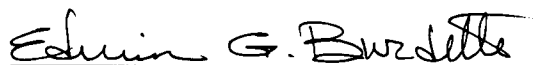


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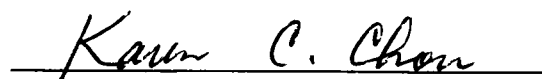
I am submitting herewith a dissertation written by Abdulrazak B. Abdulghafour entitled "Modeling Highway Construction Tasks to Determine Project Duration." I have examined the final copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Civil Engineering.

  
J. Harold Deatherage, Major Professor

We have read this dissertation  
and recommend its acceptance:

  
Edwin G. Burdette

  
J. M. Goodpastor

  
Kaim C. Chou

  
J. Harley Rich

Accepted for the Council:

  
Associate Vice Chancellor and  
Dean of The Graduate School

# **MODELING HIGHWAY CONSTRUCTION TASKS TO DETERMINE PROJECT DURATION**

A Dissertation  
Presented for the  
Doctor of Philosophy  
Degree  
The University of Tennessee, Knoxville

Abdulrazak B. Abdulghafour  
May 1998

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## **DEDICATION**

To my sons,  
Ihem and Osama

## ACKNOWLEDGMENTS

I am indebted to many individuals who have made the completion of this dissertation possible. I would like to thank Dr. J. Harold Deatherage, my committee chair, for his guidance and insight throughout the course of this research. I would also like to thank the members of my committee - - - Dr. Edwin G. Burdette, Dr. David W. Goodpasture, Dr. Karen Chou, and Dr. Stanley Rabun - - - for their time and advice throughout this project. Dr. Burdette's attention to detail and editorial assistance are especially appreciated. Three of my colleagues in the graduate program - - - Eric Bonanno, Eric Brown, and Richard Gatlin - - - provided much appreciated assistance in the data collection for this project, and I wish them the best in their educational endeavors.

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Finally, I am very grateful to my wife for her support and encouragement.

## ABSTRACT

This study serves three purposes that are relevant to highway construction operations. The first purpose is to model highway construction to determine task duration for the purpose of scheduling. Although scheduling requires a proper determination of task duration and productivity, productivity is difficult to determine because of the collective effect of many variables, such as weather, site conditions, method of construction, equipment, labor, the arrival of materials, and management decisions. The Average and Distribution Model of Productivity (ADMP) combines the effects of many variables on the productivity of a daily highway construction task and measures these effects with a 95% confidence level of task completion. This study considered nine major highway construction tasks, and data were collected on up to 12 data sets for each task. The data were mainly collected on the cycle times of the production units, the cycle times of the processors, the allocation of resources, and the occurrences of delay.

The second purpose of this study is to use the ADMP and efficiency analysis to evaluate the validity of claims for time-related disputes in highway construction projects. Management problems and poor resource allocation are the cause of most delays on the part of the contractor. Efficiency analysis is a useful tool for evaluating productivity and claims for highway construction projects.

The third purpose of this study is to calculate the cost of a task based on observed site conditions and to define the influence of task duration on cost. The

results of this study showed that duration significantly influences the cost of equipment and labor, but insignificantly affects the cost of materials.

The determination of task duration and productivity is essential for project scheduling, estimating the cost of a project, and evaluating claims. The experience-based method has shown significant shortcomings in determining task duration properly. The ADMP is an excellent method for evaluating, determining, and predicting task duration and evaluating cost estimates and claims in highway construction. The simplicity of combining the effects of the many variables that influence highway construction is the most important contribution of this method.

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# **CHAPTER 1**

## **INTRODUCTION**

### **1.1 BACKGROUND**

The annual decline in construction productivity has been characterized as unbalanced and unsatisfactory. Although modern technology has contributed to increased productivity in many industries, the construction industry has suffered a loss in productivity in general. The productivity of highway construction in particular has declined during the past 30 years (Adrian, 1987). One of the main reasons for this decline is the unpredictable variables that affect construction operations. Overruns in task duration constantly delay the project's scheduling, and variability in construction makes typical scheduling techniques ineffective tools for evaluating project duration. Therefore, understanding the variables that affect task duration is the key to explaining the decline in the production rate.

Because of the many variables involved, determining task duration is one of the main difficulties in highway construction. The estimation of task duration affects not only the actual duration of a construction project, but also affects overrun cost, traffic, and a contractor's willingness to bid the job. Because construction projects are influenced by so many factors, such as environmental conditions, construction resources, and management decisions, it is difficult to predict project duration by experience only.

The Department of Civil Engineering at the University of Tennessee, Knoxville, is being funded by the Tennessee Department of Transportation (TDOT) to study task duration in highway construction operations in the four regions of Tennessee. The primary purpose of this study is to collect field data, which will contribute to the development of better scheduling procedures.

Highway construction projects are a unit price bid, in which the cost of each individual task is estimated and added together to determine a total project price. Also, the time associated with each task is estimated and combined to determine the project duration. Therefore, in order to estimate the cost of the entire project more accurately, it is necessary to correctly estimate the time and cost involved in the individual tasks that make up the project.

Researchers recently realized that estimating the duration of construction projects requires more and better information than conventional methods provide. Engineers in highway construction often use their experience, which is sometimes called the discrete method, to estimate project time. Applying this method, where the production rate has been established for each task by experience and historical data, has three important shortcomings:

- 1) Variability is not clearly considered.
- 2) The production cycle time is not defined.
- 3) The elements of the task are not considered at the operation level.

Overestimations of project duration tend to cause contractors to extend the length of the project to the estimated time and, as a result, increase costs, traffic problems, and inconvenience to the public. Underestimations of project duration increase the chance that qualified bidders may withdraw their bids. These problems may also cause the DOT significant increases in the bid price and increase the possibility of a legal dispute. Optimal estimations of project duration, on the other hand, may improve the quality of work, help avoid inconvenience to the public, and help control project cost. Thus, it is essential for the DOT to be able to determine task duration more accurately and thus improve its current experience-based method of estimating project duration and cost. This study can also help DOTs to schedule highway projects more properly.

## **1.2 OBJECTIVES**

The first and main objective of this research is to model highway construction operations to determine task duration for the purpose of project scheduling. The research relies on extensive data collection from actual highway projects, which is used to estimate actual production, in order to establish a confidence level of task duration that eliminates the effects of unpredictable variability. The second objective is to investigate the effect of task duration on cost estimates and to compare the estimated cost based on data collection to the contractor bid price. The third objective

is to evaluate highway construction claims as a result of project time overruns (Figure 1-1).

### **1.3 DISSERTATION ORGANIZATION**

This dissertation contains eight chapters. Following the Introduction in Chapter 1, Chapter 2 explains and evaluates the state-of-the-art methods and procedures for determining project duration and productivity. Chapter 3 presents highway construction as a system, and the practices of highway departments are discussed in relation to the construction of highway projects. In Chapter 4, the modeling of highway construction tasks is explained using the Average and Distribution Model of Productivity (ADMP). The application of this method using nine highway tasks is demonstrated in Chapter 5. In Chapter 6, the validity of the data is evaluated, and the ADMP is used to evaluate and resolve duration claims for highway construction projects. The influence of task duration on construction cost is discussed in Chapter 7. Finally, a summary, conclusions, and recommendations are presented in Chapter 8.

