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Final Report

FHWA/IN/JTRP-2004/11

Determination of INDOT Highway Construction Production Rates and Estimation of Contract Times

By

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Joint Transportation Research Program SPR-2621

Conducted in Cooperation with the Indiana Department of Transportation and the U.S. Department of Transportation Federal Highway Administration

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16. Abstract

The duration of a highway construction project depends primarily on the quantity or magnitude of the construction work and the productivity of the construction crew. In addition, many other factors may also affect the construction duration, such as the type of construction, traffic features, location (urban or rural site), and weather conditions. When a state highway construction project contract is bid, a reasonable time must set and specified in the contract documents for completion of the contracted project. The time for contract completion (often called "contract time") is estimated based on the average completion times of individual construction items within a specific project. Through this study, the Indiana Department of Transportation (INDOT) highway construction production rates were calculated and two methods for contract time estimations were developed based on the recorded eight-year INDOT construction data. Various statistics of production rates were provided to capture the main features of the highway construction production. The statistics include means, standard deviations, confidence intervals, mean baseline production rates, and production rates for different probabilities. The major factors that affect highway construction production rates were examined and their effects were analyzed. It was found that the production rates were affected by weather conditions in terms of temperatures and seasons, contractors, locations of construction projects (urban and rural), types of highways, and traffic conditions. Therefore, production rates under different conditions, such as seasons, roadway types and locations, were obtained to reflect the differences in production rates. The models for estimating highway construction contract times were developed. One of the methods uses regression equations to estimate contract times of highway construction projects. The other method estimates contract times with mean production rates of critical construction activities.

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Determination of INDOT Highway Construction Production Rates and Estimation of Contract Times

Introduction

The Indiana Department of Transportation (INDOT) utilizes the average production rates of itemized highway and bridge work as a general guide for setting workdays for construction contracts. When setting contract time, INDOT highway engineers follow a set of general steps to adjust the estimated workdays by considering other factors in addition to the average production rates.

This study was conducted to improve the accuracy of estimating contract time through a comprehensive analysis on construction production rates of INDOT highway projects. In order to improve the contract time estimation, the average production rates was updated with the most recent INDOT construction data. Even though the construction industry is relatively slow in changing, the construction production rates have been

gradually improved along with the development and applications of new technologies in construction methods, equipment, and materials. This made it necessary to update the average production rates to reflect the improvement in productivity and to provide more accurate input and basis for estimating contract time.

The objective of this study was to generate more accurate values of productivity rates and to provide more reliable methods for estimating contract time. This was achieved by analyzing recorded construction data, updating productivity values, and identifying major factors affecting construction productivities.

Findings

Through this study, various statistics of production rates were provided to capture the main features of the highway construction production. statistics include means, standard deviations, confidence intervals, mean baseline production and production rates for different probabilities. It was found that the major factors that affect highway construction production rates includes weather conditions in terms of temperatures and seasons, contractors, locations of construction projects (urban and rural), types of highways, and traffic conditions. Production rates under different conditions, such as seasons, roadway types and locations, were obtained to reflect the differences in production rates. The mean of the recorded production rates of a given construction activity is most often used as a representative value. However, the production rates of a construction activity may vary

considerably. The disperse degree of production rates is reflected by the values of standard deviations or variances. The confidence interval of the estimated mean for a given confidence level can be calculated with the values of calculated mean and standard deviation. The confidence intervals for a 95% confidence level were computed for the construction activities. These confidence intervals provide a reliable range of the mean production rates for highway engineers and managers. Similarly, the critical production rates under different probabilities were obtained in this study. The critical production rate under each probability means that a production rate will be less than the critical value with the given Therefore, the values provide the probabilities for production rates to be different values, including relatively small and large values of production rates.

Efforts were made in this study to analyze the INDOT recorded construction durations. expected, the construction durations are affected by the same factors as the production rates. The distribution analysis indicates that production rates of various highway construction activities can be described or represented by different distribution models, including normal, lognormal, exponential distributions. Two methods were developed for contract time estimation based on the data of construction durations and production rates. One is a regression method using the total construction cost of a project to estimate contract time. The other method uses the mean production

rates to calculate the durations needed for critical construction activities. The contract time generated from either one of the two methods is actually an estimated mean duration needed for the construction project. This mean duration is then adjusted by the factors related to construction conditions, including roadway type, project traffic location, volume, season and construction. Based on the statistical characteristics, the confidence intervals for the estimated contract time can also determined to provide users the information on the possible range of the contract time.

Implementation

The values of production rates are stored in a Microsoft Access file so that the users can easily find the information. A Visual Basic computer program is also provided for contract time estimation. Therefore, implementation of the research results is made easy with the computer programs. It is recommended that INDOT use the new production rates to replace the existing

values and also update the production rates periodically in the future to reflect the changes in production rates. The Visual Basic computer program should be used to estimate contract times of INDOT highway construction projects.

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CHAPTER 1 INTRODUCTION

1.1 Background

The duration of a highway construction project depends primarily on the quantity or magnitude of the construction work and the productivity of the construction crew. In addition, many other factors may also affect the construction duration, such as the type of construction, traffic features, location (urban or rural site), and any special features of the project. When a state highway construction project contract is bid, a reasonable time must set and specified in the contract documents for completion of the contracted project. The time for contract completion (often called "contract time") is estimated based on the average completion times of individual construction items within a specific project.

The Indiana Department of Transportation (INDOT) utilizes the average production rates of itemized highway and bridge work as a general guide for setting workdays for construction contracts. When setting contract time, INDOT highway engineers follow a set of general steps to adjust the estimated workdays by considering other factors in addition to the average production rates. The factors to be considered include type of work, magnitude, location, traffic features, traffic control, controlling operations, permit restrictions, and access on the construction site. Obviously, the adjustment of the contract time is largely judgmental and subjective. Therefore, the estimated contract time could vary considerably from different engineers. Although setting contract time is not an exact science, some techniques are available for improving the accuracy of estimating contract time or duration of construction projects. The most commonly applied method is the use of statistical analyses to identify the significances of various factors that affect production rates. The combined as well as individual effects of

these factors can therefore be systematically estimated and quantitatively incorporated in estimating contract time.

This study was conducted to improve the accuracy of estimating contract time through a comprehensive analysis on construction production rates of INDOT highway projects. In order to improve the contract time estimation, the average production rates was updated with the most recent INDOT construction data. Even though the construction industry is relatively slow in changing, the construction production rates have been gradually improved along with the development and applications of new technologies in construction methods, equipment, and materials. This made it necessary to update the average production rates to reflect the improvement in productivity and to provide more accurate input and basis for estimating contract time.

In addition, the effects of various factors on production rates were quantitatively analyzed to provide different production rates under different construction conditions. The research results would minimize the subjective or judgmental errors in estimating contract times and improve the accuracy of the estimated contract time the new methods rely on more quantitative and less subjective input. Furthermore, the production rates vary from contractor to contractor because of the differences in staffing, equipment, and management among construction companies. The reliability of utilizing the average production value to estimate contract time depends on the distribution of the individual productivity values. The greater the variance of a distribution is, the lower the reliability of using the average value as a representative value will be. Therefore, it is necessary to find the distributions of production rates and to establish the guidelines for controlling the reliabilities for setting contract time. The resulted distributions of construction

productivity will enable highway engineers and planners to estimate a range of contract time, instead of a fixed and single value of a contract time, for a given construction project with a specified confidence or reliability.

Therefore, the objective of this study was to generate more accurate values of productivity rates and to provide more reliable methods for estimating contract time. This was achieved by analyzing recorded construction data, updating productivity values, identifying major factors affecting construction productivities, and establishing reliability guidelines based on the distributions of productivity values.

1.2 Scope of Study

In order to fulfill the objectives of the research project, the following tasks were performed.

1. Literature Review: A comprehensive literature review was conducted to secure pertinent materials related to the analysis of production rates of highway construction activities and the establishment of methods for estimating contract time. Production rates of highway construction activities are influenced by a variety of factors. Hinze and Carlisle (1990) studied nighttime paving production rates. Their study investigated road rehabilitation or maintenance activities performed at least in part during the night on major metropolitan highways or arterials. The study found that traffic volume, type of work, material delivery, lighting, supervision, communication, and worker morale were among the factors that affect nighttime versus daytime paving production rates.

Smith (1999) investigated the results obtained from over 140 separate earthmoving operations taken from four different highway construction projects. The results indicated that there is a strong linear relationship between operating conditions and production rates.

Lee et al. (2000) looked at a Portland cement concrete pavement rehabilitation project to determine the effects of different construction methods on production rates. The analyses showed that material delivery resources, such as dump trucks for demolition and concrete delivery trucks, were the major constraints that limited production. An increase in the concrete slab thickness from 203 to 305 mm reduced the level of production by about 50%. A concurrent-construction working method was more productive than a sequential-construction working method. The number of lanes to be paved affected the production capability. Continuous closures were more productive and less inconvenient to the public than weekend-only closures.

Lee et al. (2002) also examined the production rates of asphalt concrete pavement rehabilitation operations. The analysis explored the effects on construction productivity of rehabilitation materials, design strategy (crack seat and overlay, full-depth replacement), layer profiles, AC cooling time, resource constraints, and alternative lane closure tactics. Deterministic and stochastic analysis programs were developed. It was concluded from the study that efficient lane closure tactics designed to work with the pavement profile can minimize the nonworking time to increase the construction production efficiency.

El-Rayes and Moselhi (2001) presented a decision support system for quantifying the impact of rainfall on production rates of common highway construction operations, including earthmoving, construction of base courses, construction of drainage layers, and paving operations.

Hanna et al. (2002) developed a quantitative definition of projects impacted by change orders and showed that percent change, type of trade, estimated and actual peak manpower, processing time of change, overtime, overmanning, and percent change related to design issues are the main factors contributing to the production rates.

McCrary et al. (1995) conducted research to develop a systematic approach to the determination of contract time and to explore innovative contracting procedures. Their study produced a computer program to help the Louisiana Department of Transportation and Development to evaluate contract time estimation.

Werkmeister et al. (2000) performed a study for the Kentucky Transportation Cabinet to develop a new method for determining of construction contract time for its highway construction contracts. A computer program was developed to provide a conceptual estimating tool for prediction of construction contract time. The program uses predetermined project classifications and lists major activities that are believed to control the project schedule. Production rates and activity relationships were determined and embedded in the program.

Data Source and Collection: The INDOT Construction Daily Reports were
utilized as the primary source of productivity data. The Construction Daily
Reports were stored in Microsoft Access files. Each of the Access files contains

six Access tables with appropriate information on highway construction projects and daily progress reports. The data files contain 1,818 highway construction projects between 1995 and 2002 with thousands of records, including project descriptions, construction items, project magnitudes, weather information, and daily quantities of material utilizations. The construction data includes seven full-year data from 1995 to 2001 and partial-year data for 2002. In addition, INDOT annual reports of highway traffic counts and statistics were used to obtain traffic information at construction sites. Considerable effort was made to select necessary data items from the huge amount of records and put them in the desired format for data analysis.

- 3. Analysis of Production Rates: Based on the available data, various types of statistical characteristics related to production rates were obtained for a total of 152 highway construction activities. The calculated statistical characteristics include 1) mean production rates, 2) standard deviations, 3) 95% confidence intervals of production rates, and 4) production rates under different probabilities. The effects of major factors, such as contractors, location of projects, type of highways, and weather conditions, on production rates were analyzed. The production rates under ideal conditions were also obtained, which can be used as a basis for contract time adjustments. The distributions of production rates were analyzed and determined through statistical analysis.
- 4. **Contract Time Estimation:** In order to develop methods for contract time estimation, the effects of various factors on contract time were analyzed. The general ranges and mean values of contract times of Indiana's highway projects

were examined and analyzed. The unit contract times and related statistical values for different types of highway projects were calculated. Then several estimation methods were developed based on the statistical results. The estimation results from the developed methods were tested against actual project durations to validate the estimation accuracies.

CHAPTER 2 ANALYSIS OF PRODUCTION RATES

A highway construction production rate is the quantity produced or constructed over a unit time period. It is obviously a major factor affecting the duration of a highway construction project. Herbsman and Ellis (1995) revealed that approximately 88% of the states and provincial Departments of Transportation (DOTs) use production rates to estimate contract time. In order to reliably estimate contract time, accurate production rates of various construction items must be determined. Construction production rates are mainly affected by the following factors:

- The effects of individual factors, such as project complexity, project location (urban or rural), weather conditions, construction company's efficiency, equipment, and material delivery.
- The combined impact of these factors on the construction process.

Based on the construction data from the INDOT Construction Reports, the production rates of INDOT highway construction projects were analyzed as described in the following sections.

2.1 Distributions of Production Rates

To apply statistical principles, the distributions of the measurements or quantities are the basis for choosing appropriate theories. A distribution of a set of quantities will provide a graphical illustration of the subject's range, mean, dispersion, and other characteristics. Affected by many factors, production rates of different highway projects

may vary significantly over a certain range. For a set of observed or measured data points, an appropriate statistical distribution can be determined through the following steps:

- 1. Draw a frequency distribution plot using the available data values;
- 2. Select a possible distribution model according to the frequency distribution plot;
- 3. Calculate the estimations of the key distribution model parameters;
- 4. Test the goodness of the fit to determine if the selected model is appropriate for the given data. If the model is not appropriate, a different distribution model will be selected and tested.

Based on the frequency distributions, it was found that three most commonly utilized statistical distribution models could be used to represent the INDOT highway production rates, such as exponential distribution, normal distribution, and lognormal distribution. The negative exponential distribution has the following form:

$$P(x \ge s) = e^{-s/S} \tag{2.1}$$

where $P(x \ge s)$ is the probability of a random variable x equal to or greater than a specified value s, and S is the mean of the observed values of variable x.

The normal distribution $N(\mu, \sigma)$ is characterized by the mean μ and standard deviation σ of a random variable x. With the following conversion, the normal distribution $N(\mu, \sigma)$ can be transformed into the standard normal distribution N(0, 1), with mean 0 and standard deviation 1.

$$Z_{i} = \frac{X_{i} - \mu}{\sigma} \tag{2.2}$$

where μ and σ^2 can be estimated with observed x values:

$$\hat{\mu} = \overline{x} = \frac{\sum_{i=1}^{N} x_i}{N}$$
 (2.3)

$$\hat{\sigma}^2 = S_s^2 = \frac{\sum_{i=1}^{N} (x_i - \overline{x})^2}{N - 1}$$
 (2.4)

The lognormal distribution is used to describe systems where the logarithm of the measured variable is normally distributed. If the measured variable is x_i , then s_i =log x_i is assumed to be normally distributed with estimated mean $\hat{\mu}$ and variance $\overline{\sigma}^2$:

$$\hat{\mu} = \bar{s} = \frac{\sum_{i=1}^{N} s_i}{N} = \frac{\sum_{i=1}^{N} \log x_i}{N}$$
 (2.5)

$$\hat{\sigma}^2 = S_s^2 = \frac{\sum_{i=1}^{N} (s_i - \bar{s})^2}{N - 1} = \frac{\sum (\log x_i - \bar{s})^2}{N - 1}$$
(2.6)

To compare a frequency distribution to a hypothesized distribution, the χ^2 (chi-square) test was utilized. It is based on the comparison of the observed frequencies of sample values with frequencies expected from the population density function that is specified in the null hypothesis. The goodness-of-fit test is conducted using the following equation:

$$\chi^2 = \sum_{i=1}^k \frac{(O_i - E_i)^2}{E_i}$$
 (2-7)

where

 O_i and E_i are the observed and expected frequencies in interval i, respectively; k is the number of discrete intervals into which the data were separated; χ^2 is the calculated value with the given sample data that can be approximated by the χ^2 distribution with (k-j-1) degrees of freedom, where j is the number of parameters in the hypothesized distribution that were determined from the data.

With a given significance level α , if $\chi^2 \leq \chi^2_{1-\alpha}$ (k-j-1), then the fit is good or the selected distribution model is appropriate for the data. Otherwise, the fit is poor or the selected distribution is not appropriate for the data. To illustrate the distribution model selection and goodness-of-fit test, the frequency plot is drawn in Figure 2-1 for production item "QC/QA HMA Surface", which is to place hot mix asphalt pavement surfaces under quality control and quality assurance program.

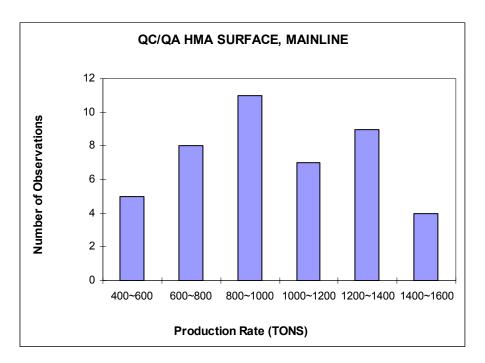


Figure 2-1 Frequency Distribution of Production Rates

The bell-shaped and symmetric frequency distribution pattern suggests that a normal distribution be a possible distribution for the production rates. Practically, a significant level of α =0.05 is often utilized for goodness-of-fit test. With α =0.05, $\chi^2_{1-\alpha}$ (k-j-1) = 9.488 and the calculated χ^2 is 8.269. Since χ^2 = 8.269 < $\chi^2_{1-\alpha}$ (k-j-1) = 9.488, the normal distribution is accepted by the goodness-of-fit tests for the given significant level.

The distributions of various production rates can be obtained in the same manner as described in the above example. The distributions of production rates for INDOT highway construction projects are listed in Table 2-1 with their corresponding goodness-of-fit test results. As can be seen in the table, the majority of the production rates have normal distributions and only a few of them have lognormal or exponential distributions.

2.2 Mean Production Rates

Currently, INDOT uses a list of mean production rates of common highway construction items. Since production rates change with time because of changes in construction methods, materials, management, equipment, and technology, it is necessary to update the values of the production rates with the most recent data. Based on the thousands of construction records, common highway and bridge construction items were first identified and their mean production rates were then calculated. The mean production rates were computed in terms of appropriate production quantity per working day. A working day is defined as an 8-hour continuous highway construction operation within a calendar day. The mean 8-hour working day production rates for highway construction activities were determined as shown in Tables 2-2 through Table 2-5 using the most recent available construction progress data from 1995 to 2002. The production

rates are listed in four categories, i.e., roadways, bridges, excavations, and removals. The existing INDOT production rates are also listed in the tables for information and comparison purpose. The production rate values indicate that almost all of the new production rates are greater than their existing values. Although the differences between the new and the existing values are generally not significant, they certainly show a trend of production rate increases in highway construction. This should be attributed to the improvement of construction technology and efficiency.

