Crew Production Rates for Contract Time Estimation: Beam Erection, Deck, and Rail of Highway Bridges

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Abstract: Both the importance and process of estimating highway construction time have increased in significance as roadway user costs themselves have become more significant. In estimating construction time, few parameters are more significant than work item crew production rates and factors significantly affecting those rates. A standardized data collection tool was used to acquire a total of 67 data points from 25 ongoing Texas highway projects between February 2002 and May 2004, for three selected critical work items: beam erection, bridge deck, and bridge rail. With the data, several hypothesized drivers of the crew production rates were analyzed. While the factor of shape of deck (straight versus curved) was identified as a statistically significant driver of bridge deck crew production rate, no statistically significant drivers were found for work items of beam erection and bridge rail. The study also found that both formwork and rebarwork crew sizes have significant relationships with bridge deck production rate. Findings from this study will enable highway agencies to enhance accuracy of *contract time* estimation for highway bridge construction. The methodology for obtaining field-based production rates will also be beneficial for future researchers.

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Introduction

Both the importance and process of estimating construction time of a highway project have increased in significance as roadway user costs themselves have become more significant. Thus, transportation agencies have been placing a great premium on controlling construction durations (Herbsman and Ellis 1995). Increased usage of calendar day type contracts and introduction of accelerated construction provisions with high amounts of liquidated damages into many construction contracts serve as evidence of schedule concern. However, such efforts have limited effect if construction contract time estimation is too lengthy. It is imperative to have realistic production rates in order to develop accurate construction time estimates. Consideration of a wide range of factors likely to affect construction duration is also important for time estimation (Herbsman and Ellis 1995).

There have been numerous publications reporting such factors. Thomas et al. (1989) listed 42 factors under three categories: within-project, project-to-project, and regional. Sonmez (1996) also summarized 23 factors under three categories: management-related, project-related, and labor-related. Herbsman and Ellis (1995) found 17 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. Further, many researchers studied in different ways how they factors affect the productivity and how those could be interpreted and used for better management. Sanders and Thomas (1991) found the importance of repetitive design in improving productivity. Over a period of 570 workdays, they collected daily productivity data on 11 masonry projects, including apartments, offices, hotels, a National Guard Armory, and research laboratories located in central Pennsylvania. Data analyses showed that repetitive design could improve masonry productivity by 30%, while designs that require extensive layout and masonry unit cutting reduce productivity by 40%. Regarding the effect of overtime on productivity, a study conducted by Proctor & Gamble at their Green Bay, Wisconsin, operation (Business Roundtable 1974, 1980) reported that a reduction of 30% in productivity was found on projects operated on a basis of 50–60 hours per week. In 1988, the Construction Industry Institute (CII 1988) tracked the moving average productivity of various crews from seven different industrial projects for three years and concluded that productivity did not necessarily decrease with an overtime schedule. Between 1989 and 1992, Thomas observed a total of 151 weeks of electrical and pipe crews' productivity on 11 different industrial projects and found that the average loss of efficiency due to overtime ranged from 0 to 15% (CII 1994; Thomas and Raynar 1997).

Thomas and colleagues (Thomas et al. 1989; Sanders et al. 1989) studied 570 workdays of data on 11 commercial masonry

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projects and found no significant relationship between crew size and productivity, although it is well established in the industry that, as crew size increases, productivity (output/work hour) decreases, mainly due to congestion, interferences, and conflicts between crews, tools, and materials. Koch and Moavenzadeh (1979) studied equipment technology usage in highway construction and reported that the use of technology between the 1920s and 1970s increased. More recently, Allmon et al. (2000) suggested that technological advance was the main reason for increased long-term labor productivity. Goodrum and Haas (2002) examined 1990s data published by RS-Means, Richardson, and Dodge and also found evidence to suggest that equipment technology changes resulted in long-term improvements in productivity.

Some limitations in such construction productivity studies are that there are many factors, measurement of factors can be different, and the quantitative relationships between factors are not well understood. Perhaps the chief problem is that there is often little data that can be analyzed with sufficient statistical confidence in order to determine a quantitative relationship. In construction operations, not only is it hard to record detailed information, but also a number of factors within a project will vary (Thomas and Smith 1990). Another reason might be the difficulty of isolating the impact of any single factor from others due to the varied nature of construction (Herbsman and Ellis 1995). Methodology of data analysis is also one of the problems. Finding the proper productivity analysis approach is still a topic for such research (Sanders et al. 1989).