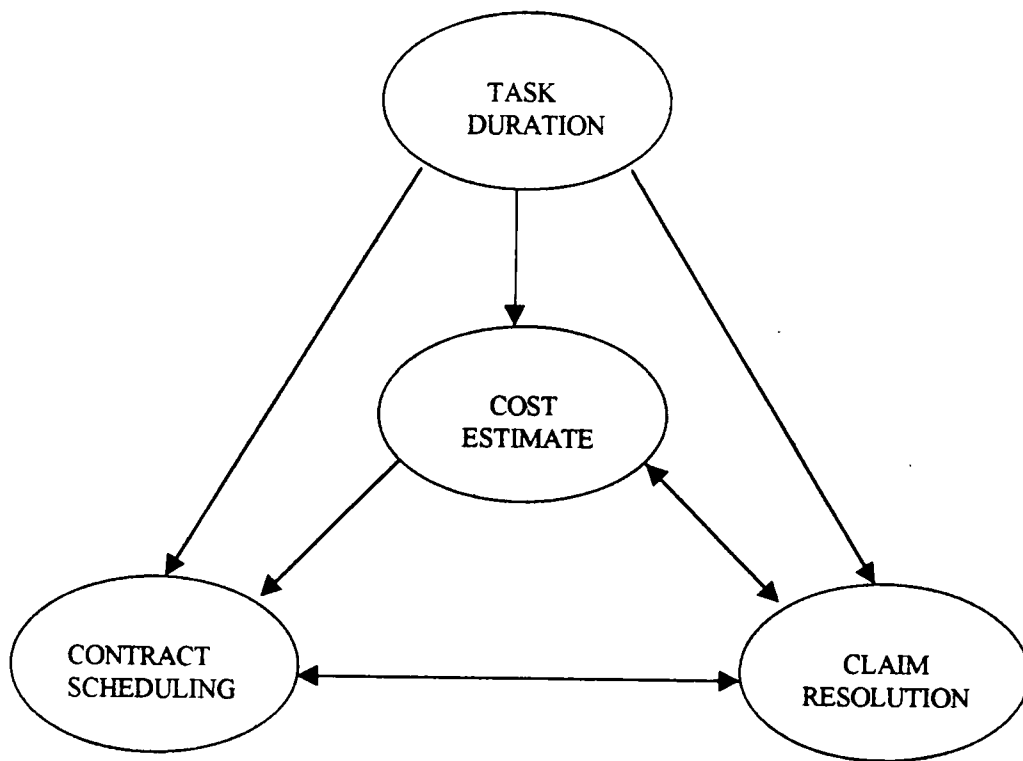


Figure 1-1. The Relationship Between Task Duration and Scheduling, Cost Estimates, and Claims

## **CHAPTER 2**

### **STATE OF THE ART**

#### **2.1 INTRODUCTION**

A literature survey has indicated that limited research has been done on highway construction task duration. While engineers and planners have developed several techniques for scheduling and measuring productivity, determining highway construction task duration at the unit of measurement level has not been studied in-depth on the practical level.

Productivity and task duration are affected by many factors, such as weather conditions, the allocation of resources, and the method of construction. These factors are influenced by other factors, such as site conditions and the nature of the operation. Moreover, in a construction operation, one factor can affect one task more than it affects another task. Because of the many factors affecting task duration and the extent of the variability in how they affect it, task duration is very difficult to evaluate and measure.

Some researchers have addressed construction productivity with respect to the effect of a single factor, such as weather or site conditions. Others have evaluated productivity with respect to labor productivity alone. However, no researchers have studied at the practical level the cumulative effects of all the variables that affect task

duration in highway construction projects. This chapter reviews some of the methods and techniques that have been used to evaluate construction productivity and task duration.

## **2.2 THE HIERARCHY OF CONSTRUCTION**

Because of the complicated nature of construction projects, a detailed explanation of the overall construction process is required for the understanding of the organizational nature of a construction company. According to Halpin and Woodhead (1976), the decision making process in construction operations can be broken down into “hierarchical levels.” Decisions, such as whether or not to bid on a project, how much to bid, how many workers will be necessary, and what kind of equipment will be most efficient, must be made. The decisions that must be made at levels above the project are “management considerations,” and the decisions that must be made within the project, such as how to utilize resources in the most efficient way, are “operational considerations.”

Halpin and Woodhead identify four hierarchical levels; (1) Organizational, (2) Project and Activity, (3) Operation and Process, and (4) Task. The Organizational Level deals with issues such as the cost and duration of a project, marketing strategies, legal and policy questions, and “interactions” between the head office and the field manager. The Project Activity Level deals with process. At this level, decision makers interpret contracts, review drawings and specifications, define and

break down activities, decide how to allocate resources, determine how to control costs, and combine time and production estimates for purposes of scheduling a project. A senior manager at this level might delegate some authority to a junior manager. The Operation and Process Level deals with the method of construction, the use of appropriate resources for each task, and the analysis of the work process. This work is usually performed under the direction of the superintendent. The process part of this level deals with the sequencing technology and the completion of a portion of task work. The foreman is the person who performs the work process. The task level deals with the decisions about each unit of work and portion of the work. The collection of all the individual task elements results in the completion of a project. Figure 2.1 provides a more detailed breakdown and description of these levels.

The hierarchy of construction enlightens and explains the construction operation at various levels. In each level, construction management and its application define a sequence of the workability of a construction operation. The hierarchy of construction defines the relationship between management and the task process. The modeling of tasks can be a useful tool for determining productivity, estimating cost, scheduling projects, and evaluating the performance of the company's operations.

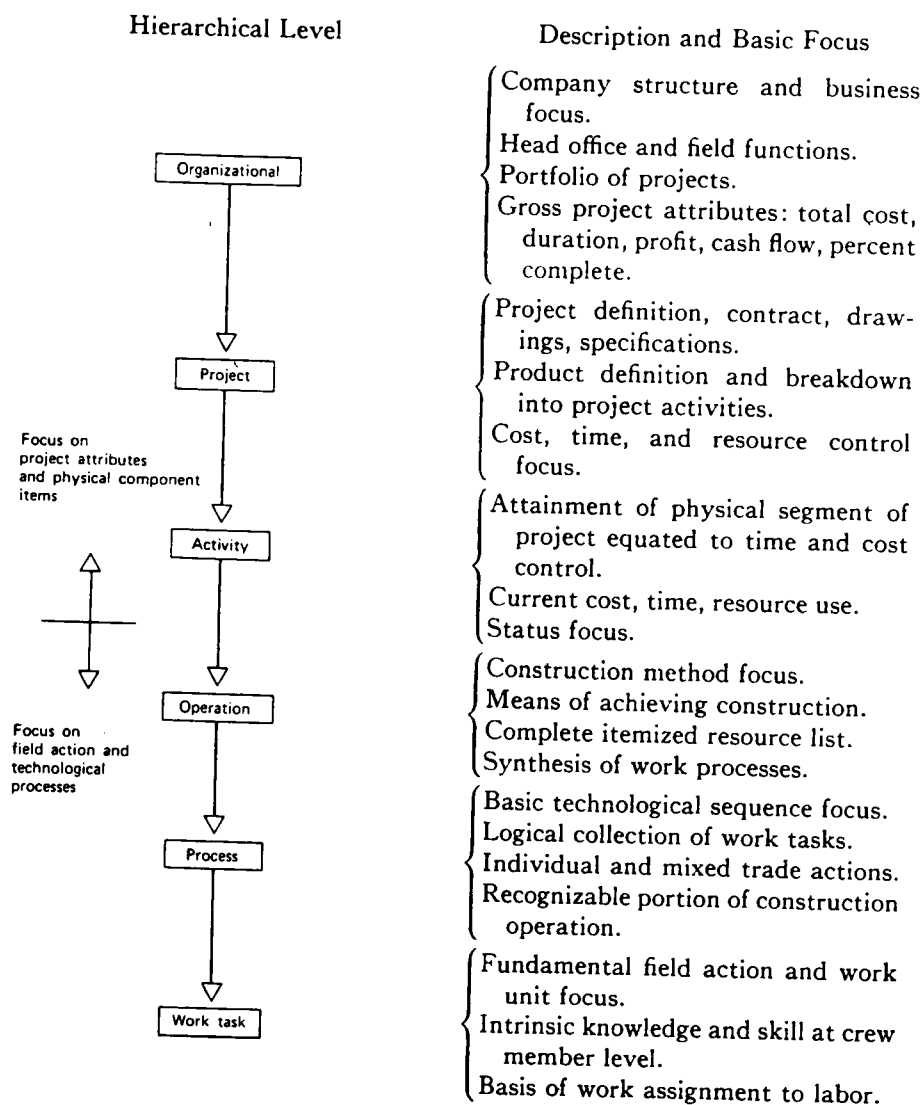


Figure 2-1. Hierarchical Levels in Construction Management  
(Halpin and Woodhead, 1976, p. 8).

## **2.3 SCHEDULING OF A CONSTRUCTION OPERATION**

Scheduling and planning a construction operation are defined as the supply of activity for a given operation and project plan, including the start of a project, the end of a project, the start of a task, and the completion of a task. Planners and engineers combine the task duration and the sequence of an activity to determine the schedule for a project or portion of a project. Scheduling also can be characterized as the production rate for a task.

Many scheduling techniques have been used in construction. The bar chart method is the most popular and has been used widely since the beginning of this century. It was first introduced to the construction industry in the U.S. in the early 1930s.

One of the major advantages of the bar chart method is its simplicity, and it may be ideal for a small project or a repetitive task. The shortcomings of this method are that tasks are not broken down into details, which makes it hard to control time overruns, and the relationship among the activities is not always clear.

