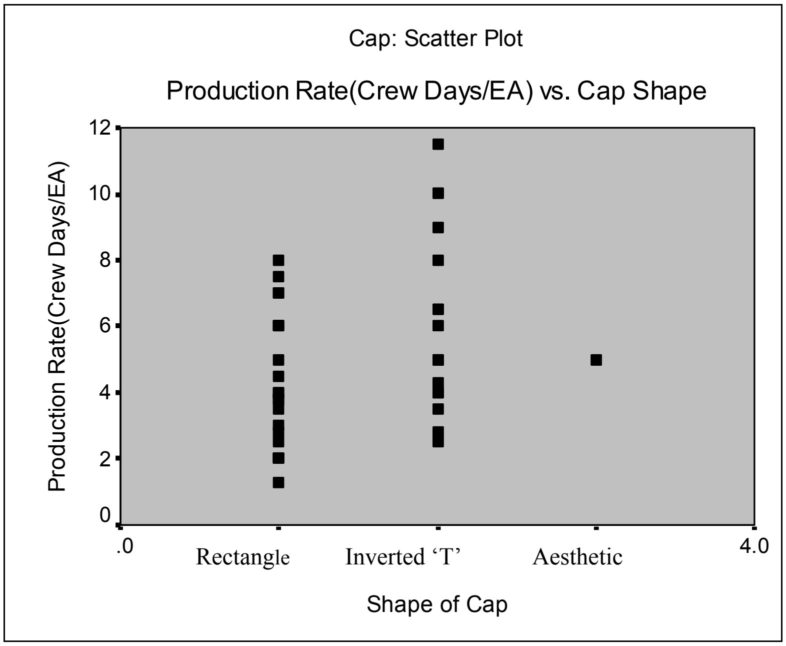


Figure 4.32 Cap: Scatterplot (vs. Cap Shape)

4.2.8.5 Abutment

Owing to insufficient sample size, statistical analysis would not yield meaningful results. Furthermore, no candidate driver was found to be statistically significant enough to carry out detailed analysis.

4.2.10 Item 422: Reinforced Concrete Slabs

Although TxDOT specifications do not differentiate among different types of reinforced concrete slabs, this research distinguished data between bridge deck and rail.

Bridge Deck

Four candidate drivers, width of deck poured (ft), shape of deck poured (straight or curved), formwork crew size, and rebar work crew size, were found to be statistically significant.

Width of Deck Poured (ft)

The best-fitted relationship between the observed production rates and width of deck poured was linear. The fitted linear model for this driver is shown in Figure 4.33. The model fell within the 95 percent confidence interval with an R^2 of 0.41. The coefficients of this model were statistically different from zero at the 95 percent confidence interval because the *p* values of testing coefficients for the driver and constant term were less than 0.01. This model is applicable only to widths within the range of 22 to 108 ft., because data collected falls within this range. The estimated production rates of the fitted linear model can range from 458 to 1,877 sf/crew day.

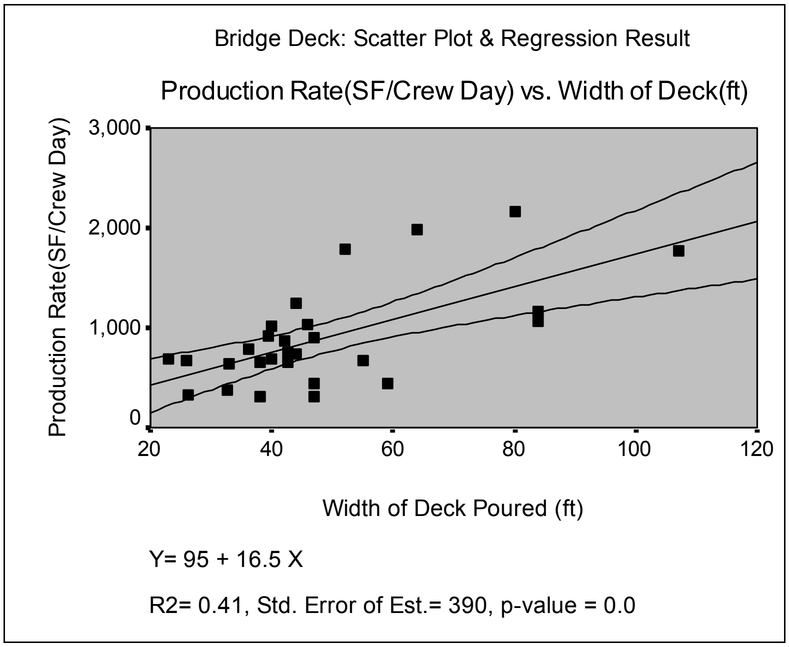


Figure 4.33 Bridge Deck: Scatterplot and Regression Results [vs. Width of Deck Poured (ft)]

Shape of Deck Poured

The *t* test was employed to test the difference in mean production rate between the two types of deck shape — namely, straight and curved. On the basis of the assumption of equal variances between two groups, the *p* value of the *t* test was less than 0.1. Therefore, the average production rates of deck construction are different between the two categories at the 90 percent confidence interval.

The mean production rate for straight deck is 962 sf/crew day, and the mean production rate for curved deck is 338 sf/crew day. The difference of mean production rate between the two categories is 624 sf/crew day.

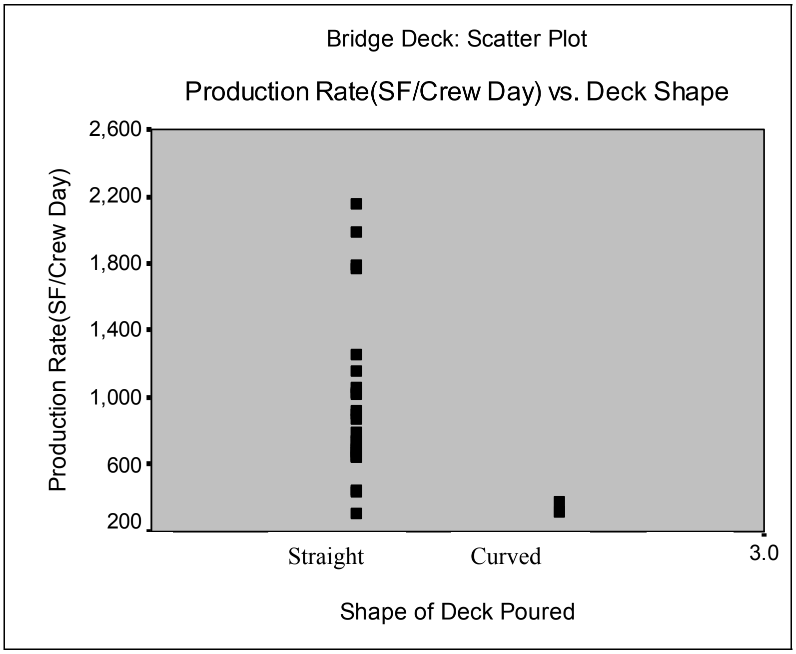


Figure 4.34 Bridge Deck: Scatterplot [vs. Shape of Deck (Straight/Curved)]

Formwork Crew Size

The relationship between the observed production rates and formwork crew size was found to be linear. The fitted linear model for this driver is shown in Figure 4.35. The model fell within the 95 percent confidence interval with an R^2 of 0.60. The coefficients of this model were statistically different from zero at the 95 percent confidence interval. This model is applicable only to crews of 5 to 18 formwork workers. The estimated production rates of this fitted linear model can range from 1,034 to 2,071 sf/crew day.

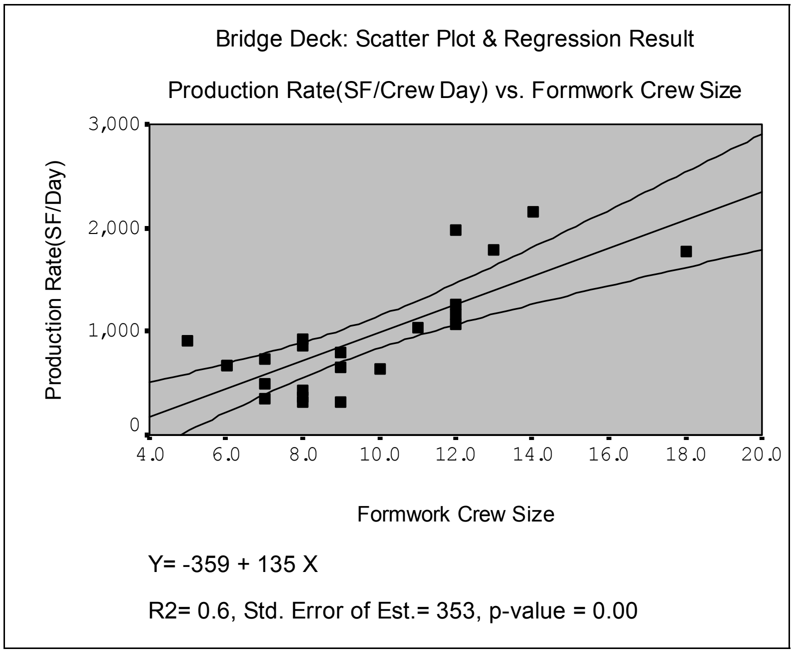


Figure 4.35 Bridge Deck: Scatterplot and Regression Results (vs. Formwork Crew Size)

Rebar Work Crew Size

The relationship between the observed production rates and rebar work crew size was also linear, as shown in Figure 4.36. The model fell within the 95 percent confidence interval with an R^2 of 0.51. The coefficients of this model were statistically different from zero at the 95 percent confidence interval. This model is applicable only for five to fifteen workers in a crew. The estimated production rates of the fitted linear model can range from 314 to 1,724 sf/crew day.

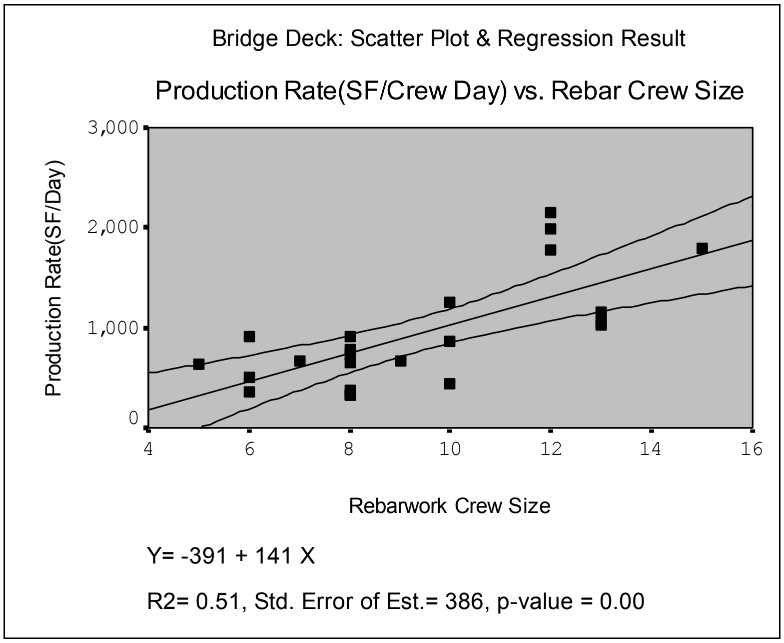


Figure 4.36 Bridge Deck: Scatterplot and Regression Results (vs. Rebar Work Crew Size)

4.2.11 Item 423: Retaining Wall

Because most retaining walls built by TxDOT are mechanically stabilized earth (MSE) walls, it was the only type of retaining wall investigated in this research.

Only one factor, size of wall, was found to be a significant driver for MSE walls. Size of wall is measured as the total square feet of a particular MSE wall.

The linear model was found to have the best-fitted relationship between the observed production rates and size of wall. The fitted linear model for this driver is shown in Figure 4.37. The model fell within the 95 percent confidence interval with an R^2 of 0.51. The coefficients of this model were statistically different from zero at the 95 percent confidence interval because the *p* values of testing coefficients for the driver and constant term were less than 0.01. This model is applicable only to walls from 430 to 3,400 sf. The estimated production rates of the fitted linear model can range from 305 to 557 sf/crew day.

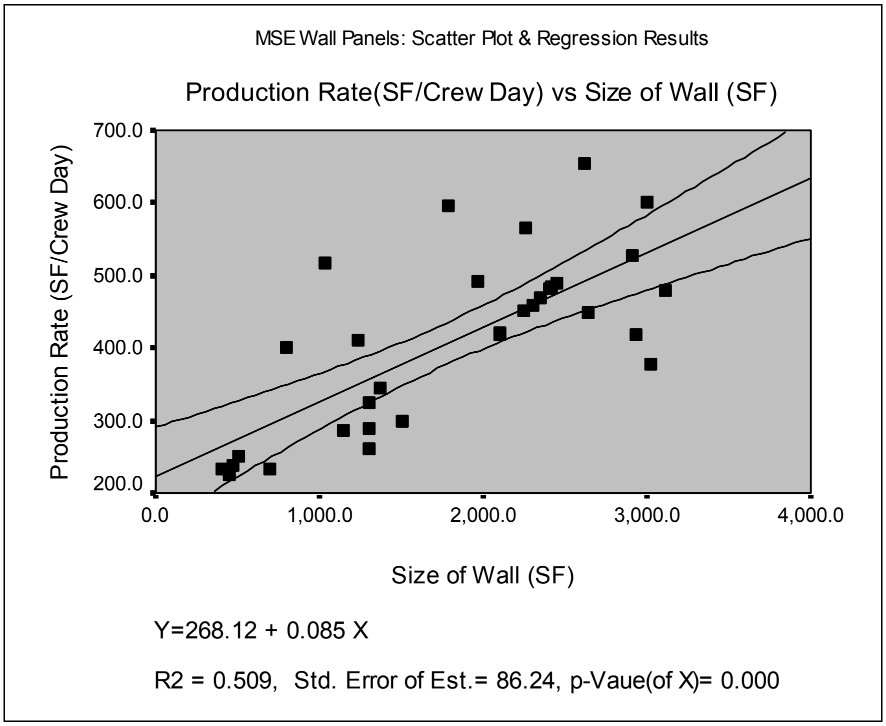


Figure 4.37 Mechanically Stabilized Earth Wall Panels: Scatterplot and Regression Results [vs. Size of Wall (sf)]

Production Rates of Copings, Footings, and Leveling Pads

The MSE wall production rate does not include the production of leveling pads, footings, and copings. Further investigation was carried out to determine the production rates of copings, footings, and leveling pads. These are discussed in the followings subsections.

Copings

Owing to the limited number of data points (eleven), the only driver found to be significantly driving the production rate was the length of coping of the wall. The logarithmic model was found to have the best-fitted relationship between the observed production rates and length of coping. The fitted logarithmic model for this driver is shown in Figure 4.38. The model fell within the 95 percent confidence interval with an R^2 of 0.633. This model is applicable only to coping lengths from 300 to 3,800 lf. The estimated production rates of the fitted logarithmic model can range from 218 to 385 lf/crew day. Natural log is applicable to this formula.

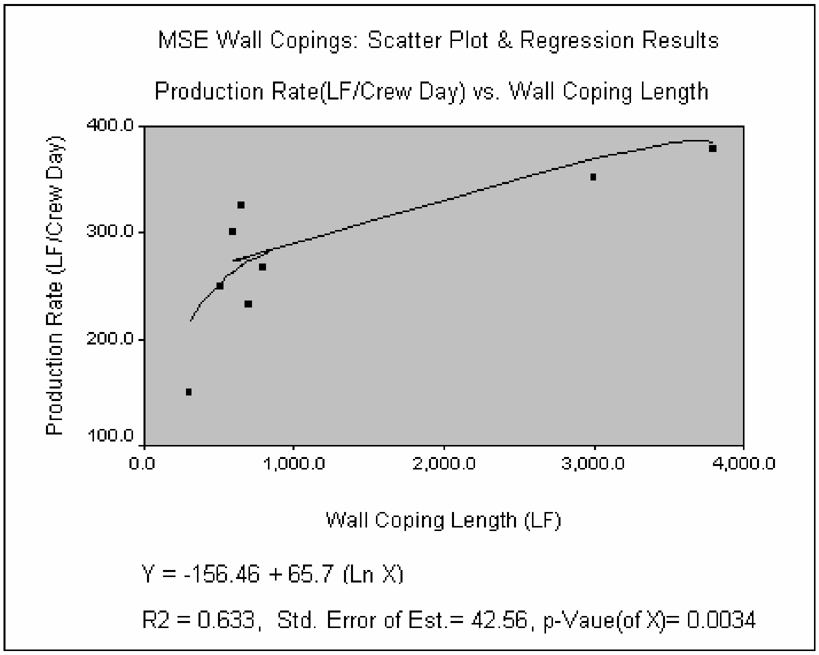


Figure 4.38 Mechanically Stabilized Earth Wall Panels: Scatterplot and Regression Results [vs. Wall Coping Length (lf)]

Footings and Leveling Pads

Although one driver was found to be relatively significant, an attempt to place this driver on the regression plot found that the correlation coefficient (R^2) value was 0.38, which was too low to confirm the relation between the production rate and the candidate driver. Moreover, the *p* value was higher than the required 0.05, which suggests that the model did not lie within the 95 percent confidence interval. Thus, no relationship could be established. The range of production rate was from 68 to 300 lf/crew day, and the mean was 178 lf/crew day. The longest footing and leveling pad observed was 800 lf, and the shortest was 160 lf. The minimum number of days used to construct the footings/leveling pads was two days, and the maximum was five days. Estimators are suggested to use two days for the shorter lengths, three to four days for the medium length ones, and five days for the long ones.

4.2.12 Item 425: Beam Erection

Three candidate drivers, average number of beams per span, total number of beams erected, and height from ground (ft), were selected from among many factors.

The analyses' results showed that the three candidate drivers had very weak linear relationships with the crew production rates because none of the R^2 values of the models was higher than 0.25. The unit of the production rate (spans/ crew day) used for the data collection may have contributed to the finding of no significant factors affecting beam erection production rates. Most of the production rates were obtained from observations of less than a full day (ten hours) of work. Therefore, a few hours' delay caused by any kind of factor would not be revealed in the rates. For instance, if two spans of twelve beams were erected in nine crew work hours, and two spans of eight beams were erected within seven hours, both production rates would be the same (two spans/crew day), suggesting that average number of beams per span did not affect the production rates of beam erection.

Although none of the factors was found to be a driver of beam erection crew production rates, the research committee agreed that the unit and its rates were practical and realistic for use in contract time determination.

4.2.13 Bridge Rail

Although it seemed that the shape of the bridge rail would be significant, it failed to fall within the 90 percent confidence interval and thus was rejected. However, when a sufficient sample size becomes available, a conclusion may later be drawn.

4.2.14 Item 462: Concrete Box Culverts

Two types of concrete box culverts were studied in this research: cast in place and precast culverts.

4.2.12.1 Precast Concrete Box Culverts

Three significant drivers — length of culvert runs, soil types, and clay content in work zone — were found to be related to production rates.

Length of Culvert Runs

The linear model was found to have the best-fitted relationship between the observed production rates and length of culvert runs. The fitted linear model for this driver is shown in Figure 4.39. The model fell within the 95 percent confidence interval with an R^2 of 0.708. The coefficients of this model were statistically different from zero at the 95 percent confidence interval because the p values of testing coefficients for the driver and constant term were less than 0.01. This model is applicable only to wall sizes within the range of 80 to 1,620 lf. Production can range from 12 to 243 lf/crew day.

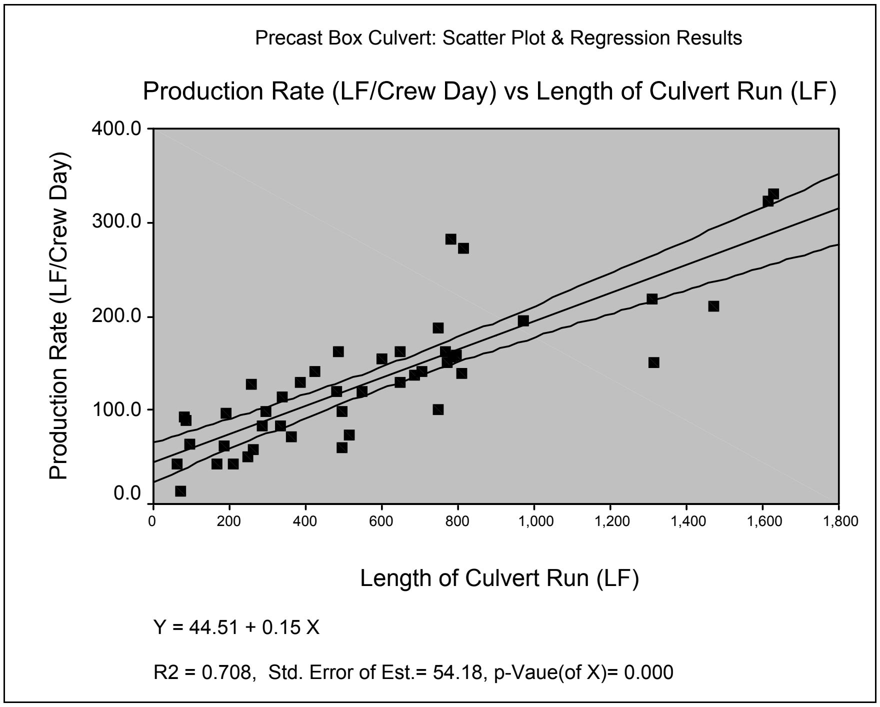


Figure 4.39 Precast Box Culverts: Scatterplot and Regression Results [vs. Length of Culvert Run (lf)]

Soil Types

Stiffness of the soil was found to affect the production rate of precast concrete box culverts. The *t* test was employed to test the difference in mean production rate between loose and stiff soil. On the basis of the assumption of equal variances between two groups, the *p* value of the *t* test was less than 0.1. Therefore, it can be concluded that the average production rates of precast culvert installation are different between the two categories at the 90 percent confidence interval.

The mean production rate for precast culverts installation in loose soil is 107 lf/crew day, and in stiff/rocky soil it is 175 lf/crew day. The difference in mean production rate between the two categories is 68 lf/crew day.

