Crew Production Rates for Contract Time Estimation: Bent Footing, Column, and Cap 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 the rates. A standardized data collection tool was used to acquire a total of 93 data points from 22 ongoing Texas highway projects between February 2002 and May 2004, for selected critical work items: Footing, column-rectangle, column-round, and cap. With the data, several hypothesized drivers of the crew production rates were analyzed. The statistically significant drivers found from the analyses include: footing size (m^3/ea), excavation depth (m), and number (No.) of footings per bent for footing work item; column size (m^3/ea), column height (m), No. of columns per bent for column-rectangle; column height (m), diameter (m), and No. of columns per bent for column-round; cap size (m^3/ea), cap length (m), and shape of cap (rectangle versus inverted T) for cap. 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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CE Database subject headings: Bridge construction; Bridges, highway; Productivity; Estimation; Quantitative analysis; Contracts; Time factors.

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. Increased public inconvenience and safety issues caused by highway projects are often unbearable to local communities. 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 and his colleagues (1989) listed 42 factors under three categories: Within-project; project-to-project; and regional. Sonmez (1996) also summarized 23 factors under three categories of 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.

Many researchers also studied in different ways how those factors affect productivity. Regression analysis is one of the common methods in exploring the relationship. Koehn and Brown (1985) developed two nonlinear regression model equations; cold or cool–hot or warm as a function of temperature and humidity, based on 172 data points obtained from previous publications. Sanders and Thomas (1993) developed a regression model to predict masonry productivity. Regression techniques were also employed to quantify 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 manpower, and estimated S curve (x=percent time of total duration and y=percent hours of total work hours). Besides the regression analysis, many researchers have applied alternative methods, such as the factor model, the neural network model, and expert system.

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

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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). Further, many studies were conducted based on 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 detailed scope of production rates, such as, what were 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 is 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) develop a standard data collection procedure and relevant tools, (2) collect field-based information on crew production rates, and (3) identify major factors driving the crew production rate of each selected highway bridge related work item, namely, footing, column-rectangle, column-round, and cap. Developing prediction models of work item production rates, such as multiple regression models, was not in 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).

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

Work item	Scope: Included	Scope: Not included
Footing	Excavation/excavation protection work/false work/installation of forms and rebar/inspection of forms and rebar/handling and placing of concrete	Site preparation/drill shaft rebar cleaning/fine grade and seal slab/dewatering only work hours/preparation of rebar and forms/rebar fabrication/all necessary work for the protection of concrete placed under any weather conditions/curing/removal of forms/removal of flase work/backfilling
Column	False work/installation of forms and rebar/inspection of forms and rebar/handling and placing of concrete	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/finishing of column surface/installation of drainage pipe/removal of false work/nonmetal form
Cap	False work, if any/installation of forms and rebar/inspection of forms and rebar/handling and placing of concrete	Site preparation/preparation of rebar and forms/rebar fabrication/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/nonmetal form

Methodology

Influence Diagram

Influence diagrams were used to identify factors that are believed to be affecting production rates (Huh 2004). Potential factors were first identified based on an intensive literature review and discussion with Texas Department of Transportation (TxDOT) personnel. Then such factors were refined through the 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 established in collaboration TxDOT personnel, and encompassed selection of projects to be investigated and observation of selectedwork items. For each targeted district, a meeting with selected district personnel was arranged in order to introduce the study and select projects. 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 2 to 3 months; work items to be pursued; 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 production during the 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.