In the late 1950s, two new scheduling techniques were made available for the construction industry: (1) the Critical Path Method (CPM) and (2) the Program Evaluation Review Technique (PERT). The CPM has been used widely in construction, especially in highway construction. The PERT, on the other hand, has not been used much at the practical level. Both methods use the network scheduling technique and have similar application procedures. The main difference is that the

CPM is an activity-based method where the critical path is the longest duration of a particular activity, while the PERT is a time-oriented method in which an activity is evaluated with respect to activity sequences. These sequences are evaluated based on the time associated with them. Numerous computer programs have been developed to utilize these two methods. In both methods, tasks are broken down into several activities using a network graphical procedure. The breakdown of activities helps the manager to monitor the schedule during the operation. Although the development of the CPM and the PERT during the early 1960s was considered a breakthrough for scheduling techniques, later research pointed out shortcomings of these methods.

Joseph P. Frein (1980) indicated that networking schedules did not live up to their high expectations and that statistical analysis showed that duration estimates based on these techniques had only a 50% chance of being accurate. Moreover, McGough (1982) and Melin and Whiteake (1981) consider the bar chart technique more useful than the CPM. Therefore, the bar chart technique is still widely used in the construction industry.

According to Mustafa Pultar (1990), it is disadvantageous to use the CPM for complex projects because tasks need to be divided into many smaller parts. These details complicate the scheduling and planning procedure.

Khisty (1970) was the first to use a sophisticated graphical scheduling technique, the Line-of-Balance Method (LOB), for pre-cast beam operations in a construction project. Carr and Meyer (1974) applied the same method to the

construction of multi-story houses. The LOB is used only for repetitive task construction and may, therefore, be useful for highway construction projects.

Johnston (1981); Stradal and Cocha (1982); and Handa and Barcia (1986b) developed mathematical procedures that use linear programming, as opposed to graphical solutions, to improve the scheduling and productivity of construction operations. The main advantage of this method is that it optimizes construction productivity. The application of linear programming has not been welcomed by most planners due to the difficulty associated with it.

Because scheduling is crucial for construction operations, various scheduling techniques have been developed. Some techniques, such as the Bar-Chart, the CPM, and the PERT, have been widely used. Others, such as the LOB Method and linear programming techniques, have only been studied on the theoretical level. Each method has advantages and disadvantages. However, none of the scheduling methods can provide a satisfactory schedule if the time associated with the task has not been properly determined. Therefore, task duration studies are essential to improve not only scheduling, but also to provide a better understanding of variability in highway construction.

## **2.4 CONTRACT TIME**

Contract time is the maximum time allowed to complete a project. This time can be expressed in working days, calendar days, or a specific target date for the

completion of the project. Determining contract time has been a concern of many departments of transportation, as well as the Federal Highway Administration (FHWA). The increased cost and inconvenience associated with increased project time have concerned many officials in highway construction. At present, there is no satisfactory method available to determine highway construction time. Many methods currently being used rely on the ability of experts to estimate contract time.

The experiences of engineers, combined with the historical data on former projects, is the foundation of most attempts to estimate the amount of time required to complete a highway construction project. Herbsman and Ellis (1995) surveyed Departments of Transportation in most states and in some foreign countries and found that experience has been the key method used for determining contract time. They found that many DOTs use scheduling techniques and estimate time based on the experience of the engineer. Others use either the historical data of projects that have been previously completed or a combination of the historical data and the experience of the engineer to determine contract time.

Herbsman and Ellis also evaluated the influence of using the A + B Method to decrease contract time for some projects in which incentive and disincentive were involved. This method established the time cost by combining the contract cost and the daily road user cost. After examining several case studies, Herbsman and Ellis concluded that the use of the A + B Method showed a substantial reduction of contract time. He also recommended more research in the area of determining time.

## 2.5 QUEUING THEORY

At the beginning of the 20th century, the increased demand for telephone service in Copenhagen, Denmark, led to frustration for the customers who found the telephone lines busy when they wanted to make a call. A. K. Erlang, a Danish mathematician, used probability theory to determine how long a customer should wait to make a call and the probability of calls at any given time. Ultimately, he sought to determine the operator's capacity to handle calls without producing an inconvenient queue for customers. This model of the telephone operator and the calling customers is called an opened queuing model, or infinite population model, where the number of calls outside the system is undetermined.

The most common queuing model is the closed model, or finite model, in which there is a fixed number of customers to be served. In this model, the arrival rate drops to zero if all served customers are already queued up in the system.

The finite queuing model is a very useful tool in the stochastic process, which is the theory that deals with the probability of a random variable that evolves in time. The stochastic process, which is also known as a Markovian process, is a milestone in the development of the Queuing Theory. The Markovian model, also known as the Markov chain, was developed by Andrei Andreyevich Markov, a Russian mathematician. In 1922, A. A. Markov used the probability concept of a random variable to determine the future variables by the present variables. Furthermore, he tried to establish uniform probability laws. In 1923, Norbert Wiener widely applied

the Markov process to probability, and Andrei Kolmogorov provided the final procedure of the Markov process in the 1930s.

The Queuing Theory and the Markovian process have been widely applied in management science, industry, and manufacturing; and an advanced computer program has been developed to improve management techniques. The finite population queuing model has recently been applied to the construction process.

Figure 2-2 shows an earthmoving operation in which four dump trucks (calling units) are being served by a single front end loader (processor).

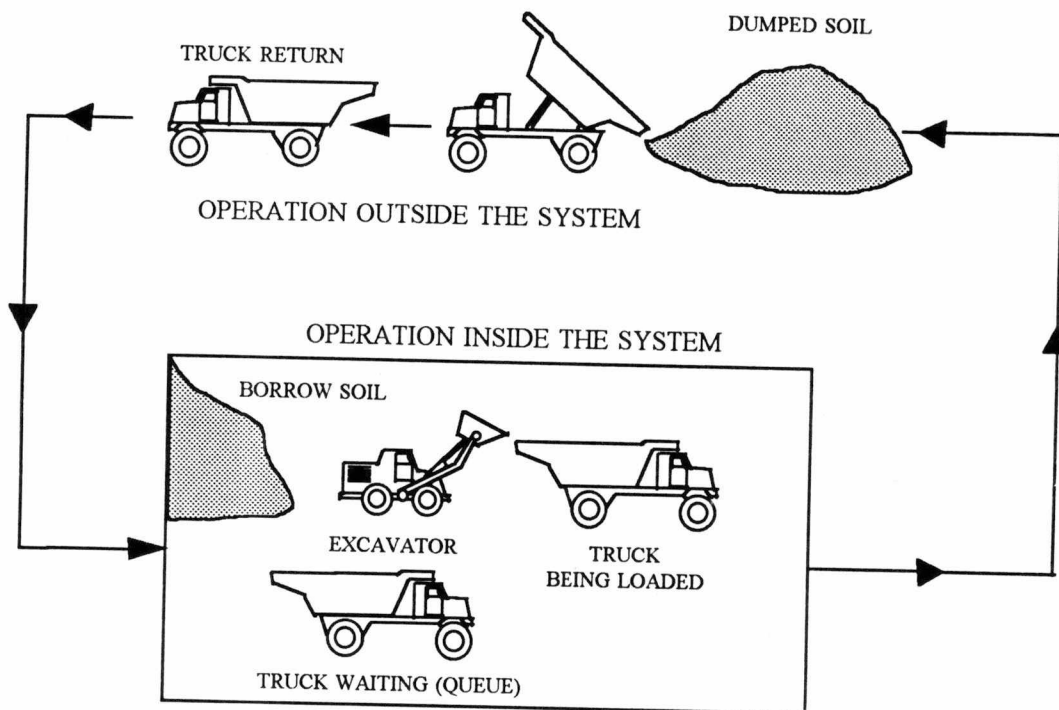


Figure 2-2. A Typical Queuing Model for a Finite System  
(An Excavator Loading Four Trucks in an Earthmoving Operation)

Once the trucks enter the system, they wait in queue until their turn to be served. Once the front end loader serves a truck, the truck will leave the system, and the next truck in the queue will be served. In this operation, the Queuing Model requires the cycle time of the trucks (calling units) and the cycle time of the loader (processor) to run the model. From Figure 2-2, it can clearly be seen that there are two trucks outside the system and two in the system; one of them is being served and one is waiting in the queue. The average of the mean arrival time of the calling units ( $T_a$ ), the mean processor time ( $T_s$ ), the arrival rate ( $\lambda$ ), and the processor rate ( $\mu$ ) are calculated directly from the data. Using these values, a Markovian model can be drawn to simulate the process. Once the model is completed, the equation of state is set up, and the resulting simultaneous equations are solved. From the equation, the probability of the number of units in the system is determined. The probability ranges between a probability of no units ( $P_o$ ) and a probability of “n” number of units ( $P_n$ ), where “n” is the total number of units in the system. The probability of no units in the system ( $P_o$ ) can be determined in two ways:

- (1) Solving the general equation.

$$P_o = \left[ \sum_{i=0}^m \frac{M!}{(M-i)!} \left( \frac{\lambda}{\mu} \right)^i \right]^{-1} \quad (2.1)$$

$$P_i = \left[ \frac{M!}{(M-i)!} \left( \frac{\lambda}{\mu} \right)^i \right] P_0 \quad (2.2)$$

where  $P_0$  = Probability of no units in the system

$P_i$  = Probability of (i) units in the system

$M$  = Total number of units

$i$  = Total number of units in the system

- (2) Using the Markovian Model and the equations of states to calculate the matrix and determine  $P_0$ .