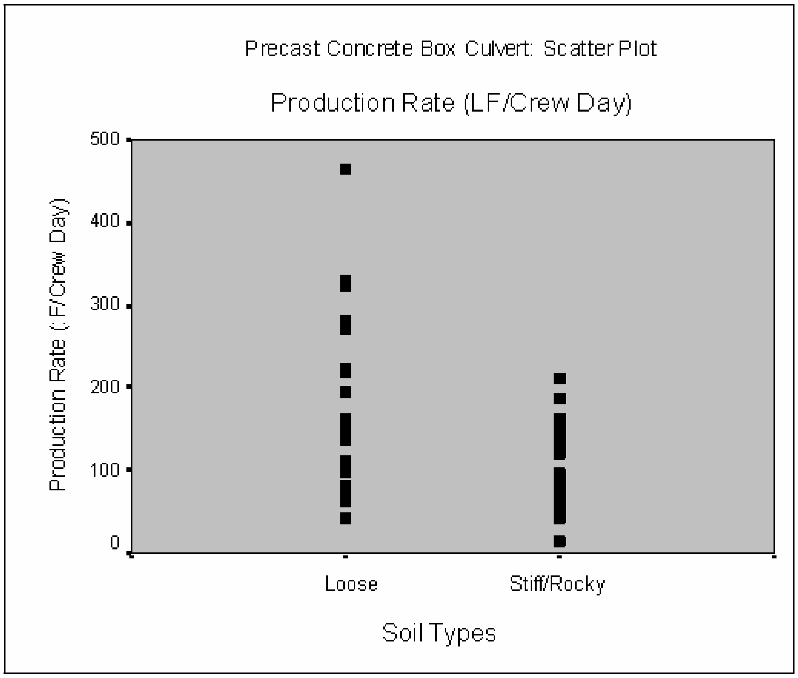


Figure 4.40 Precast Box Culverts: Scatterplot (vs. Soil Types)

Clay Content on Work Zone

The *t* test was employed to test the difference in mean production rate for precast box culverts installed on different levels of clay content. On the basis of the assumption of equal variances between two groups, the *p* value of the *t* test was 0.001, which is less than 0.1. Therefore, it can be concluded that the average production rates of precast box culverts installation is influenced by clay content in the soil at the 90 percent confidence interval.

The mean production rate of culverts in moderate/high clay content is 167.5 lf/crew day, and mean production rate of culverts in low clay content is 78.3 lf/crew day. The difference between the means is 89.2 lf/crew day.

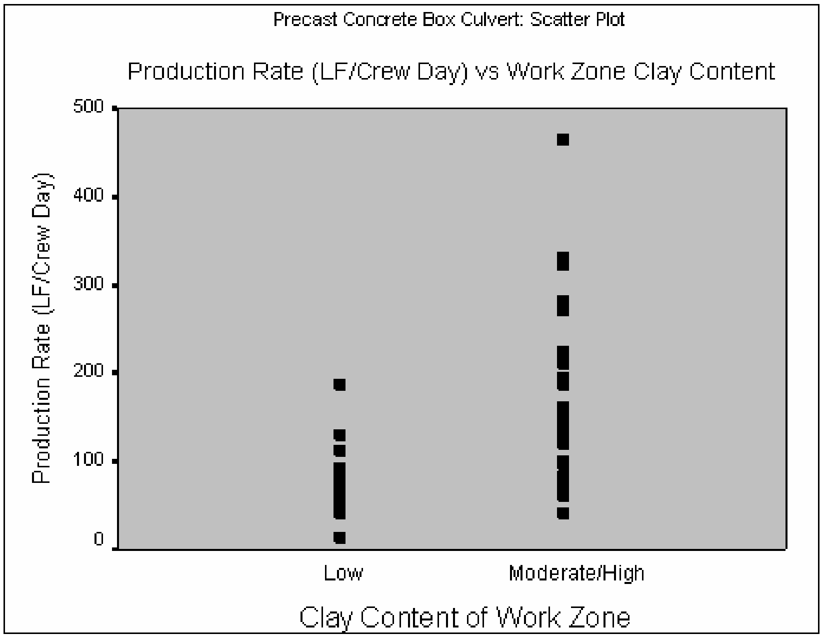


Figure 4.41 Precast Box Culverts: Scatterplot (vs. Clay Content on Work Zone)

4.2.12.2 Cast in Place Box Culverts

Length of box culvert was the only significant driver that drove the production rate of cast in place box culvert. Logarithmic relationship was found between box culvert length and cast in place box culvert production rates. The fitted model for this driver is shown in Figure 4.39. The model fell within the 95 percent confidence interval with an R^2 of 0.78. The coefficients of this model were statistically different from zero at the 95 percent confidence interval, and the p value was less than 0.01. This model is applicable only to culvert length from 10 to 690 lf. The estimated production rates of the fitted logarithmic model can range from 15.43 to 30.08 lf/crew day.

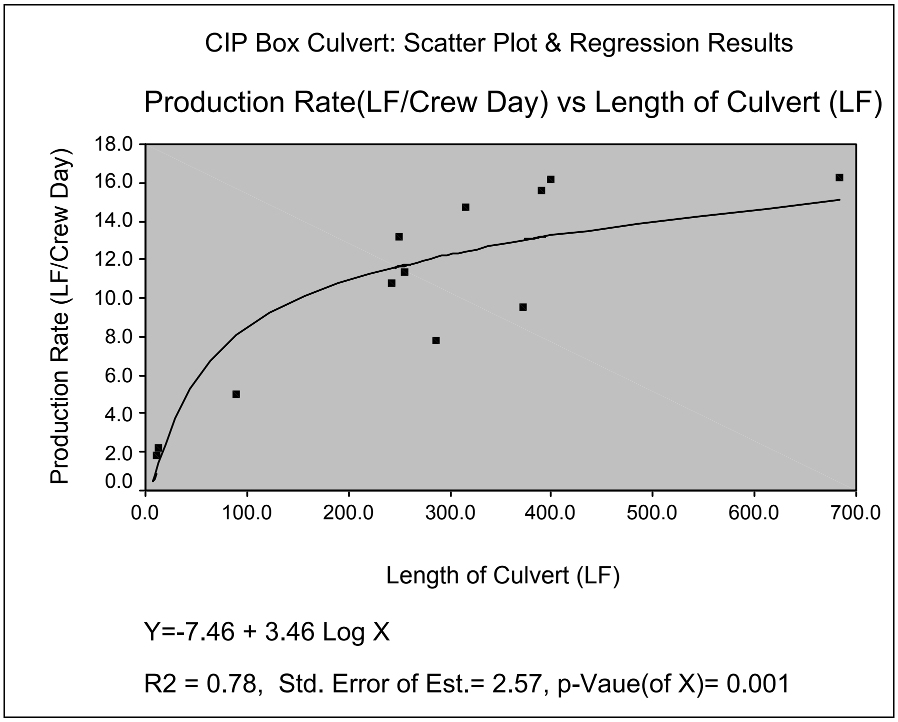


Figure 4.42 Cast in Place Box Culverts: Scatterplot and Regression Results [vs. Length of Culvert Run (lf)]

4.2.15 Item 464: Reinforced Concrete Pipes

Three drivers — length of pipe run, line orientation, and work zone accessibility — were found to have significant impacts on the reinforced concrete pipes installation process.

Length of Pipe Run

The logarithmic model was found to have the best-fitted relationship between the observed production rates and length of pipe run. The fitted linear model for this driver is shown in Figure 4.43. The model fell within the 95 percent confidence interval with an R^2 of 0.44. This model is applicable only to length of pipe run from 68 to 2,600 lf. The estimated production rates of the fitted logarithmic model can range from 46.1 to 204.52 lf/crew day.

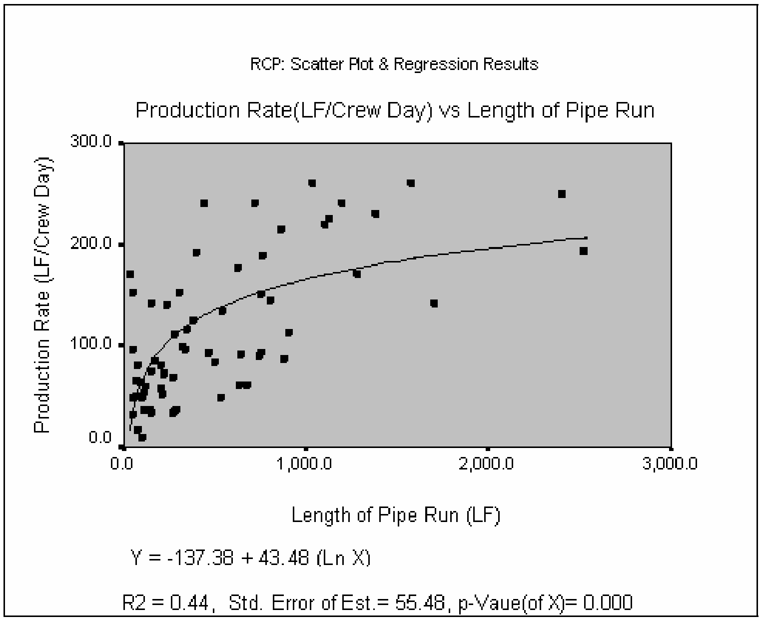


Figure 4.43 Reinforced Concrete Pipe: Scatterplot and Regression Results [vs. Length of Pipe Run (lf)]

Line Orientation

The direction of the pipe run was found to be an important production rate driver. When a pipe runs parallel to a road, the operation meets a more consistent terrain and soil surface and thus production rates are expected to be high. But when pipe runs perpendicular to the road, the operations are less consistent owing to differences in the surface, the chances of meeting a hard surface, or a higher frequency of old pipes, and thus lower production rates are expected.

The *t* test was employed to test the difference in mean production rate between the two line orientations. The average production rates of pipe installation were significantly different between the two categories at the 90 percent confidence interval.

The mean production rate for pipes installed parallel to the road is 136 lf/crew day, and the mean production rate for pipes installed perpendicular to the road is 75 lf/crew day. The difference of means is 61 lf/crew day.

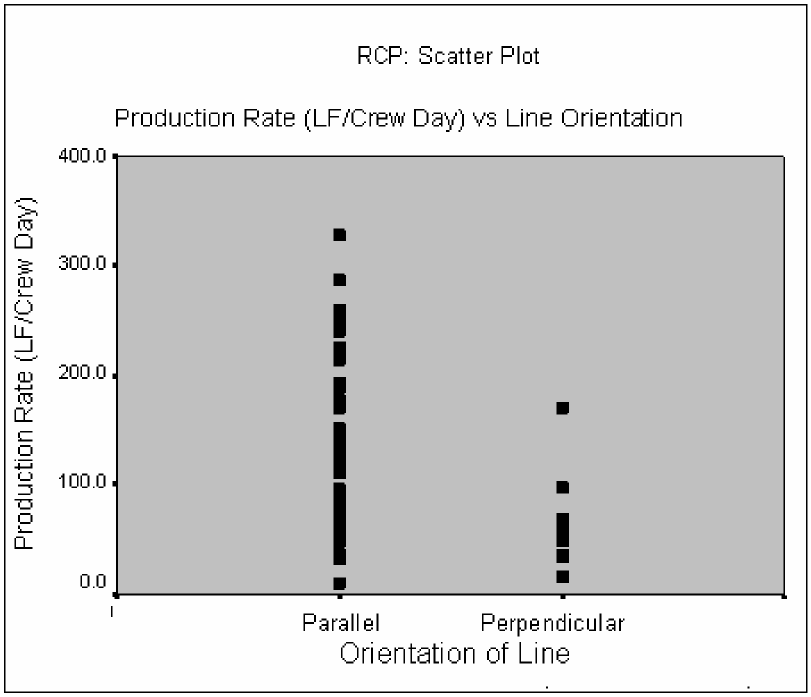


Figure 4.44 Reinforced Concrete Pipe: Scatterplot (vs. Orientation of Line)

Work Zone Accessibility

The *t* test was employed to test the difference in mean production rate between different levels of work zone accessibility. The mean production rate of pipe installation was found to be different between the two categories at the 90 percent confidence interval.

The mean production rate for pipe installation on moderate/difficult work zone accessibility is 104.5 lf/crew day, and the mean production rate on easy work zone accessibility is 135.2 lf/crew day. The difference between the means is 30.8 lf/crew day.

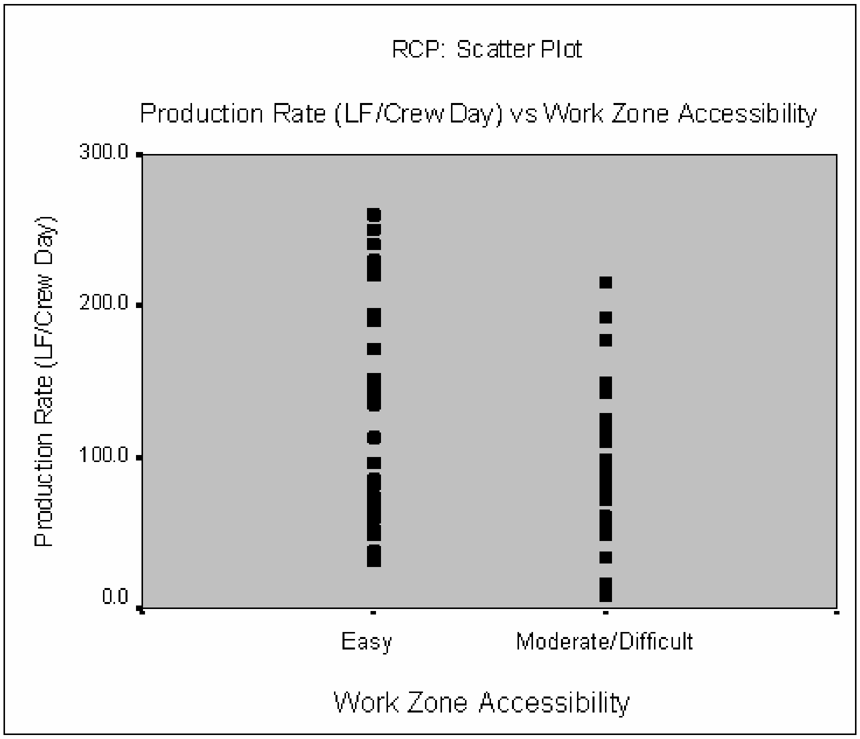


Figure 4.45 Reinforced Concrete Pipe: Scatterplot (vs. Work Zone Accessibility)

4.2.16 Item 465: Inlets and Manholes

Three factors were found to significantly drive the production rates of inlets and manholes. These drivers were total quantity (ea.) of inlets/manholes for line, inlets with manholes installation or manholes installation only, and cast in place or precast.

Total Quantity (ea.) of Inlets/Manholes for Line

The logarithmic model was found to show the best-fitted relationship between the observed production rates and total quantity (ea.) of inlets and/or manholes for line. The fitted linear model for this driver is shown in Figure 4.46. The model fell within the 95 percent confidence interval with an R^2 of 0.78. The coefficients of this model were statistically different from zero at the 95 percent confidence interval because the *p* values of testing coefficients for the driver and constant term were less than 0.01. This model is applicable only to total inlets/manholes for line from 1 to 23 ea.. The estimated production rates of the fitted logarithmic model can range from 1.105 to 4.24 ea./crew day.

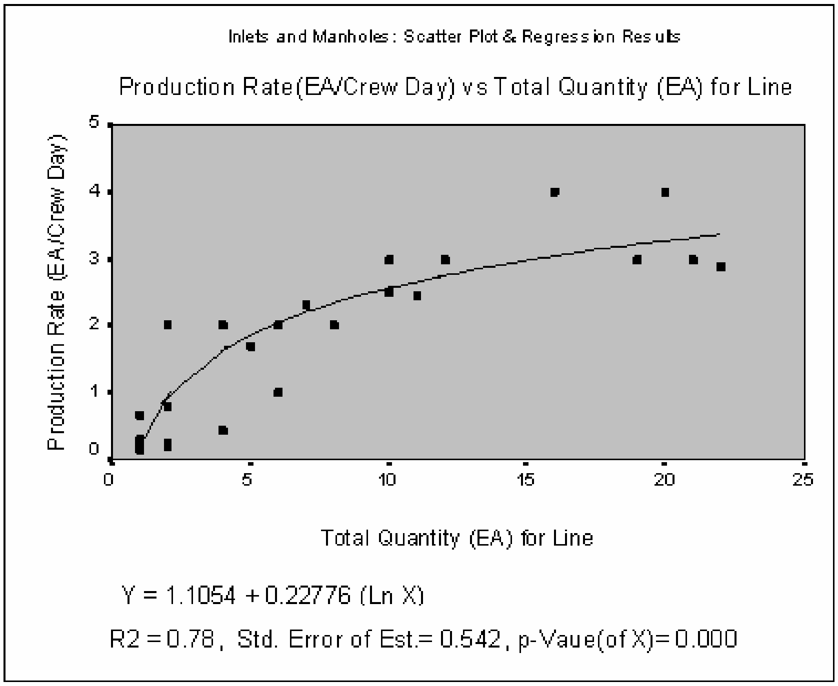


Figure 4.46 Inlets and Manholes: Scatterplot [vs. Total Quantity (ea.) for Line]

Inlets/Manholes or Manholes Only

The *t* test was employed to test the difference in mean production rate between installation of inlets/manholes or manholes alone. On the basis of the assumption of equal variances between the two groups, the *p* value of the *t* test was less than 0.1. Therefore, it can be concluded that the average production rates of inlets and manholes were different between the two categories at the 90 percent confidence interval.

The mean production rate of inlets or inlets with manholes installation is 2.53 ea./crew day, and mean production rate for manholes only installation is 0.874 ea./crew day. The difference of mean production rate between the two categories is 1.656 ea./crew day.

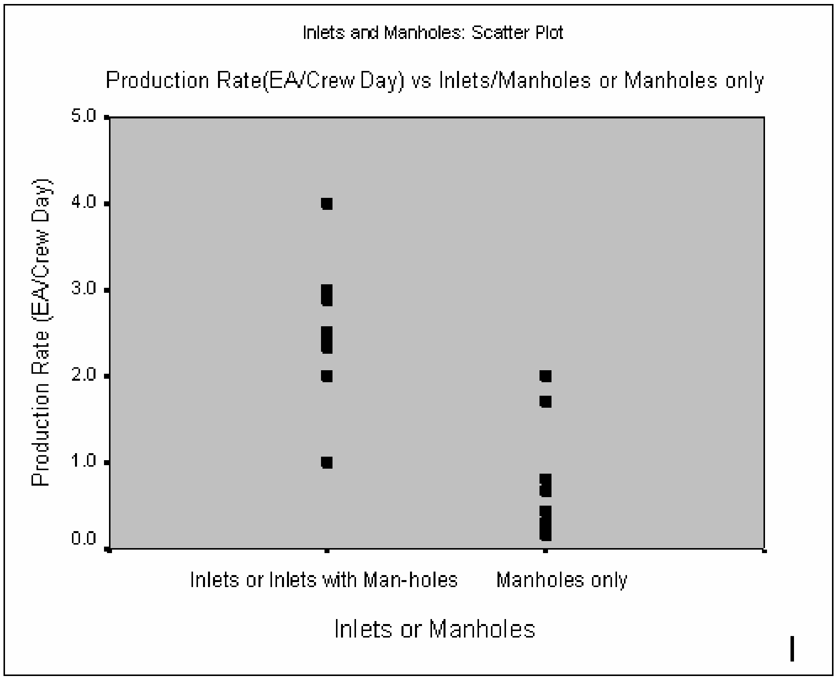


Figure 4.47 Inlets and Manholes: Scatterplot (vs. Inlets or Manholes for Line)

Cast in Place or Precast

The *t* test was employed to test the difference in mean production rate between cast in place or precast inlets and manholes. On the basis of the assumption of equal variances between two groups, the *p* value of the *t* test was less than 0.1. Therefore, it can be concluded that the average production rates of cast in place or precast inlets and manholes were different between the two categories at the 90 percent confidence interval.

The mean production rate for cast in place inlets and manholes is 0.768 ea./crew day, and the mean production rate of precast manholes and inlets only is 2.52 ea./crew day. The difference of mean production rate between the two categories is 1.752 ea./crew day.

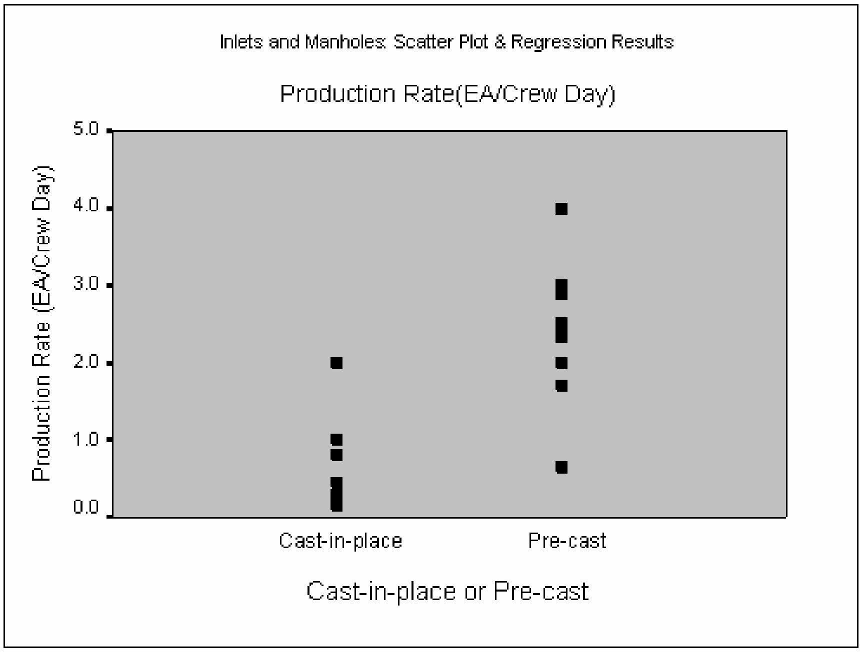


Figure 4.48 Inlets and Manholes: Scatterplot (vs. Cast in Place or Precast)

4.2.17 Item 466: Head Walls and Wing Walls

For head walls and wing walls, only one driver, total wall surface area, was found to have a significant effect on the production rates.