TABLE 2-1 Goodness-of-Fit Tests for Production Rates Distribution

CONSTRUCTION ACTIVITY	DISTRIBUTION TYPE	χ^2	$\chi^2_{1-\alpha}(\mathbf{k}-\mathbf{j})$
ROADWAY		7.	7,
AGGREGATE SHOULDER	Normal Distribution	7.326	7.815
BACKFILL, ROCK	Normal Distribution	6.994	7.815
BARRIER WALL-PERMANENT	Normal Distribution	8.621	9.488
BITUMINOUS APPROACHES	Normal Distribution	6.802	7.815
BITUMINOUS BASE	Normal Distribution	10.022	11.070
BITUMINOUS BINDER	Normal Distribution	8.433	9.488
CHAIN LINK FENCE	Normal Distribution	7.417	7.815
CLASS "A" CONCRETE IN STR'S	Normal Distribution	8.319	9.488
CONCRETE DRIWAYS	Normal Distribution	8.824	9.488
CONCRETE GUTTER	Normal Distribution	6.385	7.815
CONCRETE MEDIAN BARRIER	Normal Distribution	6.923	7.815
CONCRETE PATCHING	Lognormal Distribution	9.868	11.070
EMBANKMENT	Normal Distribution	6.677	7.815
EXCAVATION, BORROW LARGE AREAS	Normal Distribution	8.211	9.488
EXCAVATION, CHANNEL	Normal Distribution	7.964	9.488
EXCAVATION, COFFERDAM	Normal Distribution	9.042	9.488
EXCAVATION, COMMON SMALL AREAS	Normal Distribution	5.662	7.815
GEOTEXTILES FOR UNDERDRAIN	Normal Distribution	6.301	7.815
GRANULAR BACKFILL	Normal Distribution	9.257	11.070
GRAVEL OR CRUSHED STONE BASE COURSE	Normal Distribution	8.961	11.070
GRAVEL OR CRUSHED STONE SHOULDERS	Normal Distribution	7.855	9.488
HMA INTERMEDIATE, MAINLINE	Normal Distribution	6.269	7.815
PAVED SIDE DITCH	Normal Distribution	10.453	11.070
QC/QA HMA SURFACE, MAINLINE	Normal Distribution	8.269	9.488
REINFORCED CEMENT CONCRETE PAVEMENT	Exponential Distribution	9.014	11.070
REMOVAL, CURB & GUTTER	Normal Distribution	6.338	7.815
REMOVAL, PAVEMENT (CONC.)	Normal Distribution	8.214	9.488
REMOVAL, SIDEWALK	Normal Distribution	7.626	9.488
REMOVAL, SURFACE (MILLING)	Normal Distribution	8.729	9.488
SODDING	Normal Distribution	8.357	9.488
SOIL STABILIZATION	Normal Distribution	6.799	7.815
STABILIZED ROADBED	Normal Distribution	7.116	7.815
BRIDGE:			
BEAM ERECTION-PRECAST	Normal Distribution	7.267	7.815
BENT PILING	Lognormal Distribution	9.963	11.070
BRIDGE DECK OVERLAY	Normal Distribution	9.409	11.070
BRIDGE HANDRAILS	Normal Distribution	6.408	7.815
DRIVING STEEL PILES	Normal Distribution	7.167	7.815
DRIVING TIMBER PILES	Normal Distribution	7.970	9.488
REINFORCING STEEL	Normal Distribution	7.496	9.488
SEEDING & SODDING	Normal Distribution	6.330	7.815

TABLE 2-2 Mean Daily Production Rates (Roadways)

CONSTRUCTION ACTIVITY	UNIT	PRODUCTION RATE	EXISTING RATE
ROADWAYS			
AGGREGATE SHOULDER	TONS(Mg)	840(760)	800(725)
BACKFILL, ROCK	TONS(Mg)	580(525)	
BARRIER DELINEATOR	EACH	20	
BARRIER WALL-PERMANENT	LFT(m)	200(60)	
BITUMINOUS APPROACHES	TONS(Mg)	230(210)	200(180)
BITUMINOUS BASE	TONS(Mg)	820(745)	800(725)
BITUMINOUS BINDER	TONS(Mg)	1,180(1,065)	800(725)
BITUMINOUS BINDER WITH FIBERS	TONS(Mg)	1,840(1,665)	
BITUMINOUS PATCHING	TONS(Mg)	70(60)	
BITUMINOUS SHOULDERS	TONS(Mg)	750(675)	700(635)
BITUMINOUS SURFACE	TONS(Mg)	1,060(960)	1,000(905)
BITUMINOUS WEDGE & LEVEL	TONS(Mg)	530(475)	500(455)
BITUMINOUS WIDENING	TONS(Mg)	940(855)	900(815)
BOX CULVERTS	CYS(m ³)	50(40)	
CATCH BASINS	EACH	5	5
CHAIN LINK FENCE	LFT(m)	1,330(405)	1,200(365)
COMPACTED AGGREGATE FOR BASE	TONS(Mg)	350(315)	
COMPACTED AGGREGATE FOR SHOULDER	TONS(Mg)	490(440)	
CONCRETE DRIWAYS	SYS(m ²)	250(210)	180(150)
CONCRETE GUTTER	LFT(m)	590(180)	500(150)
CONCRETE MEDIAN BARRIER	LFT(m)	910(275)	800(245)
CONCRETE PATCHING	SYS(m ²)	120(100)	100(85)
CONCRETE PAVEMENT	SYS(m ²)	2,870(2,400)	2,500(2,100)
CONCRETE SIDEWALK	SYS(m ²)	1,080(905)	1,000(840)
CONTRACTION JOINT	LFT(m)	290(90)	
CRACK & SEATING PVMT	SYS(m ²)	6,580(5,500)	6,000(5,000)
CRACKS, TRANSVERSE, ROUT CLEAN AND SEAL	LFT(m)	9,180(2795)	
CULVERTS	LFT(m)	220(65)	200(60)
CURB AND GUTTER	LFT(m)	330(100)	300(90)
CURB AND GUTTER, COMBINED	LFT(m)	330(100)	300(90)
CURB RAMP, CONCRETE	SYS(m ²)	24(20)	20(17)
CURB, INTEGRAL, C, CONCRETE	LFT(m)	200(60)	
DRILLED HOLES	EACH	270	250
ELECTRIC CABLE	LFT(m)	2,600(790)	
EMBANKMENT	CYS(m ³)	2,380(1,820)	2,200(1,680)
GABIONS	CYS(m ³)	80(60)	
GEOTEXTILES	SYS(m ²)	500(420)	

TABLE 2-2 (continued)

CONSTRUCTION ACTIVITY	UNIT	PRODUCTION RATE	EXISTING RATE
GEOTEXTILES FOR UNDERDRAIN	SYS(m ²)	150(130)	
GRANULAR BACKFILL	CYS(m ³)	330(250)	300(230)
GRAVEL OR CRUSHED STONE BASE COURSE	TONS(Mg)	800(725)	
GRAVEL OR CRUSHED STONE SHOULDERS	TONS(Mg)	800(725)	
GRAVEL OR CRUSHED STONE SURFACE COURSE	TONS(Mg)	800(725)	
GROUND OR CRUSHED STONE	TONS(Mg)	860(780)	800(725)
GUARDRAIL	LFT(m)	520(160)	400(120)
GUARDRAIL, CHANNEL	LFT(m)	240(75)	
GUARDRAIL, RESET	LFT(m)	380(115)	
HANDHOLE	EACH	6	
HMA INTERMEDIATE, MAINLINE	TONS(Mg)	1,400(1,270)	
INLET	EACH	6	5
JACKED PIPE	LFT(m)	50(15)	50(15)
JOINT AND CRACK CLEANING AND SEALING	LFT(m)	210(65)	
LAYING SIGNAL CONDUIT	LFT(m)	220(65)	200(60)
LOOP TESTING	EACH	17	
MANHOLES	EACH	3	3
MARKINGS	LFT(m)	7,200(2,195)	6,000(1,825)
PAVED SIDE DITCH	LFT(m)	380(115)	350(105)
QC/QA HMA SURFACE, MAINLINE	TONS(Mg)	980(890)	
REINFORCED CEMENT CONCRETE PAVEMENT	SYS(m ²)	160(130)	
RIP-RAP	TONS(Mg)	240(215)	200(165)
RUBBLIZING PAVEMENT	SYS(m ²)	3,200(2,675)	3,000(2,510)
SEAL COAT	SYS(m ²)	12,030(10,055)	
SEEDLING	ACRES(HA)	10(4)	10(4)
SIGN,PANEL,ENCAPSULATED LENS WITH LEGEND	LFT(m)	560(170)	
SLOPE WALL	SYS(m ²)	50(40)	
SODDING	SYS(m ²)	1,020(853)	900(750)
SOIL STABILIZATION	CYS(m³)	4,870(3,725)	4,500(3,440)
STABILIZED ROADBED	SYS(m ²)	5,000(4,180)	
STABILIZED SHOULDERS	SYS(m ²)	1,600(1,340)	
STORM SEWERS	LFT(m)	200(60)	
SUBBASE	TONS(Mg)	860(780)	800(725)
TEMP. CONC. BARRIER	LFT(m)	2,590(790)	2,400(730)
TEMP. CROSSOVERS	EACH	1/5	1/5
TRAFFIC SIGNAL HEAD ALTERATIONS	EACH	4	
TRAFFIC SIGNAL POSTS	EACH	4	
TRENCH AND BACKFILL	LFT(m)	450(135)	
UNDERDRAINS	LFT(m)	1,090(330)	1,000(305)
UNDERSEAL	TONS(Mg)	45(41)	40(36)

TABLE 2-3 Mean Daily Production Rates (Bridges)

CONSTRUCTION ACTIVITY DESCRIPTION	UNIT	PRODUCTION RATE	EXISTING RATE
BRIDGES	J	THE STATE OF THE S	
ACROW BRIDGE	LFT(m)	7.5(2.3)	
BEAM ERECTION-PRECAST	LFT(m)	400(120)	
BEAM ERECTION-STEEL	LFT(m)	150(45)	
BENT CAP	CYS(m ³)	10(8)	
BENT COFFERDAMS	SYS(m²)	300(250)	
BENT FORM & POUR	CYS(m³)	10(8)	
BENT FORM & POUR FOOTING	CYS(m³)	10(8)	
BENT PILING	LFT(m)	500(150)	
BRIDGE BARRIER	LFT(m)	80(25)	
BRIDGE DECK	CYS(m ³)	14(11)	
BRIDGE DECK OVERLAY	SYS(m²)	360(295)	
BRIDGE HANDRAILS	LFT(m)	230(70)	
BRIDGE RAIL	LFT(m)	600(185)	
CLASS "A" CONCRETE IN STR'S	CYS(m ³)	170(125)	150(115)
CLASS "B" CONCRETE IN STR'S	CYS(m³)	110(85)	100(75)
CONCRETE, C, IN SUPERSTRUCTURE	CYS(m³)	80(60)	100(13)
CONSTRUCT FILL	CYS(m³)	500(385)	
DEWATER, FORM & POUR BENT STEM	CYS(m³)	10(8)	
DITCH PAVING	SYS(m²)	200(165)	
DRILLED SHAFTS-BRIDGE	EACH	0.3	
DRIVING CONCRETE PILES	LFT(m)	300(90)	
DRIVING STEEL PILES DRIVING TIMBER PILES	LFT(m)	400(120) 350(105)	
ERECTING HANDRAIL	LFT(III)	80(25)	
ERECTING STRUCTURE STEEL	` '	27,500(12,470)	
EXPANSION BOLTS	LBS(Kg) EACH	27,300(12,470)	
FLOWABLE MORTAR	CYS(m³)		
FOOTINGS	CYS(m³)	150(115) 30(25)	
FORM & POUR DIAPHRAGMS	CYS(m³)	5(4)	
FORM & POUR FOOTING	CYS(m³)	10(8)	
FORM & POUR TOP WALL	CYS(m³)	15(11)	
LIGHTING STANDARDS	EACH	5	
PARAPET	LFT(m)	100(30)	
PILING	LFT(m)	300(90)	
PLACE BITUMINOUS MIX	TONS(Mg)	1,300(1,180)	
PLACE COMPACTED AGGREGATE	TONS(Mg)	2,000(1,815)	
PLACE DECK W/O SUPPORT CUTTOUTS	CYS(m ³)	150(115)	
PRISMATIC REFLECTOR	EACH	930	
REBAR	LBS(Kg)	20,000(9,080)	
REINFORCED CONCRETE APPROACHES	CYS(m ³)	30(23)	
REINFORCEMENT BARS (SUBSTRUCTURE)	LBS(Kg)	2,500(1,135)	
REINFORCEMENT BARS (SUPERSTRUCTURE)	LBS(Kg)	5,000(2,270)	
REINFORCING STEEL	LBS(Kg)	14,780(6,710)	
REINFORCING STEEL REINFORCING STEEL, EPOXY COATED	LBS(Kg)	9,220(4,185)	1
NEINI ORGING STEEL, EPOXT GUATED	LD3(Ng)	3,220(4,100)	

TABLE 2-3 (continued)

CONSTRUCTION ACTIVITY	UNIT	PRODUCTION RATE	EXISTING RATE
REMOVE BULKHEADS & PLACE CONCRETE	CYS(m ³)	10(8)	
RETAINING WALLS	SYS(m ²)	17(14)	
SEEDING & SODDING	SYS(m ²)	2,500(2,090)	
SIGN LARGE	EACH	0.4	
SIGN SMALL	EACH	20	
WINGWALLS	SYS(m ²)	17(14)	

TABLE 2-4 Mean Daily Production Rates (Excavations)

CONSTRUCTION ACTIVITY	UNIT	PRODUCTION RATE	EXISTING RATE
EXCAVATIONS			
BORROW	CYS(m ³)	990(760)	
BORROW LARGE AREAS	CYS(m ³)	2,610(1,995)	2,500(1,910)
CHANNEL	CYS(m ³)	650(495)	650(495)
COFFERDAM	CYS(m ³)	80(60)	
COMMON SMALL AREAS	CYS(m ³)	520(400)	500(380)
PEAT	CYS(m ³)	860(660)	800(610)
ROCK	CYS(m ³)	1,130(860)	1,000(765)
SUBBALLAST	TONS(Mg)	270(245)	
SUBGRADE TREATMENT	CYS(m ³)	1,160(890)	1,000(765)
UNCLASSIFIED	CYS(m ³)	3,460(2,645)	3,000(2,300)
WATERWAY	CYS(m ³)	660(505)	
WET	CYS(m ³)	80(65)	

TABLE 2-5 Mean Daily Production Rates (Removals)

CONSTRUCTION ACTIVITY	UNIT	PRODUCTION RATE	EXISTING RATE
REMOVALS			
CURB & GUTTER	LFT(m)	860(265)	800(245)
FENCE	LFT(m)	150(45)	
HEADWALL	EACH	3	
PAVEMENT (CONC.)	SYS(m ²)	920(770)	800(675)
SIDEWALK	SYS(m ²)	1,690(1,415)	1,500(1,255)
STUMP	EACH	12	
SURFACE (MILLING)	SYS(m ²)	10,900(9,110)	10,000(8,350)
TOP SOIL	CYS(m ³)	380(290)	
TREE	ACRES(HA)	1.5(0.6)	

2.3 Statistical Characteristics of Production Rates

In the previous section, the production rates were presented in terms of mean values. Statistically, mean is only one of the key parameters used to describe the characteristics of a population. Other parameters, including variance or standard deviation and confidence intervals, are often utilized along with mean to capture the main properties of a population through observed or measured samples. For a normal distribution, the mean represents the central value of the observations with the highest frequency; while the standard deviation or variance indicates the degree of distribution disperse. A greater variance implies that the data values are scattered far from the mean value, while a smaller variance means that the data values are distributed in a closer range around the mean value. To fully describe the production rates of various highway production activities, the standard deviations and confidence intervals were also calculated in addition to the mean values.

For n recorded values of production rates, the sample variance is calculated using the following equation:

$$S^{2} = \frac{\sum_{i=1}^{n} (X_{i} - \overline{X})^{2}}{n-1}$$
 (2-8)

where:

 S^2 = the sample variance;

n =the number of observations or recorded values;

 X_i = the ith observation;

 \overline{X} = the mean of the sample.

The standard deviation of a sample is the positive square root of the sample variance:

$$S = \sqrt{S^2} = \sqrt{\frac{\sum_{i=1}^{n} (X_i - \overline{X})^2}{n-1}}$$
 (2-9)

Since \overline{X} is an estimation of the true mean of the population, it is often desired to estimate the range that the true mean may locate within for a given confidence level. The range is called the confidence interval of the estimated mean related to the true population mean. With calculated sample mean and standard deviation values, a $100(1-\alpha)$ % confidence interval for mean production rate μ is given by:

$$\overline{X} - t_{\alpha/2, n-1} \frac{S}{\sqrt{n}} < \mu < \overline{X} + t_{\alpha/2, n-1} \frac{S}{\sqrt{n}}$$
 (2-10)

where:

 α = the level of significance;

 $t_{\alpha/2, n-1}$ = the 100(1- $\alpha/2$) the percentile of the t distribution with n-1 degrees of freedom.

In practice, α =0.05 is often used as the significant level, which would yield an interval of the estimated mean with a confidence level of 95%. The mean value, standard deviation and 95% confidence intervals for production rates are shown in Tables 2-6 through 2-9. As implied by Equation 20-10, the width of each confidence interval in the tables depends on the standard deviation. A greater standard deviation would result in a wider confidence interval.