A. Markovian Model

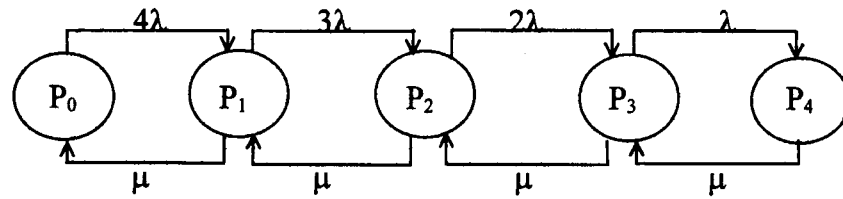


Figure 2-3. Markov Model for Finite System ( $M = 4$ ).

- B. The Equations of States (Inflow=Outflow). The equations of states for the model in Figure 2-3 are

$$S_0: 4\lambda P_0 - \mu P_1 + 0P_2 + 0P_3 + 0P_4 = 0 \quad (2.3)$$

$$S_1: -4\lambda P_0 + (3\lambda + \mu)P_1 - \mu P_2 + 0P_3 + 0P_4 = 0 \quad (2.4)$$

$$S_2: 0P_0 - 3\lambda P_1 + (2\lambda + \mu)P_2 - \mu P_3 + 0P_4 = 0 \quad (2.5)$$

$$S_3: 0P_0 + 0P_1 - 2\lambda P_2 + (\lambda + \mu)P_3 - \mu P_4 = 0 \quad (2.6)$$

$$S_4: 0P_0 + 0P_1 - 0P_2 - \lambda P_3 + \mu P_4 = 0 \quad (2.7)$$

$$S: P_0 + P_1 + P_2 + P_3 + P_4 = 1 \quad (2.8)$$

C. Solve the matrix using Equation 2.8 and four of the equations between Equation 2.3 and Equation 2.7 to determine the probabilities  $P_0, P_1, \dots, P_n$ .

D. From the equations of states,  $P_0, P_1, P_2, P_3, \dots, P_n$  can be determined. The final stage in the model is to use the probability of the number of units in the system to calculate the duration of a task as follows:

$$L = \frac{P_r}{(1 - P_0)\mu C} \quad (2.9)$$

$L$  = Length of time (duration)

$P_r$  = Production required to be finished

$P_0$  = Probability of no units in the system

$\mu$  = Average processor rate (load/hour)

$C$  = Capacity of calling unit

The Queuing Model can only be calculated for the loss of productivity when the calling units waiting in queue and the processor are constantly working. In another case, when the processor is able to serve more units than are being used, a

storage of production can increase productivity and prevent the processor from being idle. In this case, the model includes a hopper in the system as well.

The Markovian Model is only useful for analyzing productivity in operations that have (1) repetitive cycles and (2) contain one or more processors and calling units working simultaneously with different cycle procedures.

## **2.6 CONSTRUCTION PRODUCTIVITY**

The low annual increase in construction productivity has caught the attention of many researchers. Although evaluating and measuring productivity has not been an easy task, research has shed light on the important elements that affect construction productivity. However, most of the research data have consisted of academic study, interviews, and surveys. Research for determining productivity at the practical level has been limited to only a few of the factors that influence labor productivity.

Therefore, many questions remain unanswered. Researchers agree that construction productivity cannot be measured and evaluated adequately without an intensive practical data collection from a real construction operation. Unlike most industries, construction has experienced very low increases or losses in productivity in recent years. This low increase in productivity is due to the dynamic outdoor nature of construction operations, the uniqueness and complexity of each project, and the lack of understanding and evaluation of variability in construction operations. Large projects in particular experience even more loss in productivity because of

communication problems between the many people involved in the project. In an average daily operation, the channels of communication may include engineers, contractors, sub-contractors, crews, safety regulators, environmental inspectors, and suppliers. The interaction among them contributes to increased variability, which directly affects the production rate. Therefore, construction productivity is very difficult to define. The factors that influence construction productivity have been the topic of many studies in the past three decades.

Analyzing and evaluating these factors are important steps in determining construction productivity. Some of the factors that influence productivity are labor, equipment, management, environment, safety and regulations, and change orders. A great deal of research has been conducted using questionnaires, surveys, and interviews, but most of this research dealt only with labor productivity.

Several studies used the activity model to show the percentage of direct work in relation to other activities of labor. Borcharding and Garner (1981) used surveys and questionnaires to measure the productivity of three different crafts in a nuclear power plant construction operation. They studied carpenters, electricians, and pipe fitters because they represented the majority of the manpower in the operation. Over 1,000 craftsmen participated in the survey. Borcharding and Garner used the activity model to evaluate direct work in relation to other activities. This study showed that 42% of the time was direct work.

Also, in 1986 Liou and Borcharding conducted a study to determine the percentage of direct work and delay time for a nuclear power plant and fossil fuel power unit. The data were collected in two parts. In Part 1, a questionnaire was given to experts in the work force. In Part 2, actual labor operations were observed to determine the direct work time and to relate it to other activities. This study, which contained 45 work sampling data points provided by 11 nuclear plants and four fossil fuel power plants, showed that only 32.3% of the nuclear power plant operations and 37.7% of the fossil fuel power plant operations was direct work; the rest of the time was delay or support work (Figure 2-4).

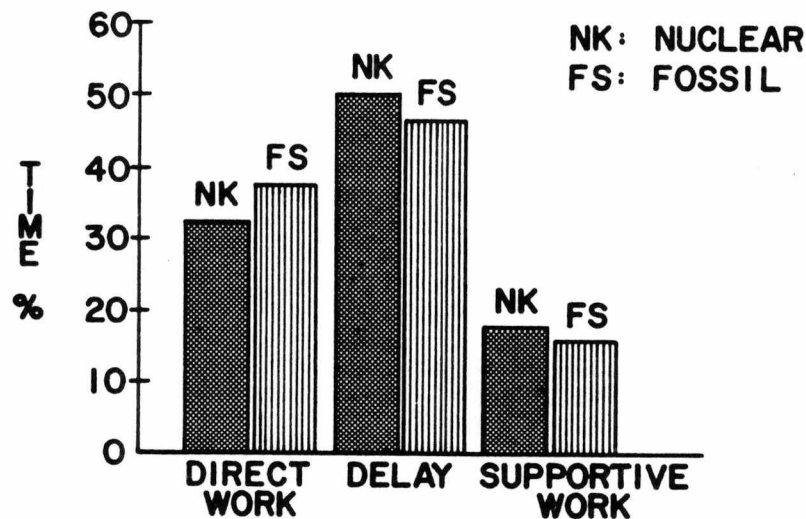


Figure 2-4. Work Sampling Results of Nuclear and Fossil Fuel Plants (Fwu-Shin Liou and John D. Borcharding. *Journal of Construction Engineering and Management*, March 1986, p. 94)

In the Borcharding/Garner and the Liou/Borcharding studies, labor was the main factor of productivity considered. Borcharding and Garner concluded that low motivation affects productivity, especially in large projects, and that a good atmosphere contributes to increased productivity in the work force. Finally, Borcharding and Garner indicated that work sampling information is a useful tool for predicting productivity.

Christian and Hachey (1995) evaluated the effect of the delay time on the production rate in a concrete placement operation. Like Borcharding and his colleagues, Christian and Hachey also used labor productivity as the basis of determining construction productivity at several construction sites in Fredericton, New Brunswick, Canada. A total of 32 data points were recorded. Data acquisition was done using a video tape, a stopwatch, and by interviewing labor experts.

Time was classified as (1) effective, (2) essential contributory, (3) waiting, and (4) idle.

(1) Effective time is the direct work of labor.

(2) Essential contributory time is the time spent doing the preliminary work necessary to perform direct work, such as moving a crane to reach various places along a bridge.

(3) Waiting time is the time when laborers are waiting to perform work because of delays, such as the late arrival of materials.