The logarithmic model was found to have the best-fitted relationship between the observed production rates and wall surface area. The fitted logarithmic model for this driver is shown in Figure 4.49. The model fell within the 95 percent confidence interval with an R^2 of 0.61. The coefficients of this model were statistically different from zero at the 95 percent confidence interval because the p values of testing coefficients for the driver and constant term were less than 0.01. This model is applicable only to wall sizes from 70 to 480 sf. The estimated production rates of the fitted logarithmic model can range from 6.35 to 61.18 sf/crew day.

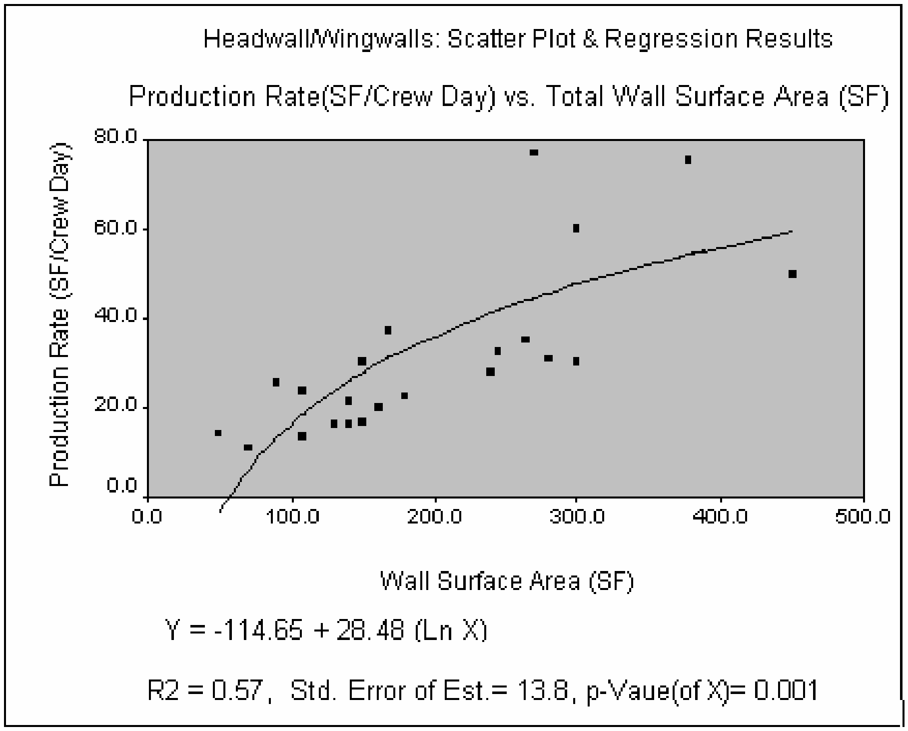


Figure 4.49 Head Walls/Wing Walls: Scatterplot [vs. Wall Surface Area (sf)]

4.2.18 Item 529: Concrete Curbs and Gutters

Only one driver was found to have a significant effect on the production rate of concrete curbs and gutters; this was WAQ.

The logarithmic model was found to have the best-fitted relationship between the observed production rates and WAQ. The fitted logarithmic model of this driver is shown in Figure 4.50. The model fell within the 95 percent confidence interval with an R^2 of 0.61. The coefficients of this model were statistically different from zero at the 95 percent confidence interval. This model is applicable only to wall sizes from 1,000 to 4,500 lf. The estimated production rates of the fitted logarithmic model can range from 800 to 2,100 lf/crew day.

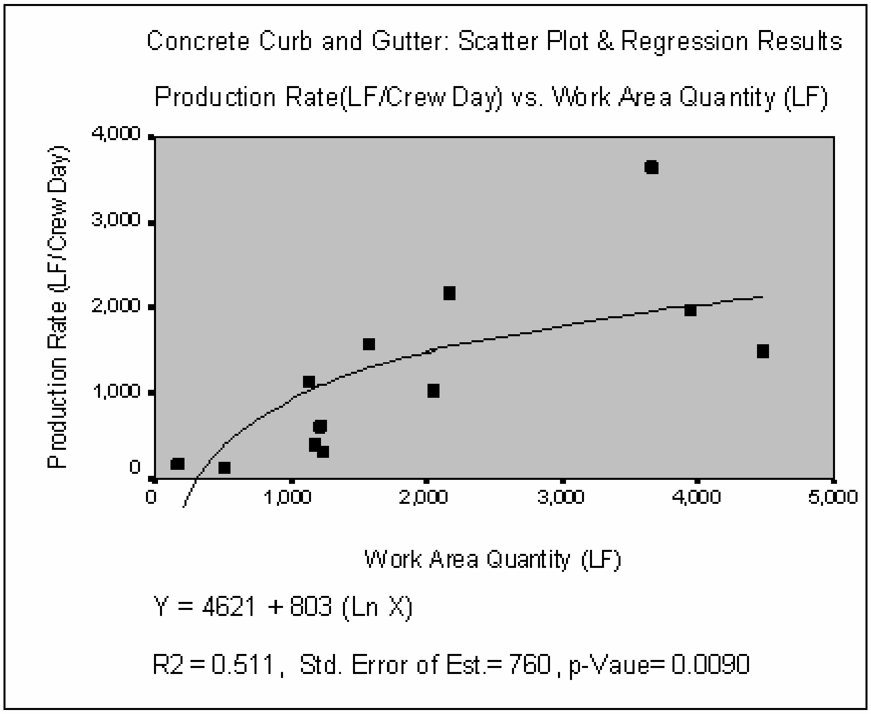


Figure 4.50 Concrete Curb and Gutter: Scatterplot and Regression Results [vs. Work Area Quantity (lf)]

4.2.19 Item 666/668: Pavement Markings

There are two types of pavement markings discussed in this section: permanent reflectorized pavement markings and raised pavement markings. Because data were obtained from interviews and insufficient data points were collected, no statistical analysis was used to examine the production rates for pavement markings.

4.2.17.1 Permanent Reflectorized Pavement Markings

The production rates for pavement markings were obtained from interviews conducted with two companies operating in Austin, Waco, and Houston. The inputs from these companies revealed that the production rates were highly variable because the working hours for the pavement marking operations in which these companies performed had high variation. As a result, hourly rate was used as the time unit.

There are two types of pavement markings that TxDOT commonly installs: Type I and Type II. The major tasks involved in Type II pavement marking operations are layout and placement. The driving task for Type I pavement marking operations is the beading process, because refilling the beads often takes at least one hour. Each side of roadway is marked out before pavement markings are placed.

The interviewees suggested that the drivers for pavement markings include the thickness of the markings, layout time, the total number of refills required (for Type I pavement), and whether the pavement is a single or double line. The interviewees provided the following production rates for Type I pavement markings.

Type I (4-in. line)

60 mil: 3.0 miles/hour
90 mil: 1.5 miles/hour
100 mil: 1.2 miles/hour

Type I (6-in. line):

60 mil: 2.0 miles/hour
90 mil: 1.0 miles/hour
100 mil: 0.8 miles/hour

Type I (8-in. line):

60 mil: 1.5 miles/hour
90 mil: 0.8 miles/hour
100 mil: 0.6 miles/hour

The suggested resources for the above production rates are five to six workers, one thermoplastic truck, and two traffic mounted attenuators.

The interviewees provided the following production rates for Type II pavement markings.

Type II (15 mil only)

4-in. line: 8 miles/hour
6-in. line: 6 miles/hour
8-in. line: 4 miles/hour

The suggested resources for the above production rates are four workers, one thermoplastic truck, and two traffic mounted attenuators.

Field data were collected for Type I (4-in. line) markings on one project site, and the production rates for the sixty miles of markings were between 2,660 and 15,721 lf/day. No driver and resource information could be obtained from this data because the rates came directly from the foreman's diary, which did not contain such information. The Contract Time Determination System (CTDS) production rates for pavement markings were 5,000, 10,000, and 20,000 lf/day or 0.98, 1.9, and 3.8 miles/day. The CTDS rate is too pessimistic.

4.2.17.2 Raised Pavement Markings

Production rates for raised pavement markings were obtained from an interview conducted with one company. The suggested production rates were as follows.

1. 40-ft. span: 2,500–3,000 ft./day
2. 80-ft. span: 1,500–2,000 ft./day

The suggested resources for these production rates include four workers, one trailer, and two traffic mounted attenuators.

4.3 Multiple Regressions

The effects of multiple drivers can cause production rates to vary. In this section, new models are developed from the significant drivers found in Section 4.2.

Multiple regressions models were not developed for work items with insufficient data points. The minimum number of data points was based on the suggested values provided by Green (1991).

Correlations were tested between significant drivers. When factors were correlated, the model with the highest R^2 values and lowest p value for each factor was chosen as the representative model for the selected work items. The data were tested for all assumptions and violations before multiple regression analyses were carried out.

4.3.1 Item 132: Embankment

WAQ and work zone congestion were found to be significant drivers for embankment and were used for the multiple regression analyses. One outlier and two data points pertaining to severely congested work zones were removed before the multiple regression analyses were conducted. The work zone congestion categories were recoded as binary values. Minorly congested work zones were recoded as 0, and moderately congested work zones were recoded as 1.

The fitted model, shown as Equation 4.1, was statistically significant at the 95 percent confidence interval with an R^2 of 0.4. The coefficients of the fitted model were statistically different from zero at the 95 percent confidence interval because the p values of the coefficients for WAQ and the constant term were less than 0.05.

$$\text{Production Rate} = -575 + 254 * \text{Ln}(\text{WAQ}) - 313 * (\text{WZC}) \quad (4.1)$$

WAQ = Work area quantity
WZC = Work zone congestion

This model is applicable only for WAQs within the range of 1,064 to 33,938 cy, and it is also not applicable for work zones with severe congestion. Therefore, the estimated production rates of this model should range from 882 to 2,075 cy/crew day.

4.3.2 Item 340: Hot Mix Asphalt Pavement

WAQ and course type greatly affected the production rates of hot mix asphalt pavement, as discussed earlier. Because a logarithmic relationship existed between WAQ and production rates, the original values of WAQ were transformed into logarithmic values for the multiple regression model. The course type categories were transformed into binary values. Base course construction was recoded as 1, and surface course construction was recoded as 0.

The fitted model, shown as Equation 4.2, was statistically significant at the 95 percent confidence interval. The R^2 and adjusted R^2 were 0.488 and 0.452, respectively.

$$\text{Production Rate} = 1263 + 269 * \text{Ln (WAQ)} - 181 * \text{(CT)} \quad (4.2)$$

WAQ = Work area quantity
CT = Course type

This model is only applicable to WAQs within the range of 227 to 5,840 tons. The estimated production rates for surface course construction of this model should range from 196 to 1,070 tons/crew day, and for base course construction from 377 to 1,251 tons/crew day.

4.3.3 Item 416: Drilled Shaft Foundations

The two significant drivers found for drilled shafts — location of work operation and total length of shafts in cluster — were used for the multiple regression. Two data points were found to be outliers and were removed from the multiple regression analysis. The different categories for location of work operation were transformed into binary values. Parallel to an operating road was recoded as 0, and ample space was recoded as 1.

The fitted model, shown as Equation 4.3, was statistically significant at the 95 percent confidence interval with an R^2 of 0.567. The coefficients of the fitted model were statistically different from zero at the 95 percent confidence interval because the *p* values of the coefficients for location of work operation and the constant term were less than 0.05.

$$\text{Production Rate} = 56.91 + 0.00903 * \text{(TLC)} - 22.756 * \text{(LWO)} \quad (4.3)$$

TLC = Total length of shafts in cluster (ea.)
LWO = Location of work operation

This model is applicable only for WAQs within the range of 50 to 1,870 lf. Therefore, the estimated production rates of this model can range from 34.606 to 73.16 lf/crew day.

4.3.4 Item 462: Precast Concrete Box Culverts

There are three significant drivers for precast concrete box culverts. Attempts to combine the effects of all three significant drivers failed because the *p* values for one of the drivers did not fall within the required 90 percent confidence interval. As a result, only two significant drivers were used to develop each model. Two models were found to be statistically significant.

First Model: Total Length of Pipe Run (lf) and Clay Content in Soil

No data points were found to be outliers. The different clay content categories were transformed into binary values. Low clay content was recoded as 0, and high/moderate clay content was recoded as 1.

The fitted model, shown as Equation 4.4, was statistically significant at the 95 percent confidence interval with an R^2 of 0.667. The coefficients of the fitted model were statistically different from zero at the 95 percent confidence interval with *p* values of the coefficients less than 0.05.

$$\text{Production Rate} = 37.087 + 0.1 * (\text{TRC}) + 48.93 * (\text{CC}) \quad (4.4)$$

TRC = Total length of culvert run (lf)
CC = Clay content

This model is applicable only for WAQs within the range of 80 to 1,620 lf. Therefore, the estimated production rates of this model can range from 45.09 to 248.02 lf/crew day.

Second Model: Total Length of Pipe Run (lf) and Soil Types

Four data points were found to be outliers and were removed from the data. The categories for soil types were transformed into binary values. Loose soil was recoded as 0 and stiff/hard Soil was recoded as 1.

The fitted model, shown as Equation 4.5, was statistically significant at the 95 percent confidence interval. The R^2 was 0.55. The coefficients of the fitted model were statistically different from zero at the 95 percent confidence interval because the p value of the coefficients were less than 0.05.

$$\text{Production Rate} = 86.845 + 0.104 * (\text{TPR}) - 35.562 * (\text{ST}) \quad (4.5)$$

TPR = Total length of pipe run (lf)
ST = Soil type

This model is applicable only for WAQs within the range of 80 to 1,620 lf. Therefore, the estimated production rates of this model can range from 59.61 to 255.33 lf/crew day.

4.3.5 Item 464: Reinforced Concrete Pipes

Attempts were made to build the multiple regression models using the three significant factors for reinforced concrete pipe. However, only the coefficients of the two significant drivers — namely, total quantity (lf) of pipe run and work zone accessibility — were found to fall within the 90 percent confidence interval, and thus only two significant drivers were applied to the model.

Two data points were identified as outliers and were removed from the data. The categories for work zone accessibility were transformed into binary values. Easy work zone accessibility was recoded as 0, and moderate/difficult was recoded as 1.

The fitted model, shown as Equation 4.6, was statistically significant at the 95 percent confidence interval with an R^2 of 0.432. The coefficients of the fitted model were statistically different from zero at the 95 percent confidence interval because the p values of coefficients for location of work operation and the constant term were less than 0.1.

$$\text{Production Rate} = -126.22 + \text{Log}_{10}\ 103.558 * (\text{TPR}) - 27.932 * (\text{WZA}) \quad (4.6)$$

TPR = Total quantity of pipe run (lf)
WZA = Work zone accessibility

This model is applicable only for WAQs within the range of 68 to 2,600 lf. Therefore, the estimated production rates of this model can range from 28 to 227.4 lf/crew day.

All the multiple regression formulas are summarized in Table 4.2.

Table 4.2 Summary of All Formulas and the Ranges of Application

Item #	Work Item	Factor	Formula (unless otherwise stated, log shall mean natural log)	Applicable Range
110	Excavation	Work area quantity	−3,995 + 649 Ln X	820–16,789 cy
132	Embankment	Work area quantity	−1,531 + 309 Ln X	1,064–33,938 cy
260	Lime treated subgrade	Work area quantity	−6,457 + 878 Ln X	1,332–50,101 sy
		Length of work area	−3,446 + 661 Ln X	1,632–50,490 lf
247	Flexible base	Work area quantity	−5,544 + 856 Ln X	1,579–41,607 Lift-sy
		Lift-length of work area	−3,939 + 823 Ln X	263–11,371 lf
276	Cement treated base	Work area quantity	−6,991 + 1231 Ln X	250–3,250 lf
340, 345	Hot mix asphaltic concrete	Work area quantity	−1,198 + 278 Ln X	227–5,840 tons
360-1	Slip form concrete pavement (CRCP only)	Work area quantity	−2,274 + 408 Ln X	1,159–18,592 sy
		Length of work area	−1,193 + 306 Ln X	473–7,783 lf
360-2	Conventional form concrete pavement	Work area quantity	−610 + 139 Ln X	211–4,320 sy
409	Prestressed concrete piling	Total number of piles in cluster	3.711 + 0.042 X	13–152 ea.
416	Drilled shaft foundation	Total length in cluster	62.76 + 0.094 X	50–1,800 lf
420-1	Footing	Excavation depth	0.8 + 0.19 X	5–15 lf
420-2	Column — Round	Height	0.03 + 0.026 X	5–40 lf
420-3	Cap	Size	3.2 + 0.04 X	1–125 cy/ea.
		Length	1.6 + 0.07 X	8–105 lf
422-1	Bridge deck cast in place	Width of deck	95 − 16.5 X	22–108 lf
		Formwork crew size	−359 + 135 X	5–18 workers
		Rebar crew size	−391 + 141 X	5–15 workers
423	MSE wall	Size of wall	268.12 + 0.085 X	430–3,400 sf
423-1	MSE wall — copings	Length of coping	−156.46 + 65.7 Ln X	300–3,800 lf
462-1	Precast concrete box culverts	Length of culvert run	44.51 + 0.15 X	80–1,620 lf
462-2	Cast in place concrete box culverts	Length of culvert run	−7.46 + 3.46 Ln X	10–690 lf
464-1	Reinforced concrete pipe	Length of pipe run	−137.38 + 43.48 Ln X	68–2,600 lf
465	Inlets and manholes	Total number of inlets/manholes in line	1.1054 + 0.2276 Ln X	1–23 ea.
466	Wing wall/head wall	Wall surface area	−114.65 + 28.48 Ln X	70–480 sf
529	Concrete curb and gutter	Work area quantity	−4,621 + 803 Ln X	1,000–4,500 lf

4.4 Summary of Drivers and Formulas

Table 4.2 suggests similarities between the drivers considered by CTDS and those found in this research. The descriptions for the drivers adopted by CTDS are not as clear, however. For example, for excavation, quantity of work is a driver for CTDS, but it does not clearly specify whether the quantity of work refers to the quantity for the entire project or a given work zone. The research found that quantity in the work zone drives the production rate and quantity for the entire project does not. As a result, the quantity of work stipulated in the CTDS might have meant quantity of work in a work zone. In another example, one of the drivers for RCP found in CTDS is location. The research defined location more narrowly and found that work zone accessibility and line orientation could better describe the location conditions, because these drivers had significant relationships with production rates.

However, some differences between the drivers were also found. For example, although soil is considered one of the drivers in CTDS for foundation construction, the research found that all of the drivers for the foundations turned out to be unrelated to soil. Although soil is generally perceived to be a driver of foundation production rate, the research found that presence of other, more significant, drivers reduced the importance of soil as a significant driver.

In summary, the research confirmed many drivers identified by CTDS and suggested others. These results should allow estimators to develop more accurate production rates for these work items.

Table 4.3 Summary of Drivers of Contract Time Determination System and Research

Item #	Work Item	Sensitive Factors CTDS Considered	Sensitive Factors the Research Found
110	Excavation	Soil, quantity of work	WAQ*
132	Embankment	Soil, quantity of work	WAQ*, WZC†
247	Flexible base	Location, quantity of work	WAQ*, lift-length of WA‡
260	Lime treated subgrade	Soil, quantity of work	WAQ*, length of WA‡
276	Cement treated base	Soil, quantity of work	WAQ*, lift-length of WA‡
340, 345	Hot mix asphaltic concrete	Location, quantity of work	WAQ*, course type
360-1	Slip form concrete pavement (CRCP only)	Location, quantity of work	WAQ*, length of WA‡
360-2	Conventional form concrete pavement	Location, quantity of work	WAQ*, configuration
409	Prestressed concrete piling	Soil	Total piles in cluster
416	Drilled shaft foundation	Soil	Total shafts in cluster, location conditions of operation
420-1	Footing	Soil	Size, height, excavation depth, and number of footings per bent
420-2	Column — rectangle	Complexity, quantity of work	Size, height, number of columns per bent
420-2	Column — round	Complexity, quantity of work	Height, diameter, number of columns per bent
420-3	Cap	Complexity, quantity of work	Size, length, shape
420-4	Abutment (cast in place)	Complexity, quantity of work	—
422-1	Bridge deck (cast in place)	Quantity of work	Width of deck, shape, and crew size
423	MSE wall	Soil	Size of wall
423-1	MSE wall — copings	—	Length
425	Beam erection	Location	—
450	Bridge railing	Quantity of work	—
462-1	Precast concrete box culverts	Soil	Length of run, soil types, clay content
462-2	Cast in place concrete box culverts	Soil	Length of run
464-1	RCP 18–42 in.	Location, soil	Length of run, WZA**, line orientation
464-2	RCP 48–72 in.	Location, soil	
465	Inlets and manholes	Location, soil	Total quantity in run, types
466	Wing wall/head wall	Soil	Wall surface area
529	Concrete curb and gutter	Location, quantity of work	WAQ*
666/668	Pavement markings	Quantity of work	—

*WAQ, work area quantity. **WZA, work zone accessibility. †WZC, work zone congestion. ‡WA, work area

4.5 Predicting Production Rates Using the Drivers and Formulas

This research developed several useful tools for construction time estimation. These tools are summarized in Tables 4.3, 4.4, and 4.5. Estimators can apply these tools to develop practical and useful production rates. At the same time, they could apply their experience and judgment to modify the calculated production rates according to specific project conditions that they may be more familiar with.

The estimator can rely on any of the three tools, shown in the following tables, to determine a realistic production rate. The following is an example of the calculation of a production rate for precast box culvert. A designer plans for an 800 lf culvert in stiff, rocky soil. The estimated production rate based on that condition is 164.51 lf/crew day. The mean production rate for culvert construction on stiff/rocky soil is 107 lf/crew day. The estimator can also rely on the multiple regression formula to calculate the expected production rate. Using the multiple regression formula with the combined effects of length of culvert run and stiff/rocky soil, the calculated production rate is 117.09 lf/crew day.

The calculated production rates ranged from a low of 107 lf/crew day, when the full impact of soil condition was considered, to a high of 164.51 lf/crew day, when the impact of soil was not considered. As a result, the estimator can use his/her personal experience to make the best estimation, given the project environment. Factors that the estimator find to be applicable to the production operation, such as crew productivity and regional adjustments, should be used to adjust the calculated production rates. The estimator can also determine whether the project requires a faster or slower completion time. If schedule is accelerated, 117 lf/crew day may be applicable, otherwise 107 lf/crew day may be considered ideal.