TABLE 2-6 Statistics of Production Rates (Roadways)

CONSTRUCTION ACTIVITY	UNIT	MEAN VALUE	STANDARD DEVIATION	95% CONFIDENCE INTERVAL
ROADWAYS				
AGGREGATE SHOULDER	TON	840	102	748 ≤ µ ≤ 932
BACKFILL, ROCK	TON	580	250	479 ≤ μ ≤ 681
BARRIER DELINEATOR	EACH	20	2	19 ≤ µ ≤ 21
BARRIER WALL-PERMANENT	LFT	200	12	182 ≤ µ ≤ 218
BITUMINOUS APPROACHES	TON	230	111	204 ≤ µ ≤ 256
BITUMINOUS BASE	TON	820	519	553 ≤ µ ≤ 1,087
BITUMINOUS BINDER	TON	1,180	303	1,086 ≤ µ ≤ 1,274
BITUMINOUS BINDER WITH FIBERS	TON	1,840	776	1,427 ≤ µ ≤ 2,253
BITUMINOUS PATCHING	TON	70	8	52 ≤ μ ≤ 88
BITUMINOUS SHOULDERS	TON	750	92	668 ≤ µ ≤ 832
BITUMINOUS SURFACE	TON	1,060	113	920 ≤ μ ≤ 1,200
BITUMINOUS WEDGE AND LEVEL	TON	530	273	430 ≤ μ ≤ 630
BITUMINOUS WIDENING	TON	940	366	756 ≤ µ ≤ 1,124
BOX CULVERTS	CYS	50	12	43 ≤ μ ≤ 57
CHAIN LINK FENCE	LFT	1,330	225	1,211 ≤ μ ≤ 1,449
COMPACTED AGGREGATE FOR BASE	TON	350	126	270 ≤ μ ≤ 430
COMPACTED AGGREGATE FOR SHOULDER	TON	490	159	434 ≤ µ ≤ 546
CONCRETE DRIWAYS	SYS	250	48	206 ≤ μ ≤ 294
CONCRETE GUTTER	LFT	590	96	511 ≤ μ ≤ 669
CONCRETE MEDIAN BARRIER	LFT	910	221	786 ≤ µ ≤ 1,034
CONCRETE PATCHING	SYS	120	24	105 ≤ μ ≤ 135
CONCRETE PAVEMENT	SYS	2,870	286	2,718 ≤ µ ≤ 3,022
CONCRETE SIDEWALK	SYS	1,080	109	1,051 ≤ µ ≤ 1,109
CONTRACTION JOINT	LFT	290	115	244 ≤ μ ≤ 336
CRACKS, TRANSVERSE, ROUT CLEAN AND SEAL	LFT	9,180	5,636	$6,059 \le \mu \le 1,2301$
CURB AND GUTTER	LFT	330	464	198 ≤ μ ≤ 462
CURB AND GUTTER, COMBINED	LFT	330	10	305 ≤ μ ≤ 355
CURB, INTEGRAL, C, CONCRETE	LFT	200	79	172 ≤ μ ≤ 228
CURB RAMP, CONCRETE	SYS	24	6	18 ≤ µ ≤ 30
DRILLED HOLES	EACH	270	38	240 ≤ µ ≤ 300
ELECTRIC CABLE	LFT	2,600	219	2,471 ≤ µ ≤ 2,729
EMBANKMENT	CYS	2,380	189	1,910 ≤ µ ≤ 2,850
GABIONS	CYS	80	17	71 ≤ μ ≤ 89
GEOTEXTILES	SYS	500	151	399 ≤ μ ≤ 601
GEOTEXTILES FOR UNDERDRAIN	SYS	150	28	80 ≤ µ ≤ 220
GRANULAR BACKFILL	CYS	330	46	283 ≤ μ ≤ 377
GRAVEL OR CRUSHED STONE BASE COURSE	TON	800	92	722 ≤ μ ≤ 878
GRAVEL OR CRUSHED STONE SHOULDERS	TON	800	88	726 ≤ μ ≤ 874
GRAVEL OR CRUSHED STONE SURFACE COURSE	TON	800	90	731 ≤ μ ≤ 869

TABLE 2-6 (continued)

CONSTRUCTION ACTIVITY	UNIT	MEAN VALUE	STANDARD DEVIATION	95% CONFIDENCE INTERVAL
GROUND OR CRUSHED STONE	TON	860	87	719 ≤ µ ≤ 1,001
GUARDRAIL	LFT	520	169	379 ≤ µ ≤ 661
GUARDRAIL, CHANNEL	LFT	240	64	230 ≤ µ ≤ 250
GUARDRAIL, RESET	LFT	380	147	322 ≤ µ ≤ 438
HMA INTERMEDIATE, MAINLINE	TON	1,400	282	1,164 ≤ µ ≤ 1,636
JACKED PIPE	LFT	50	8	45 ≤ µ ≤ 55
JOINT AND CRACK CLEANING AND SEALING	LFT	210	101	138 ≤ µ ≤ 282
LAYING SIGNAL CONDUIT	LFT	220	34	185 ≤ µ ≤ 255
PAVED SIDE DITCH	LFT	380	47	337 ≤ µ ≤ 423
PIPES, CULVERTS	LFT	220	18	201 ≤ µ ≤ 239
PIPES, UNDERDRAINS	LFT	1,090	137	997 ≤ μ ≤ 1,183
QC/QA HMA SURFACE, MAINLINE	TON	980	349	875 ≤ µ ≤ 1,085
REINFORCED CEMENT CONCRETE PAVEMENT	SYS	160	14	149 ≤ µ ≤ 171
RIP-RAP	TON	240	134	206 ≤ μ ≤ 274
RUBBLIZING PAVEMENT	SYS	3,200	227	2,966 ≤ µ ≤ 3,434
SEAL COAT	SYS	12,030	6,024	$7,400 \le \mu \le 16,660$
SIGN,PANEL,ENCAPSULATED LENS WITH LEGEND	LFT	560	235	475 ≤ µ ≤ 645
SLOPE WALL	SYS	50	7	43 ≤ µ ≤ 57
SODDING	SYS	1,020	1,136	529 ≤ µ ≤ 1,511
SOIL STABILIZATION	CYS	4,870	396	4,371 ≤ µ ≤ 5,369
STABILIZED ROADBED	SYS	5,000	375	4,523 ≤ μ ≤5,477
STABILIZED SHOULDERS	SYS	1,600	122	1,504 ≤ µ ≤ 1,696
STORM SEWERS	LFT	200	19	185 ≤ µ ≤ 215
SUBBASE	TON	860	169	787 ≤ µ ≤ 933
TEMP. CONC. BARRIER	LFT	2,590	271	1,751 ≤ µ ≤ 3,429
CRACK & SEATING PVMT	SYS	6,580	526	6,043 ≤ µ ≤ 7,117
MARKINGS	LFT	7,200	876	6,447 ≤ µ ≤ 7,953
UNDERSEAL	TON	45	6	42 ≤ µ ≤ 48
TRENCH AND BACKFILL	LFT	450	53	412 ≤ µ ≤ 488

TABLE 2-7 Statistics of Production Rates (Bridges)

CONSTRUCTION ACTIVITY	UNIT	MEAN VALUE	STANDARD DEVIATION	95% CONFIDENCE INTERVAL
BRIDGES				
BEAM ERECTION-PRECAST	LFT	400	38	361 ≤ µ ≤ 439
BEAM ERECTION-STEEL	LFT	150	12	137 ≤ µ ≤ 163
BENT COFFERDAMS	SYS	300	35	279 ≤ µ ≤ 321
BENT PILING	LFT	500	46	448 ≤ µ ≤ 552
BRIDGE BARRIER	LFT	80	9	74 ≤ µ ≤ 86
BRIDGE DECK	CYS	14	2	12 ≤ µ ≤ 16
BRIDGE DECK OVERLAY	SYS	360	140	213 ≤ μ ≤ 507
BRIDGE HANDRAILS	LFT	230	21	208 ≤ µ ≤ 252
BRIDGE RAIL	LFT	600	86	509 ≤ μ ≤ 691
CLASS "A" CONCRETE IN STR'S	CYS	170	26	147 ≤ μ ≤ 193
CLASS "B" CONCRETE IN STR'S	CYS	110	19	95 ≤ μ ≤ 125
CONCRETE, C, IN SUPERSTRUCTURE	CYS	80	11	73 ≤ μ ≤ 87
CONSTRUCT FILL	CYS	500	62	447 ≤ μ ≤ 553
DITCH PAVING	SYS	200	18	191 ≤ μ ≤ 209
DRIVING CONCRETE PILES	LFT	300	27	281 ≤ μ ≤ 319
DRIVING STEEL PILES	LFT	400	29	368 ≤ µ ≤ 432
DRIVING TIMBER PILES	LFT	350	26	333 ≤ μ ≤ 367
ERECTING HANDRAIL	LFT	80	3	78 ≤ µ ≤ 82
ERECTING STRUCTURE STEEL	LBS	27,500	2,678	25,820 ≤ µ ≤ 29,180
EXPANSION BOLTS	EACH	27	2	26 ≤ µ ≤ 28
FLOWABLE MORTAR	CYS	150	23	132 ≤ μ ≤ 168
FOOTINGS	CYS	30	4	28 ≤ μ ≤ 32
PARAPET	LFT	100	16	90 ≤ μ ≤ 110
PILING	LFT	300	46	260 ≤ μ ≤ 340
PLACE BITUMINOUS MIX	TON	1,300	112	1,171 ≤ μ ≤ 1,429
PLACE COMPACTED AGGREGATE	TON	2,000	319	1,793 ≤ μ ≤ 2,207
PLACE DECK W/O SUPPORT CUTTOUTS	CYS	150	18	138 ≤ µ ≤ 162
PRISMATIC REFLECTOR	EACH	930	132	813 ≤ µ ≤ 1,047
REBAR	LBS	20,000	3,460	18,161 ≤ µ ≤ 21,839
REINFORCED CONCRETE APPROACHES	CYS	30	6	27 ≤ μ ≤ 33
REINFORCEMENT BARS (SUBSTRUCTURE)	LBS	2,500	226	2,247 ≤ µ ≤ 2,753
REINFORCEMENT BARS (SUPERSTRUCTURE)	LBS	5,000	473	4,536 ≤ µ ≤ 5,464
REINFORCING STEEL	LBS	14,780	2,230	12,795 ≤ μ ≤ 16,765
REINFORCING STEEL, EPOXY COATED	LBS	9,220	1,670	$8,084 \le \mu \le 10,356$
RETAINING WALLS	SYS	17	4	15 ≤ µ ≤ 19
SEEDING & SODDING	SYS	2,500	228	2,321 ≤ μ ≤ 2,679
SIGN SMALL	EACH	20	3	18 ≤ µ ≤ 22
WINGWALLS	EACH	17	2	15 ≤ µ ≤ 19

TABLE 2-8 Statistics of Production Rates (Excavations)

CONSTRUCTION ACTIVITY	UNIT	MEAN VALUE	STANDARD DEVIATION	95% CONFIDENCE INTERVAL
EXCAVATIONS				
BORROW LARGE AREAS	CYS	2,610	298	$2,321 \le \mu \le 2,899$
CHANNEL	CYS	650	92	591 ≤ μ ≤ 709
COFFERDAM	CYS	80	3	76 ≤ µ ≤ 84
COMMON SMALL AREAS	CYS	520	106	466 ≤ µ ≤ 574
PEAT	CYS	860	104	787 ≤ µ ≤ 933
SUBBALLAST	TONS	270	149	224 ≤ µ ≤ 316
BORROW	CYS	990	394	898 ≤ µ ≤ 1,082
ROCK	CYS	1,130	139	1,001 ≤ μ ≤ 1,259
SUBGRADE TREATMENT	CYS	1,160	270	1,016 ≤ µ ≤ 1,304
UNCLASSIFIED	CYS	3,460	305	$3,140 \le \mu \le 3,780$
WATERWAY	CYS	660	290	300 ≤ μ ≤ 1,020
WET	CYS	80	23	61 ≤ µ ≤ 99

TABLE 2-9 Statistics of Production Rates (Removals)

CONSTRUCTION ACTIVITY	UNIT	MEAN VALUE	STANDARD DEVIATION	95% CONFIDENCE INTERVAL
REMOVALS				
CURB & GUTTER	LFT	860	188	790 ≤ µ ≤ 930
FENCE	LFT	150	21	98 ≤ μ ≤ 202
PAVEMENT (CONC.)	SYS	920	185	796 ≤ µ ≤ 1,044
SIDEWALK	SYS	1,690	80	1,654 ≤ µ ≤ 1,726
STUMP	EACH	12	8	10 ≤ µ ≤ 14
SURFACE (MILLING)	SYS	10,900	1,062	9,817 ≤ μ ≤ 11,983
TOP SOIL	CYS	380	29	362 ≤ µ ≤ 398

The common feature of the three types of distributions selected for the INDOT production rates, i.e., normal, lognormal and exponential distributions, is that most of the values are scattered around the mean within a range of one or two standard deviations. Outside of this range, there exist some values that are relatively either very small or very large compared to the mean. Based on a given distribution, the probability that the production rate is less than a specific value can be obtained. Such a probability can be expressed as:

$$P(X_i \le \alpha) = p \tag{2-11}$$

Equation 2-11 means that the probability that the production rate X_i is less that α is p. The production rates under different probabilities are presented in Tables 2-10 through 2-13. In these tables, listed are the probability values of 20%, 40%, 60%, 80%, and 95% and their corresponding production rate of construction activities. For example, for construction activity, aggregate shoulder, the probability that the production rate is less than 754 tons per working day is 20%. In other words, there is 20% chance that the production rate of placing aggregate shoulder is less than 745, or 80% chance that the production rate is greater than 745.

TABLE 2-10 Production Rates under Different Probabilities (Roadways)

CONSTRUCTION ACTIVITY	UNIT	MEAN	P (%)				
ROADWAYS			20%	40%	60%	80%	95%
AGGREGATE SHOULDER	TON	840	754	814	866	926	1,008
BACKFILL, ROCK	TON	580	370	517	643	790	991
BITUMINOUS APPROACHES	TON	230	137	202	258	323	413
BITUMINOUS BASE	TON	820	383	689	951	1,257	1,436
BITUMINOUS BINDER	TON	1,180	925	1,103	1,257	1,435	1,629
BITUMINOUS BINDER WITH FIBERS	TON	1,840	1,187	1,643	2,037	2,493	2,927
BITUMINOUS PATCHING	TON	70	63	68	72	77	83
BITUMINOUS SHOULDERS	TON	750	673	727	773	827	901
BITUMINOUS SURFACE	TON	1,060	965	1,031	1,089	1,155	1,246
BITUMINOUS WEDGE AND LEVEL	TON	530	300	461	599	760	862
BITUMINOUS WIDENING	TON	940	632	847	1,033	1,248	1,442
BORROW	CYS	990	658	890	1,090	1,322	1,538
BOX CULVERTS	CYS	50	40	47	53	60	69
CHAIN LINK FENCE	LFT	1,330	1,141	1,273	1,387	1,519	1,700
COMPACTED AGGREGATE FOR SHOULDER	TON	490	356	450	530	624	750
CONCRETE DRIWAYS	SYS	250	210	238	262	290	329
CONCRETE GUTTER	LFT	590	509	566	614	671	726
CONCRETE MEDIAN BARRIER	LFT	910	724	854	966	1,096	1,174
CONCRETE PATCHING	SYS	120	100	114	126	140	160
CONCRETE PAVEMENT	SYS	2,870	2,629	2,798	2,942	3,111	3,340
CONCRETE SIDEWALK	SYS	1,080	988	1,052	1,108	1,172	1,259
CONTRACTION JOINT	LFT	290	193	261	319	387	479
CRACK & SEATING PVMT	SYS	6,580	6,137	6,447	6,713	7,023	7,445
CRACKS, TRANSVERSE, ROUT CLEAN AND SEAL	LFT	9,180	4,436	7,752	10,608	13,924	15,270
CURB AND GUTTER	LFT	330	101	212	448	571	624
CURB AND GUTTER, COMBINED	LFT	330	322	327	333	338	346
CURB RAMP, CONCRETE	SYS	24	19	22	26	29	34
CURB, INTEGRAL, C, CONCRETE	LFT	200	133	180	220	267	310
DRILLED HOLES	EACH	270	238	260	280	302	333
EMBANKMENT	CYS	2,380	2,221	2,332	2,428	2,539	2,691
GABIONS	CYS	80	66	76	84	94	108

TABLE 2-10 (continued)

CONCEDUCTION ACTIVITY		MEAN	(contin	iucu)	D (0/)		
CONSTRUCTION ACTIVITY	UNIT	MEAN	P (%)				
ROADWAYS			20%	40%	60%	80%	95%
GEOTEXTILES	SYS	500	373	462	538	627	748
GEOTEXTILES FOR UNDERDRAIN	SYS	150	126	143	157	174	196
GRANULAR BACKFILL	CYS	330	291	318	342	369	406
GROUND OR CRUSHED STONE	TON	860	787	838	882	933	1,003
GUARD RAIL, CHANNEL	LFT	240	186	224	256	294	345
GUARDRAIL	LFT	520	378	477	563	662	798
GUARDRAIL, RESET	LFT	380	256	343	417	504	610
HMA INTERMEDIATE, MAINLINE	TON	1,400	1,163	1,329	1,471	1,637	1,864
JACKED PIPE	LFT	50	43	48	52	57	63
JOINT AND CRACK CLEANING AND SEALING	LFT	210	125	184	236	295	346
LAYING SIGNAL CONDUIT	LFT	220	191	211	229	249	276
MARKINGS	LFT	7,200	6,463	6,978	7,422	7,937	8,340
PAVED SIDE DITCH	LFT	380	340	368	392	420	457
PIPES, CULVERTS	LFT	220	205	215	225	235	250
PIPES, UNDERDRAINS	LFT	1,090	975	1,055	1,125	1,205	1,315
QC/QA HMA SURFACE, MAINLINE	TON	980	686	892	1,068	1,274	1,454
REINFORCED CEMENT CONCRETE PAVEMENT	SYS	160	148	156	164	172	183
RIP-RAP	TON	240	127	206	274	353	460
RUBBLIZING PAVEMENT	SYS	3,200	3,009	3,142	3,258	3,391	3,573
SEAL COAT	SYS	12,030	6,959	10,504	13,556	17,101	21,939
SIGN,PANEL,ENCAPSULATED LENS WITH LEGEND	LFT	560	362	500	620	758	947
SLOPE WALL	SYS	50	44	48	52	56	62
SODDING	SYS	1,020	364	732	1,308	1,976	2,120
SOIL STABILIZATION	CYS	4,870	4,537	4,770	4,970	5,203	5,521
SUBBALLAST	TON	270	145	232	308	395	515
SUBBASE	TON	860	718	817	903	1,002	1,138
TEMP. CONC. BARRIER	LFT	2,590	2,362	2,521	2,659	2,818	3,036
UNDERSEAL	TON	45	40	43	47	50	55