(4) Idle time is the time when the crew is not working.

The activity model, which is shown in Figure 2-5, shows that 63% of the time was direct work, 29% was waiting, 4% was idle, and 4% was contributory work.

Christian and Hachey indicated that the “basic steps” for placing concrete are consistent in spite of the different construction methods used. He determined that the primary cause of variation in concrete productivity was waiting for materials to arrive. In addition, he indicated that historical data serve as a good tool for predicting the construction productivity of future projects, and that the productivity of labor can be improved by better supervision to decrease idle time.

Thomas et al (1990) examined various production crafts in three nuclear plants and 159 work samplings. First, he evaluated the activity model, which has often been used to evaluate direct work in relation to other activities (Figure 2-6).

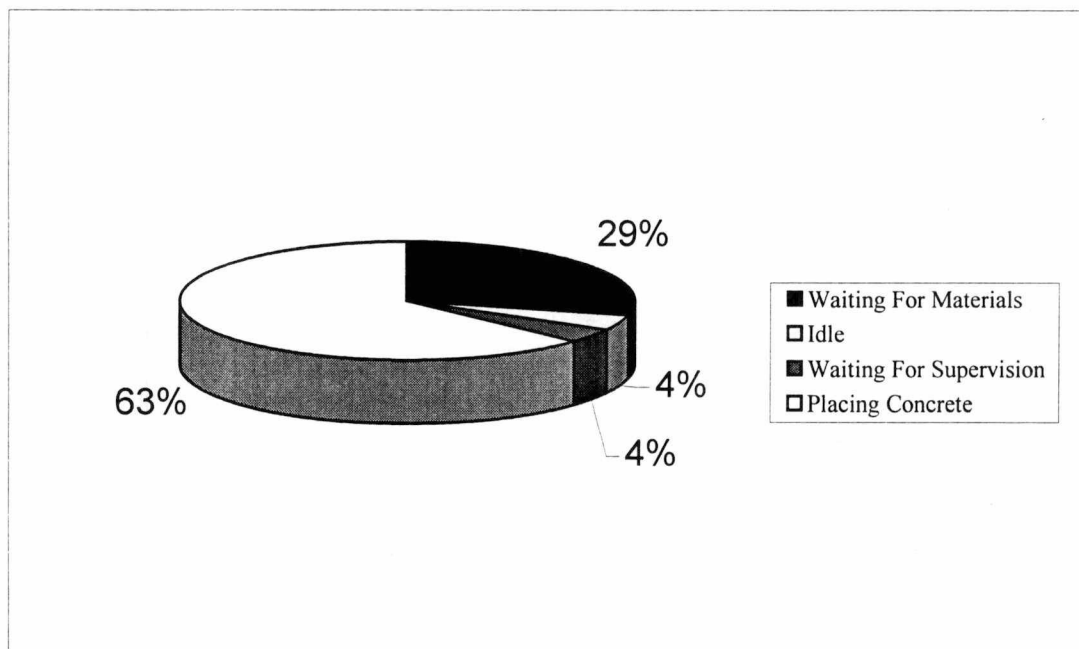


Figure 2-5. Activity Model for Concrete Workers (John Christian and Daniel Hachey. *Journal of Construction Engineering and Management*, March 1995, p. 24)

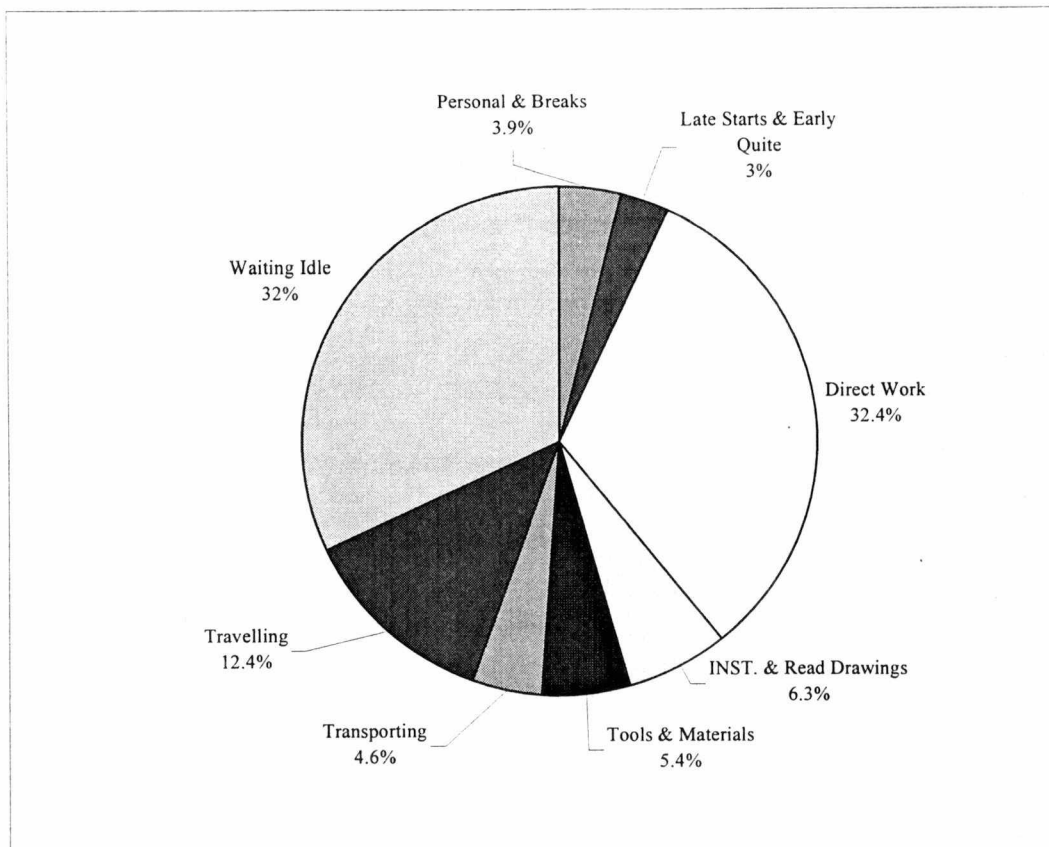


Figure 2-6. Graphical Representation of the Activity Model (H. Randolph Thomas et al. *Journal of Construction Engineering and Management*, December 1990, p. 714)

As a result of their study, they found that there is no defined relationship between performance factors and direct work or waiting and direct work. Moreover, they indicated that “direct work operates as a random variable, and there is no correlation between direct work and performance.” Thomas’ and his colleagues’ findings, however, contradict many studies, which suggest that these relationships do exist.

Finally, construction productivity remains difficult to determine. Although labor productivity is an important factor that affects construction productivity,

construction productivity is also affected by other factors, such as equipment and management, that may be more crucial than labor production. Therefore, new ideas, procedures, techniques, experiences, and statistical applications are essential for developing a reliable analytical and practical method for addressing construction productivity while taking into consideration all the factors that influence it. Furthermore, each type of operation needs to be considered individually in determining construction productivity. For example, the fact that variables which affect highway construction are not the same as those that affect building construction should be considered.

## **2.7 METHOD PRODUCTIVITY DELAY MODEL (MPDM)**

Adrian (1974) developed the Method Productivity Delay Model (MPDM). According to Adrian, the “MPDM provides the average construction firm with the means of measuring, predicting and improving a given method productivity.”

The MPDM’s fundamental approach is to analyze production cycles in two groups: (1) delay cycles and (2) non-delay cycles. The cut-off point between delay and non-delay cycles depends directly on the data collector’s experience. In addition, contractors’ viewpoints were considered during the development of the MPDM.

There are four stages in applying the MPDM: (1) Data Collection, (2) Method Processing, (3) Model Structure, and (4) Model Implementation and Benefits.

(1) Data Collection. Three types of information are recorded during the data collection: the production unit; the production cycle, which is the time required for a production unit to finish one cycle; and documentation of the delays and their causes, such as environmental, labor, equipment, and management.

(2) Model Processing. At this stage, statistical analysis is conducted using the mean of overall cycles, the mean of non-delay cycles, the average variation from the mean, the probability of occurrences, and the relative severity of the delay cycles.