However, the estimator should note that the suggested production rates are applicable only to one run of culvert. Because different culvert runs have different lengths, each run should have a different set of production rates.

Table 4.4 Summary of All Discrete Drivers and the Range of Production Rates

Item #	Work item	Factor	Lowest Average	Highest Average
132	Embankment	Work zone congestion	872 cy/crew day	1,424 cy/crew day
340, 345	Hot mix asphaltic concrete	Course type	646 tons/crew day	882 tons/crew day
360-2	Conventional form concrete pavement	Configuration	192 sy/crew day	420 sy/crew day
416	Drilled shaft foundation	Location of operation	100 lf/crew day	133 lf/crew day
420-1	Footing	Size	1.714 ea./crew day	3.143 ea./crew day
		Number of footing/bent	1.65 ea./crew day	3.18 ea./crew day
420-2	Column — rectangle	Size	1.45 ea./crew day	4.44 ea./crew day
		Height	1.23 ea./crew day	3.92 ea./crew day
		Number of columns/bent	0.98 ea./crew day	2.05 ea./crew day
420-2	Column — round	Diameter	0.36 ea./crew day	0.814 ea./crew day
		Number of columns/bent	0.344 ea./crew day	0.68 ea./crew day
420-3	Cap	Shape	4.26 ea./crew day	6.04 ea./crew day
422-1	Bridge deck cast in place	Shape	338 lf/crew day	962 lf/crew day
462-1	Precast concrete box culverts	Soil types	107 lf/crew day	175 lf/crew day
		Clay content	78.3 lf/crew day	167.5 lf/crew day
464	Reinforced concrete pipe	Line orientation	75 lf/crew day	136 lf/crew day
		Work zone Accessibility	104.5 lf/crew day	135.2 lf/crew day
465	Inlets and manholes	Inlets or manholes	0.874 ea./crew day	2.53 ea./crew day
		Cast in place or precast	0.768 ea./crew day	2.52 ea./crew day

Table 4.5 Summary of Formulas and Ranges of Application for Multiple Regressions

Item #	Work Item	Formula (unless otherwise stated, log shall mean natural log)	Applicable Range
132	Embankment	Production rate = −575 + 254 × ln (work area quantity) − 313 × (work zone congestion)	1,064–33,938 cy
340, 345	Hot mix asphaltic concrete	Production rate = −1263 + 269 × ln (work area quantity) − 181 × (course type)	227–5,840 tons
416	drilled shaft foundation	Production rate = 56.91 + 0.00903 × (total length of shafts in cluster) − 22.756 × (location of work operation)	50–1,800 lf
462-1	Precast concrete box culverts	Production rate = 37.087 + 0.1 × (total length of culvert run [lf]) + 48.93 × (clay content) Production rate = 86.845 + 0.104 × (total length of pipe run [lf]) − 35.562 × (soil types)	80–1,620 lf 10–690 lf
464	Reinforced concrete pipe	Production rate = −126.22 + Log_{10} 103.558 × (total quantity [lf] of pipe run) − 27.932 × (work zone accessibility)	68–2,600 lf

5. HIGHWAY PRODUCTION RATE INFORMATION SYSTEM

The development of an information system is the final objective of this research. The information system serves as a tool that organizes and disseminates the key findings from this research. The system is called the Highway Production Rate Information System (HyPRIS). To ensure user-friendliness of the system, HyPRIS was developed with Microsoft Visual Basic using the Microsoft Excel platform.

5.1 Information Identification for HyPRIS

The key findings from the research were grouped into four different information elements. The first information element involves information that would be used by the Texas Department of Transportation (TxDOT) to estimate production rates. Such information includes decile tables, regression plots, results of the regression analyses, and box plots. The second information element contains the glossary of terms that describes some statistical terminologies and terms adopted by the research. The third information element consists of the descriptions of the individual assessed work items. The fourth information element includes useful information from the Contract Time Determination System (CTDS).

The first three information elements are presented according to work item. whereas the fourth element is presented in a separate window that is not linked to any of the work items.

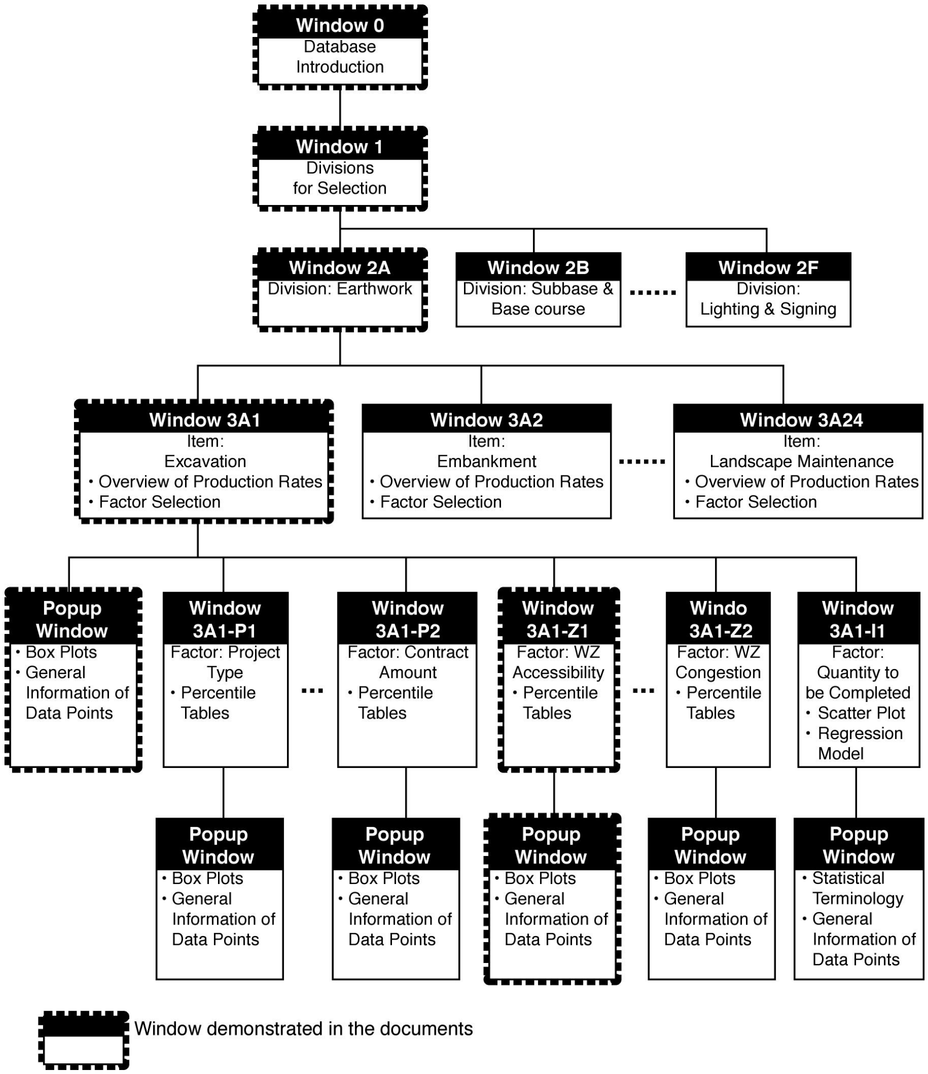


Figure 5.1 HyPRIS Structure

The system is structured in four main levels, as shown in Figure 5.1. The first level generally groups the work items into divisions so that users can easily search for the work items that they are looking for. The second level separates the work items into the work item numbers that are prescribed in the TxDOT Specifications Handbook (2004). Users can immediately identify the work item numbers and descriptions in this level. The third level contains the key production rate information that users are looking for. This information is arranged according to the following system: (1) overall information for the work item, (2) information particular to a significant driver of the work item, and (3) information particular to describing the work item. The following sections will give more detailed description of the entire system.

5.2 HyPRIS Framework

Figure 5.2 shows the HyPRIS entry window that is presented once the link to the file is executed. This window frame explains the details of the research, provides information on what to expect, and links the user to the information elements in the database. There are five buttons on this window. The largest button links the first window to the three information elements that are grouped in different work items. Three buttons at the bottom provide links to useful CTDS information and guidelines about the usage of formulas in the system. The Exit button constantly appears in most of the windows. This is to provide the users with an option to exit if they would like to stop using the system.

The fourth information element contains CTDS lead–lag relationships and production rates. Because the research does not have the lead–lag relationships between different work items and does not have the production rates of the other sixteen work items used in the CTDS, this information element provides temporary help for the users until this information is developed.

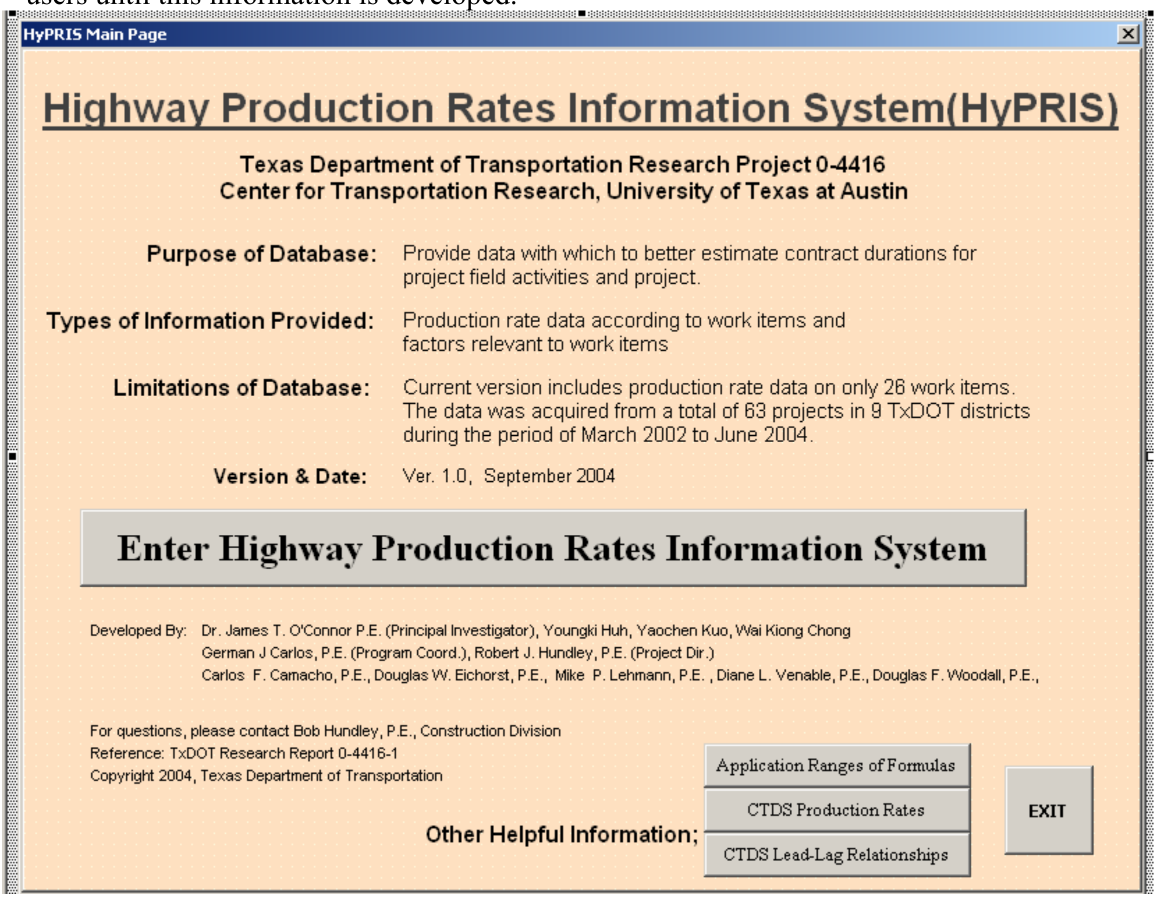


Figure 5.2 HyPRIS Main Frame

Once users enter into the main information window, five main work item divisions will appear on the window, as shown in Figure 5.3. These windows (Figures 5.2 and 5.3) are first-level windows.

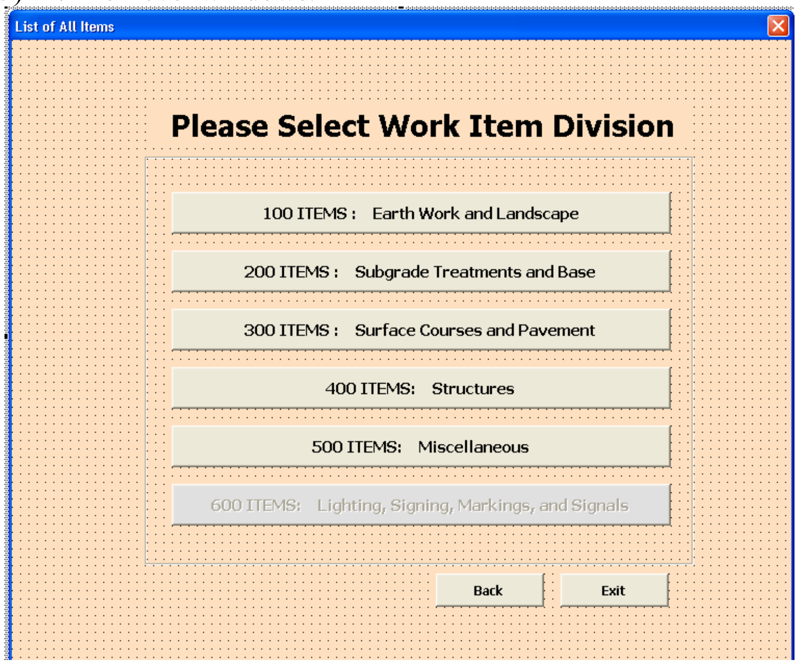


Figure 5.3 Work Item Division, First Window

The users can select from the work item divisions in this window to gain access into the detailed work item numbers. Each work item division contains all the work items under each division. For example, Work Item Number 464 (Reinforced Concrete Pipes) is a subitem in the "400 Items: Structures" division.

Once the users enter the 400 Items Division, they will find the second-level windows. All work items are arranged according to the work item numbers, and the descriptions of the work items lie beside the work item numbers. An example is shown in Figure 5.4.

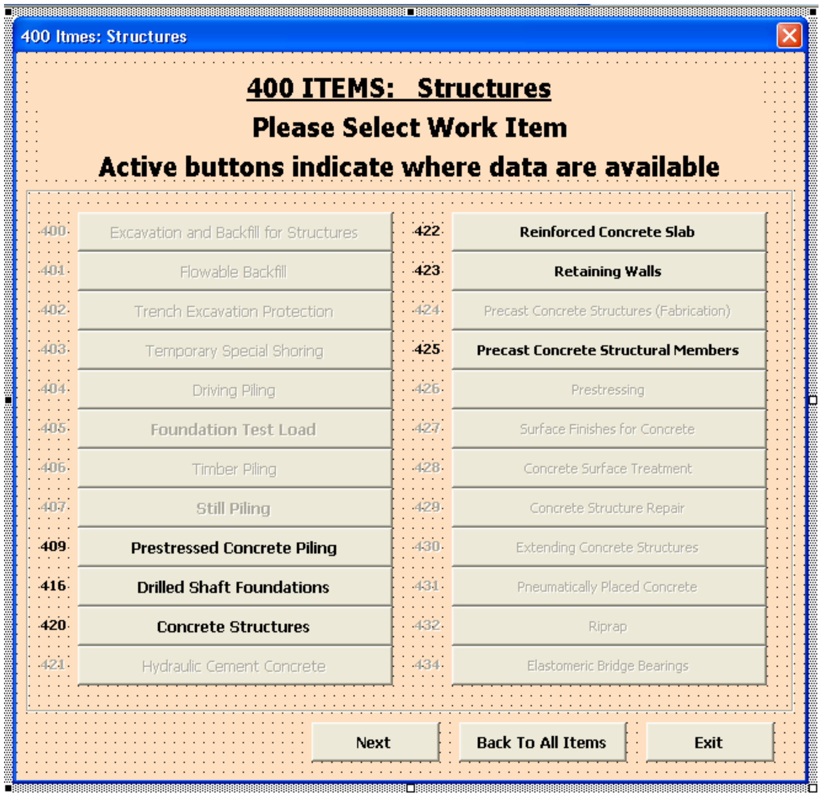


Figure 5.4 Work Item Numbers Window

Once the users identify the work items they want, a click on the work items button will lead them to third-level windows, as shown in Figure 5.5.

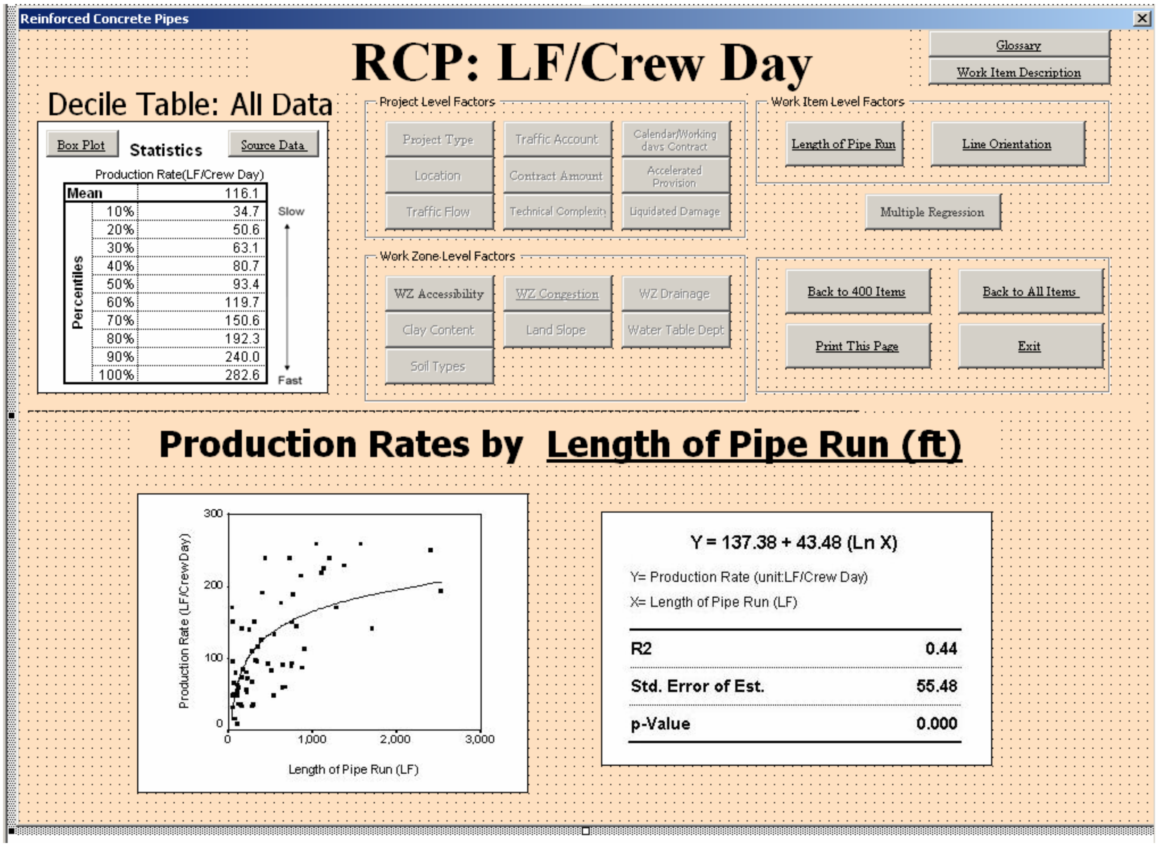


Figure 5.5 Work Item (Reinforced Concrete Pipe) Main Frame

The three information elements, discussed earlier in this chapter, are documented in this level of window frame. The decile table on the left-hand corner shows the distribution range of the observed production rates. One decile table was developed for all the data points, and one table was developed for each significant categorical driver found for the work item. The significant drivers will appear as active buttons with bolded wording in the subframes of Work Item Level Factors, Work Zone Level Factors, and Project Level Factors. A pop-up frame will appear if the active button is clicked. For example, the scatterplot and formula will appear when the button Length of Pipe Run is clicked. This is another third-level window. Scatterplots alongside a regression formula are used to represent the relationship between the significant driver and the production rate.

A click on the Line Orientation button will pop up the frame for the significant factor line orientation, as shown in Figure 5.6. Because line orientation is a categorical driver, decile tables are used to represent the relationship between the driver and production rate. This is another third-level window.

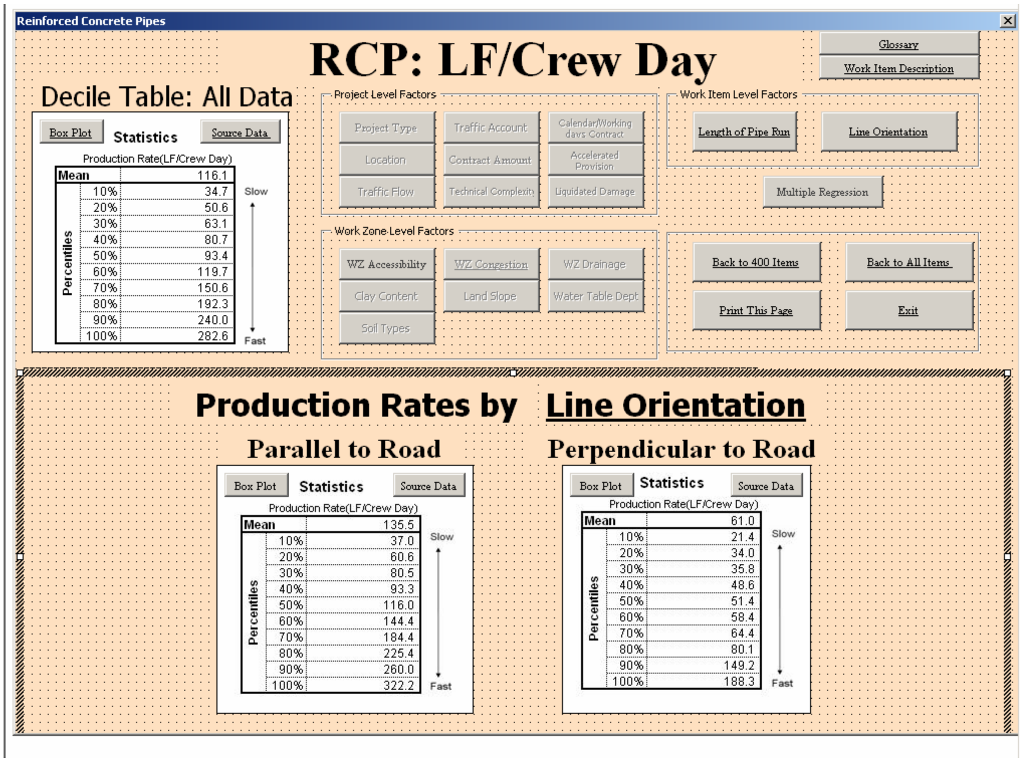


Figure 5.6 Frame for Line Orientation

The Box Plot and Source Data buttons on the top left- and right-hand sides of the decile tables, shown in Figure 5.6, provide links to other essential information. These windows can be seen in Figures 5.7 and 5.8. This information provides helpful guidance to the users. The Box Plot button provides link to the box plot for the set of decile table, and the Source Data button provides link to the types of projects that the data points were gathered from. This is a pop-up window.