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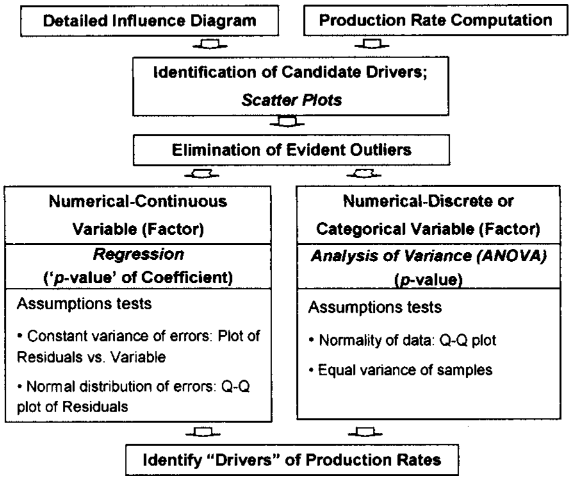

Fig. 1. Data analysis methodology

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 organized at three levels: Project, work zone, and work item. The work zone level forms include the *work 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 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 3 months and several minor modifications were made to the data collection procedure and tool.

Data Analyses

Fig. 1 shows the overall process of applying statistical methods in identifying drivers. Candidate drivers were identified by visually inspecting scatterplots. Then, analysis of variance (ANOVA) and simple regression were employed to test the statistical significance of candidate drivers' relationships with production rates. The significance level (α level; probability of wrongly rejecting the null hypothesis that the researcher is willing to accept) used in this study was 0.1.

Assumptions tests: There are two underlying assumptions for ANOVA test: (1) The normality of population from which the observed data is drawn; and (2) the equal variance of populations. The assumptions should be checked for gross violations whenever possible, although the assumptions are never satisfied exactly in any application (Albright et al. 2003). The normality assumption can be tested by examining *Q–Q* plots of the observed data, which is commonly accepted for real world data (Thomas 2003). It plots the standardized values of the data set versus values that would be expected if the data were perfectly normally distributed. If data tends to be normally distributed, values will fall on or near a straight line (Albright et al. 2003). For equal variance, if the largest standard deviation is less than twice the smallest standard deviation, equal variance can be assumed (Thomas 2003). Likewise, for the simple regression analysis, the following are three assumptions to be tested for better interpretation of a regression model: (1) Appropriation of a linear model; (2) constant variance of errors; and (3) normal distribution of errors.

Table 2. 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	4	8
Yoakum	1	1	1
Austin	3	4	35
Dallas	6	3	17
Houston	8	4	29
Waco	1	2	3
Total	22	—	93

Rational for Production Rate Computation

Production rates of work items were calculated based on the formula of "total crew workdays/total output." Calculating production rates as defined requires two input values; "output" and "crew workdays." The output value represents the quantity of work completed during a certain number of workdays and was measured in "units completed; EA." The unit is more time estimate-friendly than that of the common industry practices and most cost control systems, that is, "volume of concrete," thereby facilitating quick measurement of work quantities. Although a minimal effort was needed to measure the output in such a simple unit, clear guidelines were required on assessing crew workdays.

Correcting for Delays

Crew workdays were assessed based on a rule called the *half-day rule*. If, in a given day, the delay effect caused by any of factors, such as weather (rain, too wet, snow, wind, etc.), unworkable soil condition, traffic accident, construction accident, equipment down time, material unavailable, trade problem, and absenteeism, amounted to less than 2 hours, the day was considered one workday. When the delay was less than or equal to 5 hours but greater than 2, the day was counted as a half-workday. Otherwise, it was counted as a nonworkday. Factors such as holidays, no-working day (due to unforeseen condition, TxDOT direction, etc.), no-working weekend, and day off were not included in the rates. A workday having more than 2 hours of overtime was to be adjusted based on actual overtime hours, but no such overtime was observed.

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Table 3. Data Points Overview

Work item	Total number of data points	Total quantity	Total number of workdays	Total number of districts	Total number of projects
Footing	15	22 footings	52	4	6
Column-rectangle	19	33 columns	70.5	4	5
Column-round	19	126 columns	56	4	8
Cap	40	59 caps	258.5	5	13

Correcting for Crew Size

The "workdays" assessed according to the *half-day rule* was input together with the output into the formula (total crew workdays/total output), resulting in a production rate of each work item. Yet, such a calculated production rate may still need to be adjusted for crew size, since even the same work items might differ in crew size from project to project. Interestingly, the crew size of the work items observed did not vary much between projects. Moreover, perhaps surprisingly, larger crew sizes did not lead to better production rates. In many cases, the crew size of such a work item had an insignificant impact on its production rates. One possible explanation would be that a larger crew size of such a work item helps 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.