(3) Model Structure. At this stage, productivity, overall method productivity, ideal cycle variability, and overall cycle variability are calculated as follows:

$$\text{Ideal productivity} = \frac{1(\text{hour})}{\text{Mean non - delay cycle time}} \times C \quad (2.10)$$

$$\text{Overall method productivity} = \frac{1}{\text{mean overall cycle time}} \times C \quad (2.11)$$

C= Capacity of one cycle.

$$Ideal\ cycle\ variability = \frac{\sum \left| \left( \frac{non - delay}{cycle\ time} \right) - \left( \frac{mean - non\ delay}{cycle\ time} \right) \right|}{\frac{number\ of\ non - delay\ cycles}{Mean\ non - delay\ cycle\ time}} \quad (2.12)$$

$$Overall\ cycle\ variability = \frac{\sum \left| \left( \frac{overall\ cycle}{time} \right) - \left( \frac{mean - nondelay}{cycle\ time} \right) \right|}{\frac{number\ of\ total\ cycles}{Mean\ overall\ cycle\ time}} \quad (2.13)$$

#### (4) Model Implementation and Benefits.

The MPDM is a method that calculates ideal and overall productivity for given data. It can predict variation in ideal and overall cycle times and help contractors identify delays in the operation. Although changing resources will affect the prediction of productivity; this prediction can be evaluated by looking at variability.

## 2.8 COMPUTER SIMULATION

Computer simulation has recently been used for analyzing and evaluating construction operations. The CYCLONE (Cyclic Operation Network) simulation was first developed by D.W. Halpin in 1973. In 1990 and 1992, respectively, Halpin also

developed and improved CYCLONE software for microcomputers to estimate the duration of work tasks and productivity. The most distinctive characteristic of CYCLONE is its ability to determine productivity and evaluate the duration of a task with regard to work activity and idleness of production resources.

CYCLONE has six model-building elements, as shown in Figure 2-7. The normal and combi elements represent work activity, the queue element represents resources waiting in line to execute the work task, the arrows link various elements of the model, the function element consolidates the flow of units at a certain point, and the counter element counts the number of cycles for a production unit.

The identification of each element's function is very important to the construction of the model. CYCLONE simulation analysis is applied in four stages:

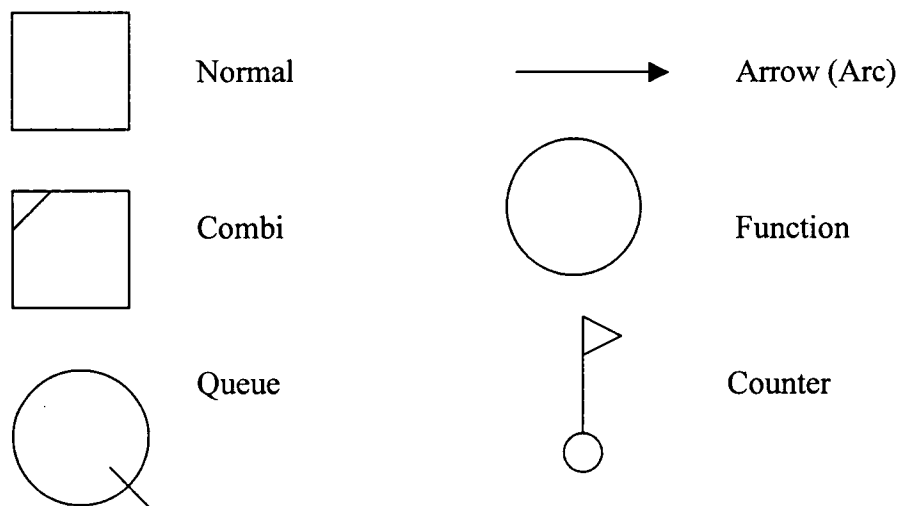


Figure 2-7. Elements of the CYCLONE Model

- (1) Data Collection. The CYCLONE model requires detailed data collection and the documentation of time at various points within the cycle.
- (2) Model Layout. The basic elements of the model are used to construct a model of the operation.
- (3) Initialization of the Activity Elements. The elements in the model are initialized and entered into the computer using problem-oriented language.
- (4) Running the Program. After each computer run, CYCLONE presents simulation results pertaining to the performance of the process.

The results include productivity and statistical data, such as the time of a cycle, the percentage of time for each element, and the average number of units waiting at the queue. CYCLONE can be applied using both deterministic and probabilistic models.

## **2.9 EVALUATION OF EXISTING METHODS**

Three approaches --- the Experience Approach, the Cyclic Approach, and the Micro Cyclic Approach --- have been used by researchers to study construction productivity and duration:

- (1) The Experience Approach. In this approach, task duration is estimated based on historical data and the experience of experts. This approach, which is often called the "Discrete Method," has dominated the practice of most highway departments.

(2) The Cyclic Approach. In this approach, the task is broken down into cycles, and the completion time of each cycle is considered in the analysis.

Examples of this approach are the MPDM and the Queuing Theory.

(3) The Micro Cyclic Approach. In this approach, the cycle is broken down into several activities, and each activity is identified, measured, and evaluated. The main method that uses the Micro Cyclic Approach to analyze construction productivity is the CYCLONE.

In evaluating several methods and techniques that address productivity and duration, scheduling techniques are often confused with task duration. However, in reality, scheduling cannot be done until the time for a task has been established.

Arditi and Albulak (1986) compared the LOB Method to the CPM for rural highway projects in which 100 km of highway were resurfaced. According to Arditi and Albulak, the LOB Method estimated that the project would require 386 working hours to finish, while the actual duration of the project was 408 hours --- a delay of 5%. For a similar project, the CPM estimated that the project would require 450 hours --- a delay of 16%. Arditi and Albulak indicated that "the LOB technique allows a better grasp of the project than any other scheduling technique because the scheduler has access to activities rates of production." This statement cannot be true, however, because the production rate is not controlled only by scheduling, but also by variability. This variability can greatly influence the completion time of a project, regardless of the scheduling method used. In his study, he indicated that the variation

of the project completion time was only 5% using the LOB Method, while the variation was 16% using the CPM. However, he also indicated that the delays in the projects were caused by problems totally unrelated to the scheduling method. The delays in the project for which he used the LOB Method were caused by two fatal accidents, while the delays in the project for which he used the CPM were caused by equipment delays. Because scheduling techniques such as bar charts, the CPM, and the LOB Method vary in application, one may work better than the other for a particular project. However, when using scheduling techniques as a planning tool to evaluate and monitor the progress of construction operations, it is essential to first determine the time associated with each task. Some scheduling techniques can monitor production better than others, but variability in construction affects duration much more than the method of scheduling.

Other studies, which use the cost of the project to determine time are not realistic in highway construction, since time is not the only factor influencing cost. The cost of labor and equipment is significantly influenced by time, whereas the cost of material is only slightly affected by time. Therefore, construction productivity cannot be evaluated by the cost of a project, but rather through analysis of variability.

Construction productivity that evaluates labor productivity only cannot be adequate for highway construction. In earth moving operations, for example, the size of the equipment and the management method play a significant role in the production rate. In some tasks, labor may have the greatest influence on the

production rate, but this is not always the case for highway construction. The activity model, on the other hand, cannot be a useful tool to evaluate productivity for two main reasons: (1) the work sampling in previous studies used labor only and (2) the individual, not the crew, was evaluated, which is misrepresentative of labor productivity. Thomas' and his colleagues' (1990) conclusion that the direct work has no defined relation with the performance and waiting times appears to be a reasonable one.

The Queuing Theory is a very useful tool for determining productivity. It is a cyclic time method in which two dependent cycles are simultaneously monitored.

The advantages of this method include the following:

- (1) It analyzes the efficiency of the processor and calling unit in relation to the production rate using the cycle time.
- (2) It determines the number of calling units required to maximize production based on the processor capacity.
- (3) It evaluates the capacity of the processor for efficiency analysis.
- (4) It determines the probability of the number of units in the system.

The shortcoming of the queuing analysis is that it evaluates non-stop operations only. Thus, it may not represent the overall operation time if, for example, there are cases in which the operation stops in the middle of the day because of rainy weather or a breakdown of the major equipment. However, the Queuing Method can be a useful tool for day-by-day evaluations of productivity and task duration.

The Method Productivity Delay Model (MPDM) developed by Adrian (1974) is also a cyclic time method. When Adrian first developed his method it was the state-of-the-art because it considered several factors that influence productivity. His method has two main problems, however, when applied to highway construction. First, his decision to use the mean of non-delay cycles was arbitrary because the cut-off point between delay and non-delay cycle is undefined. As a result of this decision, the number of delay cycles reached 50% of the overall cycles in most of the data he collected, which is unrealistic for highway construction projects. Second, because he evaluated only a few data points for each task, his findings cannot be applied to conditions and delays in other sites where different conditions exist.

The MPDM remains the best method for determining and evaluating construction productivity for the following reasons:

- (1) It evaluates delay considering four factors that may influence time: material, labor, equipment, and environment.
- (2) It is a cyclic method.
- (3) It is easy to apply when the data have been collected.