TABLE 2-11 Production Rates under Different Probabilities (Bridges)

CONSTRUCTION ACTIVITY	UNIT	MEAN	P (%)					
BRIDGES			20%	40%	60%	80%	95%	
BEAM ERECTION-PRECAST	LFT	400	368	390	410	432	463	
BEAM ERECTION-STEEL	LFT	150	140	147	153	160	170	
BRIDGE BARRIER	LFT	80	72	78	82	88	95	
BRIDGE DECK	CYS	14	12	13	15	16	17	
BRIDGE DECK OVERLAY	SYS	360	242	325	395	478	520	
BRIDGE HANDRAILS	LFT	230	212	225	235	248	265	
BRIDGE RAIL	LFT	600	528	578	622	672	730	
CLASS "A" CONCRETE IN STR'S	CYS	170	148	163	177	192	213	
CLASS "B" CONCRETE IN STR'S	CYS	110	94	105	115	126	141	
COMPACTED AGGREGATE FOR BASE	TON	350	244	318	382	456	557	
CONCRETE, C, IN SUPERSTRUCTURE	CYS	80	71	77	83	89	98	
CONSTRUCT FILL	CYS	500	448	484	516	552	602	
DITCH PAVING	SYS	200	185	195	205	215	230	
FLOWABLE MORTAR	CYS	150	131	144	156	169	188	
FOOTINGS	CYS	30	27	29	31	33	37	
PARAPET	LFT	100	87	96	104	113	126	
PILING	LFT	300	261	288	312	339	376	
PLACE BITUMINOUS MIX	TON	1,300	1,076	1,233	1,367	1,524	1,738	
PLACE COMPACTED AGGREGATE	TON	2,000	1,731	1,919	2,081	2,269	2,525	
PLACE DECK W/O SUPPORT CUTTOUTS	CYS	150	135	145	155	165	180	
PRISMATIC REFLECTOR	EACH	930	819	897	963	1,041	1,147	
REBAR	LBS	20,000	17,087	19,123	20,877	22,913	24,690	
REINFORCED CONCRETE APPROACHES	CYS	30	25	28	32	35	38	
REINFORCEMENT BARS (SUBSTRUCTURE)	LBS	2,500	2,310	2,443	2,557	2,690	2,872	
REINFORCEMENT BARS (SUPERSTRUCTURE)	LBS	5,000	4,602	4,880	5,120	5,398	5,778	
REINFORCING STEEL	LBS	14,780	12,903	14,215	15,345	16,657	18,448	
REINFORCING STEEL, EPOXY COATED	LBS	9,220	7,814	8,797	9,643	10,626	11,967	
RETAINING WALLS	SYS	17	14	16	18	20	23	
SIGN SMALL	EACH	20	17	19	21	23	25	
WINGWALLS	SYS	17	15	16	18	19	20	

TABLE 2-12 Production Rates under Different Probabilities (Excavations)

CONSTRUCTION ACTIVITY	UNIT	MEAN	P (%)					
EXCAVATIONS			20%	40%	60%	80%	95%	
BORROW LARGE AREAS	CYS	2,610	2,359	2,535	2,685	2,861	3,100	
CHANNEL	CYS	650	573	627	673	727	801	
COFFERDAMS	CYS	300	276	293	307	324	346	
COMMON SMALL AREAS	CYS	520	431	493	547	609	694	
PEAT	CYS	860	772	834	886	948	1,031	
ROCK	CYS	1,130	1,013	1,095	1,165	1,247	1,359	
SUBGRADE TREATMENT	CYS	1,160	933	1,092	1,228	1,387	1,580	
UNCLASSIFIED	CYS	3,460	3,203	3,383	3,537	3,717	3,962	
WATERWAY	CYS	660	416	587	733	904	1,137	
WET	CYS	80	61	74	86	99	118	

TABLE 2-13 Production Rates under Different Probabilities (Removals)

CONSTRUCTION ACTIVITY	UNIT	MEAN	P (%)					
REMOVALS			20%	40%	60%	80%	95%	
CURB & GUTTER	LFT	860	702	812	908	1,018	1,169	
FENCE	LFT	150	132	145	155	168	185	
PAVEMENT (CONC.)	SYS	920	764	873	967	1,076	1,224	
SIDEWALK	SYS	1,690	1,623	1,670	1,710	1,757	1,822	
STUMP	EACH	12	5	10	14	19	20	
SURFACE (MILLING)	SYS	10,900	10,006	10,631	11,169	11,794	12,647	
TOP SOIL	CYS	380	356	373	387	404	428	

2.4 Baseline Production Rates

As discussed above, mean and standard deviation are the two most commonly utilized parameters of statistics. For common types of statistical distributions, the mean represents the middle value with the highest frequency and the standard deviation reflects the degree of disperse caused by various factors. In addition to mean and standard deviation, some times it is also necessary to know the production rates with minimum

negative effects. In other words, it is desirable to obtain the production rates under ideal construction conditions. The production rates under ideal construction conditions are called the baseline production rates. The baseline production rates can be obtained from the recorded construction data as described by Thomas and Završki (1999) follow the steps below:

- 1. Determine 10% of the total working days.
- 2. Round this number to the next highest odd number; this number should not be less than 5. This number n defines the size of number of working days in the baseline production rate subset.
- 3. The contents of baseline production rate subset are selected as the n working days that have the highest daily production rates.
- 4. For these working days, make note of the daily production rates.
- 5. The baseline production rate is the median of the daily production rate values in the baseline production rates subset.

As these steps imply, a baseline production rate is the median value of the 10% working days of a highway construction project with the highest production rates. The baseline production rates calculated in this manner for INDOT highway projects are presented in Tables 2-14 through 2-17.

TABLE 2-14 Mean Baseline Production Rates (Roadways)

CONSTRUCTION ACTIVITY DESCRIPTION	UNIT	MEAN BASELINE PRODUCTION RATES
ROADWAYS		
AGGREGATE SHOULDER	TONS(Mg)	840(760)
BACKFILL, ROCK	TONS(Mg)	610(555)
BITUMINOUS APPROACHES	TONS(Mg)	240(220)
BITUMINOUS BASE	TONS(Mg)	980(890)
BITUMINOUS BINDER	TONS(Mg)	1,200(1,090)
BITUMINOUS BINDER WITH FIBERS	TONS(Mg)	2,030(1,840)
BITUMINOUS PATCHING	TONS(Mg)	110(100)
BITUMINOUS SHOULDERS	TONS(Mg)	810(735)
BITUMINOUS SURFACE	TONS(Mg)	1,080(980)
BITUMINOUS WEDGE AND LEVEL	TONS(Mg)	600(545)
BITUMINOUS WIDENING	TONS(Mg)	980(890)
BOX CULVERTS	CYS(m ³)	54(40)
CHAIN LINK FENCE	LFT(m)	1,390(425)
COMPACTED AGGREGATE FOR BASE	TONS(Mg)	380(345)
COMPACTED AGGREGATE FOR SHOULDER	TONS(Mg)	520(470)
CONCRETE DRIWAYS	SYS(m ²)	280(235)
CONCRETE GUTTER	LFT(m)	640(195)
CONCRETE MEDIAN BARRIER	LFT(m)	1,010(310)
CONCRETE PATCHING	SYS(m ²)	120(100)
CONCRETE PAVEMENT	SYS(m ²)	2,990(2,500)
CONCRETE SIDEWALK	SYS(m ²)	1,090(910)
CONTRACTION JOINT	LFT(m)	300(90)
CRACK & SEATING PVMT	SYS(m ²)	6,910(5,775)
CRACKS, TRANSVERSE, ROUT CLEAN AND SEAL	LFT(m)	11,070(3,375)
CURB AND GUTTER	LFT(m)	380(115)
CURB AND GUTTER, COMBINED	LFT(m)	340(105)
CURB RAMP, CONCRETE	SYS(m ²)	28(23)
CURB, INTEGRAL, C, CONCRETE	LFT(m)	210(65)
DRILLED HOLES	EACH	290
EMBANKMENT	CYS(m³)	2,570(1,965)
GABIONS	CYS(m³)	82(63)

TABLE 2-14 (continued)

CONSTRUCTION ACTIVITY DESCRIPTION	UNIT	MEAN BASELINE PRODUCTION RATES
GEOTEXTILES	SYS(m ²)	540(450)
GEOTEXTILES FOR UNDERDRAIN	SYS(m ²)	200(165)
GRANULAR BACKFILL	CYS(m ³)	360(275)
GROUND OR CRUSHED STONE	TONS(Mg)	900(815)
GUARDRAIL	LFT(m)	590(180)
GUARDRAIL, CHANNEL	LFT(m)	270(80)
GUARDRAIL, RESET	LFT(m)	390(120)
HMA INTERMEDIATE, MAINLINE	TONS(Mg)	1,470(1,335)
JACKED PIPE	LFT(m)	52(16)
JOINT AND CRACK CLEANING AND SEALING	LFT(m)	250(75)
LAYING SIGNAL CONDUIT	LFT(m)	230(70)
MARKINGS	LFT(m)	7,660(2,335)
PAVED SIDE DITCH	LFT(m)	400(120)
PIPES, CULVERTS	LFT(m)	230(70)
PIPES, UNDERDRAINS	LFT(m)	1,160(355)
QC/QA HMA SURFACE, MAINLINE	TONS(Mg)	1,010(915)
REINFORCED CEMENT CONCRETE PAVEMENT	SYS(m ²)	170(140)
RIP-RAP	TONS(Mg)	260(235)
RUBBLIZING PAVEMENT	SYS(m ²)	3,290(2,750)
SEAL COAT	SYS(m ²)	12,990(10,860)
SIGN,PANEL,ENCAPSULATED LENS WITH LEGEND	LFT(m)	580(175)
SLOPE WALL	SYS(m ²)	53(44)
SODDING	SYS(m ²)	1,060(885)
SOIL STABILIZATION	CYS(m³)	4,930(3,770)
SUBBASE	TONS(Mg)	920(835)
TEMP. CONC. BARRIER	LFT(m)	2,780(845)
UNDERSEAL	TONS(Mg)	47(43)

TABLE 2-15 Mean Baseline Production Rates (Bridges)

CONSTRUCTION ACTIVITY	UNIT	MEAN BASELINE PRODUCTION RATES
BRIDGES		
BEAM ERECTION-PRECAST	LFT(m)	420(130)
BEAM ERECTION-STEEL	LFT(m)	160(50)
BENT COFFERDAMS	SYS(m ²)	320(270)
BRIDGE BARRIER	LFT(m)	80(24)
BRIDGE DECK	CYS(m ³)	16(12)
BRIDGE DECK OVERLAY	SYS(m ²)	490(410)
BRIDGE HANDRAILS	LFT(m)	240(75)
BRIDGE RAIL	LFT(m)	640(195)
CLASS "A" CONCRETE IN STR'S	CYS(m ³)	180(140)
CLASS "B" CONCRETE IN STR'S	CYS(m ³)	110(85)
CONCRETE, C, IN SUPERSTRUCTURE	CYS(m ³)	86(65)
CONSTRUCT FILL	CYS(m ³)	530(405)
DITCH PAVING	SYS(m ²)	210(175)
FLOWABLE MORTAR	CYS(m ³)	160(120)
FOOTINGS	CYS(m ³)	31(24)
PARAPET	LFT(m)	100(30)
PILING	LFT(m)	330(100)
PLACE BITUMINOUS	TONS(Mg)	1,390(1,260)
PLACE COMPACTED AGGREGATE	CYS(m ³)	2,190(1,675)
PLACE DECK W/O SUPPORT CUTTOUTS	TONS(Mg)	160(145)
PRISMATIC REFLECTOR	EACH	940
REBAR	LBS(Kg)	21,640(9,825)
REINFORCED CONCRETE APPROACHES	CYS(m ³)	32(24)
REINFORCEMENT BARS (SUBSTRUCTURE)	LBS(Kg)	2,680(1,215)
REINFORCEMENT BARS (SUPERSTRUCTURE)	LBS(Kg)	5,420(2,460)
REINFORCING STEEL	LBS(Kg)	16,360(7,425)
REINFORCING STEEL, EPOXY COATED	LBS(Kg)	9,400(4,270)
RETAINING WALLS	SYS(m ²)	18(15)
SIGN SMALL	EACH	22
WINGWALLS	SYS(m ²)	19(16)

TABLE 2-16 Mean Baseline Production Rates (Excavations)

CONSTRUCTION ACTIVITY DESCRIPTION	UNIT	MEAN BASELINE PRODUCTION RATES
EXCAVATIONS		
BORROW	CYS(m ³)	1,070(820)
BORROW LARGE AREAS	CYS(m ³)	2,810(2,150)
CHANNEL	CYS(m ³)	660(505)
COMMON SMALL AREAS	CYS(m ³)	540(415)
PEAT	CYS(m ³)	880(675)
ROCK	CYS(m ³)	1,180(905)
SUBBALLAST	TONS(Mg)	290(265)
SUBGRADE TREATMENT	CYS(m ³)	1,180(905)
UNCLASSIFIED	CYS(m ³)	3,620(2,770)
WATERWAY	CYS(m ³)	720(550)
WET	CYS(m ³)	90(69)

TABLE 2-17 Mean Baseline Production Rates (Removals)

CONSTRUCTION ACTIVITY DESCRIPTION	UNIT	MEAN BASELINE PRODUCTION RATES
REMOVALS		
CURB & GUTTER	LFT(m)	880(270)
FENCE	LFT(m)	180(55)
PAVEMENT (CONC.)	SYS(m ²)	940(785)
SIDEWALK	SYS(m ²)	1,730(1,445)
STUMP	EACH	14
SURFACE (MILLING)	SYS(m ²)	11,600(9,700)
TOP SOIL	CYS(m ³)	390(300)

2.5 Factors Affecting Production Rates

Production rates of highway construction are affected by many factors. Under different conditions, production rates may vary considerably because of the effects of these factors. Based on the INDOT construction data, it was identified that the major factors affecting production rates might include construction firms or contractors, locations of projects, and weather conditions. The effects of these factors were analyzed to determine their significance. In addition, the changes of production rates over time were examined to exhibit the trend of productivity improvement.

2.5.1 Effects of Construction Firms/Contractors: Construction firms or contractors differ in many aspects, such as management, labor skills, equipment, construction methods and techniques. Therefore, it was expected that the production rates were different for different construction firms. To examine the effects of construction firms, the production rates of two construction activities from ten construction firms are shown in Figures 2-2 and 2-3. The two figures indicate that the production rates vary for different construction firms. By comparing the two figures, it can be seen that a firm's low production rate in one construction activity does not necessarily mean it is also low in another construction activity. For example, the ninth construction firm had a low production rate in "bituminous widening" (Figure 2-2), but had a relatively high production rate in "class B concrete in structure." This implies that the productivity of a particular construction activity may not represent the overall productivity of a construction firm.

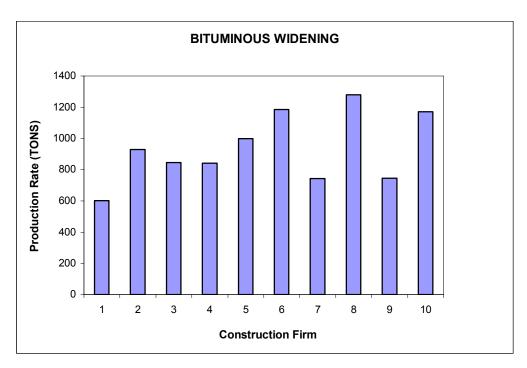


Figure 2-2 Production Rates of Different Contractors

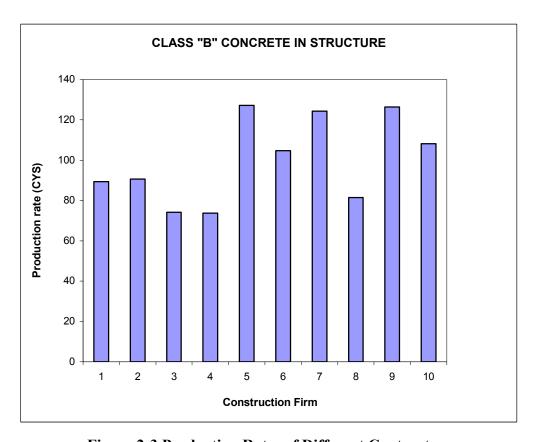


Figure 2-3 Production Rates of Different Contractors

To determine the significance of the differences in production rates of construction firms, t statistical test can be performed. To test if the production rates of any two firms are statistically equal, it is to choose between two alternatives about mean μ_1 and μ_2 of two populations:

 H_0 : $\mu_1 = \mu_2$, and

 H_a : $\mu_1 \neq \mu_2$.

The decision rule is:

If $|t^*| \le t(1-\alpha/2; n_1+n_2-2)$, conclude H_0 ; if $|t^*| > t(1-\alpha/2; n_1+n_2-2)$, conclude H_a .

where:

 $\overline{X_1}$ and $\overline{X_2}$ are the means of the samples from population 1 and 2, respectively;

 n_1 and n_2 are the samples sizes from populations 1 and 2, respectively;

 α is the significant level;

$$t^* = \frac{\overline{X_1} - \overline{X_2}}{S_p \left(\frac{1}{n_1} + \frac{1}{n_2}\right)^{0.5}}$$

 S_p is the square root of the pooled variance, which can be calculated as:

$$S_p = \sqrt{\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2}}$$

where:

 S_1^2 and S_2^2 are the variances of the samples from population 1 and 2, respectively.