Regression analysis is one of the common analysis methods that have been applied in exploring the relationship between factors and productivity. Koehn and Brown (1985) developed two nonlinear regression model equations, i.e., cold or cool–hot or warm, as a function of temperature and humidity. Sanders and Thomas (1993) developed a regression model to predict masonry productivity. Regression techniques were also employed to quantify the effects of overtime work on productivity by Thomas and Raynar (1997). Smith (1999) estimated earthmoving productivity by means of a multiple regression equation. Hanna et al. (2002) studied the relationships between project size and duration, average manpower, and peak man power, and estimated the *S* curve (x=percent time of total duration; and y=percent hours of total work hours).

However, many of the studies that deal with the aforementioned factors were often based primarily on extrapolation of historical data that had little detailed information about various factors, such as weather, crew size, and equipment types for a specific activity (Sanders and Thomas 1993). Therefore, these methods are unlikely to consider the factors that actually affect productivity. Another potential problem with using historical data is that different activity information tends to be combined (Everett and Farghal 1997). Furthermore, many studies were conducted based on a nonstandardized data collection methodology. Sanders and Thomas (1991) denoted that "findings are likely to mislead researchers if based on data collected from unrelated multiple sources using different techniques, yet treated as a single data set."

In addition to the limitations of previous studies mentioned previously, there are some others in regard to the production rate studies for construction *time* estimation. First of all, there have been few studies on production rates for estimating construction time. Many published papers in the field of productivity study focus on project performance evaluation or cost control rather than on time estimation. Figures for cost control purposes may not be as appropriate for construction *time* estimation (Huh 2004). Second, there has been little research that specified a detailed scope of production rates, such as what were the starting and ending nodes of time measurement, what work-hours were included in the measurement, whether or not overtime was considered, etc. Production rates having an unknown scope are hardly applicable for accurate construction time estimation.

Unlike previous studies, this study focused on collecting production rate data to be specifically used for estimating construction contract *time* and identifying drivers of production rates on highway projects. Data were collected by means of weekly observations from a large number of ongoing Texas projects, using a standardized data collection tool.

Objectives and Scope

The aim of the study was to develop improved information on crew production rates to further advance the accuracy of construction contract time estimation for Texas highway projects. Details were: (1) to develop a standard data collection procedure and relevant tools; (2) to collect field-based information on crew production rates; and (3) to identify major factors driving the crew production rate of each selected work item, namely, beam erection, bridge deck, and bridge rail. Developing prediction models of work item production rates, such as multiple regression models, was not the intention of the study, mainly because of data sample size limits. The number of data points collected and used for the analysis is believed to be insufficient to develop a reliable multiple regression model, as about 15 data points per independent variable are needed for a reliable equation (Stevens 2002).

Methodology

Critical Work Items Selection

Given the limited study resources and time, only work items that are often critical in construction sequencing were selected. Based on a list of work items in the Texas Department of Transportation Standard Specification, a total of 25 work items were initially examined for the study (Huh 2004). Survey forms were sent to 17 Texas Department of Transportation (TxDOT) personnel, with 14 responding. Three critical work items were selected for this paper by the writers, namely, beam erection, bridge deck, and bridge rail. The work item survey form and associated results can be found in the reference.

Influence Diagram

Influence diagrams were used to identify factors that are believed to affect production rates (Huh 2004). Potential factors were first identified based on an intensive literature review and discussion with TxDOT personnel. Then such factors were refined through a preliminary data collection process, which involved observations, interviews with site personnel, and data analyses.

Data Collection Procedure

Data was collected through observations during weekly site visits to numerous TxDOT projects. The data collection procedure was