At the time of construction time determination, whether or not to adjust production rates for crew size may be also affected by the availability of crew size information. Empirical production rates that adjust for crew size may not be useful to estimators who do not know crew size information at the time of estimation. In fact, it is often the case that crew composition is unknown to the estimators at the time of contract time determination. Thus, without being constrained by such a need, the estimators should be able to refer to empirical production rates, as long as the production rates vary marginally with crew size as with footing, column-rectangle, column-round, and cap work items.

Data Analyses Results

Data Overview and Crew Production Rates

The data collected as part of this study came from 22 highway projects under construction in Texas from 2002 to 2004. The contract amounts of the projects ranged from one million to 261 million dollars. Tables 2 and 3 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 presented in Table 4.

Table 4. Summary of Crew Production Rate

Work item	Crew production rate (crew days/ea)			
	Mean	Minimum	Maximum	Standard deviation
Footing	2.6	0.7	5.0	1.2
Column-rectangle	2.9	0.7	6.5	1.8
Column-round	0.5	0.2	1.3	0.3
Cap	5.0	1.3	11.5	2.5

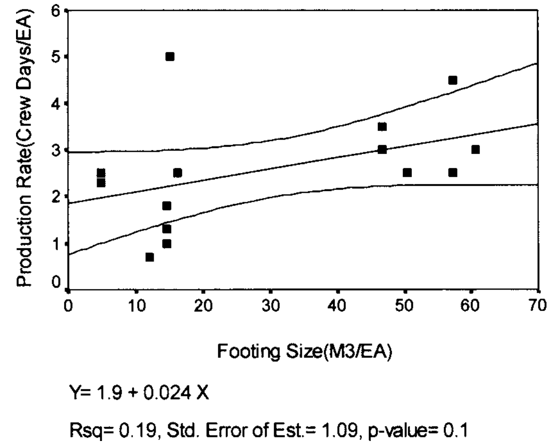

Fig. 2. Footing: scatterplot and regression results (versus footing size)

Footing

From visual inspection of various scatterplots, three candidate drivers were selected: footing size (m^3/ea); excavation depth (m); and number of footings per bent. To test the significance of the candidate drivers, each continuous numerical variable was regressed on production rate, and the results are shown in Figs. 2 and 3. The middle straight line in the graphs is the linear regression line and the curved two lines represent the 95% confidence interval of the predicted production rate values. For the analysis of the discrete variable, 'number of footings per bent,' ANOVA was employed. Testing all the assumptions needed for the analyses showed that they were met to a reasonable extent.

Size of Footing (m^3/ea)

The footing production rates are not well explained by size of footing (m^3/ea) as shown in Fig. 3. The scatterplot also suggests that there are likely two different populations in size, one less than m^3/ea and the other between 40 and 60 m^3/ea. Therefore ANOVA was employed to determine if the mean difference between the two populations is significant. The difference found is significant at the level of 0.1, since the value of significance in the Table 5, that is, p value of 0.002, is smaller that 0.1.

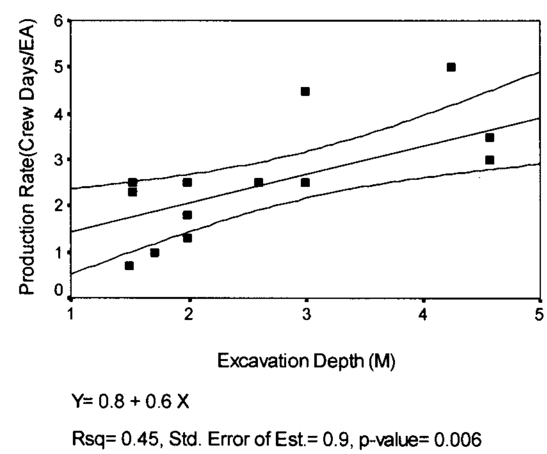

Fig. 3. Footing: scatterplot and regression results (versus excavation depth)