Based on the t test procedure, the mean production rates were compared among all of the major construction firms with a significant level of 0.05. The test results

indicate that the production rates are statistically different for different construction firms.

Therefore, construction firms have significant effects on highway production rates.

2.5.2 Effects of Construction Project Locations: The locations of highway construction projects are classified as urban and rural in INDOT highway construction data base. Whether a highway construction project is located in urban or in rural area may affect material supply, distance of material delivery, cycle time of delivery trucks, The statistical tests to determine mean traffic condition, and work zone layout. production rates at urban and rural locations were performed. Based on the test results, it is concluded that the production rates differ significantly in urban and rural areas. The production rates in urban and rural areas for major highway construction activities are listed in Table 2-18. Generally, the production rates in rural areas are higher than those in urban areas. This should be attributed to the fact that the traffic volumes in urban areas are much higher that those in rural areas. The traffic conditions in urban areas would require different traffic control, limit the number of roadway lanes to be closed for construction, cause traffic congestion and material delivery delays, and put more restrictions on time periods for construction. Table 2-18 provides a useful source when specific productivity information is needed in terms project locations for construction process management and planning.

TABLE 2-18 Production Rates in Urban and Rural Areas

Construction Activity	Locations					
Construction Activity	Urban	Rural				
BACKFILL, ROCK	560(TONS)	600(TONS)				
BITUMINOUS APPROACHES	200(TONS)	260(TONS)				
BITUMINOUS BASE	760(TONS)	900(TONS)				
BITUMINOUS BINDER	1,130(TONS)	1,230(TONS)				
BITUMINOUS BINDER WITH FIBERS	1,670(TONS)	2,000(TONS)				
BITUMINOUS PATCHING	60(TONS)	80(TONS)				
BITUMINOUS SURFACE	1,000(TONS)	1,120(TONS)				
BITUMINOUS WEDGE AND LEVEL	510(TONS)	610(TONS)				
BITUMINOUS WIDENING	910(TONS)	960(TONS)				
BORROW	890(CYS)	1,100(CYS)				
BRIDGE DECK OVERLAY	340(SYS)	370(SYS)				
COMPACTED AGGREGATE FOR BASE	270(TONS)	420(TONS)				
COMPACTED AGGREGATE FOR SHOULDER	420(TONS)	540(TONS)				
CONCRETE PATCHING	110(SYS)	130(SYS)				
CONCRETE PAVEMENT	2,680(SYS)	3,100(SYS)				
CONCRETE SIDEWALK	1,060(SYS)	1,090(SYS)				
CURB AND GUTTER	290(LFT)	360(LFT)				
CURB AND GUTTER, COMBINED	310(LFT)	350(LFT)				
CURB RAMP, CONCRETE	20(SYS)	28(SYS)				
EMBANKMENT	2,170(CYS)	2,600(CYS)				
EXCAVATION, COMMON SMALL AREAS	490(CYS)	540(CYS)				
EXCAVATION, SUBGRADE TREATMENT	1,140(CYS)	1,180(CYS)				
EXCAVATION, UNCLASSIFIED	3,270(CYS)	3,640(CYS)				
EXCAVATION, WATERWAY	620(CYS)	700(CYS)				
GABIONS	76(CYS)	82(CYS)				
GEOTEXTILES	470(SYS)	540(SYS)				
GEOTEXTILES FOR UNDERDRAIN	140(SYS)	170(SYS)				
REMOVAL, CURB & GUTTER	780(LFT)	960(LFT)				
REMOVAL, PAVEMENT (CONC.)	870(SYS)	980(SYS)				
REMOVAL, SIDEWALK	1,580(SYS)	1,820(SYS)				
RIP-RAP	200(TONS)	260(TONS)				
SODDING	990(SYS)	1,040(SYS)				
SUBBALLAST	250(TONS)	290(TONS)				
SUBBASE	840(TONS)	890(TONS)				
SURFACE MILLING, BITUMINOUS	2,860(SYS)	3,400(SYS)				

2.5.3 Effects of Weather Conditions: Adverse climatic conditions negatively affect many highway construction activities. Some highway construction operations can not be performed under certain weather conditions. For example, both HMA and Portland cement concrete pavements should not be placed when the air temperature is below a certain level. Also, soil stabilization with lime should not be operated under windy conditions. Moreover, highway construction production rates will not be the same under different weather conditions. Weather conditions may be represented by individual or combined indices, including air temperature, relative humidity, wind velocity, barometric pressure, and precipitation. In this study, only the air temperature information was available from the INDOT construction daily reports. Therefore, only the effects of air temperatures were analyzed. The production rates at different air temperatures are listed in Table 2-19. As can be seen in the table, the highest production rates occurred at air temperature between 70 and 80°F. As temperature increased to 95°F, most of the production rates decreased in comparison with those at 70 or 80°F. Apparently, this is attributed to the comfortable level of construction workers because most people would feel most comfortable at around 70°F. Figure 2-4 is plotted with selected two production activities to illustrate the changes of production rates with air temperatures. The two curves exhibit that the production rates increase as the air temperature increases up to 70°F. Then the production rates tend to slowly decrease beyond 70°F.

TABLE 2-19 Production Rates at Different Temperatures

O a material to the Antibelia	1114	Temperature (°F)								
Construction Activity	Unit	10	20	30	40	50	60	70	80	95
BACKFILL, ROCK	TON	400	470	520	550	580	600	620	610	590
BITUMINOUS APPROACHES	TON	-	-	-	220	220	230	230	220	220
BITUMINOUS BASE	TON	-	-	-	-	810	820	840	820	810
BITUMINOUS BINDER	TON	-	-	-	-	1,160	1,160	1,190	1,150	1,150
BITUMINOUS BINDER WITH FIBERS	TON	-	1	-	1,760	1,810	1,830	1,890	1,810	1,810
BITUMINOUS PATCHING	TON	-	ı	-	62	65	71	74	76	75
BITUMINOUS SURFACE	TON	-	-	-	1,020	1,060	1,080	1,080	1,070	1,070
BITUMINOUS WEDGE AND LEVEL	TON	-	-	-	540	550	560	580	560	550
BITUMINOUS WIDENING	TON	-	-	-	800	890	920	960	940	930
BORROW	CYS	700	800	900	950	990	1,010	1,040	1020	1020
BRIDGE DECK OVERLAY	SYS	250	290	320	340	360	390	400	390	380
COMPACTED AGGREGATE FOR BASE	TON	240	280	310	330	370	390	410	400	380
COMPACTED AGGREGATE FOR SHOULDER	TON	340	390	440	470	490	510	540	520	500
CONCRETE PATCHING	SYS	-	-	-	100	110	120	130	120	120
CONCRETE PAVEMENT	SYS	-	-	2,410	2,610	2,810	2,940	3,000	2,980	2,960
CONCRETE SIDEWALK	SYS	-	ı	1,100	1,170	1,200	1,230	1,300	1,280	1,260
CONTRACTION JOINT	LFT	200	240	260	280	290	310	330	320	300
CRACKS, TRANSVERSE, ROUT CLEAN AND SEAL	LFT	6,42 0	7,430	8,260	8,810	9,170	9,240	9,310	9,280	9,250
CURB AND GUTTER	LFT	-	-	210	270	320	350	360	340	330
CURB AND GUTTER, COMBINED	LFT	-	-	210	260	310	340	350	340	330
CURB, INTEGRAL, C, CONCRETE	LFT	-	-	180	190	200	210	220	220	200
CURB RAMP, CONCRETE	SYS	-	-	22	23	24	24	24	24	23
EMBANKMENT	CYS	1,67 0	1,930	2,140	2,290	2,380	2,440	2,490	2,470	2,460
EXCAVATION, COMMON SMALL AREAS	CYS	390	420	440	480	510	540	560	550	540
EXCAVATION, ROCK	CYS	790	910	1,010	1,080	1,100	1,110	1,150	1,130	1,120
EXCAVATION, SUBGRADE TREATMENT	CYS	820	940	1,050	1,120	1,170	1,200	1,290	1,290	1,260
EXCAVATION, UNCLASSIFIED	CYS	2,42 0	2,800	3,110	3,320	3,460	3,640	3,700	3,690	3,690
EXCAVATION, WATERWAY	CYS	460	540	600	640	660	700	720	710	690
EXCAVATION, WET	CYS	59	68	76	81	88	94	108	102	99
GABIONS	CYS	55	64	71	76	81	89	92	90	87
GEOTEXTILES	SYS	350	410	450	480	500	540	570	560	550
GEOTEXTILES FOR UNDERDRAIN	SYS	110	120	140	150	160	180	200	190	170

TABLE 2-19 (continued)

Construction Activity	Unit	Temperature (°F)								
Construction Activity	Unit	10	20	30	40	50	60	70	80	95
GUARDRAIL	LFT	360	420	470	500	500	510	530	520	510
GUARDRAIL, CHANNEL	LFT	170	200	220	230	250	260	290	270	250
GUARDRAIL, RESET	LFT	270	310	340	370	390	400	460	440	420
HMA INTERMEDIATE, MAINLINE	TON	-	-	-	1,340	1,370	1,400	1,420	1,410	1,390
JOINT AND CRACK CLEANING AND SEALING	LFT	140	170	190	200	210	240	290	270	260
PRISMATIC REFLECTOR	EACH	650	750	830	890	920	970	1,020	1,010	990
QC/QA HMA SURFACE 9.5 mm, MAINLINE	TON	-	-	-	950	980	990	1,020	1,000	990
REINFORCING STEEL, EPOXY COATED	LBS	6,45 0	7,470	8,300	8,850	9,230	9,290	9,360	9,340	9,310
REMOVAL, CURB & GUTTER	LFT	610	700	780	830	840	880	910	890	860
REMOVAL, FENCE	LFT	100	120	130	140	150	160	160	150	150
REMOVAL, PAVEMENT (CONC.)	SYS	640	750	830	880	930	950	970	960	960
REMOVAL, SIDEWALK	SYS	1,18 0	1,370	1,520	1,620	1,670	1,680	1,720	1,690	1,660
REMOVAL, STUMP	EACH	8	10	11	12	12	12	14	13	12
RIP-RAP	TON	170	190	210	230	240	260	270	270	260
SIGN,PANEL,ENCAPSULAT ED LENS WITH LEGEND	LFT	400	460	510	540	570	590	620	610	580
SODDING	SYS	660	770	820	990	1,010	1,030	1,070	1,060	1,040
SUBBALLAST	TON	190	220	240	260	270	290	300	280	270
SUBBASE	TON	-	-	690	810	840	870	940	930	920
SURFACE MILLING, BITUMINOUS	SYS	-	-	-	3,000	3,110	3,130	3,160	3,150	3,120
TEMP. CONC. BARRIER	LFT	1,46 0	1,810	2,140	2,260	2,370	2,490	2,650	2,610	2,580
TOP SOIL	CYS	270	310	340	370	380	390	420	410	400

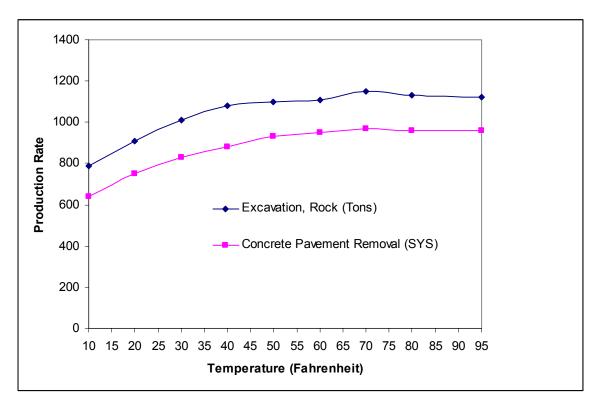


Figure 2-4 Production Rates at Different Air Temperatures

2.5.4 Effects of Seasons: Air temperatures are directly related to the seasons. Thus, the effects of air temperatures on production rates imply that the season is apparently one of the major factors affecting production rates. Table 2-20 summarizes the mean production rates of various highway construction activities in the four seasons. This table reveals that the production rates are highest in the summer and lowest in the winter. As expected, the seasonal production rates indicate that the summer and fall seasons are more suitable for highway constructions than the other two seasons.

TABLE 2-20 Production Rates in Different Seasons

Companyabilan Ashinika	Unit	Season					
Construction Activity	Unit	Spring	Summer	Fall	Winter		
BACKFILL, ROCK	TON	540	630	600	460		
BITUMINOUS APPROACHES	TON	220	240	240	180		
BITUMINOUS BASE	TON	770	890	840	660		
BITUMINOUS BINDER	TON	1130	1260	1230	930		
BITUMINOUS BINDER WITH FIBERS	TON	1740	2010	1930	1470		
BITUMINOUS PATCHING	TON	67	76	73	56		
BITUMINOUS SURFACE	TON	1010	1140	1100	850		
BITUMINOUS WEDGE AND LEVEL	TON	490	570	540	420		
BITUMINOUS WIDENING	TON	890	1010	980	740		
BORROW	CYS	950	1060	1030	790		
BRIDGE DECK OVERLAY	SYS	340	390	370	290		
COMPACTED AGGREGATE FOR BASE	TON	330	380	360	280		
COMPACTED AGGREGATE FOR SHOULDER	TON	450	540	510	390		
CONCRETE PATCHING	SYS	120	140	120	90		
CONCRETE PAVEMENT	SYS	2710	3200	2990	2270		
CONCRETE SIDEWALK	SYS	1010	1180	1120	860		
CONTRACTION JOINT	LFT	280	310	300	230		
CRACKS, TRANSVERSE, ROUT CLEAN AND SEAL	LFT	8710	9910	9540	7300		
CURB AND GUTTER	LFT	310	360	340	260		
CURB AND GUTTER, COMBINED	LFT	320	340	340	270		
CURB, INTEGRAL, C, CONCRETE	LFT	190	220	210	160		
CURB RAMP, CONCRETE	SYS	23	26	25	19		
EMBANKMENT	CYS	2240	2570	2460	1890		
EXCAVATION, COMMON SMALL AREAS	CYS	490	570	540	420		
EXCAVATION, ROCK	CYS	1080	1210	1180	900		
EXCAVATION, SUBGRADE TREATMENT	CYS	1090	1260	1190	930		
EXCAVATION, UNCLASSIFIED	CYS	3290	3720	3610	2750		
EXCAVATION, WATERWAY	CYS	630	720	680	530		
EXCAVATION, WET	CYS	76	86	83	64		
GABIONS	CYS	74	87	82	64		
GEOTEXTILES	SYS	480	540	520	400		
GEOTEXTILES FOR UNDERDRAIN	SYS	130	160	160	120		
GUARDRAIL	LFT	490	570	540	420		
GUARDRAIL, CHANNEL	LFT	230	260	240	190		
GUARDRAIL, RESET	LFT	340	410	400	300		

TABLE 2-20 (continued)

Construction Activity	Unit	Season					
Construction Activity	Oilit	Spring	Summer	Fall	Winter		
HMA INTERMEDIATE, MAINLINE	TON	1330	1510	1460	1120		
JOINT AND CRACK CLEANING AND SEALING	LFT	200	230	210	170		
PRISMATIC REFLECTOR	EACH	860	1010	970	730		
QC/QA HMA SURFACE 9.5 mm, MAINLINE	TON	930	1060	1020	780		
REINFORCING STEEL, EPOXY COATED	LBS	8740	9940	9400	7340		
REMOVAL, CURB & GUTTER	LFT	810	930	890	690		
REMOVAL, FENCE	LFT	140	160	160	120		
REMOVAL, PAVEMENT (CONC.)	SYS	870	990	940	740		
REMOVAL, SIDEWALK	SYS	1610	1810	1760	1340		
REMOVAL, STUMP	EACH	11	13	12	10		
RIP-RAP	TON	230	260	250	190		
SIGN,PANEL,ENCAPSULATED LENS WITH LEGEND	LFT	520	610	580	450		
SODDING	SYS	960	1100	1060	820		
SUBBALLAST	TON	260	290	280	220		
SUBBASE	TON	820	930	880	690		
SURFACE MILLING, BITUMINOUS	SYS	2970	3360	3220	2490		
TEMP. CONC. BARRIER	LFT	2460	2800	2690	2080		
TOP SOIL	CYS	350	410	390	310		

2.5.5 Trend of Production Rates: Although the change in highway construction is relatively slow, the construction industry has been inevitably influenced by the improvements in technology, materials, and management. Therefore, the efficiency of highway construction is expected to increase with time. In order to examine the trend of highway construction productivity, the mean production rates of major highway construction activities are shown in Table 2-21 for a period of consecutive seven years (between 1995 and 2001). In addition, Figure 2-5 is plotted with the mean production rates of three selected highway construction activities for the seven years. Both the table and the figure illustrate that production rates followed a gradually increasing trend. This proves that highway construction efficiency has been gradually and stably improving. It is therefore necessary to update the highway construction production rates periodically.