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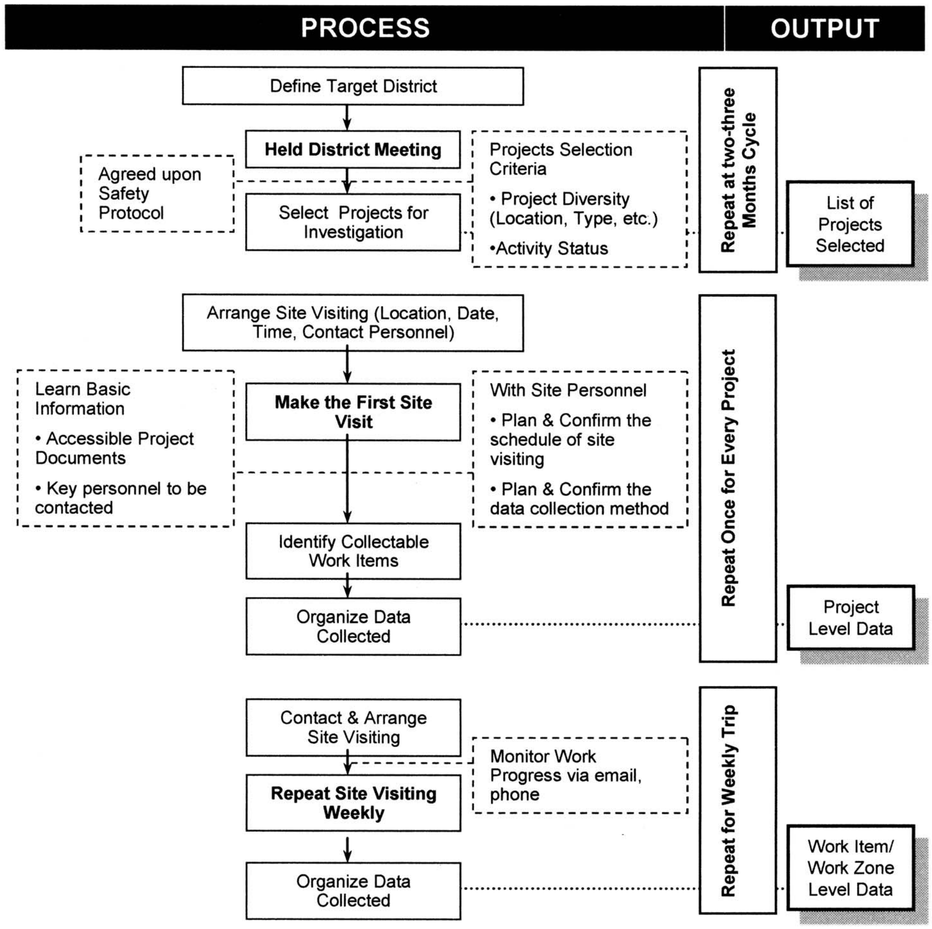

Fig. 1. Site visit and data collection process

established in collaboration with TxDOT personnel and encompassed selection of the projects to be investigated and observation of selected work items. Fig. 1 delineates each step of the procedure shown with the level of its frequency and output where applicable. For each targeted district, a meeting with selected district personnel was arranged in order to select projects. Candidate projects were proposed by the researcher in order to prescreen projects that were either just begun or about to be completed. The meetings were held in each district office, and agenda items included the following:

- Description of the research;
- Data collection methodology, including process and tool;
- Safety protocol for site visit;
- Candidate projects proposed;

Table 1. Work Item Production Rate Scope: Included versus Not Included

	Scope	
Work item	Included	Not included
Beam erection	Equipment(s) setup/handling beam(s) for erection in site/erection/false work and bracing	Erection planning/site preparation/equipment moves 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/connection with bents/inspection
Bridge deck	False work, overhang/installation of form work (precat panel or PMD)/construction joints and cork liner work/installation of reinforcing steel/prestress work required on deck/attachment of temporary rail or screed supports/installation and testing of screed machine/inspection/handling and placing of concrete	Site preparation/equipment moves in/posttensioning/bridge rail and hand rail work/bridge protective assembly/drainage pipe work/waterproofing and pavement/curing including fogging and interim curing/all necessary work for protection of concrete placed under any weather conditions/removal of forms/removal of false work
Bridge rail	Placement of concrete only	Removal of old railing/cleaning site before or after work/temporary railing/material handling/rebar setting/anchorage to structure/equipment setup/anything related to curing/protective work for railing

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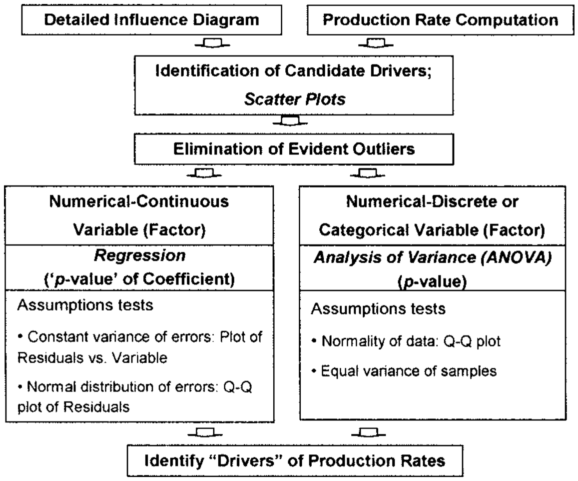

Fig. 2. Data analysis methodology

- Selection of projects to be investigated;
- Contact points for each project selected;
- Tentative site visit schedule for each project; and
- General comments and feedback.