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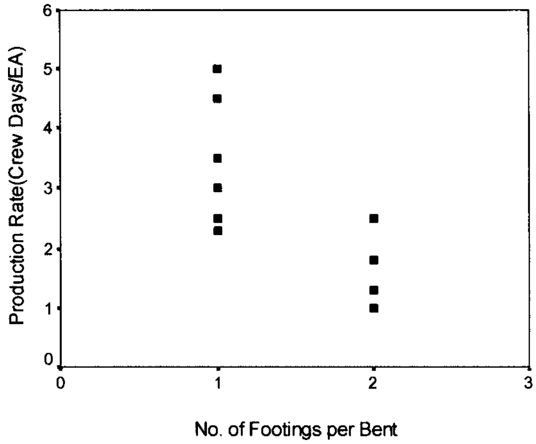

Fig. 4. Footing: scatterplot and regression results (versus number of footings per bent)

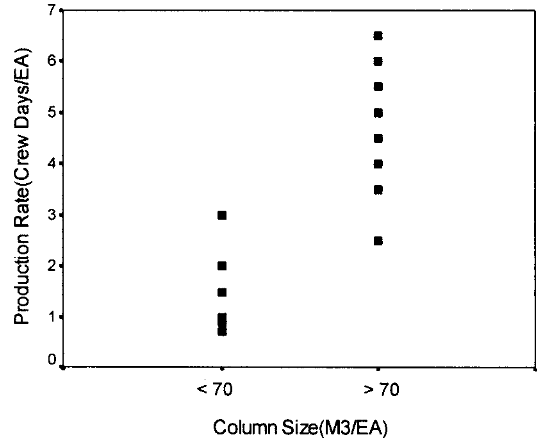

Fig. 5. Column-rectangle: scatterplot (versus column size category)

Excavation Depth (m)

Regarding the factor of excavation depth (m), the R^2 value of its regression model and p value of the coefficient are 0.45 and 0.006, respectively, which support that it is a driver of footing production rate (Fig. 3).

Number of Footings per Bent

The result of ANOVA reveals that the mean difference between samples grouped by the number of footings per bent are statistically significance at the 0.1 level as shown in Table 5. The category of three footings per bent was excluded from the analysis due to insufficient data points with this category (Fig. 4).

Column-Rectangle

Three candidate drivers were selected from visual inspection of various scatterplots: column size (m^3/ea); column height (m); and number of columns per bent.

Column Size (m^3/ea) and Column Height (m)

To test the significance of the candidate drivers, two simple regression models were developed. The R^2 of the model with column size (m^3/ea) is 0.6 and 0.46 for the model with height. The p values for regression coefficients of the two independent variables are close to zero. However, the models violate the assumption of the equal variance of dependent variable (production rates). With the heteroscedasticity of dependent variable in a regression model, the statistical tests become invalid. One way to address this particular type of heteroscedasticity is to equalize the increasing variances of dependent variable with independent variable by weighting the dependent variable by the inverse of the square root of X_i^2 independent variable, known as the *weighted least-squares* (WLS) method. Then, the WLS technique is essentially the same as the ordinary least-squares method which provides the *best linear unbiased estimates* of linear regression coefficients (Wonnacott 1981). However, applying the WLS method to the Column-Rectangle data yields regression models with R^2 less than 0.3.