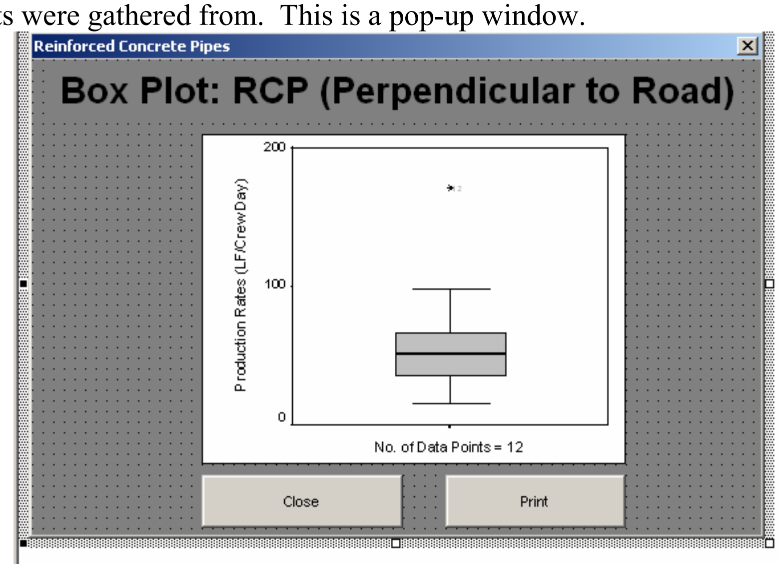


Figure 5.7 Box Plot for RCP

Reinforced Concrete Pipes

Data Points for Orientation of Line: Perpendicular to Road

Total Data **Sample Size**	**12**
Number of Representative **Districts**	5
Total Number of Investigated **Projects**	5

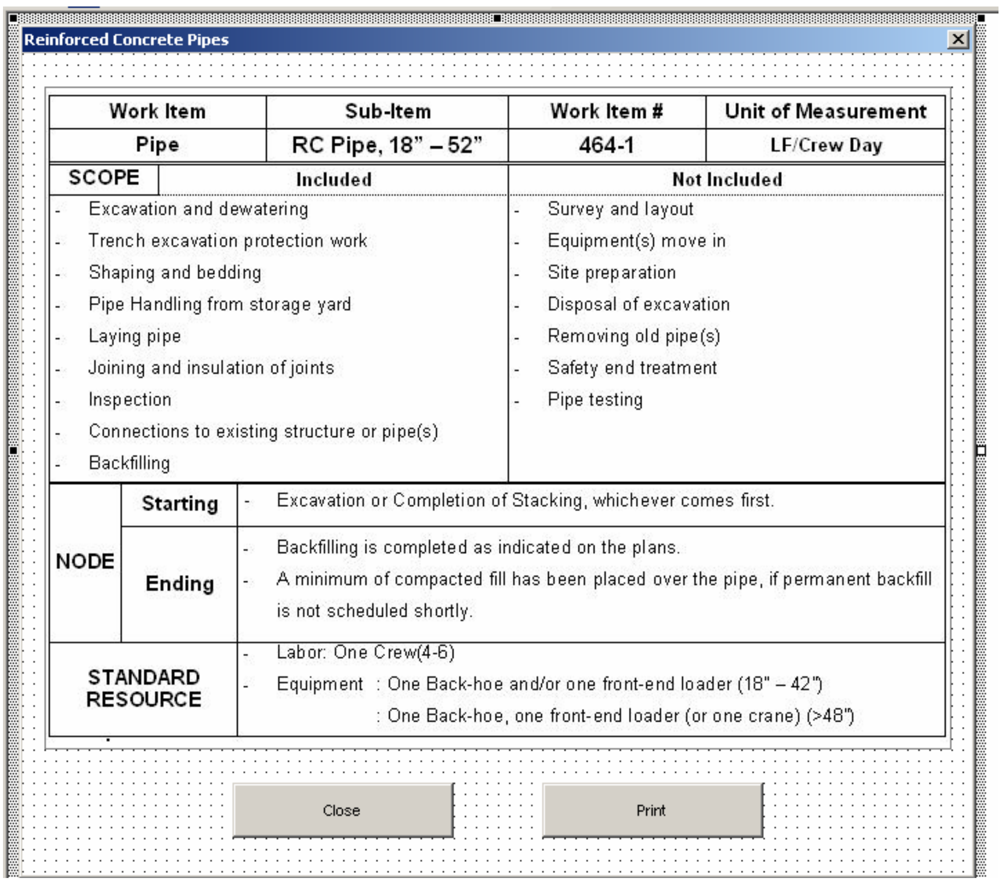
Project Type	Number of Data Points
Convert Nonfreeway to Freeway	
Rehailitate Existing Road	2
Interchanges	
Upgrade Freeway to Standards	2
Bridge Widen/Rehibilitation	1
New Location Freeway	2
Upgrade Nonfreeway to Standards	
Widen Freeway	2
Widen Nonfreeway	3

Close

Figure 5.8 Source Data for RCP

The Source Data screen shows the total number of data points, the total number of districts and projects the data were collected from, and the types of projects these data points were collected from. Such information may help users in deciding whether the data are relevant to their estimations.

Two buttons on the top right hand corner — namely, Glossary and Work Item Description, as shown in Figure 5.6 — provide useful information to the estimators. These are also pop-up windows.



Reinforced Concrete Pipes

Work Item	Sub-Item	Work Item #	Unit of Measurement
Pipe	RC Pipe, 18" – 52"	464-1	LF/Crew Day

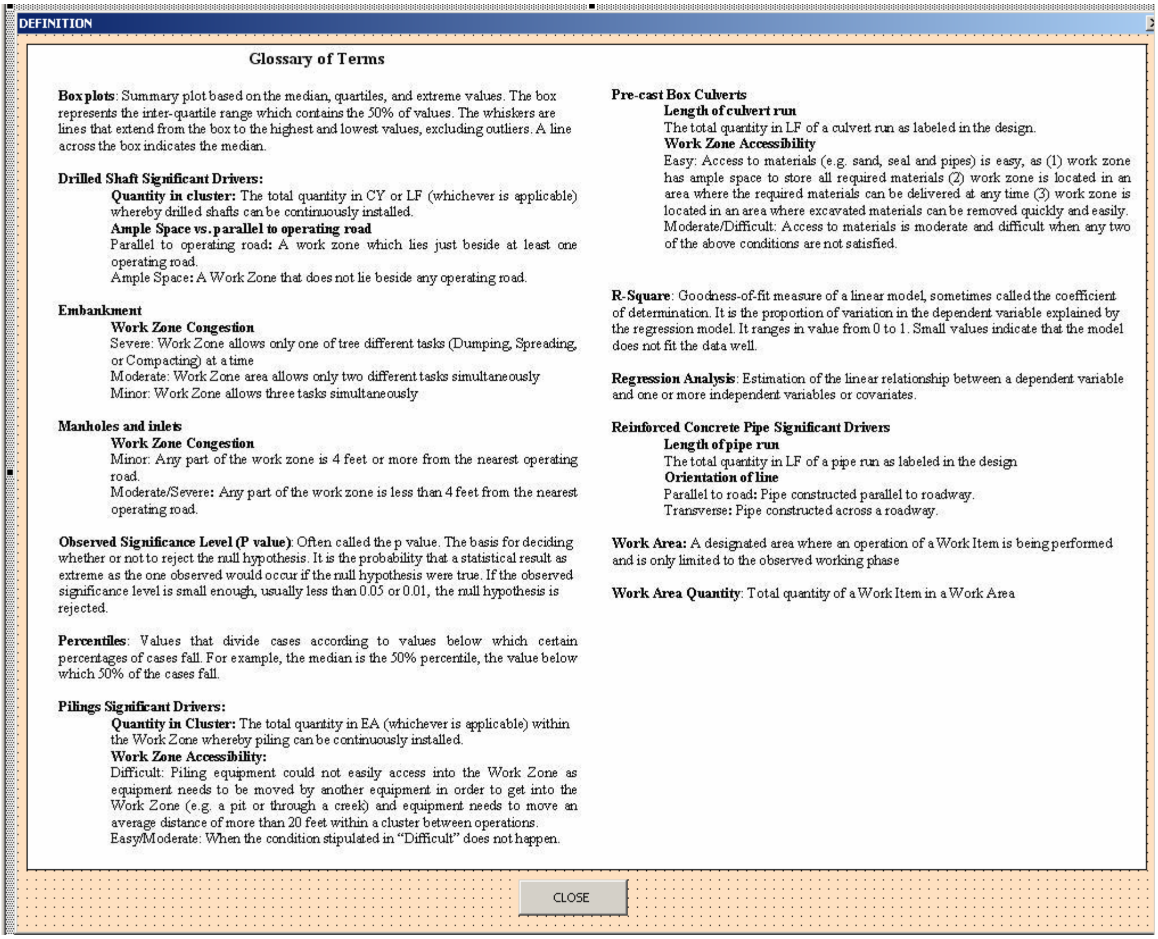
SCOPE	Included	Not Included
	- Excavation and dewatering - Trench excavation protection work - Shaping and bedding - Pipe Handling from storage yard - Laying pipe - Joining and insulation of joints - Inspection - Connections to existing structure or pipe(s) - Backfilling	- Survey and layout - Equipment(s) move in - Site preparation - Disposal of excavation - Removing old pipe(s) - Safety end treatment - Pipe testing

NODE	Starting	- Excavation or Completion of Stacking, whichever comes first.
	Ending	- Backfilling is completed as indicated on the plans. - A minimum of compacted fill has been placed over the pipe, if permanent backfill is not scheduled shortly.
STANDARD RESOURCE		- Labor: One Crew(4-6) - Equipment : One Back-hoe and/or one front-end loader (18" – 42") : One Back-hoe, one front-end loader (or one crane) (>48")

Close Print

Figure 5.9 Window for Work Item Description

The Work Item Description window highlights the scope of work included in the measurement of the production rate for the work item. It also states the standard resource generally applied to such production rates.



DEFINITION

Glossary of Terms

Box plots: Summary plot based on the median, quartiles, and extreme values. The box represents the inter-quartile range which contains the 50% of values. The whiskers are lines that extend from the box to the highest and lowest values, excluding outliers. A line across the box indicates the median.

Drilled Shaft Significant Drivers:
Quantity in cluster: The total quantity in CY or LF (whichever is applicable) whereby drilled shafts can be continuously installed.
Ample Space vs. parallel to operating road
Parallel to operating road: A work zone which lies just beside at least one operating road.
Ample Space: A Work Zone that does not lie beside any operating road.

Embankment
Work Zone Congestion
Severe: Work Zone allows only one of tree different tasks (Dumping, Spreading, or Compacting) at a time
Moderate: Work Zone area allows only two different tasks simultaneously
Minor: Work Zone allows three tasks simultaneously

Manholes and inlets
Work Zone Congestion
Minor: Any part of the work zone is 4 feet or more from the nearest operating road.
Moderate/Severe: Any part of the work zone is less than 4 feet from the nearest operating road.

Observed Significance Level (P value): Often called the p value. The basis for deciding whether or not to reject the null hypothesis. It is the probability that a statistical result as extreme as the one observed would occur if the null hypothesis were true. If the observed significance level is small enough, usually less than 0.05 or 0.01, the null hypothesis is rejected.

Percentiles: Values that divide cases according to values below which certain percentages of cases fall. For example, the median is the 50% percentile, the value below which 50% of the cases fall.

Pilings Significant Drivers:
Quantity in Cluster: The total quantity in EA (whichever is applicable) within the Work Zone whereby piling can be continuously installed.
Work Zone Accessibility:
Difficult: Piling equipment could not easily access into the Work Zone as equipment needs to be moved by another equipment in order to get into the Work Zone (e.g. a pit or through a creek) and equipment needs to move an average distance of more than 20 feet within a cluster between operations.
Easy/Moderate: When the condition stipulated in "Difficult" does not happen.

Pre-cast Box Culverts
Length of culvert run
The total quantity in LF of a culvert run as labeled in the design.
Work Zone Accessibility
Easy: Access to materials (e.g. sand, seal and pipes) is easy, as (1) work zone has ample space to store all required materials (2) work zone is located in an area where the required materials can be delivered at any time (3) work zone is located in an area where excavated materials can be removed quickly and easily.
Moderate/Difficult: Access to materials is moderate and difficult when any two of the above conditions are not satisfied.

R-Square: Goodness-of-fit measure of a linear model, sometimes called the coefficient of determination. It is the proportion of variation in the dependent variable explained by the regression model. It ranges in value from 0 to 1. Small values indicate that the model does not fit the data well.

Regression Analysis: Estimation of the linear relationship between a dependent variable and one or more independent variables or covariates.

Reinforced Concrete Pipe Significant Drivers
Length of pipe run
The total quantity in LF of a pipe run as labeled in the design
Orientation of line
Parallel to road: Pipe constructed parallel to roadway.
Transverse: Pipe constructed across a roadway.

Work Area: A designated area where an operation of a Work Item is being performed and is only limited to the observed working phase

Work Area Quantity: Total quantity of a Work Item in a Work Area

CLOSE

Figure 5.10 Glossary Table

The glossary table provides useful information on the statistical terminologies used in the system and for the various definitions of the factors of various work items that are useful to the designers.

5.3 HyPRIS Design — Support Functions

HyPRIS was designed to enhance users' convenience. A Print button is inserted in all windows that provide essential information to calculate production rates so that designers can print a copy of the window before proceeding to another window. This ensures that they do not have to go back and forth to search for other information. However, users are required to set the printing to landscape orientation.

The Close button on the window allows users to close the window at any time. Users are able to surf around the system using the support buttons (e.g., Back to 400 Items, Back to All Items, and Exit to exit the program, as shown in Figure 5.4).

The system also provides other essential information on the main frame (or the so-called entrance frame) of the system.

5.4 HyPRIS Design — Maintaining and Updating the System

To reduce the complexity of updating and maintaining the system, HyPRIS uses jpeg files for all information like scatterplots, decile tables, tables, box plots, and data points information sources.

5.4.1 Links Between Windows

Buttons are used to provide linkages to any of the windows and frames. The required computing language can be found in the MS Visual Basic manual.

5.4.2 Supporting Information for the Estimators

Information such as the scatterplots, decile tables, box plots, data sources, glossary, regression plots, and work item descriptions are presented in jpeg files. System administrators for the system are encouraged to read the manual for details on the size of each file and also to rely on the accompanying soft copy of the files for the pictures and future updating.

System administrators should also note that different representations of information in the system were designed using different media. The media/software types are listed in Table 5.1.

Table 5.1 HyPRIS Information and Media/Software for the Information

Information	Media/Software
Screens and buttons	MS Visual Basic
Scatterplots/box plots	SPSS (see manual for size specification) converted to jpeg format
Decile tables/source data	MS Excel Files converted to jpeg format
CTDS/glossary/work item description	Jpeg format

5.4.3 Statistical Software

HyPRIS uses SPSS for all its statistical analysis. System administrators should be familiar with this software.

6. SUMMARY AND RECOMMENDATIONS

6.1 Summary

The research concluded with the development of the HyPRIS production rate estimation tools and information system for improving the accuracy of construction contract time estimation. In addition, the research identified the significant production rates drivers and characterized associated relationships with production rates so that designers can make better use of the information.

The key differences between this research and CTDS are the following.

1. The ranges of production rates have become more realistic. Rather than providing a few production rates, this research offers formulas and ranges of production rates to guide the time estimation process. The experience of personnel developing the time estimate should also be integrated within the process.
2. This research provides a more realistic way of determining the relationships between production rates and their drivers. These relationships are presented in formulas so that the time estimation process can be simplified yet become more accurate at the same time.
3. Categorical and numerical data were analyzed separately so that their relationships with production rates were not mixed up. Multiple regressions formulas are useful for production rates affected by multiple drivers.

Most important, HyPRIS is a flexible system that encourages application of personal experience in estimating construction time estimation.

6.2 Recommendations

Future studies should be carried out to better understand the remaining sources of production rate variability, such as weather impacts and operator skill, so that production rates estimation can become even more accurate. Lead and lag time information should be investigated to enhance the performance of the contract time estimation for the entire project. Work items that were excluded from this study should be investigated so that more production rates can be added to the system, making the system even more useful.

Appendix A.

Questionnaire for Selecting Work Items for the Study

Name : ________________

District : ________________ Position : ____________________

Site/Office Address :____

Phone Number : ________________ E-mail Address : ____________________

Please check as you think it is most appropriate

Pay Items	**Definitely Track?**	**Degree of Variability in Crew Productivity**			**How often On or Near Critical Path**			
	Yea/**N**o	**L**ow	**M**oderate	**H**igh	**Rarely**	**Sometimes**	**Often**	**Usually**
Initial traffic control	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Detour	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
ROW Preparations								
Clear & Grub	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Remove old structure(small)	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Remove old pavement	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Remove old curb & gutter	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Remove old sidewalks	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Remove old drainage/utility structures	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Major structure demolition	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually

Questionnaire for Selecting Work Items for the Study (Cont'd)

Pay Items	Definitely Track?	Degree of Variability in Crew Productivity			How often On or Near Critical Path			
Excavation/embankment								
Earth excavation	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Rock excavation	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Embankment	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Drainage structures/storm sewers								
Pipe	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Box culverts	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Inlets & Manholes	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Bridge Structures								
Erect temporary bridge	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Bridge demolition	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Cofferdams	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Piling	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Footings	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Columns, caps & bents	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually
Wingwalls	**Y**es/**N**o	**L**ow	**M**oderate	**H**igh	**R**arely	**S**ometimes	**O**ften	**U**sually

Questionnaire for Selecting Work Items for the Study (Cont'd)

Pay Items	Definitely Track?	Degree of Variability in Crew Productivity			How often On or Near Critical Path			
	Yea/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Beams (erection only)	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Bridge deck (total depth)	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Bridge curb/walk	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Bridge handrail	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Remove temporary bridge	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Retaining walls	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Base Preparations								
Lime stabilization	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Flexible base material	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Cement treated base material	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
New curb & gutter	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Hot mix asphalt base	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Concrete paving	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Hot mix asphalt surface	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually

Questionnaire for Selecting Work Items for the Study (Cont'd)

Pay Items	Definitely Track?	Degree of Variability in Crew Productivity			How often On or Near Critical Path			
	Yea/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Permanent signing & traffic signals								
Small signs	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Overhead signs	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Major traffic signals	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Seeding & Landscape	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Permanent pavement markings	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Final clean up	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
Others								
___________________________	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
___________________________	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually
___________________________	Yes/No	Low	Moderate	High	Rarely	Sometimes	Often	Usually

Your Comment (*We appreciate your comment*)

Are you interested in continued participation in this study? Yes No

Thank You.

Appendix B. Results of the Survey for Selecting Work Items to be Tracked

Results of the Survey for Selectiing Work Items to be tracked

Work Items	Definitely Track? - 'Yes' Response													Total of 'Yes'
	Bob. H.	Carlos C.	Doug W.	Dan D.	Mike L.	Harry P.	Mario R.G.	David H.	Pat W.	Mike B.	Duane S.	Tom N.	Mike C.	
Initial traffic control					Yes		Yes	Yes	Yes		Yes	Yes	Yes	7
Detour					Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	8
ROW Preparations														
Clear & Grub					Yes		Yes	Yes	Yes	Yes			Yes	6
Remove old structure(small)							Yes	Yes	Yes			Yes		4
Remove old pavement					Yes		Yes	Yes	Yes		Yes	Yes		6
Remove old curb & gutter							Yes	Yes	Yes					3
Remove old sidewalks							Yes	Yes	Yes					3
Remove old drainage/utility structures		Yes			Yes		Yes	Yes	Yes					5
Major structure demolition		Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Excavation/embankment														
***Earth excavation**	Yes				Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Rock excavation	Yes				Yes		Yes	Yes		Yes			Yes	6
***Embankment**	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Drainage structures/storm sewers														
Pipe	Yes				Yes		Yes	Yes	Yes	Yes	Yes	Yes		8
Box culverts	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Inlets & Manholes	Yes				Yes		Yes	Yes	Yes	Yes	Yes	Yes		8
Bridge Structures														
Erect temporary bridge		Yes					Yes		Yes					3
Bridge demolition		Yes			Yes		Yes	Yes	Yes		Yes	Yes		7
Cofferdams					Yes		Yes		Yes		Yes			4
Piling		Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Footings					Yes		Yes	Yes	Yes	Yes	Yes		Yes	7
Columns, caps & bents	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Wingwalls		Yes			Yes			Yes	Yes	Yes	Yes		Yes	7
Beams (erection only)		Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Bridge deck (total depth)	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Bridge rail	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes		9
Bridge curb/walk							Yes	Yes	Yes					3
Bridge handrail		Yes						Yes						2
Remove temporary bridge		Yes							Yes	Yes	Yes			4
Retaining walls	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Base Preparations														
***Lime stabilization**	Yes				Yes		Yes		Yes	Yes	Yes	Yes		7
***Flexible base material**	Yes				Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
***Cement treated base material**	Yes	Yes			Yes		Yes		Yes	Yes	Yes			7
New curb & gutter	Yes				Yes		Yes	Yes	Yes		Yes		Yes	7
***Hot mix asphalt base**	Yes				Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
***Concrete paving**	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes		9
***Hot mix asphalt surface**	Yes	Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	10
Permanent signing & traffic signals														
Small signs					Yes			Yes	Yes					3
Overhead signs		Yes			Yes		Yes	Yes	Yes		Yes	Yes		7
Major traffic signals					Yes		Yes	Yes	Yes		Yes	Yes	Yes	7
Seeding & Landscape					Yes			Yes	Yes					3
Permanent pavement markings		Yes			Yes		Yes	Yes	Yes	Yes	Yes	Yes	Yes	9
Final clean up		Yes			Yes			Yes	Yes		Yes		Yes	6
Total of 'Yes'	17	21	0	0	35	0	36	37	40	25	31	25	22	
Others		Traffic Switches, Temporary Striping, CTB Move & Reset			Utility Installation /adjustment				Drill Shaft/ Surface Treatment	Planning Hot Mix Pav't	Drill Shaft			

Appendix C. Project-Level Data Collection Tool

Production Rate Tracking : Project level

CCSJ # :

Highway # :

Project ID:

Project Length :

Station Range :

District :

City/County :

Prime Contractor:

Contract Amount : $ Million

% of Project Completion : %

Project(Construction) Period : --- (Calandar/Working days)

Work Items to be tracked:

Item #	Work Item	Unit	Approx. Total Quantity	Scheduled Start Date	Scheduled End Date	Sub- Contracted?	Comments
						Yes ☐ No	
						Yes ☐ No	
						Yes ☐ No	
						Yes ☐ No	
						Yes ☐ No	
						Yes ☐ No	
						Yes ☐ No	
						Yes ☐ No	
						Yes ☐ No	
						Yes ☐ No	

Please, fill out next page.