Subsequent to introductory district meetings, a separate meeting was held for every project selected, with an area engineer and site personnel responsible for each project. Meetings with site personnel provided the opportunity to obtain information on project status, possible additional sources of information including project documents, project level data, work schedule for the next two to three months, work items to be pursued, and organization of site personnel and key personnel to coordinate with. Site visits were conducted on a weekly basis to collect data on production rates. Site personnel, mostly foremen responsible for each work item, explained daily variations in the previous week's production during the weekly site visits. In the early stage of data collection, foremen seemed well aware of what had happened to each work item operation in the previous week. In fact, the frequency of site visits was based on this observation. Data collected during each site visit was verified by cross-examining relevant project documents when deemed reliable.

Data Collection Tool

A data collection tool was developed to facilitate the data collection process and enhance the accuracy of data. The tool may be the first such comprehensive guide to measuring crew level production rates in highway construction and consists primarily of data forms used to track production rates (Huh 2004). A complete packet of the tool can be found in the reference.

Data collection tool forms contain sets of different factors that may influence the production rate of each work item and are organized at three levels: project, work zone, and work item. The work zone level forms include the w*ork item sheet* that was used to specify the scope of each work item for which data was collected (see Table 1). 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 represent actual production of the work item and are of primary concern in estimating construction *time*, as opposed to those that support cost control. The work item sheet also contains a list of possible work item-specific factors that may affect the production rate of each work item. To accommodate variability in the scope of work and

Table 2. Formulas Used To Calculate Production Rates

Work item	Unit	Production rate equation
Beam erection	spans/ crew day	(Total output)/(total crew work days)
Bridge deck	m^2/crew day	(Total output)/(total crew work days)
Bridge rail	m/crew day	(Total output)/(total crew work days)

work item level factors among work items, each work item sheet is unique for a given work item.

Pilot Data Collection and Refinement

Based on the data collection procedure and tool developed, pilot data collection was conducted to validate the effectiveness of measurement systems and to identify possible improvements to the data collection methodology. Four projects were selected and pilot tested over approximately three months, and several minor modifications were made to the data collection procedure and tool.

Data Analyses

Fig. 2 shows the overall process of applying statistical methods in identifying drivers. Candidate drivers were identified by visually inspecting scatter plots. Then, analysis of variance (ANOVA) and simple regression were employed to test the statistical significance of the candidate drivers' relationships with production rates. The significance level (α) used in this study was 0.1.

Rationale for Production Rate Computation

Production rates of each work item were calculated based on the formulas shown in Table 2. Calculating production rates as defined requires two input values: "output" and "crew work days." The output value represents the quantity of work completed during a certain number of work days and is measured in "units completed" (i.e., span, square meter, or linear meter). While a minimal effort was needed to measure the output in such simple units, clear guidelines were required in assessing crew work days.

Correcting for Delays

Crew work days were assessed based on a rule called the *half-day rule*. If, in a given day, the delay effect caused by any of

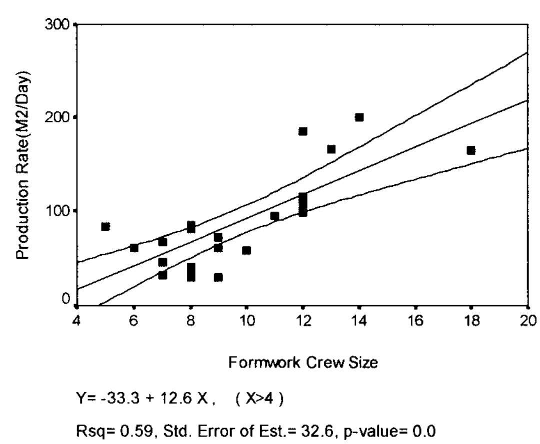

Fig. 3. Bridge deck scatter plot and regression results (versus formwork crew size)