TABLE 2-21 Production Rates in Different Years

Our street in Anticipa	1114	Year								
Construction Activity	Unit	1995	1996	1997	1998	1999	2000	2001		
BACKFILL, ROCK	TON	560	570	580	580	600	610	620		
BITUMINOUS APPROACHES	TON	220	220	230	230	220	220	230		
BITUMINOUS BASE	TON	790	810	830	840	840	860	860		
BITUMINOUS BINDER	TON	1,120	1,140	1,140	1,160	1,170	1,180	1,190		
BITUMINOUS BINDER WITH FIBERS	TON	1,770	1,780	1,830	1,840	1,850	1,870	1,890		
BITUMINOUS PATCHING	TON	61	64	68	73	76	76	77		
BITUMINOUS SURFACE	TON	1,020	1,040	1,050	1,070	1,070	1,080	1,090		
BITUMINOUS WEDGE AND LEVEL	TON	500	510	510	520	530	550	560		
BITUMINOUS WIDENING	TON	900	920	920	940	940	950	950		
BORROW	CYS	960	980	990	1,000	1,010	1,030	1,050		
BRIDGE DECK OVERLAY	SYS	290	320	340	360	390	400	380		
COMPACTED AGGREGATE FOR BASE	TON	310	340	370	380	390	400	410		
COMPACTED AGGREGATE FOR SHOULDER	TON	390	440	470	490	510	520	540		
CONCRETE PATCHING	SYS	100	110	110	120	130	130	140		
CONCRETE PAVEMENT	SYS	2,630	2,700	2,770	2,810	2,870	2,940	2,940		
CONCRETE SIDEWALK	SYS	1,010	1,030	1,060	1,080	1,080	1,100	1,120		
CONTRACTION JOINT	LFT	240	270	280	300	310	320	340		
CRACKS, TRANSVERSE, ROUT CLEAN AND SEAL	LFT	7,630	8,280	8,610	8,820	8,990	9,170	9,300		
CURB AND GUTTER	LFT	290	310	320	340	340	360	370		
CURB AND GUTTER, COMBINED	LFT	300	310	310	330	350	370	370		
CURB, INTEGRAL, C, CONCRETE	LFT	180	190	210	210	210	220	230		
CURB RAMP, CONCRETE	SYS	22	23	24	24	24	24	24		
EMBANKMENT	CYS	2,290	2,300	2,350	2,380	2,440	2,490	2,490		
EXCAVATION, COMMON SMALL AREAS	CYS	490	510	510	520	540	540	550		
EXCAVATION, ROCK	CYS	1,060	1,090	1,100	1,120	1,120	1,140	1,150		
EXCAVATION, SUBGRADE TREATMENT	CYS	1,170	1,190	1,210	1,270	1,280	1,300	1,300		
EXCAVATION, UNCLASSIFIED	CYS	3,320	3,410	3,480	3,520	3,580	3,640	3,700		
EXCAVATION, WATERWAY	CYS	640	660	680	700	700	710	720		
EXCAVATION, WET	CYS	76	82	89	96	100	104	109		
GABIONS	CYS	68	71	74	78	83	88	92		
GEOTEXTILES	SYS	500	520	540	550	560	560	570		
GEOTEXTILES FOR UNDERDRAIN	SYS	130	130	140	150	150	170	170		

TABLE 2-21 (continued)

Construction Activity	Unit	Year							
Construction Activity	Uiiit	1995	1996	1997	1998	1999	2000	2001	
GUARDRAIL	LFT	460	480	480	500	510	510	530	
GUARDRAIL, CHANNEL	LFT	200	220	230	250	260	270	300	
GUARDRAIL, RESET	LFT	320	350	370	390	400	420	460	
HMA INTERMEDIATE, MAINLINE	TON	1,340	1,370	1,380	1,390	1,400	1,410	1,420	
JOINT AND CRACK CLEANING AND SEALING	LFT	180	180	200	210	250	280	290	
PRISMATIC REFLECTOR	EAC H	890	910	940	960	980	1,000	1,020	
QC/QA HMA SURFACE, MAINLINE	TON	960	980	990	1,000	1,010	1,010	1,020	
REINFORCING STEEL, EPOXY COATED	LBS	8,860	8,730	8,840	9,010	9,120	9,270	9,370	
REMOVAL, CURB & GUTTER	LFT	730	750	780	800	840	880	910	
REMOVAL, FENCE	LFT	120	130	140	150	160	160	140	
REMOVAL, PAVEMENT (CONC.)	SYS	880	900	920	940	960	970	970	
REMOVAL, SIDEWALK	SYS	1,520	1,570	1,620	1,670	1,680	1,700	1,730	
REMOVAL, STUMP	EAC H	10	11	12	12	12	13	14	
RIP-RAP	TON	210	210	220	230	240	260	260	
SIGN,PANEL,ENCAPSULATED LENS WITH LEGEND	LFT	540	560	570	590	600	600	620	
SODDING	SYS	980	1,000	1,010	1,030	1,030	1,040	1,060	
SUBBALLAST	TON	240	250	270	270	280	280	290	
SUBBASE	TON	820	830	830	860	860	880	880	
SURFACE MILLING, BITUMINOUS	SYS	3,010	3,030	3,070	3,090	3,140	3,170	3,200	
TEMP. CONC. BARRIER	LFT	2,540	2,560	2,570	2,570	2,600	2,610	2,610	
TOP SOIL	CYS	370	370	390	400	400	410	420	

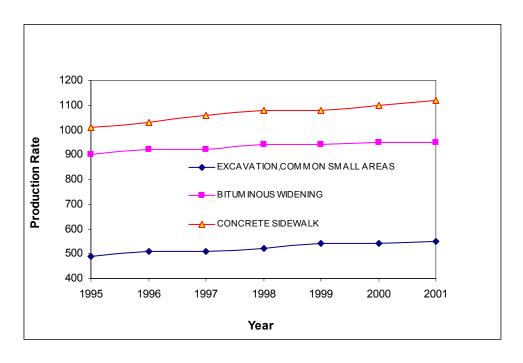


Figure 2-5 Production Rate Change Trend

2.6 Database File of Production Rates

The various forms of production rates presented in this chapter are stored in a file of Microsoft Access 2000, named "Production Rates.mdb". Double click the file, the following window will be shown with a list of tables.

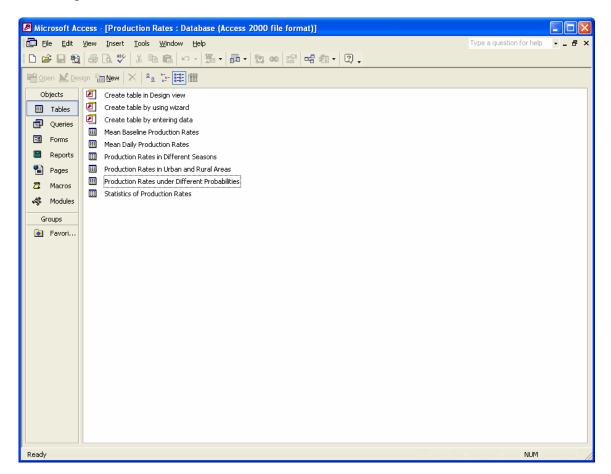


Figure 2-6 Production Rate File Window

To open any of the tables, click the table name and the production rates will be shown. The following window is an opened table, containing production rates and their units.

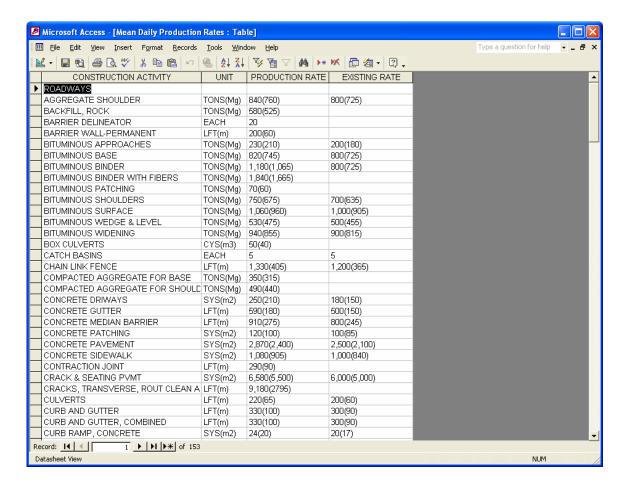


Figure 2-7 Production Rates in Access File

CHAPTER 3 DURATIONS OF HIGHWAY CONSTRUCTION PROJECTS

Contract time is the estimated duration of a highway construction project from the beginning to completion of the construction activities. In this study, contract time is defined as the number of 8-hour working days required to complete a construction project. To set up reasonable contract times, it is essential to understand the characteristics of durations of highway construction projects. Therefore, statistical analysis was conducted to determine the statistical characteristics of actual construction durations of INDOT highway construction projects. The results of the statistical analysis would then provide a basis for contract time estimation. This chapter presents the results of statistical analysis of construction durations based on the data recorded in the eight-year INDOT Construction Daily Reports.

3.1 Statistical Characteristics of Highway Construction Durations

The INDOT construction data contains the information on construction durations of highway projects. The means and standard deviations of construction durations of the major types of highway construction were obtained from the construction data as shown in Table 3-1. It should be pointed out that the values in this table were calculated from the INDOT highway projects of all sizes and thus the standard deviations are relatively large. Nevertheless, these values provide general information on average length and disperse range of highway construction durations. The large disperse ranges represented

by large standard deviations are expected because the highway construction projects vary in many aspects, including magnitudes, locations, and contractors.

TABLE 3-1 Means and Standard Deviations of Construction Durations

Type of Construction	Mean Duration (Working Days)	Standard Deviation (Working Days)
Asphalt Resurface	49	24
Bridge Painting	96	52
Bridge Rehabilitation (Deck Replacement)	97	38
Bridge Rehabilitation (Superstructure Repair)	84	28
Bridge Removal	123	31
Bridge Replacement (CR)	98	27
Bridge Replacement (SR)	105	29
Bridge Replacement (US)	121	45
Full Depth Patching, Concrete	36	19
Intersection Improvement	43	20
Milling and Asphalt Resurface	42	34
Mill Surface and Bituminous Overlay	53	37
New Road Construction	124	55
New Signal Installation	39	16
Pavement Rehabilitation	119	38
Road Rehabilitation	99	30
Small Structure Replacement (SR)	57	38
Small Structure Replacement (US)	54	39
Traffic Signal Modernization	70	33
Wedge and Level	26	12

3.2 Distributions of Construction Durations

Other than the mean and standard deviation values, the distributions of construction durations are also important for describe the statewide construction durations of the INDOT highway construction projects. A frequency distribution of construction durations exhibits the number of projects for various lengths of construction durations. A plot of frequency distribution provides a graphical description of construction durations for a given type of highway construction. Figures 3-1 and 3-2 are two examples of frequency distributions of construction durations. Figure 3-1 shows the

frequency distribution of construction durations of asphalt resurface projects, and Figure 3-2 shows that of bridge replacement projects on Indiana state roads. As can be seen from Figure 3-1, the construction durations ranged from 20 to 120 working days for asphalt resurface projects, while most of the projects were completed in about 40, 60 and 80 working days. As shown in Figure 3-2, the construction durations ranged from 60 to 160 days for bridge replacement projects on Indiana state roads. This highest construction duration frequency was 100 working days for the bridge replacement projects. Many of the bridge replacement projects were completed in about 140, 120, and 80 working days.

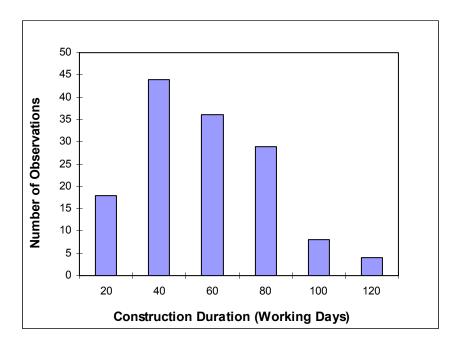


Figure 3-1 Distribution of Construction Durations of Asphalt Resurface Projects

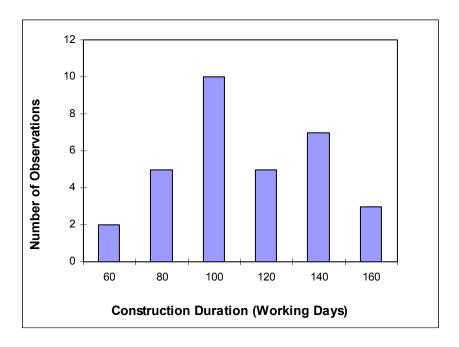


Figure 3-2 Distribution of Construction Durations of Bridge Replacement Projects on State Roads

With a plot of frequency distribution, a possible statistical distribution model can be selected and then a goodness-of-fit test can be performed to determine if the selected model is appropriate for the given type of highway construction project. For the types of highway construction projects with sufficient data, appropriate distribution models were selected and tested for goodness-of-fit. Table 3-2 lists the appropriate distribution models of construction durations for several types of highway projects with their corresponding χ^2 goodness-of-fit test results. All the distribution models in Table 3-2 are accepted as appropriate by the goodness-of-fit test with a significant level of $\alpha = 0.05$.

TABLE 3-2 Goodness-of-Fit Tests for Construction Duration Distributions

Type of Project	Model of Distribution	χ^2	$\chi^2_{1-\alpha}(\mathbf{k}-\mathbf{j}-1)$
Asphalt Resurface	Exponential Distribution	2.919	5.991
Bridge Rehabilitation (Deck Replacement)	Lognormal Distribution	3.872	9.488
Bridge Rehabilitation (Superstructure Repair)	Lognormal Distribution	6.628	6.815
Bridge Replacement (CR)	Normal Distribution	6.374	6.815
Bridge Replacement (SR)	Normal Distribution	5.662	6.815
Intersection Improvement	Exponential Distribution	3.741	6.815
Small Structure Replacement	Exponential Distribution	0.606	6.815

3.3 Unit Construction Durations

As discussed above, the statistics and distributions of construction durations provide a general description of time lengths of INDOT highway construction projects. However, construction durations of different projects are not comparable based on these values because highway construction projects vary considerably in magnitudes. Therefore, it is desirable to use a more reasonable measure to represent construction durations, so that they can be compared on a common basis.

It was believed that unit construction duration in terms working days per unit of constructed quantity would be a reasonable measure. Based on the construction data, it was found that the unit quantity could be working days per lane-mile for roadway projects and working days per foot for bridge projects. The calculated unit construction durations for different types of highway construction projects are included in Table 3-3. The values of the means and standard deviations in Table 3-3 can be used to roughly estimate contract time for the given type of project by multiplying mean by the actual length of the project.

TABLE 3-3 Unit Construction Durations

Type of Project	Mean	Standard Deviation
Added Travel Lanes	27 (working days per lane-mile)	8 (working days per lane-mile)
Asphalt Resurface	8 (working days per lane-mile)	7 (working days per lane-mile)
Bridge Rehabilitation (Deck Replacement)	0.82 (working days per foot)	0.20 (working days per foot)
Bridge Rehabilitation (Superstructure Repair)	1.02 (working days per foot)	0.24 (working days per foot)
Bridge Replacement (County Roads)	0.94 (working days per foot)	0.24 (working days per foot)
Bridge Replacement (State Roads)	1.02 (working days per foot)	0.26 (working days per foot)
Bridge Replacement (US Highways)	1.09 (working days per foot)	0.19 (working days per foot)
Intersection Improvement	17 (working days per lane-mile)	12 (working days per lane-mile)
Milling and Asphalt Resurface	13 (working days per lane-mile)	6 (working days per lane-mile)
Mill Surface and Bituminous Overlay	12 (working days per lane-mile)	4 (working days per lane-mile)
New Road Construction	33 (working days per lane-mile)	12 (working days per lane-mile)
Pavement Repair or Rehabilitation	26 (working days per lane-mile)	10 (working days per lane-mile)
Road Rehabilitation	32 (working days per lane-mile)	10 (working days per lane-mile)
Steel Bridge Replacement	1.16 (working days per foot)	0.26 (working days per foot)
Traffic Sign Modernization	11 (working days per lane-mile)	3 (working days per lane-mile)
Wedge and Level	4 (working days per lane-mile)	4 (working days per lane-mile)

It is understandable that some of the unit construction durations have relatively large standard deviations because construction durations are affected by many factors besides project magnitude. However, with the values of standard deviations, the confidence intervals for the mean unit construction durations can be obtained. The 95% confidence intervals for the mean unit construction durations are shown in Table 3-4. The intervals in this table indicate that with a 95% confidence level the estimated mean construction durations should be within the given ranges.

TABLE 3-4 Confidence Intervals for Unit Construction Durations

Project Description	95% Confidence Interval
Added Travel Lanes	19 ≤ µ ≤ 35
Asphalt Resurface	7 ≤ µ ≤ 9
Bridge Rehabilitation (Deck Replacement)	0.78 ≤ µ ≤ 0.86
Bridge Rehabilitation (Superstructure Repair)	0.96 ≤ µ ≤ 1.08
Bridge Replacement (County Roads)	0.86 ≤ µ ≤ 1.02
Bridge Replacement (State Roads)	0.92 ≤ µ ≤ 1.12
Bridge Replacement (US Highways)	0.98 ≤ µ ≤ 1.20
Intersection Improvement	11 ≤ µ ≤ 23
Milling and Asphalt Resurface	8 ≤ µ ≤ 18
Mill Surface and Bituminous Overlay	7 ≤ µ ≤ 17
New Road Construction	22 ≤ µ ≤ 44
Pavement Repair or Rehabilitation	19 ≤ µ ≤ 33
Road Rehabilitation	24 ≤ µ ≤ 40
Steel Bridge Replacement	0.92 ≤ µ ≤ 1.40
Traffic Sign Modernization	8 ≤ µ ≤ 14
Wedge and Level	2 ≤ µ ≤ 6

3.4 Factors Affecting Construction Durations

Higher production rates will certainly result in shorter construction durations. It is obvious that construction durations will be affected by all the factors that would affect highway production rates. As discussed in Chapter 2, productions rates are influenced by such factors as construction firms, locations of projects, and weather conditions. Construction durations are also affected by these factors because the direct relationship between production rates and construction durations. Moreover, construction durations include not only the days when construction activities were actually performed, but also the days when construction activities could not be performed because of adverse weather conditions or any other reasons. Thus, the number of non-working days, which is not reflected in production rates, is also part of construction duration.

The actual construction duration of a highway construction project is greatly affected by the specified contract time in the contract. A contract time is determined primarily by the magnitude and complexity of the highway construction project. Furthermore, other factors, such as the type of highway and traffic volume, are also considered in setting contract times in order to minimize the construction effects on motorists and adjacent businesses. To complete a construction project within the required contract time, a contractor may have to utilize extra resources if necessary, including extra working hours per day, equipment, materials and manpower. Based on the available information in the INDOT construction data, the effects of type of highway, traffic volume, and weather condition on construction durations are examined as follows:

3.4.1 Effects of Type of Highway: Practically, there are no identical highway construction projects in terms of design, magnitude, and complexity. To compare the construction durations of different construction projects, there must be a common basis for the projects to be comparable. It was found that total construction costs could be used as a reasonable common basis for construction duration comparisons, because construction costs are directly related to the magnitude and complexity of construction projects. The type of highway is an important factor of construction durations because it is considered to set contract time so that the impact of highway construction on motorists' safety, traffic delay, and business operations can be controlled. Construction projects on highways with higher traffic volumes are often required to have shorter contract times to minimize traffic interruptions caused by construction activities. Based on the INDOT construction data, the analysis showed that construction durations were indeed different for different types of highways. Figure 3-3 presents an example of the effects of types of highways on construction durations. The actual construction durations of bridge replacement projects are shown in the figure with respect to total construction costs for three types of highways. The bridge replacement projects on county roads had consistent longer construction durations than US Routes and State Roads for given total construction costs. The differences clearly reflect the importance of the types of roads in determining contract times because of different levels traffic volumes on the roads. Consequently, the specified contract times influence the actual construction durations because the contractors would utilize their resources according to the contract times.