Project-Level Data Collection Tool (Cont'd)

Project Level Variables Evaluation

Project CCSJ:

Variable		Unit	Optional Values				
Project Type			□ Seal Coat	□ Overlay	□ Rehabilitate Existing Road	□ Convert Non-Freeway to Freeway	
			□ Widen Freeway	□ Widen Non-Freeway	□ New Location Freeway	□ New Location Non-Freeway	
			□ Interchanges	□ Bridge Widening/ Rehabilitation	□ Bridge Replacement/ New Bridge	□ Upgrade Freeway to Standards	□ Upgrade Non-Freeway to Standards
Location			□ Rural	□ Urban	□ Metro		
Traffic Flow			□ Rarely congested	□ Only rush hours congested	□ Most hours congested		
Traffic Count (ADT)		Veh./ Day	□ < 5 K	□ 5 K ~ 20 K	□ > 20 K		
Weather	Annual Precipitation	/Year	□ < 15"	□ 15"~40"	□ > 40"		
	Winter Season Length		□ Costal	□ Central & South Texas	□ North Texas	□ Panhandle & West Texas	
% of Construction Completion at 1st Data Collection Date		%	□ 0-30	□ 30-70	□ 70-100		
Size : Construction Contract Amount		$	□ <5M	□ 5M ~ 20 M	□ 20M ~ 50 M	□ >50M	
Technical Complexity			□ Simple	□ Moderate	□ Complex		
Contract	Contract Day		□ Calendar Day	□ Working Day			
	Accelerated Constrcution Provision		□ None	□ Incentive Using Contract Administrative Cost	□ Milestones with Incentives/ Disincentives		
			□ Substantial Completion I/D	□ Lane Rental Disincentive	□ A+B Provisions		
	Liquidated damages	$/Day	□ < 300	□ 300~3K	□ 3K~6K	□ 6K~12K	□ > 12K
Soil types			□ Loose	□ Stiff	□ Rocky		
Local site Drainage Effectiveness	Clay Content (Plastic Soils)		□ Low	□ Moderate	□ High		
	Land Slope		□ Flat	□ Moderate	□ Steep		
	Water Table Depth below Grade		□ < 4'	□ 4' ~ 10'	□ > 10'		
Scheduling Technique Used			□ Bar Chart	□ CPM (Not Resource-loaded)		□ CPM (Resource-loaded)	
Work Schedule	Days per Week (typical)	Day/Week	□ 4	□ 5	□ 6	□ 7	
	Hours per Day(typical)	Hours/Day	□ 8	□ 10	□ 12	□ 2 Shifts	
Contract Admin. System			□ C.I.S.	□ Site Mgmt.			
CMS (Contractor Management Skill)			□ Good	□ Average	□ Poor		

Appendix D. Production Rate Tracking: Work Zone Level

Work Zone & Work Item Assessed **Recorder : ______________**

Project ID: ___________________________

Work Item (No.): ___________________________ District : ______________

Work Zone Description/Sketch:

Description:	Sketch
____________________________________ ____________________________________ ____________________________________	
Typical Workday Start Time: ___________	
Typical Workday Stop Time: ___________	
Is observed work item on critical path? ☐ Yes ☐ No	
Workers are from: ☐ Union ☐ Non-Union	
How much quantity included in a work item operation cycle: ____________________________________ (☐ Not Affected)	▪ *No. indicates the No. of Traffic lines* ▪ *Double line indicates that WZ is not affected by its side of traffic.*

Work Zone Level Variables Evaluation

Variable		Characterization				Comment
1	WZ Accessibility	Difficult	Moderate	Easy	Not Applicable	
2	WZ Construction Congestion	Severe	Moderate	Minor	Not Applicable	
3	Work Zone Site Drainage Effectiveness	Easily Flooded	Moderate	Quickly Drains	Not Applicable	
3.1	Clay Content in Soil	High	Moderate	Low	Not Applicable	
3.2	Land Slope	Steep	Moderate	Flat	Not Applicable	
3.3	Water Table Depth Below Grade	<4’	4’~10’	>10’	Not Applicable	

Data Analysis Status

Data Point ID:________________________	☐ *Check if data Collection completed* ☐ *Check if data Input completed*

Production Rate Tracking: Work Zone Level (Cont'd)

Work Item Sheet to be Inserted

Appendix E.

Production Rate Tracking: Work Item Level

Observation Record

<table>
<tr><td>First Date of the Observed Operation</td><td colspan="3"></td></tr>
<tr><td>Overall Work Item Completion in the project at 1st Data Collection Date</td><td>☐ 0-20% ☐ 20-80%
☐ 80-100%</td><td colspan="2">☐ 0-100%
(Observed Whole Process)</td></tr>
<tr><td colspan="4">Completion Status: Fully Labeled Sketch, Description & Note

Please take note the 'Quantity of Con'c Placed' and/ or quantities of other alternative units, whenever it is possible.</td></tr>
<tr><td>Quantity Completed</td><td></td><td>Unit</td><td></td></tr>
</table>

Production Rate Tracking: Work Item Level (Cont'd)

Observation Record

Resource Efforts for Work Item		
Crew		
Crew Type	Average Skill Level	Typical Crew Size
	Novice Typical Experienced	
	Novice Typical Experienced	
	Novice Typical Experienced	
	Novice Typical Experienced	
Equipment		
Equipment Piece	Equipment Size	Typical Number in Operation

Tracking Calendar (Work Item Level)

Year:________

Sunday		Monday		Tuesday		Wednesday		Thursday		Friday		Saturday	
/	**I** **II** **III** **VI**	/		/		/		/		/		/	
/		/		/		/		/		/		/	
/		/		/		/		/		/		/	
/		/		/		/		/		/		/	
/		/		/		/		/		/		/	
/		/		/		/		/		/		/	

I: Observation #, **II**: X, ○ or ⊖, **III**: Indication , **VI**: Comment No.

Total Working Days: ____________________

Indication

□ **- #**: **T**his Observation #	□: **H**oliday or Day Off
□: **W**eather day (< 2 Hrs of work)	□: Work Day With **S**ome Weather Effect
□: U**N**workable Soil Condition	□: **I**ncomplete Crew
□: **E**quipment Downtime/not Available	□: **M**aterial Unavailable
□: **U**tility Conflicts	□: Un**F**oreseen Condition
□: **C**onstruction Accident	□: Traffic **A**ccident
□: **O**vertime	□: Other **D**elay (specify in comments)

○ : Normal Working Day ⊖ : ½ Working Day X: Non Working Day

Comments:

□	
□	

Tracking Calendar (Work Item Level) (Cont'd)

Comments (Continued):	
☐	
☐	
☐	
☐	
☐	
☐	
☐	
☐	
☐	
☐	
☐	
General Comment	

Appendix F. Work Item Sheets

Work Item	Sub-Item	Work Item #	Unit of Measurement
Pipe	**RC Pipe, 18" – 42"**	**464-1**	**LF/Std. Res. Day**

<table>
<tr><td>SCOPE</td><td colspan="2">Included</td><td>Not Included</td></tr>
<tr><td colspan="3">- Excavation and dewatering
- Trench excavation protection work
- Shaping and bedding
- Pipe Handling from storage yard
- Laying pipe
- Joining and insulation of joints
- Inspection
- Connections to existing structure or pipe(s)
- Backfilling</td><td>- Survey and layout
- Equipment(s) move in
- Site preparation
- Disposal of excavation
- Removing old pipe(s)
- Safety end treatment
- Pipe testing</td></tr>
<tr><td colspan="2" rowspan="2">Work Item Level PRODUCTIVITY FACTOR</td><td colspan="2">Diameter of Pipe (18", 21", 30", 36", 42"), (Note;________________________________)
Connection to Existing Structure or Pipes (Yes, No), (Note;________________________)
Approximate Trench Depth (Specify;____)
Any Utility Conflict (None, Low, Average, High), (Note;___________________________)
No. of Inlet & Manhole in the section (Specify;__________________________________)
No. of Inlet & Manhole installed during observation period (Specify;________________)
No. of Pipe line (Single, Double), (Note;____)</td></tr>
<tr><td colspan="2">- Soil Type / Water Table Depth</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="2">- Excavation or Completion of Stacking, whichever comes first.</td></tr>
<tr><td>Ending</td><td colspan="2">Backfilling is completed as indicated on the plans.
A minimum of compacted fill has been placed over the pipe, if permanent backfill is not scheduled shortly.</td></tr>
<tr><td colspan="2" rowspan="2">STANDARD RESOURCE</td><td colspan="2">- Labor: One Crew(4-5)
- Equipment: One Back-hoe</td></tr>
<tr><td colspan="2">Comment ; Verified ________</td></tr>
</table>

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Pipe	**RC Pipe, 48" – 72"**	**464-2**	**LF/ Std. Res. Day**

SCOPE	Included	Not Included
	- Excavation and dewatering - Trench excavation protection work - Shaping and bedding - Pipe Handling from storage yard - Laying pipe - Joining and insulation of joints - Inspection - Connections to existing structure or pipe(s) - Backfilling	- Survey and layout - Equipment(s) move in - Site preparation - Disposal of excavation - Removing old pipe(s) - Safety end treatment - Pipe testing

Work Item Level PRODUCTIVITY FACTOR		**Diameter of Pipe (18", 21", 30", 36", 42"), (*Note*;________________________________)** **Connection to Existing Structure or Pipes (Yes, No), (*Note*;________________________)** **No. of Inlet & Manhole in the section (Specify;__________________________________)`** **Approximate Trench Depth (*Specify*;____)** **Any Utility Conflict (None, Low, Average, High), (*Note*;___________________________)** **No. of Inlet & Manhole in the section (Specify;__________________________________)** **No. of Inlet & Manhole installed during observation period (Specify;________________)** **No. of Pipe line (Single, Double), (*Note*;____)**
		- Soil Type / Water Table Depth
NODE	**Starting**	- Excavation or Completion of Stacking, whichever comes first.
	Ending	Backfilling is completed as indicated on the plans. A minimum of compacted fill has been placed over the pipe, if permanent backfill is not scheduled shortly.
STANDARD RESOURCE		- Labor: One Crew(4-5) - Equipment: One Back-hoe, One Crain(or another Back-hoe)
		Comment ; **Verified ________**

Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.

Appendix F. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Pipe	RC Pipe, Over 72"	464-3	LF/ Std. Res. Day

<table>
<tr><th>SCOPE</th><th>Included</th><th colspan="2">Not Included</th></tr>
<tr><td colspan="2">- Excavation and dewatering
- Trench excavation protection work
- Shaping and bedding
- Pipe Handling from storage yard
- Laying pipe
- Joining and insulation of joints
- Inspection
- Connections to existing structure or pipe(s)
- Backfilling</td><td colspan="2">- Survey and layout
- Equipment(s) move in
- Site preparation
- Disposal of excavation
- Removing old pipe(s)
- Safety end treatment
- Pipe testing</td></tr>
<tr><td colspan="2">Work Item Level PRODUCTIVITY FACTOR</td><td colspan="2">Diameter of Pipe (18", 21", 30", 36", 42"), (Note;________________________________)
Connection to Existing Structure or Pipes (Yes, No), (Note;________________________)
No. of Inlet & Manhole in the section (Specify;__________________________________)`
Approximate Trench Depth (Specify;____)
Any Utility Conflict (None, Low, Average, High), (Note;__________________________)
No. of Inlet & Manhole in the section (Specify;__________________________________)
No. of Inlet & Manhole installed during observation period (Specify;________________)
No. of Pipe line (Single, Double), (Note;____)
- Soil Type / Water Table Depth</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="2">- Excavation or Completion of Stacking, whichever comes first.</td></tr>
<tr><td>Ending</td><td colspan="2">- Backfilling is completed as indicated on the plans.
- A minimum of compacted fill has been placed over the pipe, if permanent backfill is not scheduled shortly.</td></tr>
<tr><td colspan="2">STANDARD RESOURCE</td><td colspan="2">- Labor: One Crew(4-5)
- Equipment: One Back-hoe, One Crain(or another Back-hoe)
Comment ; Verified ________</td></tr>
</table>

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Concrete Box Culvert	**Precast**	**462**	**LF/ Std. Res. Day**

SCOPE	Included	Not Included
	- Excavation and dewatering - Excavation protection work - Shaping and bedding - Box handling from storage yard to Work Zone - Laying box covert - Joining and insulation of joints - Connections to existing structure(s) - Inspection - Backfilling	- Equipment(s) move in - Site preparation - Disposal of excavation - Box testing - Storage and shipment of box - Removal of old structure - Safety end treatment - Wingwall work
Work Item Level PRODUCTIVITY FACTOR	**Sizes (*Specify;* ________)** **Connection to Existing Structure or Pipes (Yes, No), (*Note*;________)** **Approximate Trench Depth (*Specify*;________)** **Any Utility Conflict (None, Low, Average, High), (*Note*;________)** **No. of line (Single, Double), (*Note*;________)** - **Soil type / Water table depth**	
NODE — **Starting**	- Excavation or Completion of Stacking , whichever comes first.	
NODE — **Ending**	- Backfilling is completed as indicated on the plans. - A minimum of compacted fill has been placed over the box covert, if permanent backfill is not scheduled shortly.	
STANDARD RESOURCE	- Labor: One Crew(5-7) - Equipment: One Back-hoe, One Crain (or another Back-hoe) **Comment ;** **Verified ________**	

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Bridge Structure	**Footing-CIP**	**420-1**	**Std. Res. Days / EA**

<table>
<tr><th>SCOPE</th><th>Included</th><th colspan="2">Not Included</th></tr>
<tr><td colspan="2">- Excavation and dewatering
- Excavation protection work
- False work
- Installation of form and rebar
- Inspection of forms and rebar
- Handling and placing of concrete
- Pile cap</td><td colspan="2">- Site preparation
- Preparation of rebar and forms
- Rebar cutting and bending
- Curing
- All necessary work for the protection of concrete placed under any weather conditions
- Removal of forms
- Finishing of structure surface
- Removal of false work</td></tr>
<tr><td colspan="2">Work Item Level PRODUCTIVITY FACTOR</td><td colspan="2">Dimension of Footing (Specify; ________________)
Approximate Depth of footing (Specify; ________________)
Form used (Yes, No), (Note;________________)
- Water table depth / Soil type</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="2">- False work or Excavation, whichever starts first.</td></tr>
<tr><td>Ending</td><td colspan="2">- Concrete placement is completed.</td></tr>
<tr><td colspan="2" rowspan="2">STANDARD RESOURCE</td><td colspan="2">- Labor: One Crew for Formwork(4-5), One Crew for Rebar installation(4-5)</td></tr>
<tr><td>Comment ;</td><td>Verified ________</td></tr>
</table>

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Bridge Structure	**Column-CIP**	**420-2**	**Std. Res. Days / EA**

SCOPE	Included	Not Included
	- False work - Installation of form and rebar - Inspection of forms and rebar - Handling and placing of concrete	- Site preparation - Preparation of rebar and forms - Rebar cutting and bending - Curing - All necessary work for the protection of concrete placed under any weather conditions - Removal of forms - Finishing of structure surface - Installation of drainage pipe - Removal of false work

Work Item Level PRODUCTIVITY FACTOR		**Height of Column (*Specify;* ________________)** **Dimension of Column (Specify; ________________)** **Use of From liners (Yes, No), (*Note;*________________)** **Complex Finish (Yes, No), (*Note;*________________)**
		- **Drainage Effectiveness**
NODE	**Starting**	- False work or form work, whichever starts first.
	Ending	- Concrete placement is completed.
STANDARD RESOURCE		- Labor: One Crew for Formwork(4-5), One Crew for Rebar installation(4-5)
		Comment ; **Verified ________**

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Bridge Structure	**Cap-CIP**	**420-3**	**Std. Res. Days / EA**

SCOPE	**Included**	**Not Included**
	- False work, if any - Installation of form and rebar - Inspection of forms and rebar - Handling and placing of concrete	- Site preparation - Preparation of rebar and forms - Rebar cutting and bending - Curing - All necessary work for the protection of concrete placed under any weather conditions - Removal of forms - Finishing of structure surface - Installation of drainage pipe - Removal of false work - Non - metal form

Work Item Level PRODUCTIVITY FACTOR		**Approximate Elevation of structure (*Specify;* ________________________________)** **Use of From liners (Yes, No), (*Note;*__________________________________)** **Complex Finish (Yes, No), (*Note;*__________________________________)** **Types of Cap (*Specify*; __________________________________)** **No. of column under the Cap (*Specify*; ______________________________)** **Use of Scaffolding for false work (Yes, No), (*Note;*________________________)**
		- Drainage Effectiveness
NODE	**Starting**	- False work or form work, whichever starts first.
	Ending	- Concrete placement is completed.
STANDARD RESOURCE		- Labor: One Crew for Formwork(4-5), One Crew for Rebar installation(4-5)
		Comment ; **Verified ________**

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Beam Erection	**Precast Concrete**	**425**	**Span / Std. Res. Day**

<table>
<tr><th>SCOPE</th><th colspan="2">Included</th><th>Not Included</th></tr>
<tr><td colspan="3">- Equipment(s) setup
- Handling beam(s) for erection in site
- Erection
- False work and bracing</td><td>- Erection planning
- Site preparation
- Equipment(s) move in
- Fabrication of beam
- Transportation of beam from off-site
- Storage of beam
- Traffic control (barrier, signal etc.)
- Attachment of temporary rail or screed support
- Steel
- Connection with bents</td></tr>
<tr><td colspan="2" rowspan="2">Work Item Level PRODUCTIVITY FACTOR</td><td colspan="2">No of beams in the Span (Specify; ______)
Elevation of structure (Specify; ______)
Weight of beam (Specify; ______)
Length of beam (Specify; ______)
Type of beam ('U' type, 'I' type, Box beam), (Note; ______)
Wind speed (High, Moderate), (Note; ______)
Work time (Day light, Night), (Note; ______)</td></tr>
<tr><td colspan="2">- Number of lifting equipment</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="2">- Lifting of first beam of the span starts.</td></tr>
<tr><td>Ending</td><td colspan="2">- Last beam placed and stabilized.</td></tr>
<tr><td colspan="2" rowspan="2">STANDARD RESOURCE</td><td colspan="2">- Equipments : One to two Crain</td></tr>
<tr><td colspan="2">Comment ; Verified ________</td></tr>
</table>

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Bridge Deck	RC-CIP	422	SF / Std. Res. Day

SCOPE	Included	Not Included
	- False work - Installation of system form and reinforcing steel - Prestress work required - Inspection - Handling and placing of concrete - Construction joints and cork liner work - Attachment of temporary rail or screed supports	- Site preparation - Equipment(s) move in - Bridge rail and hand rail work - Bridge protective assembly - Drainage pipe work - Waterproofing & Pavement - Removal of false work - Curing including fogging and interim curing - All necessary work for the protection of concrete placed under any weather conditions - Post Tensioning

Work Item Level PRODUCTIVITY FACTOR		**Formwork system (Box beams, Precast panel, PMD, Wood forms, *Specify;* __________)** **No. of spans in the Unit (Specify; ____)** **Average Super elevation (Yes, No), (Note; _____________________________________)**
		- Weather / Temperature
NODE	**Starting**	- False form work or forming system, or setting of Precast panel / PMD, whichever starts first.
	Ending	- Concrete placement is completed.
STANDARD RESOURCE		- Labor: One Crew for Form work (8-9), One Crew for Rebar (8-9), One Crew for Concrete (6-7, ?) - Equipment: One Concrete Pump (?)
		Comment ; **Verified ________**

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Concrete Railing	**Slip Form**	**450**	**LF/ Std. Res. Day**

<table>
<tr><th>SCOPE</th><th>Included</th><th>Not Included</th></tr>
<tr><td colspan="2">- Anchorage to the structure, if any
- Casting
- Only placement of concrete</td><td>- Equipment setup.
- Cleaning site after the work
- Removal of old railing
- Temporary railing
- Material handling and setting in site
- Rebar setting
- Protective work for railing</td></tr>
</table>

<table>
<tr><td rowspan="2">Work Item Level PRODUCTIVITY FACTOR</td><td colspan="2">Slip form equipment type (specify; ______________________________________)
Height (36", 42"), (Note; ______________________________________)
Slope (Single, Double), (Note; ______________________________________)</td></tr>
<tr><td colspan="2">- Temperature</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td>- Placement of concrete starts.</td></tr>
<tr><td>Ending</td><td>- Concrete placement is completed.</td></tr>
<tr><td rowspan="2">STANDARD RESOURCE</td><td colspan="2">- Equipment : One Slip-form equipment</td></tr>
<tr><td colspan="2">Comment ; Verified ________</td></tr>
</table>