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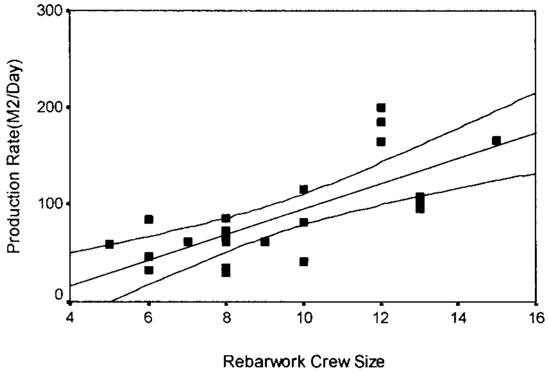

Fig. 4. Bridge deck scatter plot and regression results (versus rebarwork crew size)

the factors, such as weather (rain, too wet, snow, wind, etc.), unworkable soil condition, traffic accident, construction accident, equipment down time, material unavailable, trade problem, or absenteeism, amounted to less than two hours, the day was considered one work day. 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 nonwork day. Factors such as holidays, nonworking days (due to unforeseen conditions, TxDOT direction, etc.), nonworking weekends, and days off were not included in the rates. A work day having more than two hours of overtime was to be adjusted based on actual overtime hours, but no such overtime was observed.

Correcting for Crew Size

The "work days" assessed according to the *half-day rule* were input together with the output into either one of the formulas (see Table 2), resulting in a production rate for each work item. Yet, such a calculated production rate may still need to be adjusted for crew size, because even the same work items might differ in crew size from project to project. For the bridge deck work item, there was considerable variation in production rate with crew size (see Figs. 3 and 4). Hence, the production rate for the bridge deck work had to be normalized by comparing the sizes of its formwork and rebar crews with those most frequently observed, that is, eight for both crews. Thus, for the bridge deck, production rates, calculated based on the output and the work days, were divided by crew ratio—that is, the actual (rebar and formwork) crew size divided by 16—giving the "normalized crew production rate," as shown in the following formula

Table 3. Crew Definition and Rationale for Production Rate Adjustment for Crew Size

Work item	Crew definition	Production rate adjustment by crew size
Beam erection	One or two crane(s) in operation	Not adjusted by crew size
Bridge deck	One slip-form machine in operation	Not adjusted by crew size
Bridge rail	Formwork (8), one crew for rebar (8)	Adjusted by crew size

Table 4. Districts and Projects Visited

Districts visited in Texas	Total number of projects	Number of data points collected	
		Total work items	Total data points
San Antonio	3	3	6
Yoakum	1	1	2
Austin	3	3	20
Dallas	6	3	15
Houston	8	2	16
Lubbock	1	2	2
Waco	3	1	6
Total	25		67

$$\text{Normalized Crew Production Rate} = \frac{\left[\frac{\text{Quantity Completed}}{\text{Total Crew Work Days}}\right]}{\left[\frac{\text{Re bar+Formwork Crew Size}}{16}\right]} \tag{1}$$

Arguably, when normalizing the production rate of the bridge deck work, the formwork crew might be weighted more heavily than the rebar crew, because they take more days in the production process and hence have more influence on the production rate. Nonetheless, both crews were given equal weight, the combined crew size being simply the sum of their crew sizes. While crews may deviate in size, a feasible mix of the crews is often limited to one that brings about only an incremental change in the production rate. For example, if eight workers of each crew are most frequently observed, a ten-person formwork crew and a six-person rebarwork crew could be one possible mix but may not yield considerable improvement to the production rate. On the contrary, a mix of 12 form workers and four rebar workers may appear to have a higher production than that of the most frequently observed, but this mix may not be feasible for some reason and thus was only infrequently observed. Another reason for using equal weight in normalizing the production rate is related to the difficulty in determining the weight itself for each crew. Further, as shown in the regression equations in Figs. 3 and 4, the coefficients of both independent variables, i.e., 12.6 and 13.1, are about the same, which suggests that the effects of changes in the formwork and rebarwork crew sizes on bridge deck crew production rates are little different. Table 3 provides a summary of the crew composition for each work item and shows whether the production rate is adjusted by crew size.