Construction simulation using the CYCLONE is probably the highest level programming technique for construction applications. The main advantages of the CYCLONE are that it explains time distribution using both deterministic and probabilistic models, and it evaluates production based on the queue time of the

element. However, there are four major problems with applying the CYCLONE to highway construction projects.

- (1) Data collection for one task may require more than one person to document details within the cycle.
- (2) It requires extensive experience in modeling techniques, and the procedures may be very difficult for complex highway tasks.
- (3) Cycles are broken down into micro elements, and variability may not be defined, especially for relatively short cycles.
- (4) Any change in construction procedures may change the flow chart of a CYCLONE model and require the development of a new model in order for the program to run the simulation.

Although simulation models may require extensive experience in both modeling and on-site construction procedures, the CYCLONE can be a useful tool for case studies, and it has high potential for resolving dispute problems with regard to contract time.

Based on a review of the literature, the previously discussed methods may not be satisfactory approaches for determining highway task duration because variables that affect task duration have not been considered for the overall operation. These variables include the following:

- Site conditions
- Weather
- Management

- Construction methods
- Location
- Resource allocation
- Initial estimate and bid price
- Number of observations
- Codes and regulations

These variables make it extremely difficult to determine, estimate, and evaluate highway construction time. To account for these variables, a substantial number of site visits may be required to collect data on cycle time. When estimating task duration, these variables need to be taken into consideration using a method that is both reasonable and easy-to-apply. Furthermore, studies of task duration need to consider many data points and evaluate each task individually. Also, all the variables must be considered and a statistical analysis must be done to determine and evaluate the methods. The overall time duration needs to be established by determining a confidence level of time completion.

## **CHAPTER 3**

### **HIGHWAY CONSTRUCTION AS A SYSTEM**

#### **3.1 INTRODUCTION**

Highway construction is the operation of planning, programming, locating, designing, constructing, and maintaining an adequate transportation system capable of meeting the traffic needs of the public. Construction projects have many phases from the planning phase through the construction and post-construction phases. This chapter describes highway construction operations using the practices of the Tennessee Department of Transportation. The Department of Transportation, which operates through several divisions, is the organization that develops and constructs the highway system. This chapter explains some of these divisions, which directly relate to construction projects, such as the planning, road design, structural design, right-of-way, construction, and safety divisions. Some offices, such as the contract compliance and legal departments, are also briefly mentioned.

The Department of Transportation is organized under the overall supervision of the Commissioner, who is assisted by the Assistant to the Commissioner, the Bureau of Planning and Development, and the Bureau of Operations. Each of these bureaus is supervised by an executive director and two assistant executive directors, each of whom supervise two or three divisions. There are ten divisions in the

Department of Transportation, and each bureau supervises five of them. The Bureau of Planning and Development supervises the planning, program development, road design, structural design, and right-of-way divisions. The Bureau of Operations supervises the public transportation and railway, maintenance, aeronautics, materials, and construction divisions. In addition, the Bureau of Operations oversees several smaller departments, such as the safety, contract compliance, and maintenance offices. Transportation directors in each region manage the collective work of all of the divisions within their region. Finally, there are many offices, which are supervised by the Assistant to the Commissioner, including the Legislative Liaison, Public Information, Personnel, Legal, Central Services, Finance, Internal Audit, and the Aeronautic Commission offices. (See the Organization Chart in Figure 3-1).

The Department of Transportation also works directly with the Federal Highway Administration (FHWA), which represents the federal government in matters relating to highways with the principal function of administering highway projects for which any money is furnished by the federal government. The contract for such projects is awarded by the state with the concurrence of the FHWA. Construction is supervised by the Department of Transportation's construction division. However, engineers from the FHWA can inspect federal-aid projects at any time selected by them. The relationship between the FHWA and the Department of Transportation does not directly involve the contractor.



# DEPARTMENT OF TRANSPORTATION

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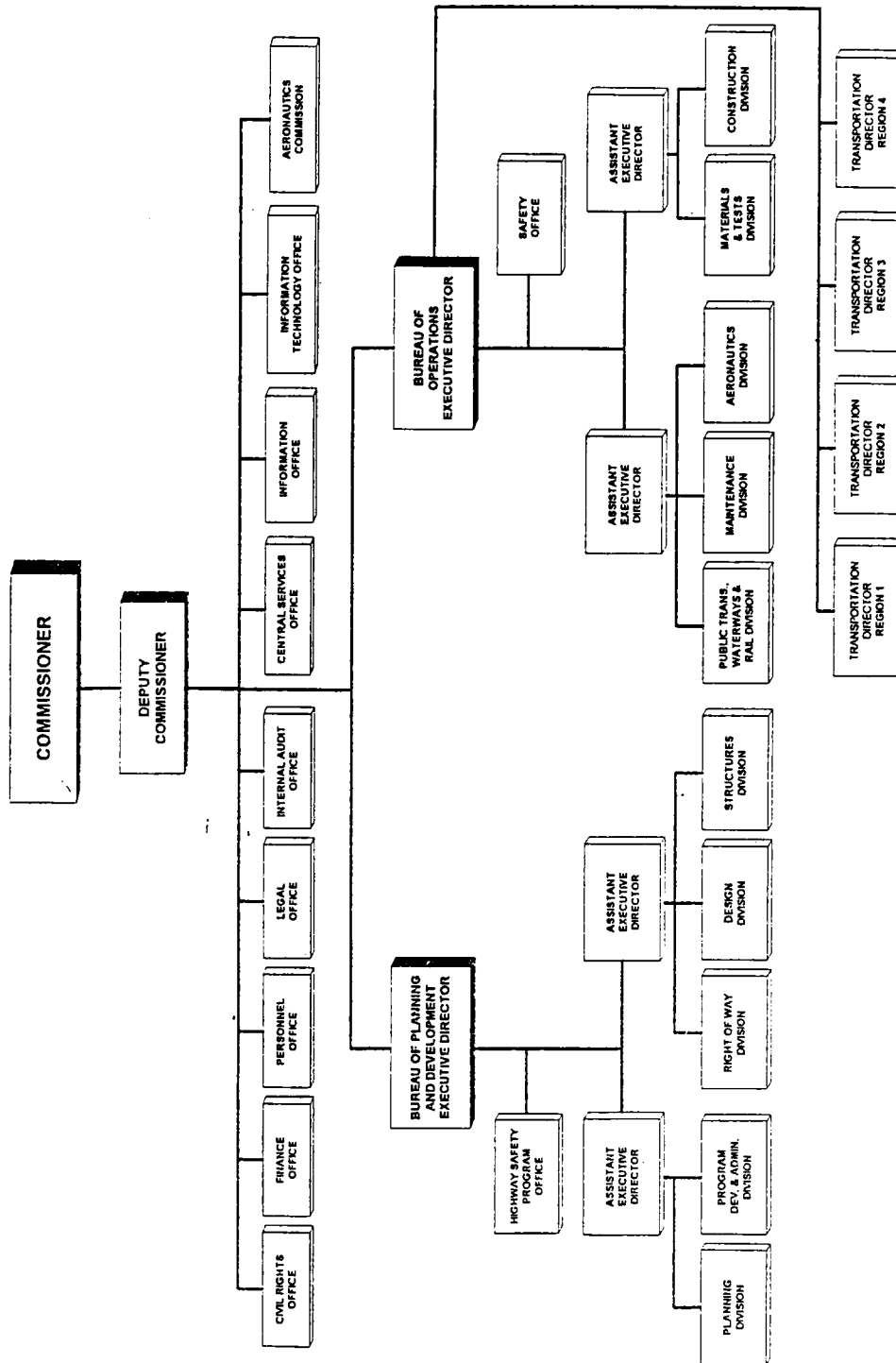


Figure 3-1. Organization Chart for the Tennessee Department of Transportation

An FHWA representative inspects the project for duration, over run costs, and to assure the implementation of the minority goal policy, which states that 10% of the work must be awarded to minority-owned businesses. This policy is implemented and monitored by the Contract Compliance Department.

### **3.2 PLANNING PHASE**

The planning phase in highway construction is carried out by the Planning Division. This division organizes the development of ongoing and future projects and is also in charge of the organization and process development of the highway project to ensure (1) adequate consideration is given to the possible economic, social and environmental effects of the proposed highway system or project; (2) the decision for each project is made in the best interest of the public; and (3) the plans for the project meet the requirements of the U.S. code of the transportation planning process and the Federal-Aid Highway Act. Each state highway department is required to develop a procedures manual for planning and development. Project development at the planning level should consider short and long-range transportation needs.