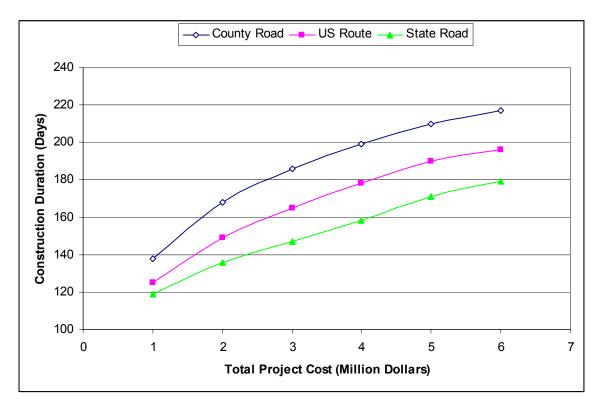


Figure 3-3 Types of Roads and Construction Durations of Bridge Replacements

3.4.2 Weather Conditions: The natural environment strongly influences the progress of construction. Probably the most common cause of project delay is inclement weather. Weather conditions such as snow, cold temperatures, and high winds can substantially affect the times required to do certain types of construction work and often cause non-working days. Among the major weather factors, including temperature, wind speed, and precipitation, only temperature data was recorded in the INDOT construction daily reports. Therefore, only the effect of temperature was examined in this study. The

average number of recorded weather related non-working days in Indiana are listed in Table 3-5 for the typical highway construction months. The non-working days in the table are based on a five-day workweek and exclude weekends and holidays. The average temperatures for these months recorded in the construction data are shown in Table 3-6.

TABLE 3-5 Average Number of Weather Related Non-Working Days

Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Non-working Days	5	3	5	3	1	1	1	3	4
Standard Deviation	3	2	3	2	1	1	2	2	2

TABLE 3-6 Monthly Mean Temperatures (°F)

Month	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Mean Temperature	39.4	48.2	60.5	72.8	75.1	75.9	66.1	56.8	37.6

The relationship between mean temperature and number of non-working days can be seen from Figure 3-4. As the figure clearly indicates, low mean temperatures result in more non-working days. That is, temperature has great effects on non-working days and thus on construction durations. It should be pointed out that precipitation and wind condition also have effects on construction activities, which are not included in this study because of lack of data.

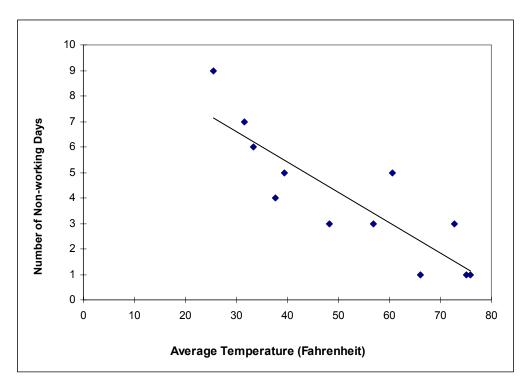


Figure 3-4 Relationship between Average Temperature and Non-working Days

CHAPTER 4 ESTIMATION OF CONTRACT TIME

In the previous chapters, the production rates and construction durations of INDOT highway projects were analyzed with the recorded construction data. Consequently, contract times can be estimated based on the results of production rates and construction durations. A specified contract time affects many aspects of a highway construction project, such as costs, construction management and planning, contractor selection, traffic control strategies, and work zone layout. A proper contract time is critical for highway agencies, contractors, motorists and local businesses. It is because highway construction activities exert impact on traffic conditions, travel delays of motorists, construction schedules, and safety of motorists and construction workers. Contract time sets a time limit for a contractor to complete a highway construction project and therefore directly affects the actual construction duration. It becomes increasingly important for highway construction in this country. As the highway system ages, there are an increasing number of highway construction projects every year, including highway resurfacing, restoration, and rehabilitation and bridge rehabilitation and replacement. In the mean time, traffic volumes are consistently increasing on most of the highways, especially on federal and state highways. Thus, most highway construction activities are being carried out adjacent to traffic, resulting in an increase in the exposure of construction workers and motorists. Consequently, longer contract time or construction duration would create more safety concerns of motorists and construction workers.

In general, contract time can be measured in several different ways:

- Working days, the time that the contractor will be working on the project,
 excluding weekends, holidays and adverse weather related non-working days.
- Calendar days, elapsed time without regard to the contractor's necessarily being on the job.
- Completion dates, a specific date in the calendar year by which the project is to be completed.

In this study, contract time is defined as the number of working days needed to complete a highway construction project. A working day is defined as eight continuous construction hours within a calendar day.

A reasonable contract time for a given highway construction project should be specified so that the contractor can complete the project in time under normal conditions. The contract time depends on the magnitude and complexity of the highway construction project and therefore should be set accordingly. The current methods for setting contract times range from simple procedures to complicated mathematical models. However, almost all of the methods are based on the past experience or historical construction data. Currently, several methods are used to estimate contract time. Two methods were developed in this study based on the INDOT construction data. One of the methods was based on statistical regression and the other was based on the critical path of construction activities.

4.1 Regression Method

Regression is a statistical method that establishes a relationship between a dependent variable and one or more independent variables, which will best fit the historical data of the observed values of the variables. Contract time is used to provide a

reasonable length of time for a contractor to complete a highway construction project. Contract time affects the actual construction duration of the project because the contractor could utilize extra resources, if necessary, in order to complete the project in time. On the other hand, a contract time should be reasonably set based on the amount of construction work so that a contractor can complete the project within the contract time under normal conditions without unusual amount of extra effort and resources. Therefore, the contract time for a construction project should be estimated and set according to the recorded construction durations of past projects with similar amount of work. Because of the complexity of highway construction, construction activities vary considerably for different highway projects. Thus, it is often difficult to find a common measure in terms of amount of materials, manpower or equipment that can be used to compare the quantities of two highway projects. As discussed in the last chapter, total construction cost can be used as a common basis to compare construction durations because it directly reflects the amount of construction work. Since contract times and actual construction durations are closely related, total construction cost should also be a good parameter for The relationship between construction durations and estimating contract time. construction costs can be either linear or nonlinear for different types of highway construction projects. For example, Figure 4-1 illustrates that the construction durations of intersection improvement projects increase with total construction costs in a nonlinear manner. Figure 4-2 shows a linear relationship between construction durations and costs for asphalt resurface projects.

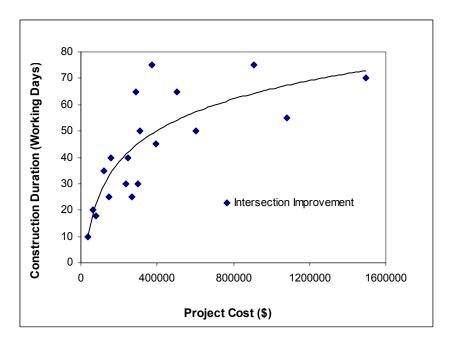


Figure 4-1 Construction Durations for Intersection Improvement Projects

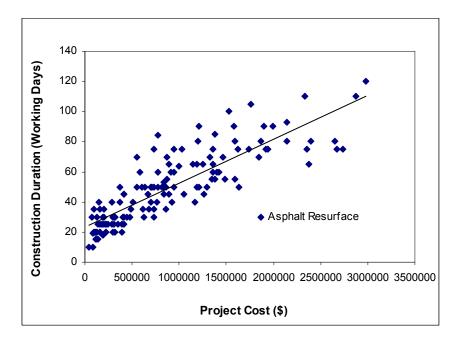


Figure 4-2 Construction Durations of Asphalt Resurface Projects

Depending on the tendency of the construction durations to vary with the total construction costs, linear or nonlinear regression theories can be applied to establish a mathematical relationship. The mathematical model through regression can then be used to estimate the contract time of a given highway project with the estimated total construction cost. For each highway construction project, the highway agency or designer will estimate the total construction cost for budget planning and bid. This estimated cost is in direct proportion to the quantity and complexity of the construction project. The estimated cost can be used to estimate the necessary contract time using the regression equation.

A basic regression model is defined as one independent variable and the regression function is linear (Neter, Wasserman and Hutner, 1985). A basic regression model can be stated as follows:

$$Y_{i} = \beta_{0} + \beta_{1}X_{i} + \varepsilon_{i} \tag{4-1}$$

where:

Y_i is the value of the response in the ith trial or observed value.

 β_0 and β_1 are parameters.

 X_i is a known constant, namely, the value of the independent variable in the ith trial or ovserved value.

 ε_i is a random error a standard normal distribution.

$$i = 1, ..., n$$
.

Nonlinear regression models are those regression equations with nonlinear parameters, such as the exponential model with additive error term:

$$Y_{i} = \beta_{0} \exp(\beta_{1} X_{i}) + \varepsilon_{i}$$
(4-2)

Equation 4-2 is not linear in the parameters β_0 and β_1 . However, there are some models that, though not linear in the parameters, can be transformed so that the parameters appear in linear fashion. An example of such a model is the exponential model with multiplying error:

$$Y_{i} = \beta_{0} [\exp(\beta_{1} X_{i})] \varepsilon_{i}$$
(4-3)

Equation 4-3 is not linear in parameters β_0 and β_1 . However, this model can be transformed into the linear form by using the logarithmic transformation:

$$\ln Y_{i} = \ln \beta_{0} + \beta_{1} X_{i} + \ln \varepsilon_{i}$$
(4-4)

Letting:

$$ln Y_i = Y_i$$

$$\ln \beta_0 = \gamma_0$$

$$\beta_1 = \gamma_1$$

$$\ln \, \epsilon_i = \epsilon_i^{\ ,}$$

Then the original model can be written in the form for a linear model:

$$Y_{i} = \gamma_{0} + \gamma_{1}X_{i} + \varepsilon_{i}$$

$$(4-5)$$

Equation 4-3 is called an intrinsically linear model because it can be expressed in the linear form by suitable transformation.

By examining the scatter data plots of different types of highway construction projects, it was found that linear or intrinsically linear models could be used to represent the relationships between construction durations and total construction costs. The most commonly used method for fitting a regression model to the observed data points is the method of least squares. The method of least squares determines the estimators of β_0 and β_1 in Equation 4-1 by minimizing the sum of the n squared deviation between the observed Y_i and the estimated Y_i :

$$Q = \sum_{i=1}^{n} [Y_i - (\beta_0 + \beta_1 X_i)]^2$$
 (4-6)

where

Q is the sum of n squared deviation.

Y_i is the ith observed value of the dependent variable.

 $\beta_0 + \beta_1 X_i$ is the estimated value of the dependent variable based on the ith observed value of the independent variable X.

Through the method of least squares, the parameters were estimated and the regression equations were derived for the major types of highway construction projects. Table 4-1 presents the regression equations and their corresponding values of correlation coefficients. The absolute value of correlation coefficient ranges from 0 to 1. The larger is the value of correlation coefficient, the better fit is the regression model to the observed data. The values of the correlation coefficients shown in Table 4-1 are fairly high and therefore indicate that the regression models fit well with the actual data. To estimate

contract time, Y, of a particular type of highway construction project, an equation in the table can be used by inputting the estimated total cost, X.

TABLE 4-1 Regression Equations for Contract Time Estimation

Project Type	Sample Size	Regression Equation	Correlation Coefficient
Asphalt Resurface	139	$Y = 3 \times 10^{-5} X + 23.291$	0.855
Bridge Painting	12	Y=0.0164X ^{0.7047}	0.717
Bridge Rehabilitation (Deck Replacement)	28	Y = 35.28Ln(X) - 360.64	0.777
Bridge Rehabilitation (Superstructure Repair)	28	Y = 26.67Ln(X) - 259.2	0.691
Bridge Replacement (US)	14	Y = 41.257Ln(X) - 445.28	0.737
Bridge Replacement (SR)	32	Y = 30.862Ln(X) - 310.53	0.638
Bridge Replacement (CR)	30	Y = 48.795Ln(X) - 537.95	0.727
Intersection Improvement	18	Y = 18.87761Ln(X) - 189.62836	0.817
Mill and Asphalt Resurface	27	$Y = 3 \times 10^{-5} X + 19.894$	0.951
New Road Construction	9	Y = 39.895Ln(X) - 455.48	0.969
Pavement Rehabilitation	9	$Y = 1.2507X^{0.3108}$	0.738
Road Rehabilitation	20	Y = 0.00001675X + 67.211	0.794
Small Structure Replacement (US)	8	$Y = 0.0319X^{0.5866}$	0.841
Small Structure Replacement (SR)	20	$Y = 9 \times 10^{-5} X + 33.696$	0.737
Wedge and Level	29	$Y = 7 \times 10^{-5} X + 10.598$	0.818

Using the regression equation for a given type of highway construction, the estimated contract time Y is actually the mean construction duration for the given construction cost X. As exhibited in Figures 4-1 and 4-2, for a fixed construction cost, there are a number of construction durations scattered around the regression curve. In addition to the mean value, the range of the construction durations can also be statistically estimated for a given confidence level. For 95% confidence level, the prediction intervals (PI) of contract time estimation were computed as shown in Table 4-2. Using the table, the lower bound and upper bound of each prediction interval can be computed by subtracting a value from and adding a value to the estimated contract time Y_{pred} , where Y_{pred} is calculated using the corresponding regression equation from Table 4-1.

TABLE 4-2 Prediction Intervals of Contract Times with 95% Confidence Level

Project Type	Lower Bound	Upper Bound
Asphalt Resurface	Y _{pred} - 10	Y _{pred} + 10
Bridge Painting	Y _{pred} - 30	Y _{pred} + 30
Bridge Rehabilitation (Deck Replacement)	Y _{pred} - 18	Y _{pred} + 18
Bridge Rehabilitation (Superstructure Repair)	Y _{pred} - 16	Y _{pred} + 16
Bridge Replacement (US)	Y _{pred} - 23	Y _{pred} + 23
Bridge Replacement (SR)	Y _{pred} - 19	Y _{pred} + 19
Bridge Replacement (CR)	Y _{pred} - 15	Y _{pred} + 15
Intersection Improvement	Y _{pred} - 9	Y _{pred} + 9
Mill and Asphalt Resurface	Y _{pred} - 10	Y _{pred} + 10
New Road Construction	Y _{pred} - 11	Y _{pred} + 11
Pavement Rehabilitation	Y _{pred} - 22	Y _{pred} + 22
Road Rehabilitation	Y _{pred} - 13	Y _{pred} + 13
Small Structure Replacement (US)	Y _{pred} - 13	Y _{pred} + 13
Small Structure Replacement (SR)	Y _{pred} - 20	Y _{pred} + 20
Wedge and Level	Y _{pred} - 5	Y _{pred} + 5

As an example, the prediction intervals of pavement rehabilitation projects were calculated for various levels of total project costs. The lower bound and upper bound values of estimated contract times with 95% confidence level and their corresponding actual construction durations are shown in Figure 4-3s. This figure shows that for the pavement rehabilitation projects all the recorded actual construction durations are included in the prediction intervals with 95% confidence level.

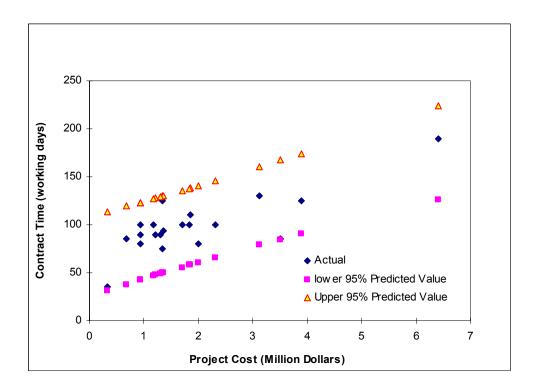


Figure 4-3 Prediction Intervals for Contract Times of Pavement Rehabilitation

4.2 Mean Production Rate Method

The construction duration of a highway construction project is directly affected by the construction firm's production rates of the construction activities. Therefore, if the construction activities in the critical path of the construction process can be identified, the time needed for the construction project can be determined using the mean production rates. For a given construction activity, the number of days needed to complete it can be estimated as follows:

$$T = \frac{Q}{P} \tag{4-7}$$

where

T = duration of the activity (working days);

Q = quantity for the activity;

P = mean daily production rate of the activity.

The key for this method is to appropriately determine the sequence of construction activities in the critical path of the construction process. The sequence of construction activities in the critical path varies from project to project. Therefore, it is impossible to provide the sequences of highway construction activities for all types of projects. For demonstration purpose, two possible construction sequences are shown in Tables 4-3 and 4-4. Table 4-3 contains a possible sequence of asphalt resurface activities with given mean production rates. Table 4-3 lists a possible sequence of bridge replacement activities. As shown in the tables, the activity durations can be either calculated by mean production rates or simply estimated from experience for some of the activities such as "road closure and/or work zone set up". The default values of activity durations in the tables can be changed according to real conditions. The contract time can be obtained by adding all activity durations in the last column of the table.