Data Analyses Results

Data Overview and Crew Production Rates

The data collected as part of this study came from 25 highway projects under construction in Texas from 2002 to 2004. The

Table 5. Data Points Overview

Work item	Total number of data points	Total quantity	Total number of work days	Total number of districts	Total number of projects
Beam erection	29	113 spans	37	6	19
Bridge deck	23	24,113 m^2	442.5	6	15
Bridge rail	15	6,154 m	15.5	4	6

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Table 6. Summary of Crew Production Rate

	Crew production rate				
Work item	Unit	Mean	Minimum	Maximum	Standard deviation
Beam erection	spans/crew day	3.2	1	6.5	1.6
Bridge deck	m^2/crew day	71	28	123	28
Bridge rail	m/crew day	416	27	816	263

contract amounts of the projects ranged from one million to 261 million dollars. Tables 4 and 5 show the overview of the projects and the data points. Crew production rates of each work item were calculated (and adjusted) as described previously and are presented in Table 6.

Perhaps surprisingly, for both beam erection and bridge rail work items, a larger number of workers did not lead to better production rates. One possible explanation would be that both operations are very much machine driven and the larger number of workers serves only to deal with its larger scale and/or higher complexity, rather than to produce more units of work, resulting in the production rate remaining about the same. Therefore, for both work items, a crew was defined by number of machines in operation only (see Table 3). In contrast, the bridge deck work item has considerable variation in production rate with the number of workers in a crew. Labor intensive operation and a relatively longer period of activities might be reasons.

As for the technology effect on productivity previously mentioned, and particularly equipment technology, it had an insignificant impact on production rates for this study, possibly due to the relatively short time frame for data collection and less variation in technology application. The data for the study was collected over the past two years, and during that time the highway construction industry has not experienced significant changes in technology. Moreover, data on production rates of work activities was collected only on activities utilizing prevalent technologies, because this study focuses on production rates for the most common work environments. For example, data pertinent to segmental bridge decks was not collected, as the study is limited to conventional concrete bridge deck operations.

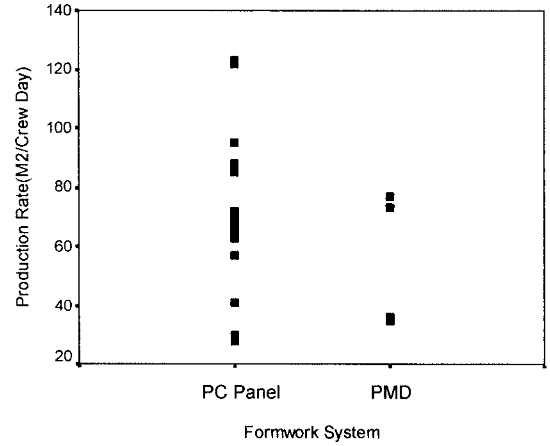

Fig. 6. Bridge deck scatter plot (versus formwork system)

Beam Erection

Three candidate drivers were selected among many factors: average number of beams per span; total number of beams erected; and height from ground (m). The factor "wind speed" was excluded from the selection because such information would not be available to estimators at the time of determining contract time. The analyses results showed that all the candidate drivers had very weak linear relationships with the crew production rates. None of the R^2 values of the models were higher than 0.2.

The unit of the production rate (spans/crew day) used for the study might contribute to the finding of no statistically significant factors affecting the beam erection production rates. Most of the production rates were obtained from observations on less than a full-day's (10 hours) 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 12 beams were erected in nine crew work hours, while the other two spans of eight beams were erected within seven hours, both production rates would be the same (2 spans/crew day), suggesting that "average number of beams per span" did not affect beam erection production rates. Although none of the factors were found to be drivers of beam erection crew production rates, the TxDOT personnel confirmed that the unit and its rates were practical and realistic in use for contract time determination.

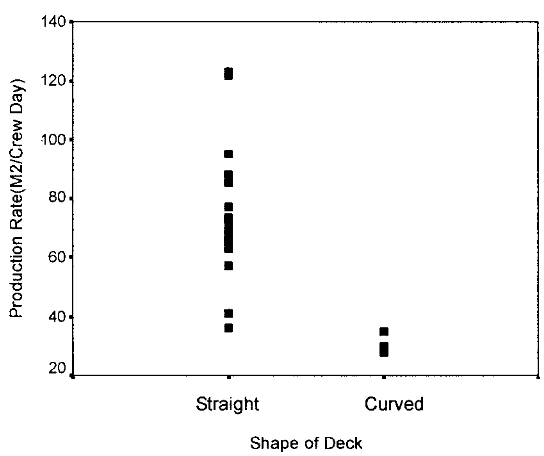

Fig. 5. Bridge deck scatter plot (versus shape of deck)