Table 5. Analysis of Variance (ANOVA) Results

			Descriptives statistics			ANOVA results (between groups)	
Work item	Factor	Categories	N	Mean	Standard deviation	F	Significance
Footing	Footing size (m^3/ea)	<20	6	1.6	0.7	15.12	0.002
		40<&<60	8	3.1	0.7		
	No. of footings per bent	1	10	3.2	0.9	9.22	0.010
		2	4	1.7	0.7		
Column-rectangle	Column size (m^3/ea)	<70	9	1.5	0.7	30.33	0.000
		>70	9	4.4	1.4		
	Column height (m)	<10	7	1.2	0.6	18.32	0.001
		>10	12	3.9	1.6		
	No. of columns per bent	1	11	4.0	1.6	10.20	0.001
		2	3	2.0	1.0		
		3	5	1.0	0.3		
Column-round	Diameter (m)	0.75	10	0.4	0.1	19.53	0.000
		0.9	7	0.8	0.3		
	Number of columns per bent	⩽3	10	0.7	0.3	8.41	0.010
		⩾4	9	0.3	0.1		
Cap	Shape of cap	Rectangle	22	4.3	2.0	5.39	0.026
		inverted T	17	6.0	2.8		

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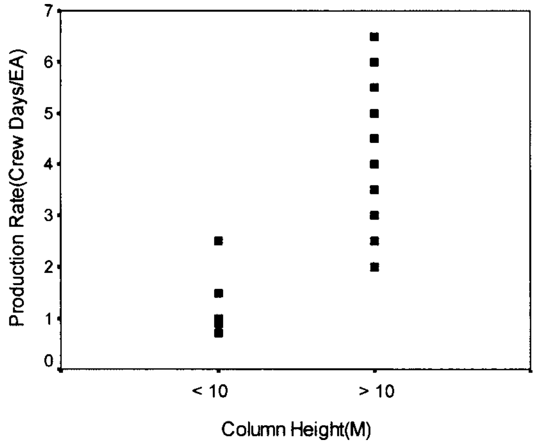

Fig. 6. Column-rectangle: scatterplot (versus column height category)

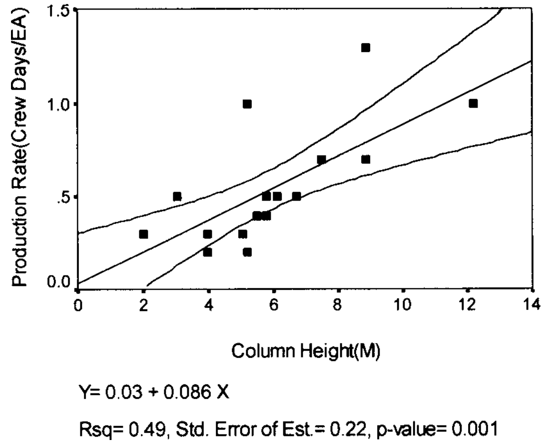

Fig. 8. Column-round: scatterplot and regression results (versus column height)

Hence, from observation on their scatterplots, the column-rectangle data was categorized into two groups: less than 70 m^3/ea and greater than 70 m^3/ea in terms of column size, and into another two groups: less than 10 m and greater than 10 m in terms of column height (Figs. 5 and 6). Then, the differences in mean production rates between two groups were tested using ANOVA. As shown in Table 5, the differences are significant at the level of 0.1 in both cases of categorization.

Number of Columns per Bent

The candidate driver of number of columns per bent was also analyzed and the results are presented in Table 5 and Fig. 7. Although the differences in mean production rates among the groups are statistically significant at the 0.1 level, the result is not reliable since the assumption of the equal variances of the samples is violated. The largest standard deviation (1.6) is much more than twice the smallest standard deviation (0.3). It seems that more data points need to be collected in order to make a sound conclusion, in particular those falling into the subcategory of two columns per bent.

Column-Round

From various scatterplots, three candidate drivers have been selected: column height (m); column diameter (m); and number of columns per bent.

Column Height (m)

Fig. 8 shows the scatterplot of production rates versus column height (m) and the results of a simple regression model. The *p* value for regression coefficient of the independent variable shows that it is statistically significant at the 0.1 level.

Column Diameter (m)

ANOVA was conducted to test whether or not the factor diameter (m) is a driver of column-round production rates. It was found that the difference in mean production rates among groups of two different sizes of diameter, 0.75 m (2.5 ft) and 0.9 m (3 ft), is statistically significant at the 0.1 level as shown in Table 5 and Fig. 9. It should be noted, however, that the assumption of equal variances for the test is violated. The category of 0.6 m (2.0 ft) was excluded from the analysis due to insufficient sample size.