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

\

Appendix F. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Excavation	**Earth Excavation**	**110**	**CY/Crew Day**

SCOPE	**Included**	**Not Included**
	- Removing top soil - Excavation from original elevation to the elevation which is at least 6" below the required sub-grade elevation - Disposal of material	- Survey & Layout - Access road construction and maintenance - Unsuitable material replacement - Reshaped by blade and then sprinkled and rolled for sub-grade surface (about 6" depth) - Temporary drainage maintenance - Shaping slop - Rock

PRODUCTIVITY FACTOR (Work Item)		- **Construction Type(Haul to Waste, Cut to Fill), (*Note:*_________________________)** - **Haul road distance (Specify: ____)**
		- Equipment number/Equipment size/Soil Type/Clay content in soil
NODE	**Starting**	- Remove top soil. - Starting the excavation of any working phase.
	Ending	- Sub-grade surface is completed. - Reach the anticipated elevation of the working phase
A Crew Definition		- Equipment: 1 Excavator (2CY Bucket), Trucks (Number is according to the distance from disposal field to Work Zone and traffic condition.)
		Comments; **Verified ________**

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

<table>
<tr><th colspan="2">Work Item</th><th>Sub-Item</th><th>Work Item #</th><th>Unit of Measurement</th></tr>
<tr><td colspan="2">Embankment</td><td>Embankment</td><td>132</td><td>CY/Crew Day</td></tr>
<tr><td>SCOPE</td><td colspan="2">Included</td><td colspan="2">Not Included</td></tr>
<tr><td colspan="3">- (Construction of roadway embankments, levees and dykes or any designated section of the roadway)
- Placing materials
- Spread material
- Sprinkling
- Compaction</td><td colspan="2">- Survey & Layout
- Constructing access road
- Temporary drainage maintenance</td></tr>
<tr><td colspan="2" rowspan="2">PRODUCTIVITY FACTOR (Work Item)</td><td colspan="3">- Material Type (Type A, Type B, Type C, Type D), (Note: __________________)
- Density Requirement (Ordinary Compaction, Density Control)
- Construction Type(Borrow to Fill, Cut to Fill), (Note: _________________________)
- Slope (Steep, Moderate, Flat), (Note: ____)</td></tr>
<tr><td colspan="3">- Equipment number/Equipment size/Work Zone Congestion/Clay content in soil/Work Zone drainage effectiveness</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="3">- Place the first load of embankment material.</td></tr>
<tr><td>Ending</td><td colspan="3">- Sub-grade surface is completed. .
- Reach the elevation of the working phase if there are more than one phases of embankment</td></tr>
<tr><td colspan="2" rowspan="2">A Crew Definition</td><td colspan="3">- Equipment: 1~2 Dozer, 1 Compactor</td></tr>
<tr><td colspan="3">Comments; Verified ________</td></tr>
</table>

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Lime-Treated for materials used as sub-grade	**Lime-Treated for materials used as sub-grade**	**260**	**SY/Crew Day**

SCOPE	Included	Not Included
	- Cutting & pulverizing - Spread Lime - Mixing - Sprinkling or aerating - Compaction - Finishing - 1ST curing and 2nd mixing	- Survey & layout - Equipment move in - Transport material - Curing (after finishing) - Density tests - Setup blue top

PRODUCTIVITY FACTOR (Work Item)		- **Number of Mixing (*Specify:* ____)** - **Lift Height (Specify: ____)** - **Type C Lime Used (Yes, No) (*Note:* ________________________________)** - **Total Length Ready For Work (*Specify:* ____________________________)** - **Average Width of Work Area (*Specify:* ____________________________)** - **Slope (Steep, Moderate, Flat), (Note: ______________________________)**
		- Work Zone Congestion/Soil Type/# of working days only for curing/# of non-working days on curing
NODE	**Starting**	- Spread lime or cut & pulverize sub-grade.
	Ending	- Finishing sub-grade surface is completed.
A Crew Definition		- Equipment: 1 Stabilizer, 1 Motor Grader, 1 or 2 Spreader, 1 Sheep-foot Roller, 1 Flat Roller
		Comments; **Verified ________**

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

<table>
<tr><th colspan="2">Work Item</th><th>Sub-Item</th><th>Work Item #</th><th>Unit of Measurement</th></tr>
<tr><td colspan="2">Aggregate Base Course</td><td>Aggregate Base Course</td><td>247, 262, 263, 275, 276</td><td>LIFT-SY/Crew Day</td></tr>
<tr><td>SCOPE</td><td colspan="2">Included</td><td colspan="2">Not Included</td></tr>
<tr><td colspan="3">- Placing materials
- Spread uniformly & shaping
- Blade & shaping
- Sprinkle
- Compact
- Dry-out (if required)
-</td><td colspan="2">- Survey & layout
- Shaping the sub-grade or existing roadbed
- Stockpiled
- All material tests excluded
- Curing (Flexible Base: Directed by Engineers, usually 2 days; CTB: 72 hours)
- Density tests
- Rework caused by failing to achieve required density</td></tr>
<tr><td colspan="2">PRODUCTIVITY FACTOR (Work Item)</td><td colspan="3">- Lift Height (Specify: ____________________________)
- Total Lift Length (Specify: _____________________)
- Average Width (Specify: ________________________)
- Number of Lifts (Specify: ______________________)
- Type of treatment (None, Lime treatment, Portland Cement), (Note: ________)
- Treatment Mixing Method (Plant mixing, Roadway mixing), (Note: _________)
- Slope (Steep, Moderate, Flat), (Note: ___________________________________)

- Location/ Soil Type/ Work Zone Congestion</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="3">- Place the first load of base material.</td></tr>
<tr><td>Ending</td><td colspan="3">- Finishing a lift of base course is completed.</td></tr>
<tr><td colspan="2" rowspan="2">A Crew Definition</td><td colspan="3">- Equipment: 1 Motor Grader, 1~2 Steel Roller, 1 Water Truck, Trucks (Number is according to the distance from Work Zone to material resource)</td></tr>
<tr><td colspan="3">Comments; Verified ________</td></tr>
</table>

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

<table>
<tr><th colspan="2">Work Item</th><th colspan="2">Sub-Item</th><th>Work Item #</th><th>Unit of Measurement</th></tr>
<tr><td colspan="2">Hot Mix Asphalt</td><td colspan="2">Hot Mix Asphaltic Concrete Pavement, Asphalt Stabilized Base</td><td>340, 345</td><td>Ton/Crew Day</td></tr>
<tr><td>SCOPE</td><td colspan="3">Included</td><td colspan="2">Not Included</td></tr>
<tr><td colspan="4">- Lay Hot Mix Asphalt
- Compaction (Roller or lightly oiled tamps)</td><td colspan="2">- Survey and layout
- Transport materials
- Cleaning surface before applying for tack coat
- Shoot tack coat (if tack coat required)
- Mixing materials in the plant
- Equipment setup</td></tr>
<tr><td colspan="2" rowspan="2">PRODUCTIVITY FACTOR
(Work Item)</td><td colspan="4">- Thickness of Lifts (Specify: ____)
- (Bond Breaker, Base Course, Surface) construction, (Note: ______________)
- Asphalt Plant Capacity (Production Rate) (Specify: _______________tons/hr)
- (Machine Laid, Blade Laid), (Note: __________________________________)
- Slope (Steep, Moderate, Flat), (Note: _________________________________)</td></tr>
<tr><td colspan="4">- Traffic Condition/ Location</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="4">- Place the first load of Hot Mix Asphalt material.</td></tr>
<tr><td>Ending</td><td colspan="4">- Complete compaction.</td></tr>
<tr><td colspan="2" rowspan="2">A Crew Definition</td><td colspan="4">- Labors: One crew (6-8)
- Equipment: 1 Lay down Machine, 1 Pneumatic Roller, 5 Trucks</td></tr>
<tr><td colspan="4">Comments; Verified ________</td></tr>
</table>

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

<table>
<tr><th colspan="2">Work Item</th><th>Sub-Item</th><th>Work Item #</th><th>Unit of Measurement</th></tr>
<tr><td colspan="2">Concrete Paving</td><td>Slip-form</td><td>360-1</td><td>SY/Crew Day</td></tr>
<tr><td colspan="2">SCOPE</td><td>Included</td><td colspan="2">Not Included</td></tr>
<tr><td colspan="3">- Setting string line
- Placing dowels
- Installing reinforcing steel
- Placing joint assemblies
- Initial equipment setup
- Placing concrete
- Finishing</td><td colspan="2">- Survey & Layout
- Surface preparation
- Equipments move in
- Ride quality test
- Core test
- Unloading reinforcing steel
- Curing
- Saw cutting</td></tr>
<tr><td colspan="2" rowspan="2">PRODUCTIVITY FACTOR (Work Item)</td><td colspan="3">- (Continuously reinforced concrete pavement, Jointed concrete pavement, Non-reinforced concrete pavement), (Note: ________________________________)
- Thickness of Concrete Pavement (Specify: ____________________________)
- Total Length Ready for Slip (Specify: ________________________________)
- Width of Pass (Specify: ____)
- Number of Moving Slip-Form Paver (Specify: _______________________)
- Quantity of Concrete Poured (Specify: _______________________________)
- Slope (Steep, Moderate, Flat) (Note: _________________________________)</td></tr>
<tr><td colspan="3">- Location</td></tr>
<tr><td rowspan="2">NODE</td><td>Starting</td><td colspan="3">- Set string line.</td></tr>
<tr><td>Ending</td><td colspan="3">- Complete concrete placement.</td></tr>
<tr><td colspan="2" rowspan="2">A Crew Definition</td><td colspan="3">- Labors: One crew for reinforcing bar (8-10), One crew for concrete feeding and placing (6-8)
- Equipment : 1 Slip-form Paver, 1 Material Transfer</td></tr>
<tr><td colspan="3">Comments; Verified ________</td></tr>
</table>

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Concrete Paving	Conventional Hand-form	360-2	SY/Crew Day

SCOPE	Included	Not Included
	- Formwork - Installing reinforcing steel - Placing concrete - Spread and finishing	- Survey & Layout - Surface preparation - Cutting & bending Reinforcing steel - Core test - Curing - Removing formwork

PRODUCTIVITY FACTOR (Work Item)		- **Spread roller used (Yes, No), (Note: ___________________________________)** - **Slope (Steep, Moderate, Flat) (Note: ___________________________________)** - **Shape (Simple Configuration, With any Curve and Sharp Angle)(Note: _____)**
		- Crew size/Work Zone congestion
NODE	Starting	- Start to setup formwork
	Ending	- Complete concrete placement.
A Crew Definition		- Labors: One crew for formwork (3-4), One crew for reinforcing bar (6-8), One crew for concrete pouring (6-10)
		Comments; **Verified ________**

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Inlets and Risers	**Limit to extensions of existing Inlets/Risers in Drainage Line**	**465**	**EA/Crew Day(s)**

SCOPE	Included	Not Included
	- Excavation and dewatering - Trench excavation protection work - Shaping and bedding - Concrete Handling and drying, formwork and rebar placing (if CIP) - Placing precast units (if precast) - Installation of joints - Inspection - Connections to existing structure or pipe(s)	- Survey and layout - Site preparation - Mobilization and setting up of equipment(s) - Disposal of excavation - Removing old pipe(s) - Testing and functionality check(s) - Backfilling - (Limit to Stage 1 : Extension)

Work Item Level PRODUCTIVITY FACTOR		**Dimension of Inlets/Risers (Specify: ____)** **Approximate Depth (Specify; ____)** **Item(s) measured: Inlets (Details: ____)** **Item(s) measured: No. _____________ Inlets)** **Select types: CIP Inlets/Precast Inlets/CIP Manholes/Precast manholes** **Select crew(s) type: Same crew/ Different Crews, for concreting, formwork and excavation**
		- Water table depth / Soil type
NODE	**Starting**	- False work or Excavation, whichever starts first.
	Ending	- Concrete placement is completed.
STANDARD RESOURCE		**Comment ;** **Verified ________**

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Manholes	**Limit to extensions of existing M/H in Drainage Line**	**465**	**Crew Day(s)/EA**

SCOPE	Included	Not Included
	- Excavation and dewatering - Trench excavation protection work - Shaping and bedding - Concrete Handling and drying, formwork and rebar placing (if CIP) - Placing precast units (if precast) - Installation of joints - Inspection	- Survey and layout - Site preparation - Mobilization and setting up of equipment(s) - Disposal of excavation - Removing old pipe(s) - Testing and functionality check(s) - Backfilling - (Limit to Stage 1 : Extension)

Work Item Level PRODUCTIVITY FACTOR		**Dimension of Inlets/Risers (Specify: ____)** **Approximate Depth (Specify; ____)** **Item(s) measured: Inlets (Details: ____)** **Item(s) measured: No. _____________ Inlets)** **Select types: CIP Inlets/Precast Inlets/CIP Manholes/Precast manholes** **Select crew(s) type: Same crew/ Different Crews, for concreting, formwork and excavation** - Water table depth / Soil type
NODE	**Starting**	- False work or Excavation, whichever starts first.
	Ending	- Concrete placement is completed.
STANDARD RESOURCE		**Comment ;** **Verified ________**

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix F. Work Item Sheets (Cont'd)

Work Item	Sub-Item	Work Item #	Unit of Measurement
Head-Wall/Wing-wall	**CIP**	**466**	**Crew Days / EA**

SCOPE	Included	Not Included
	- False work - Installation of forms and rebar - Inspection of forms and rebar - Handling and placing of concrete - Apron	- Site preparation - Preparation of rebar and forms - Rebar fabrication - All necessary work for the protection of concrete placed under any weather conditions - Curing - Removal of forms - Surface finishing - Installation of drainage pipe - Removal of false work - Precast Concrete Panel - Safety Covers / Safety End Treatment

Work Item Level PRODUCTIVITY FACTOR		**Approximate dimension (W*H :_______________), (*Note;* _____________________)** **Thickness of wall (*Specify;* ____)** **Apron (Yes: ___________SF, No), (*Note;*___________________________________)**
NODE	**Starting**	- False work or form work, whichever starts first.
	Ending	- Concrete placement is completed.
A Crew Definition		- Labor: One Crew for Formwork(4-5), One Crew for Rebar installation(4-5)
		Comment ; **Verified _______**

- *Node; In a special case, a data collector can judge the Starting and the Ending Node based on his/her professional experience.*

Appendix G. Safety Protocol

Safety Protocol for Construction Site Visits

(TXDOT Project 0-4416)
READ, FAMILIZE and OBEY THIS SAFETY PROTOCOL BEFORE SITE VISIT

Ensure compliance with all regulations concerning the standard safety procedures of TxDOT and site.

Site protocol

Arrival: On each and every visit, the GRA must report to field office and gain permission to enter the site.

Departure: Report back to the field office on departure.

Vacant Sites: If there are no site representatives on site, then access is prohibited.

Instructions: GRA must follow any instructions given to them whilst on site, from the site representative or TxDOT personnel.

Safety Procedures

Responsibility
Avoiding accidents: GRA can avoid accidents by concentrating and thinking before acting. Remember that acting on impulse and taking shortcuts causes many accidents.

Parking & Transportation: GRA should park near the field office and go to job site with TxDOT personnel.

Clothing
Safety vest: Wear safety vest all the times in the job site.

Hardhats: Wear safety hardhats all the times in the job site.

Footwear: Wear steel-toed boots if required.

Appendix G. Safety Protocol (Cont'd)

Hearing protection: Ear protection should be worn if required.

Safety glass: Wear safety glass in required area.

Loose clothing: Do not wear loose clothing.

Moving around the site

Barricades: Do not lean over or go beyond any protective handrails or barricades.

Openings: Be careful where you walk. Pay attention to openings, barriers, protective covers and changes in levels.

Access: Use correct access at all times.

Restricted areas: Keep out of restricted areas.

Movement: Running on any part of the site is prohibited. Never walk backwards in a construction area. Do not jump from equipment, platforms or scaffolds. Do not stand or walk under any loads being lifted.

Weather: Beware of slippery surfaces (particularly after or during rain). Be careful in windy weather.

Behaviors on-site: Restrict communication with workers unless it is necessary for the research.

Traffic: Be aware of moving equipment and vehicles. Traffic rules should be obeyed and strict attention should be paid to all warning signs at all times.

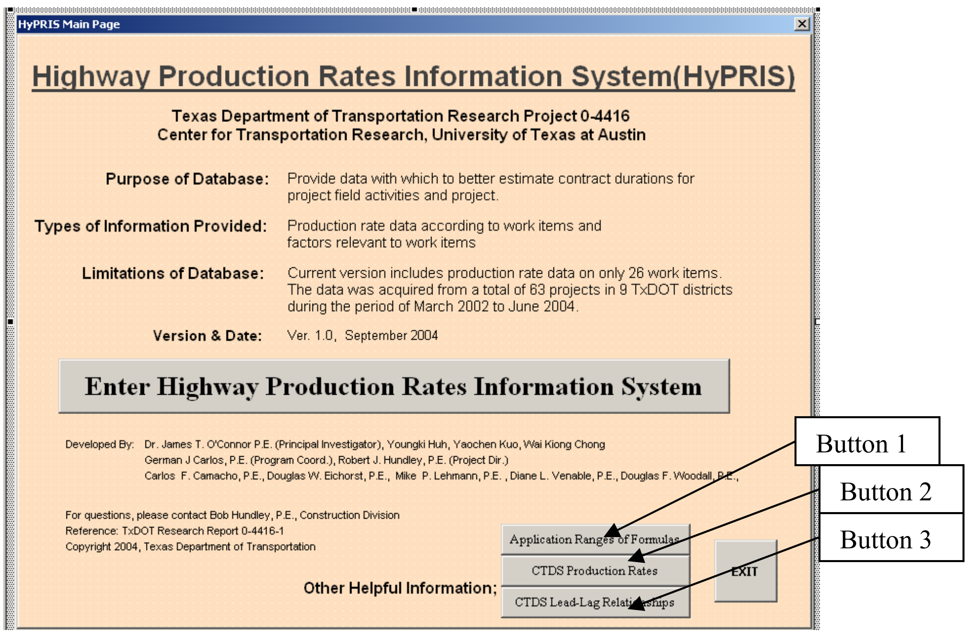
Taking pictures: GRA can freely take the pictures on the surveyed Work Items unless it is restricted.

Appendix H. Manual for using HyPRIS

1. Before opening the file, set your computer Macro Security to "Medium". Go to "Tools", choose "Options" and go to "Security". Click on "Macro Security" and set to "Medium"

2. Open the file. The window will prompt you whether you want to "Enable" or "Disable" Macro. Click on the "Enable Macro" button. All "active" buttons are in grey and have bolded wordings.

3. The window for the system will appear as below:



4. You can surf around the system the way your surf the internet.

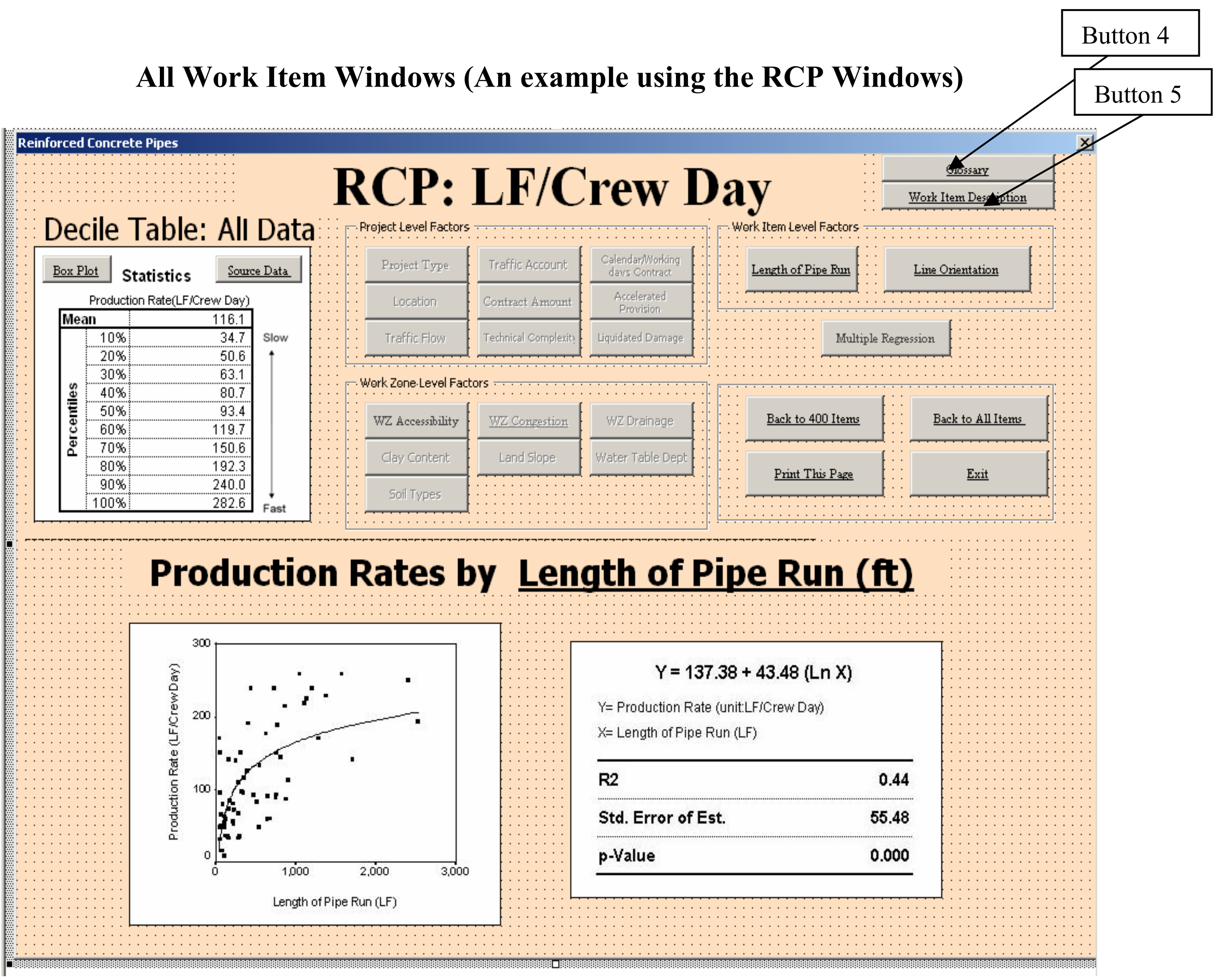
5. You can start using the information by pressing on the button "Enter Highway Production Rate Information System".