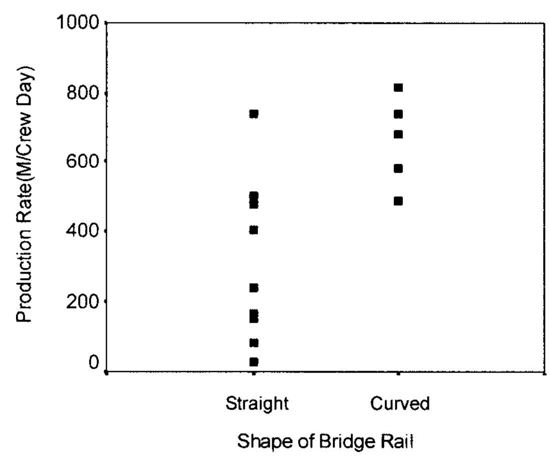

Fig. 7. Bridge rail scatter plot (versus shape of rail)

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Table 7. Analysis of Variance (ANOVA) Results

Work item (unit)	Factor	Categories	Descriptives statistics N	Mean	Standard deviation	ANOVA results (between groups) F	Significance
Bridge deck (m^2/crew day)	Formwork system	Precast panel	19	73.7	28.0	1.51	0.233
		Permanent metal deck	4	55.3	22.9		
	Shape of deck	Straight	20	76.5	24.5	9.88	0.005
		Curved	3	31.0	3.6		
Bridge rail (m/crew day)	Shape of rail	Straight	10	294.7	225.4	11.01	0.006
		Curved	5	660.1	130.9		

Bridge Deck

The bridge deck production rate was normalized by the typical crew size of 16, as discussed previously, and was used hereafter for further analyses. Four candidate drivers were selected from visual inspection of various scatter plots: width of deck poured (m); length of deck poured (m); shape of deck poured (straight versus curved); and formwork system (precast panel versus permanent metal deck, PMD). A possible candidate driver, accessiblility from the ground (yes: on foot versus no: temporary stairs/man-lift), was excluded from the selection, as such information would rarely be available to estimators when determining contract time. To test the assumption of normality of data for correlation analyses, quantile-quantile (or Q-Q) plots of the deck production rates and two candidate drivers were produced, and it was found that they are normally distributed to a reasonable extent.

Width of Deck Poured (m) and Length of Deck Poured (m)
Linear regression analyses revealed that width of deck poured (m) and length of deck poured (m) have insignificant relationships with the production rate, as their R^2 values were only 0.14 and 0.002, respectively.

Shape of Deck Poured and Formwork System
The differences in mean production rates between samples grouped by two categorical factors; shape of deck poured (curved versus straight) and formwork system (PC panel versus PMD), were tested using ANOVA, as shown in the Figs. 5 and 6 and Table 7. It was found that the former is statistically significant at a level of 0.1, while the latter is not. However, in case of the factor shape of the deck poured, the assumption of equal variances of samples for the ANOVA test is violated.

Bridge Rail

One candidate driver, shape of rail (straight versus curved), was selected and analyzed. Surprisingly, the ANOVA analysis results showed that a crew placed more linear feet per day when the rail was curved than when it was straight, which was very opposed to the industry consensus (see Fig. 7 and Table 7). When a sufficient sample size is available, a more definite conclusion can be drawn.

Summary

A data collection tool was developed based on industry input to facilitate the data collection process, enhance the accuracy of data, and enable analyses of drivers. For three selected work items—beam erection; bridge deck; and bridge rail—a total of 67 data points were collected and production rates were computed from 25 highway projects across seven districts in the state of Texas. Scatter plots, analysis of variance (ANOVA), and simple regression analyses were employed to identify drivers as well as to test the statistical significance of their relationships with each work item's production rate. While no statistically significant drivers were found for the work items of beam erection and bridge rail, one statistically significant factor was identified for bridge deck: the shape of the deck poured (straight versus curved). The study also found that both formwork and rebarwork crew sizes had significant relationships with bridge deck production rate.