TABLE 4-3 Asphalt Resurface Templates

Item No (A)	Controlling Activity (B)	Work Quantity (C)	Mean Daily Production Rate (D)	Activity Duration (Working Days) (E=C/D)
1	Road Closure and/or Work Zone Set Up			1
2	Bituminous Widening		940 (TONS)	
3	Compacted Aggregate for Base		350 (TONS)	
4	Surface Milling, Asphalt		3,130 (SYS)	
5	Temporary Pavement Marking		7,200 (LFT)	
6	Bituminous Patching		70 (TONS)	
7	HMA Intermediate, Mainline		1,400 (TONS)	
8	Maintaining Traffic			1
9	Compacted Aggregate for Shoulder		490 (TONS)	
10	Bituminous Approaches		230 (TONS)	
			Total Working Days = ∑E _i =	

TABLE 4-4 Bridge Replacement Templates

Item No (A)	Controlling Activity (B)	Work Quantity (C)	Mean Daily Production Rate (D)	Activity Duration (Working Days) (E=C/D)
1	Road Closure and/or Work Zone Set Up			1
2	Remove Present Structure			5
3	Bent Cofferdams		300 (SYS)	
4	Bent Piling		500 (LFT)	
5	Bent Form & Pour Footing		10 (CYS)	
6	Footing Cure			2
7	Dewater, Form & Pour Bent Stem		10 (CYS)	
8	Bent Cap		10 (CYS)	
9	End Bent Driving Piling		300 (LFT)	
10	End Bent Form & Pour		10 (CYS)	
11	End Bent Cure			4
12	Set Beams			3
13	Rebar		20,000 (LBS)	
14	Place Deck		150 (CYS)	
15	Form & Pour Top Wall		15 (CYS)	
16	Top Wall Cure			3
17	Bituminous Approaches		230 (TONS)	
18	Approaches Cure			4
19	Guardrail		520 (LFT)	
20	Clean Up			5
			Total Working Days = ∑E _i =	

4.3 Adjustment of Contract Time Estimation

In terms of the regression theory, an estimated contract time from the regression model is the predicted mean value of construction durations for the given total construction cost. Similarly, an estimated contract time from the mean production rate method is also the predicted mean value of contract durations for the given sequence of construction activities. Depending on the actual conditions of a given highway construction project, the needed construction time, or contract time, may be longer or shorter than the mean durations. As discussed in the previous chapters, the production

rates as well as the construction durations are affected by many factors, including type of roadways, traffic volumes, project locations, and seasons. Therefore, it is reasonable to adjust the estimated contract time based on the effects of these factors, so that the adjusted contract time will more closely reflect the real construction conditions.

In order to determine the effects of the factors quantitatively, the mean construction durations were compared with those under different conditions and their differences were obtained. The average differences were then converted into adjustment coefficients on the basis of recorded mean construction durations. The adjustment coefficients for the major factors are presented in Table 4-5.

TABLE 4-5 Adjustment Coefficients for Contract Time Estimation

Factors		Adjustment Coefficients
	Interstate	1.17
	US	1.02
Type of Roadway	SR	1.03
	CR	0.94
	Others	0.85
	Low (ADT<5,000)	0.90
Traffic Volume	Medium (5,000≤ADT<10,000)	1.00
	High (ADT≥10,000)	1.10
Location	Rural	0.93
	Urban	1.09
	Spring	1.06
Season	Summer	0.92
	Fall	0.97
	Winter	1.25

These coefficients in Table 4-5 can be used to adjust the estimated contract time generated from either the regression method or the mean production rate method in the following manner.

$$Y_{\text{adjusted}} = Y_{\text{estimated}} [1 + \sum_{i} (C_i - 1)]$$
 (4-8)

where:

Y_{adjusted} is the adjusted contract time estimation.

 $Y_{\text{estimated}}$ is the estimated contract time from the regression or man production rate method. C_i is the ith adjustment coefficient from Table 4-5.

4.4 Accuracies of Contract Time Estimations

Contract time is estimated based on the historical data of construction durations and production rates. To evaluate the methods of contract time estimations, the estimated values can be compared with the actual construction durations of highway construction projects. Figures 4-4 and 4-5 show the actual construction durations and estimated contract times from the regression method. The scattered points in Figure 4-4 are the paired values (actual duration and estimated contract time) of 30 asphalt resurface projects, and those in Figure 4-5 are the paired values of 30 bridge replacement projects. As can be seen from the two figures, for each of the 30 pavement projects (Figure 4-4) and each of the 30 bridge projects (Figure 4-5), the actual duration and estimated contract time are fairly close. Also, the values are scattered on the two figures randomly with no identifiable patterns. The closeness of paired values and the randomness of their distributions indicate that the contract times are accurately and reasonably estimated by the regression method.

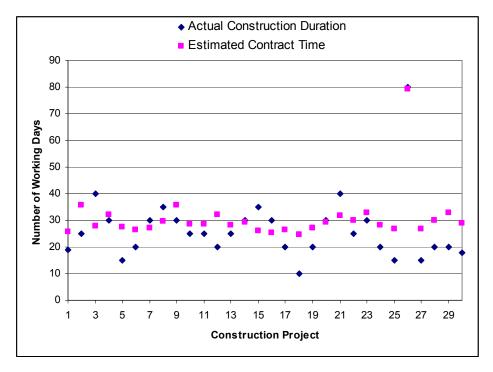


Figure 4-4 Actual Construction Durations and Estimated Contract Times of Asphalt Resurface Projects

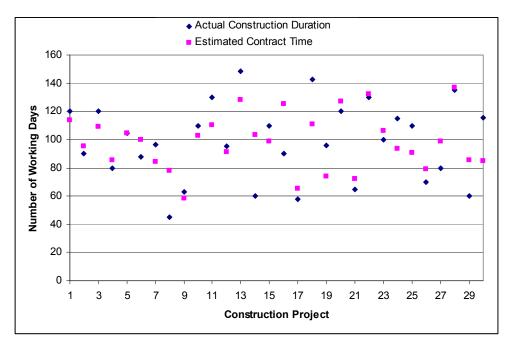


Figure 4-5 Actual Construction Durations and Estimated Contract Times of Bridge Replacement Projects

To compare the contract time estimations of the regression and mean production rate methods, the estimated contract times and actual durations are plotted in Figures 4-6 and 4-7. The estimated values and actual durations of the 30 pavement projects in Figure 4-6 and 14 bridge projects in Figure 4-7 possess similar closeness and randomness. Therefore, both the regression method and mean production rate method yield satisfactory estimations of contract times.

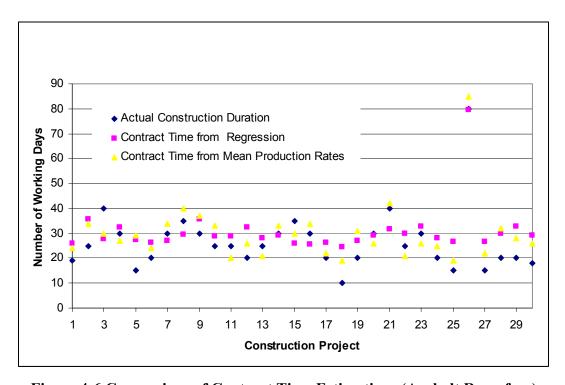


Figure 4-6 Comparison of Contract Time Estimations (Asphalt Resurface)

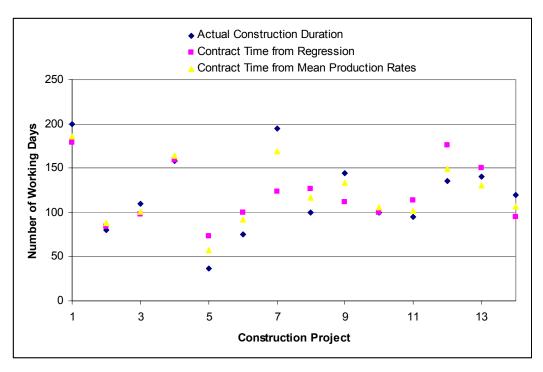


Figure 4-7 Comparison of Contract Time Estimations (Bridge Replacement)

4.5 Computer Program for Contract Time Estimation

For the convenience of applying the contract time estimation methods, a computer program was written with Microsoft Visual Basic 6.0. The contract time estimation methods are incorporated into the program. The steps for using the computer program are as follows:

1. Double click the file "contract time" to start the program and the following window will appear.

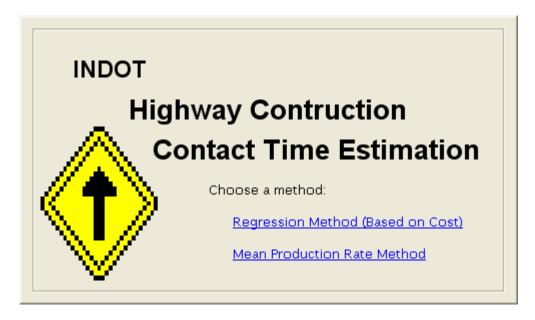


Figure 4-8 Computer Program for Contract Time Estimation

- 2. Choose one of the two methods by clicking on "Regression Method (Based on Cost)" or "Mean Production Rate Method".
- 3. If "Regression Method (Based on Cost)" is clicked, the following window will appear. Then select a Project Type using the drop-down menu, input the total estimated cost of the highway construction project, and select one of the choices under each of the four categories.

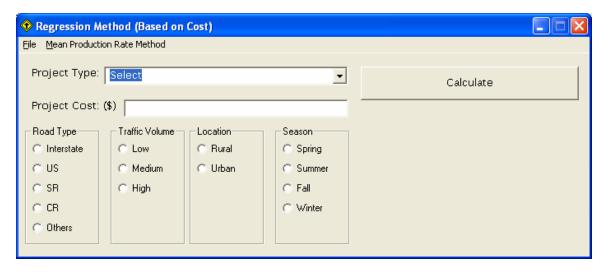


Figure 4-9 Input Window of Regression Method

4. After make all the selections, click on the "Calculate" button and the contract time will be calculated. The calculated result includes the estimated contract time and estimated interval with 95% confidence level.
An example of the estimated contract time is shown below:

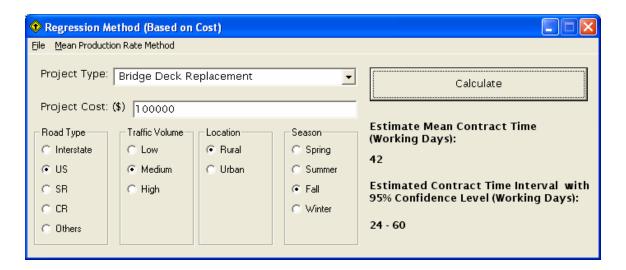


Figure 4-10 Output Window of Regression Method

5. The calculated result can be saved by clicking on "File", choosing "Save As...", and providing a file name. The saved output file is shown below:

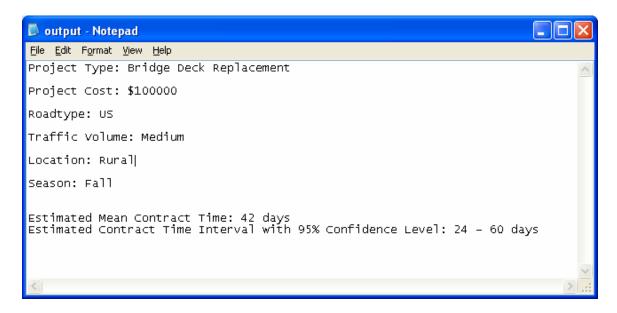


Figure 4-11 Saved Output File of Estimated Contract Time

To use "Mean Production Rate Method", the user should first determine the sequence of the critical construction activities for a given project and obtain the quantities of these activities. The critical activities and their corresponding quantities and mean production rates are then entered in the input window of the computer program. After inputting the required information for each activity and then clicking on "Add Activity" button, the estimated activity duration and cumulative working days will be calculated and shown on the screen. Therefore, the cumulative working days after the last critical activity is the estimated contract time. An example of the program window is shown below, which includes the estimated working days of two critical construction activities. Similar to the regression method, the calculated result can be saved by clicking on "File", choosing "Save As…", and providing a file name.

◆ Mean Production Rate Method	
File Regression Method How to	
Critical Activity:	
Work Quantity:	
Mean Daily Production Rate:	
OR	
Activity Duration (Working Days):	
Add Activity Clear Input Boxes Total Working Days: 15	
Activity 1: Critical Activity: Top Soil Removal Work Quantity: 800 Mean Daily Production Rate: 380 Activity Duration: 3 Total Working Days after 1 activity: 3	
Activity 2: Critical Activity: Excavation Work Quantity: 7500 Mean Daily Production Rate: 650 Activity Duration: 12 Total Working Days after 2 activites: 15	>

Figure 4-12 Example of Mean Production Rate Method

CHAPTER 5 SUMMARY AND RECOMMENDATIONS

Through this study, the INDOT highway construction production rates were calculated and two methods for contract time estimations were developed based on the recorded eight-year INDOT construction data. Various statistics of production rates were provided to capture the main features of the highway construction production. The statistics include means, standard deviations, confidence intervals, mean baseline production rates, and production rates for different probabilities. The major factors that affect highway construction production rates were examined and their effects were analyzed. It was found that the production rates were affected by weather conditions in terms of temperatures and seasons, contractors, locations of construction projects (urban and rural), types of highways, and traffic conditions. Therefore, production rates under different conditions, such as seasons, roadway types and locations, were obtained to reflect the differences in production rates.

The mean of the recorded production rates of a given construction activity is most often used as a representative value. However, the production rates of a construction activity may vary considerably. The disperse degree of production rates is reflected by the values of standard deviations or variances. The confidence interval of the estimated mean for a given confidence level can be calculated with the values of calculated mean and standard deviation. The confidence intervals for a 95% confidence level were computed for the construction activities. These confidence intervals provide a reliable range of the mean production rates for highway engineers and managers. Similarly, the critical production rates under different probabilities were obtained in this study. The

critical production rate under each probability means that a production rate will be less than the critical value with the given probability. Therefore, the values provide the probabilities for production rates to be different values, including relatively small and large values of production rates.

The recorded INDOT highway construction data showed that the production rates increased gradually and stably. This should be attributed to the improvement of materials, equipment, technology, and construction management. This also indicates the necessity for updating INDOT production rates periodically. Furthermore, the mean baseline production rates were also provided through the production analysis. The mean baseline production rates reflect the production rates under ideal conditions. They can be used to evaluate construction process with minimal interruptions and delays. For example, the minimum time period for a highway construction project may be estimated with mean baseline production rates, so that the negative effect of highway construction on motorists and local businesses can be minimized.

Contract time, the time required for a contractor to complete a highway project, should be reasonably estimated according to the quantity and complexity of the construction project. This can be achieved based on the historical data of actual construction durations of highway construction projects. Efforts were made in this study to analyze the INDOT recorded construction durations. As expected, the construction durations are affected by the same factors as the production rates. The distribution analysis indicates that production rates of various highway construction activities can be described or represented by different distribution models, including normal, lognormal, and exponential distributions. Two methods were developed for contract time estimation

based on the data of construction durations and production rates. One is a regression method using the total construction cost of a project to estimate contract time. The other method uses the mean production rates to calculate the durations needed for critical construction activities. The contract time generated from either one of the two methods is actually an estimated mean duration needed for the construction project. This mean duration is then adjusted by the factors related to construction conditions, including roadway type, project location, traffic volume, and season of construction. Based on the statistical characteristics, the confidence intervals for the estimated contract time can also determined to provide users the information on the possible range of the contract time.

The values of production rates are stored in a Microsoft Access file so that the users can easily find the information. A Visual Basic computer program is also provided for contract time estimation. Therefore, implementation of the research results is made easy with the computer programs. It is recommended that INDOT use the new production rates to replace the existing values and also update the production rates periodically in the future to reflect the changes in production rates. The Visual Basic computer program should be used to estimate contract times of INDOT highway construction projects.

REFERENCES

Bellanca, L., Gottula, K. (1981). NCHRP Synthesis of Highway Practice 79: *Contract Time Determination*, Transportation Research Board, National Research Council, Washington, D.C.

Hanna, S. Award, Camlic, R., Peterson, A. Pehr, and Nordheim, V. Erik. (2002). *Quantitative Definition of projects Impacted by Changing Orders. J. Constr. Engrg. and Mgmt.*, ASCE, 128(1), 57–64.

Herbsman, Z. J., and Ellis, R. D. (1995). NCHRP Synthesis of Highway Practice 215: Determination of Contract Time for Highway Construction Projects. Transportation Research Board, National Research Council, Washington, D.C.

Hinze, J. W., and Carlisle, D. L. (1990). *An evaluation of the important variables in nighttime construction*. Transportation Northwest (TRANSNOW), University of Washington, Seattle.

EI-Rayes, K. and Moselhi, O. (2001). *Impact of Rainfall on the Productivity of Highway Construction*. Journal of Construction Engineering and Management, ASCE, 127(2), 125–131.

Lee, Eul-Bum, Ibbs, C. William, Harvey, T. John, and Roesler, R. Jeff. (2000). *Construction Productivity and Constraints for Concrete Pavement Rehabilitation in Urban Corridors*, Transportation Research Record, 1712, pp 13-22.

Lee, E-B; Harvey, JT; Ibbs, CW; St. Martin, J. (2002). *Construction Productivity Analysis for Asphalt Concrete Pavement Rehabilitation in Urban Corridors*. Transportation Research Record, 1813, pp 285-294.

McCrary, S. W., Corley, M. R., Leslie, D.A., and Aparajithan, S. (1995). *Evaluation of Contract Time Estimation and Contracting Procedures for Louisiana Department of Transportation and Development Construction Projects*. Report by Louisiana Tech University, for Louisiana Transportation Research Center in cooperation with the Federal Highway Administration, U.S. Department of Transportation.

Neter, J., Wasserman, W., and Kutner, M. H. (1985). Applied Linear Statistical Models. Second Edition, Richard D. Irwin, Inc. Homewood, Illinois.

Ozwalt, J. H., Johnson, L. R., and Hotard, D. G. (1975). A Method to Determine Contract Work Days - Implementation. Report by Engineering and Industrial Research Station, Mississippi State Highway Department in cooperation with the Federal Highway Administration, U.S. Department of Transportation.

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

Thomas, H. R., Jones, J. R., Willenbrock, J. H., Hester, W. T., and Logan, P. A. (1985). *Analysis of Time and Schedule Performance on Selected Highway Projects*, Report No. FHWA-TS-85-217, Reported by Nittany Engineers and Management Consultants, Inc., State College, PA, for Federal Highway Administration, U. S. Department of Transportation.

Thomas, H. R. and Završki, Ivica. (1999). Construction Baseline Productivity: Theory and Practice. J. Constr. Engrg. and Mgmt., ASCE, 125(5), 295–303.

Werkmeister, RF; Luscher, BL; Hancher, DE. (2000). *Kentucky Contract Time Determination System*. Transportation Research Record 1712, pp 185-195