6. Other helpful information provided in this window:

Appendix H. Manual for using HyPRIS (Con't)

7. Application Range of Formulas: As shown in the first HyPRIS window. It warns the users about the range whereby the applicable range of the formulas (see button 1).
8. CTDS Production Rates: It provides the Production Rates from the previous system and users can rely on the CTDS Production Rates to estimate work items which this system does not have (see button 2).
9. CTDS Lead-Lag Relationships: It provides information on the Lead-Lag Relationships that were developed by the CTDS (see button 3).
10. Information are arranged according to Work Items numbers listed in the TxDOT Specifications (2004).

All Work Item Windows (An example using the RCP Windows)



Appendix H. Manual for using HyPRIS (Con't)

11. Glossary: It provides definitions for the statistical terms and the terminologies used to describe the factors for the work items (Button 4).

12. Work Item Description: It displays the scope for the production rates and resources for the work item (Button 5).

13. To make sure that the Printing Output functions correctly, users are to set the printer to "Landscape" at the Printer Option in the Control Panel.

Appendix I. Manual for Updating HyPRIS

System uses Microsoft Visual as its software platform. Administrators should be familiar with language of the program and methods to activate and deactivate buttons on the program.

Administrators should also be familiar with SPSS.

Measurements adopted for different information:

Scattered Plots: On the SPSS "Output Screen", first, convert the file to the required format using the SPSS chart editor and drop down manual "Format: Apply Chart Template", use the format titled "Box plot for DB" from CD the provided, next, set the graphic to 65% and save as "Chart".

Box Plots: On the SPSS "Output Screen", first, convert the file to the required format using the SPSS chart editor and drop down manual "Format: Apply Chart Template", use the format titled "scatter plot_dbp" from CD the provided, next, set the graphic to 65% and save as "Chart".

Datapoints Sources and Information Tables: Open the excel file "Input for Database", search for the worksheet "DP", key in the information as instructed in the worksheet. Copy the table and paste it in Paint as a jpeg file. The size setting for the jpeg file should be: width 395, height 350

Decile Tables: : Open the excel file "Input for Database", search for the worksheet "Regression Table", key in the information as instructed in the worksheet. Copy the table and paste it in Paint as a jpeg file. The size setting for the jpeg file should be: width 295, height 196.

Regression Formulas and Statistics: Open the excel file "Input for Database", search for the worksheet "Regression Table", key in the information as instructed in the worksheet. Copy the table and paste it in Paint as a jpeg file. The size setting for the jpeg file should be: width 295, height 196.

Multiple Regression Formulas and Statistics: Open the excel file "Input for Database", search for the worksheet "Multiple Regression", key in the information as instructed in the worksheet. Copy the table and paste it in Paint as a jpeg file. The size setting for the jpeg file should be: width 420, height 200.

Glossary Table: Enter information into the word file "Glossary of Terms (Final)" and arranged according the alphabetical order. Convert the entire information into jpeg file.

All inputs into the system are in jpeg format.

Appendix J. Survey on Contract Time Determination System Usage and Improvement

Distr.	Contact	% Proj Using CTDS	Level of Future CTDS Usage	How could CTDS be improved?	Future CTDS Usage Contgnt Upon Improvmts?	% of Projects Using CPM Approach (vs. CTDS)?
ABL	Daniel Richardson	0%	N/A	The District Engineer has mandated that all project construction time estimates be developed in this district using Suretrak.	No	100%
AMA	Lane Provence	0%	N/A	We do not use CTDS. We have developed Road Const Production Rates based on the last 5 yrs const reports. We use these production rates in Primavera to establish the const working days schedule. The only time we use CTDS is to look at production rates which we do not have established in our const records for our Road Const Production Rates.		100%
ATL	David Neshvba	0%	Same		No	10%
AUS	Mark Seerey	20%	Same		No	5%
BMT	John Ritter	100%	Same		No	0%
BWD	Donald Krause	30%	Same	The CTDS system is not easily adapted. The projects we deal with do not normally fit the projects that CTDS has preset in its program. It is hard to remove or alter items on the list for a particular type of project. It is not easy to change or correct mistakes. Units for items should be changeable. Only a certain number of basic items should be preset with other items that can be optional. CTDS does address Lighting or Electrical type items very well. The CTDS program should be able to link to estimator, so items do not have to be entered more than once.	Yes	5-10%
BRY	Paul Warden	25%	Less	We have no opinions. Our district does not use the CTDS system (excel spreadsheet). Our consultants use the CTDS system 100% of the time unless a CPM is required.		
CHS	Chuck Steed	0%	N/A	We are having a districtwide training on CPM in Nov. Once that is complete, we plan on utilizing it to estimate const time.		0%
CRP						

Appendix J. Survey on Contract Time Determination System Usage and Improvement (Cont'd)

Distr.	Contact	% Proj Using CTDS	Level of Future CTDS Usage	How could CTDS be improved?	Future CTDS Usage Contgnt Upon Improvmts?	% of Projects Using CPM Approach (vs. CTDS)?
DAL	Siddig Dali	5%	Less	A. System Program needs updating from Lotus to Excel. B. We prefer a program with popup menus that give the options of Project Types, Daily Prod Rates for Standard Work Items and Base Production rates and Sensitivity Factors. C. Currently we are using an Excel sheet with formulas that include the data tables provided by the AC No. 17-93.	Yes	5%
	Sam Moghadassi	10%	Less	1. This program is not user friendly. 2. Without some sort of back-calculation, the contract time generated is unrealistic. 3. Daily production rate table does not make any sense for small projects such as CMAQ. 4. Some of the % complete of the preceding activity needs to be thoroughly reviewed.	Yes	50%
	Paul Smith	95%	Same	No	No	0%
	James Janovsky	100%	Same	1. Increase production rate or have a more accurate production rate. 2. Allow accelerated construction 3. Include Project Scheduling sheet	No	0%
ELP	Efrain Esparaza	25%	Same	We used to use CTDS a lot more before, but now we use "Suretrak" and "Primavera". Overall, we use CTDS for smaller projects.	Yes	75%
FTW	William Riley	100%	Same	The daily production rates are unrealistic for the FTW district. The district has come up with rates that fit our conditions and contractors. System could be improved by setting production rates for each district.	No	0%
HOU						
LRD						
LBB	Tedd Carter	0%	N/A	N/A	No	100%

Appendix J. Survey on Contract Time Determination System Usage and Improvement (Cont'd)

Distr.	Contact	% Proj Using CTDS	Level of Future CTDS Usage	How could CTDS be improved?	Future CTDS Usage Contgnt Upon Improvmts?	% of Projects Using CPM Approach (vs. CTDS)?
LFK	Robert Neel	5%		To be useful the production rates need to be more representative of specific size of job and region of state. Also since our district has switched to calendar days on all projects a system based solely on production rate is not very useful. We are trying to implement the use of Suretrak. We would rather have help with creating calendars, production rates and critical path relationships for the newer methods and programs.	No	95%
ODA	Matt Carr	0%	N/A	We have not been using the program since 1997 when it was being supported by CST. Any versions of CTDS that run in excel have not been provided to us.	Yes	0%
PAR						
PHR	LeighAnn Goodwin	100%	Less	We are currently in the process of switching to 100% use of SureTrak to calculate all our contract time.	Yes	100%
	David Scheel (Area Office)	0%	N/A	I have never used the CTDS system, nor has anyone else in my office. Therefore, I cannot give any suggestions for improvement.	No	100%
	Mark Narendorf (New Braunfels)	5%	Same	No comments on CTDS specifically, however as more of a question, are there any updated rates on the work items using actual pay item units? Such as linear feet for drill shafts instead of CY, etc? Or for that matter anywhere we can look to see a set of the rates from our district compiled from past construction projects?	No	95%
SJT	Gary Enos	0%	N/A	The SJT district follows the procedure detailed in TxDOT circular 17-93 for the determination of contract time. We have not implemented CTDS.	No	80%
	Claude Cosgrove (Hondo)	0%	N/A	We do not currently use CTDS. We are using Primavera to estimate contract time.		100%
YKM	Blaise Dreitner	0%	N/A	Yoakum TxDOT projects are simpler to do by hand because of their small size. We do use Excel in some/most cases.	Yes	0%

Appendix J. Survey on Contract Time Determination System Usage and Improvement (Cont'd)

Distr.	Contact	% Proj Using CTDS	Level of Future CTDS Usage	How could CTDS be improved?	Future CTDS Usage Contgnt Upon Improvmts?	% of Projects Using CPM Approach (vs. CTDS)?
SAT	John Saldano	<5%	Less	We are using CPM software more and more, even on small projects that do not require CPM usage. Designers are still using the daily production rates from the CTDS system to calculate task completion in days, but this only covers certain tasks and some are blanket tasks. We are not sure if improving the CTDS system is the answer. We would suggest that daily production rates be analyzed using current construction industry practices and standards. Also, new tasks and breaking up some blanket tasks should be done to cover more of the incidentals associated with construction projects and how they affect time determination. Also, a more uniform approach to setting up calendars in CPM generated schedules. This may involve using historical data from construction projects on actual number of days worked per month for a year.	No	95%
	David Scheel (Area Office)	0%	N/A	I have never used the CTDS system, nor has anyone else in my office. Therefore, I cannot give any suggestions for improvement.	No	100%
	Mark Narendorf (New Braunfels)	5%	Same	No comments on CTDS specifically, however as more of a question, are there any updated rates on the work items using actual pay item units? Such as linear feet for drill shafts instead of CY, etc? Or for that matter anywhere we can look to see a set of the rates from our district compiled from past construction projects?	No	95%
WFS	John Barton	0%	N/A	We do not currently use CTDS in WFS district simply because we not know what it is. We continue to develop our project const time estimates by preparing worksheets in accordance with the directives by AC 17-93. We may be missing out on a great opportunity, but we are currently completely unaware of the details, abilities, drawbacks or benefits of this system. Therefore, it is impossible to provide any other input to questions 2 and 4. We would love to hear more about CTDS.	N/A	0%
TYL	William Battles	15%	Same	The main concern the designers have is the rate of production. Each Area Office has a general idea of the rates that their contractors use in their schedule submissions but this information is rarely consistent with actual field rates. We would request that a data base of actual field production rates be developed to be provided to designers.		

References

Abdelhamid, T. S., and Everett, J. G. (1999). “Time Series Analysis for Construction Productivity Experiments.” *J. Constr. Engrg.and Mgmt*., ASCE, 125(2), 87-95.

AbouRizk, S., Knowles, P., and Hermann, U. R. (2001). “Estimating Labor Production Rates For Industrial Construction Activities.” *J. Constr. Engrg. and Mgmt*., ASCE, 127(6), 502-511.

Albright, S. C., Winston, W. L., and Zappe, C. (1999). *Data Analysis & Decision Making*. Pacific Grove, CA.

Allmon, E., Haas, C. T., Borcherding, J. D., and Goodrum, P. M. (2000). “U.S. Construction Labor Productivity Trends, 1970–1998.” *J. Constr. Engrg. and Mgmt*., ASCE, 126(1), 97-104.

Borcherding, J. D. (1976). “Improving Productivity in Industrial Construction.” *Journal of Construction Devision*, ASCE, 102(CO4), 599-614.

Borcherding, J. D., and Alarcon, L. F. (1991). “Quantitative Effects on Construction Productivity.” *The Construction Lawyer*, American Bar Association, 11(1), 35-48.

Borcherding, J. D., and Garner, D. F. (1981). “Work Force Motivation and Productivity on Large Projects.” *Journal of Construction Division*, ASCE, 107(CO3), 443-453.

Borcherding, J. D., and Oglesby, C. H. (1974). “Construction Productivity and Job Satisfaction.” *Journal of the Construction Division*, ASCE, 100(CO3), 413-431.

Borcherding, J. D., Sebastian, S. J., and Samelson, N. M. (1980). “Improving Motivation and Productivity on Large Projects.” *Journal of the Construction Division*, ASCE, 106(CO1), 73-89.

Bhurisith, L., and Touran, A. (2002). “Case Study of Obosolescence and Equipment Productivity.” *J. Constr. Engrg. and Mgmt*., ASCE, 128(4), 357-361.

The Business Roundtable (1980). “Scheduled Overtime Effect on Construction Project.” *Construction Industry Cost Effectiveness Task Force Report*, November.

The Business Roundtable (1982). “Measuring Productivity in Construction.” *Report A-1*, September.

Chambers, J., Cleveland, W., Kleiner, B., and Tukey, P. (1983). *Graphical Methods for Data Analysis*. Wadsworth.

Chang. L. M., and Borcherding, J. D. (1986). “Craftsman Questionnaire Sampling.” *J. Constr. Engrg. and Mgmt*., ASCE, 112(4), 543-556.

Cho, S. (2000). “Development of the Project Definition Rating Index (PDRI) for Building Projects.” *Doctoral Dissertation*, The University of Texas at Austin, Austin, TX, May 2000.

Christian J., and Hachey D. (1995). “Effects of Delay Times on Production Rates in Construction.” *J. Constr. Engrg. and Mgmt*., ASCE, 121(1), 20-26.

Christian J., and Hachey D. (1996). “A Computer-aided System to Improve Production Rates in Construction.” *Advances in Engineering Software*., V. 25, 207-213.

The Construction Industry Institute (1988). “The Effects of Scheduled Overtime and Shift Schedule on Construction Craft Productivity.” Construction Industry Institute, The University of Texas at Austin.

The Construction Industry Institute (1990). “Productivity Measurement: An Introduction.” Construction Industry Institute, The University of Texas at Austin.

El-Rayes, K., and Moselhi, O. (2001). “Impact of Rainfall On the Productivity of Highway Construction.” *J. Constr. Engrg. and Mgmt*., ASCE, 127(2), 125-131.

Gidado, K. I. (1996). “Project Complexity: The Focal Point of Construction Production Planning.” *J. Construction Management and Economics*, V.14, 213-225.

Goodrum, P. M. (2001). “The Impact of Equipment Technology on Productivity in the U.S. Construction Industry.” *Doctoral Dissertation*, The University of Texas at Austin, Austin, TX, May 2001.

Goodrum, P. M., and Haas, C. T. (2002). “Partial Factor Productivity and Equipment Technology Change at Activity Level in U.S. Construction Industry.” *J. Constr. Engrg. and Mgmt*., ASCE, 128(6), 463-472.

Gransberg, D. D. (1996). “Optimizing Haul Unit Size and Number Based on Loading Facility Characteristics.” *J. Constr. Engrg. and Mgmt*., ASCE, 122(3), 248-253.

Green, S. B. (1999). “How Many Subjects Does It Take to Do A Regression Analysis?” *Multivariate Behavioral Research*, Lawrence Erlbaum Associates, 26(3), 499-510.

Grimm, C. T., and Wagner, N. K. (1974). “Weather Effects on Mason Productivity.” *Journal of Construction Division*, ASCE, 100(3), 319-335.

Hancher, D. E., McFarland, W. F., and Alabay, R. T. (1992) “Construction Contract Time Determination” Texas Department of Transportation Research Report.

Halligan, D. W., Demsetz, L. A., and Brown, J. D. (1994). "Action-Response Model and Loss of Productivity in Construction." *J. Constr. Engrg. and Mgmt*., ASCE, 120(1), 47-64.

Hanna, A. S., Camlic, R., Peterson P. A., and Nordheim, E. V. (2002). "Quantitative Definition of Projects Impacted by Change Orders." *J. Constr. Engrg. and Mgmt*., ASCE, 128(1), 57-64.

Hendrickson, C., Martinelli, D., and Rehak, D. (1987). "Hierarchical Rule-based Activity Duration Estimation." *J. Constr. Engrg. and Mgmt*., ASCE, 113(2), 288-301.

Herbsman, Z. J., and Ellis, R. (1995). "Determination of Contract Time for Highway Construction Projects." *National Cooperative Highway Research Program Synthesis of Highway Practice 215, Transportation Research Board,* National Research Council, Washington, DC (October), 43PP.

Jiang, Y. (2003). "The Effects of Traffic Flow Rates at Freeway Work Zones on Asphalt Pavement Construction Productivity." *Transportation Quarterly*, V.57, n.3, Summer, P83-103.

Jonasson, S., Dunston, P. S., Ahmed, K., and Hamilton, J. (2002). "Factors in Productivity and Unit Cost for Advanced Machine Guidance." *J. Constr. Engrg. and Mgmt*., ASCE, 128(5), 367-374.

Koehn, E., and Brown, G. (1985). "Climatic Effects on Construction." *Journal of Construction Engineering and Management,* ASCE, 111(2), 129-137.

Koehn, E., and Ahmed, F. (2001). "Production Rates for Urban/Rural Projects in Developing Areas" *International Transaction*, AACE, INT.03, 01-06.

Lee, E.-B., Lobbs, C. W., Harvey, J. T., and Roesler, J. R. (2000). "Construction Productivity and Constraints for Concrete Pavement Rehabilitation in Urban Corridors." *Transportation Research Record*, n.1712, P13-22.

Liou, F. S., and Borcherding, J. D. (1986). "Work sampling Can Predict Unit Rate Productivity." *J. Constr. Engrg. and Mgmt*., ASCE, 112(1), 90-103.

Marzouk, M., and Moselhi, O. (2003). "Object-oriented Simulation Model for Earthmoving Operations." *J. Constr. Engrg. and Mgmt*., ASCE, 129(2), 173-181.

National Cooperative Highway Research Program Synthesis of Highway Practice 79. (1981). "Contract Time Determination." *Transportation Research Board,* National Research Council, Washington, DC (October), 45PP.

National Electrical Contractors Association. (1974). "The Effect of Temperature on Productivity." *Test Report*, Washington, DC.

Oglesby, C. H., Parker, H. W., and Howell, G. A. (1989). *Productivity improvement in construction.* McGraw-Hill Publishing Inc., New York, NY.

Ovararin, N., and Popescu, C. M. (2001). "Field Factors Affecting Masonry Productivity." *International Transaction*, AACE, EST-09.

Peurifoy, R. L., and Schexnayder, C. J. (2002). C*onstruction Planning, Equipment, and Methods. 6th Edition,* McGraw-Hill Publishing Inc., New York, NY.

Proverbs, G. D., Holt, G. D., and Olomolaiye, P. O. (1997). "European Construction Contractors: A Productivity Appraisal of in-situ Concrete Operations." *J. Construction Management and Economics*, V.17, 221-230.

R.S. Means Company, Inc. (2002). *R.S. Means Heavy Construction Cost Data*, 59th Annual Edition, *R.S. Means Company, Inc*., Kingston, MA.

Sanders, S. R., and Thomas, H. R. (1991). "Factors Affecting Masonry-Labor Productivity." *J. Constr. Engrg. and Mgmt*., ASCE, 117(4), 626-644.

Sanders, S. R., and Thomas, H. R. (1993). "Masonry Productivity Forecasting Model." *J. Constr. Engrg. and Mgmt*., ASCE, 119(1), 163-179.

Schexnayder, C., and Webber, S. L. (1999). "Effect of Truck Payload Weight on Production." *J. Constr. Engrg. and Mgmt*., ASCE, 125(1), 1-7.

Smith, S. D. (1999) "Earthmoving Productivity Estimation Using Linear Regression Techniques." *J. Constr. Engrg. and Mgmt*., ASCE, 125(3), 133-141.

Smith, S. D., Wood, G. S., and Gould, M. (2000). "A New Earthworks Estimating Methodology." *J. Construction Management and Economics*, V.18, 219-228.

Thomas, H. R. (1991). "Labor Productivity and Work Sampling: The Bottom Line." *J. Constr. Engrg. and Mgmt*., ASCE, 117(3), 423-444.

Texas Department of Transportation (1993). "Standard Specifications for Construction of Highways, Streets and Bridges." Texas.

Thomas, H. R. (2000). "Schedule Acceleration, Work Flow, and Labor Productivity." *J. Constr. Engrg. and Mgmt*., ASCE, 126(4), 261-267.

Thomas, H. R., Mathews, C. T., and Ward, J. G. (1986). "Learning Curve Models of Construction Productivity." *J. Constr. Engrg. and Mgmt*., ASCE, 112(2), 245-258.

Thomas, H. R., Maloney, W. F., Horner, R. M. W., Smith, G. R., Handa, V. K., and Sanders, S. R. (1990). "Modeling Construction Labor Productivity" *J. Constr. Engrg. and Mgmt*., ASCE, 116(4), 705-726.

Thomas, H. R., and Raynar, K. A. (1997). "Schedules Overtime and Labor Productivity: Quantitative Analysis." *J. Constr. Engrg. and Mgmt*., ASCE, 123(2), 181-188.

Thomas, H. R., Riley, D. R., and Sanvido, V. E. (1998). "Loss of Labor Productivity Due to Delivery Methods and Weather." *J. Constr. Engrg. and Mgmt*., ASCE, 125(1), 39-46.

Thomas, H. R., and Yiakoumis I. (1987). "Factor Model of Construction Productivity." *J. Constr. Engrg. and Mgmt*., ASCE, 113(4), 623-639.

Thomas, H. R., and Završki, I. (1999). "Construction Baseline Productivity: Theory and Practice." *Journal of Construction Engineering and Management,* ASCE, 125(5), 295-303.

Tucker, R. L. et al. (1982). "Implementation of Foreman-Delay Surveys." *J. Construction Devision*, ASCE, 108(4), 577-591.

Wannacott, T. H., and Wannacott, R. J. (1987). *Regression: A Second Course in Statistics*. Malabar, FL.

Werkmeister, R. F., Luscher, B. L., and Hancher, D. E. (2000). "Kentucky Contract Time Determination System." *Transportation Research Record*, n.1712, P185-195.

Werkmeister, R. F., Luscher, B. L., and Hancher, D. E. (2000). "Kentucky Contract Time Determination System." *Transportation Research Record*, n.1712, P185-195.

Winch, G., and Carr, B. (2001). "Benchmarking on-site productivity in France and the UK: A CALIBRE Approach." *J. Construction Management and Economics*, V.19, 577-590.