Contributions

The findings from this study, including weekly observed crew production rates along with identified rate drivers, will enable highway agencies to enhance the accuracy of contract time estimation for highway bridge construction. Moreover, the methodology for obtaining field-based information on crew production rates with standardized data collection tools will be of value for future studies in the area.

Recommendations

Through the course of the study effort, the following recommendations have been identified:
- Continued data collection will lead to definite conclusions on some of the study's findings;
- Concentrating on only the major factors identified by this study could mitigate the data collection efforts;
- Continued data collection on some other critical work items is also recommended; and
- Comprehensive study of the sequence lead and lag times of each work item is needed; this additional information will enable estimators to synthesize activity durations and eventually to more accurately determine construction contract time.

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References

Allmon, E., Haas, C. T., Borcherding, J. D., and Goodrum, P. M. (2000). "U.S. construction labor productivity trends, 1970–1998." *J. Constr. Eng. Manage.*, 126(2), 97–104.

Business Roundtable. (1974). "Effect of scheduled overtime on construction projects in coming to grips with some major problems in the construction industry." *Project Rep.*, New York.

Business Roundtable. (1980). "Scheduled overtime effect on construction projects." *C-2 Rep., Construction Industry Cost Effectiveness Project*, New York.

Construction Industry Institute (CII). (1988). "The effects of scheduled overtime and shift schedule on construction craft productivity." *Source Document 43*, Austin, Tex.

Construction Industry Institute (CII). (1994). "Effects of scheduled overtime on labor productivity: A quantitative analysis." *Source Document 98*, Austin, Tex.

Everett, J. G., and Farghal, S. H. (1997). "Data representation for predicting performance with learning curves." *J. Constr. Eng. Manage.*, 123(1), 46–52.

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. Eng. Manage.*, 128(6), 463–472.

Hanna, A. S., Peterson, P., and Lee, M. (2002). "Benchmarking productivity indicators for electrical/mechanical projects." *J. Constr. Eng. Manage.*, 128(4), 331–337.

Herbsman, Z. J., and Ellis, R. (1995). *Synthesis of Highway Practice 215: Determination of contract time for highway construction projects*, Transportation Research Board, Washington, D.C.

Huh, Y. (2004). "Highway bridge construction production rates for contract time estimation." Ph.D. thesis, Dept. of Civil Engineering, University of Texas at Austin, Austin, Tex.

Koehn, E., and Brown, G. (1985). "Climatic effects on construction." *J. Constr. Eng. Manage.*, 111(2), 129–137.

Koch, J. A., and Moavenzadeh, F. (1979). "Productivity and technology in construction." *J. Constr. Div., Am. Soc. Civ. Eng.*, 105(4), 351–366.

Sanders, S. R., and Thomas, H. R. (1991). "Factors affecting masonry-labor productivity." *J. Constr. Eng. Manage.*, 117(4), 626–644.

Sanders, S. R., and Thomas, H. R. (1993). "Masonry productivity forecasting model." *J. Constr. Eng. Manage.*, 119(1), 163–179.

Sanders, S. R., Thomas, H. R., and Smith, G. R. (1989). "An analysis of factors affecting labor productivity in masonry construction." *PTI Rep. 9003*, Pennsylvania Transportation Institute, University Park, Pa.

Smith, S. D. (1999). "Earthmoving productivity estimation using linear regression techniques." *J. Constr. Eng. Manage.*, 125(3), 133–141.

Sonmez, R. (1996). "Construction labor productivity modeling with neural networks and regression analysis." Ph.D. thesis, Dept. of Civil Engineering, Iowa State University, Ames, Iowa.

Stevens, J. (2002). "Applied multivariate statistics for the social sciences." *eBook: Lawrence Erlbaum Associates Inc.*, 〈http://www.netlibrary.com〉 (Mar. 30, 2004).

Thomas, H. R., and Raynar, K. A. (1997). "Scheduled overtime and labor productivity: A quantitative analysis." *J. Constr. Eng. Manage.*, 123(2), 181–188.

Thomas, H. R., and Smith, G. R. (1990). "Loss of construction labor productivity due to inefficiencies and disruptions: The weight of expert opinion." *PTI Rep. 9019*, Pennsylvania Transportation Institute, University Park, Pa.

Thomas, H. R., Smith, G. R., and Sanders, S. R. (1989). "An exploratory study of productivity forecasting using the factor model for masonry." *PTI Rep. 9005*, Pennsylvania Transportation Institute, University Park, Pa.

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