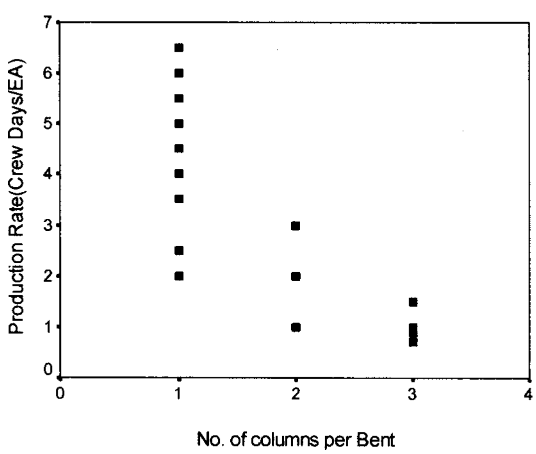

Fig. 7. Column-rectangle: scatterplot (versus number of columns per bent)

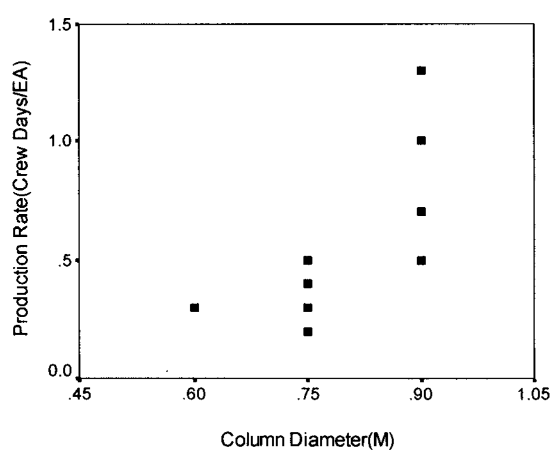

Fig. 9. Column-round: scatterplot (versus column diameter)

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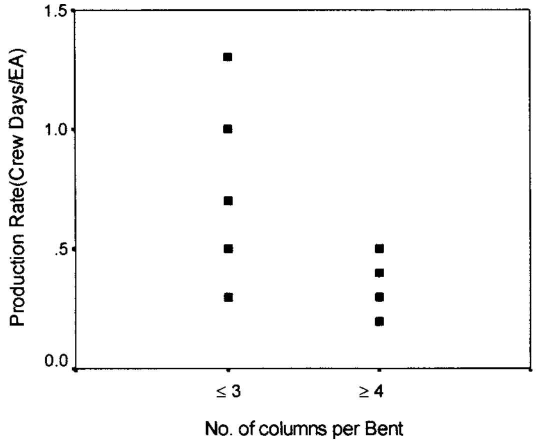

Fig. 10. Column-round: scatterplot (versus number of columns per bent category)

Number of Columns Per Bent

Production rate data were also categorized into two groups in terms of number of columns per bent, less than or equal to 3, and greater than or equal to 4, due to insufficient data points (Fig. 10). Although the result shows the mean difference is significant at the 0.1 level, the assumption of equal variances for the test is not met (Table 5).

Cap

Three candidate drivers were selected from visual inspection of various scatterplots: Cap size (m^3/ea); cap length (m); and shape of cap (rectangle, inverted T). To test the significance of those candidate drivers, each of the two numerical variables was regressed on the production rates. For the categorical factor of cap shape (rectangle/inverted T), ANOVA was conducted. Testing all the assumptions for the analyses shows that they are met to a reasonable extent.

Cap Size (m^3/ea) and Cap Length (m)

Both simple regression models show that about 50% of the cap production rates are explained by either of the variables and the coefficients of the independent variables are significant at the 0.1 level as shown in Figs. 11 and 12.

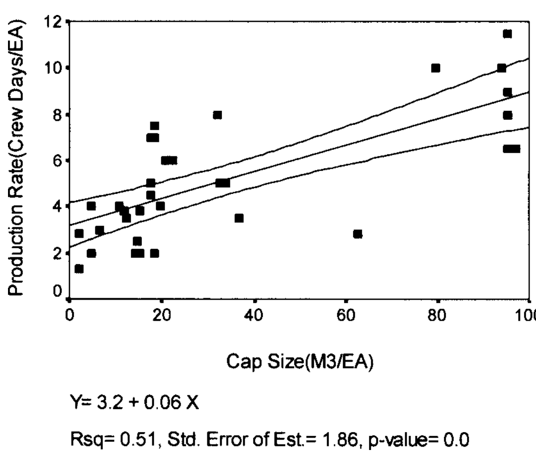

Fig. 11. Cap: scatterplot and regression results (versus cap size)

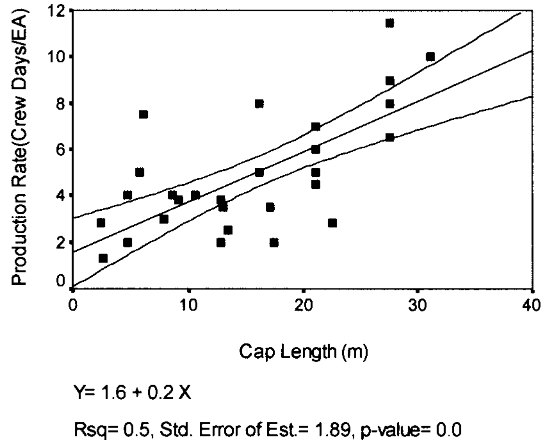

Fig. 12. Cap: scatterplot and regression results (versus cap length)

Shape of Cap (Rectangle, Inverted T)

The result of ANOVA shows that the difference in mean production rates between two groups in terms of the shape of cap: rectangle and inverted T, is statistically significant at the level of 0.1 (Table 5 and Fig. 13). The category of aesthetic was excluded from the analysis due to insufficient sample size.

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 selected work items, namely footing, column-rectangle, column-round, and cap, a total of 93 data points were collected and production rates were computed from 25 highway projects across six districts in the State of Texas. scatterplots, 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 the each work item production rates. The following summarizes the drivers found from the study.

- Footing: Footing size (m^3/ea), excavation depth (m), and number of footings per bent;
- Column-rectangle: Column size (m^3/ea), column height (m), and number of columns per bent;

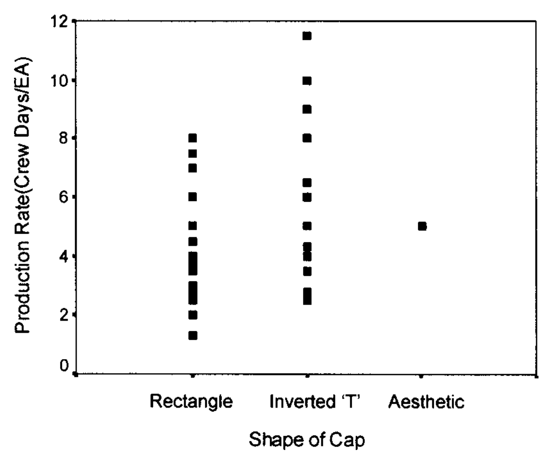

Fig. 13. Cap: scatterplot (versus shape of cap)

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- Column-round: Column height (m), column diameter (m), and number of columns per bent; and
- Cap: Cap size (m^3/ea), cap length (m), and shape of cap (rectangle: inverted T)

Contributions

Findings from this study, including weekly observed crew production rates along with identified rate drivers will enable highway agencies to enhance 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 enable one to make definite conclusions on some of the identified possible drivers;
- Concentrating on only the major factors identified by this study could mitigate the data collection efforts;
- When sufficient data are available, more complex prediction models could be developed for the benefit of the industry, such as multiple regression models; 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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