The development of the project at the planning level goes through four main stages.

- (1) "Systems Planning Stage." In this stage, a comprehensive plan for the orderly development of a transportation system consistent with state, regional, and local goals and objectives is developed. In addition,

alternative highway plans are developed, tested, and evaluated. Several studies on the project are conducted considering traffic, functional classification, project need, financial resource analysis, and environmental effects. The effects of alternative plans are identified and evaluated by in-house experts of the Department of Transportation and experts from other agencies at the federal, state, and local levels.

- (2) "Route Planning Stage." In this stage, a plan is developed for a particular route, which includes route location, project definition, and functional design. Other important considerations are environmental effects, traffic, and costs.
- (3) "Design Location Stage." In this stage, the horizontal and vertical alignment of the proposed construction is established, and preliminary design plans are prepared. At the end of this stage, a design study report is prepared describing the general design criteria for the project, and preliminary plans are then prepared to show the proposed alignment, the general design criteria including provisions for minimizing adverse environmental effects, the safety procedures, and the right-of-way lines.
- (4) "Planning Layout Stage." After a review of the alternative plans, the project will be submitted to the state legislature and the road design, structural bridge, right-of-way, and construction divisions for the determination of cost estimates and project duration. In this phase, the

public is involved directly to consider whether the construction is in the public interest. Informal meetings and public hearings are held to discuss the advantages and disadvantages of changes in the layout and function of connecting roadways; the amount of right-of-way acquisition needed; and the social, economic, and environmental effects of the project.

The Planning Phase of the highway construction project can be very complicated due to public involvement, right-of-way acquisitions, and environmental considerations. Engineers and planners must strive to minimize the effect of the highway on the environment and explain to the public that alternative projects which serve the interest of the public may conflict with the convenience of individuals. Because of the complicated nature of planning procedures, the planning time for a project can be extremely long, and, in some cases, can even exceed the construction time of the project.

### **3.3 DESIGN PHASE (STRUCTURAL BRIDGE AND ROADWAY)**

Once a project has been planned, the design phase begins. There are two main design divisions in the Department of Transportation: the Roadway Design Division and the Structural Design Division. The Roadway Design Division is responsible for designing the layout of the road, drainage system, and topography. The design divisions in general facilitate the function of the project by developing plans and

guidelines for construction. Engineers in the Department of Transportation develop criteria and procedures to achieve the main objectives of the design: appropriate function, adequate strength and durability, and low maintenance. Design in highway construction is based mainly on the AASHTO Code for roadway and structure.

The first step of the design engineer is to review the proposed planning of a project and to collect information about it. Information, such as survey, traffic, and geological data; right-of-way lines; structural requirements and capacity; rainfall; and location can be obtained from project records. Once a thorough study of the site is conducted and information is gathered and reviewed, the preliminary design is prepared. Once guidelines for the design are established, a set of drawings is proposed. The Roadway Design Division prepares the roadway design, right-of-way, and construction drawings. The Structural Division prepares bridge and structural details. Once the roadway and structural designs are finished, a set of plans and drawings are prepared and combined. After being edited and revised, the plans are printed and sent to the construction division to establish cost and project duration.

Increases in the cost of new construction have led most highway departments to consider restoring and repairing existing roads and structures rather than building new ones. A significant percentage of construction dollars are now being used for the restoration and rehabilitation of existing roads and bridges. Because methods for restoring and resurfacing highways and bridges to extend their service and enhance highway safety have not been clearly established, both design divisions have faced

significant challenges in establishing procedures and guidelines that can adequately applied to rehabilitation projects. It has also become clear that some of the existing bridges may not be adequate to resist a dynamic load. Therefore, more research is needed to enhance the use of new technology to achieve adequate design procedures not only for new structures, but also for existing structures.

The design departments rely mostly on the experience of their engineers and planners to establish guidelines and to provide project documentation. In some projects, they work closely with consulting engineers. The departments also provide a set of drawings for each project.

### **3.4 RIGHT-OF-WAY**

The Division of Right-of-Way is responsible for the acquisition of rights-of-way for most state or state-aid highway construction projects and for managing the non-highway use of the state's right-of-way. The division operates through several field offices which are directly responsible for the acquisition of rights-of-way in accordance with established policy and procedure. The central office is responsible for coordinating all phases of right-of-way, establishing the policies and operation procedures of the division, and monitoring the field office operation.

Right-of-way contracts are open to bidders with such qualifications as experience, a license, and awareness of the guidelines and procedures for right-of-

way. The selected vendor will be contacted and an agreement reached on the terms of the contract. If an agreement is not been reached, a second vendor will be selected.

After all bids are opened, the Department of Right-of-Way personnel will announce the low bidder. The bid is reviewed for errors and adequate manpower.

The Design Division sends the field office the relocation section, which includes a survey of all the business, residential, and other property involved. A preliminary cost estimate is established. Then, the acquisition stage is established by the Division of Right-of-Way.

Negotiation with the owner begins, and a program of relocation assistance and payments, which include moving costs, is developed. If the negotiations fail, the property owner will be notified that the purchase of the property is imminent, and the matter will be settled in court. Once the right-of-way is acquired, the manager sends the construction department the right-of-way certification for the project. The construction department will then schedule a construction bid opening date.

### **3.5 CONSTRUCTION PROCESS AND OPERATION**

#### **3.5.1 Construction Organization**

The Construction Division is responsible for the administration of contract work. It assumes responsibility at the time the contract is awarded in accordance with the procedures established by the Department of Transportation, and its responsibility ceases when the project has been accepted by the department under established

policy. The Regional Engineer is the operational project engineer, who is the department's representative on the project. Personnel will be assigned to the project engineer representative of the Director of Highways in each of the four regions of the state. Among the Regional Engineer's assistants is one assigned to contract administration and designated as Regional Construction Engineer. Operating under the Regional Construction Engineer and his or her assistants are the project engineers.

### **3.5.2 Construction Document and Contract**

The highway contract is a unit bid price. Although the project contains many tasks, which are treated individually in terms of pay, the collective price for all tasks makes the overall bid price. The construction plans, which describe the details of the project and contain the estimated quantity of the tasks, are available for contractors to review. Once the contractors review the plans, they bid on the project in a competitive manner. The department awards the project to the "lowest reliable bid." Once the bids are opened and announced publicly, the lowest bidder is assumed to be awarded the bid if he or she meets some requirements, such as the ability to provide a bond and adequate resources to finish the job within a reasonable time. If all requirements have been met by the contractor, he or she is invited to proceed with the work. This is called the "work order." A copy of the work order is sent to both the contractor and the project engineer by the regional office.

### **3.5.3 Construction Processes**

The contractor who is awarded the project is required to submit his or her plan of operation or schedule of the project. This plan should be both complete and practical so that the project will be well-managed and completed on time. It should be properly detailed to show the sequence of operations. The basic plan of operation should also be implemented by the contractor, who should provide advance notification to the Project Engineer of the exact starting time for each phase of the operation so that the proper inspection and field work may be arranged.

As soon as work begins on each project, the Project Engineer notifies the state construction engineer of the beginning date and the date that charging time against the project was started. This can be arranged in the pre-construction conference with the contractor. Many other people are also involved in the pre-construction conference, such as sub-contractors, state project engineers, administration inspectors, materials engineers, and representatives of the legal, safety, and contract compliance offices. Some of the subjects to be discussed in the pre-construction conference are duration of the project, time change for the working day, legal relations and responsibilities, special requirements for unusual conditions, inspection procedures, safety, equal employment opportunities, and the goal for minorities in federally funded projects. The contractor can then move the equipment and start work. The contractor is expected to perform the work according to the contract document, plans, specifications, and time established by the department.

### 3.5.4 Construction Inspection

Project inspection is one of the main responsibilities of the Construction Division. The purpose of inspection is to ensure that the work is done according to plans and specifications and to document productivity to determine contract time and establish a payment procedure for contractors. It is the responsibility of the Project Engineer to ensure that the construction work on each structure or portion of a structure is thoroughly inspected. Each project has many inspectors. A specialty inspector checks materials, procedures, and the finished task. Materials, such as concrete and asphalt, are inspected for strength, temperature, and workability. The final work is also inspected. The inspector should have a thorough understanding of accepted procedures to ensure proper compliance with all specifications. The quality of work and materials must meet the requirements found in the following TDOT manuals: *Standard Roadway and Structural Drawing* and *Standard Specifications for Road and Bridge Construction*. The inspector is also required to charge time for each working day to establish project duration of the contract. Furthermore, he is expected to properly document the procedures and resources. A properly kept diary of inspections can help the Department of Transportation to avoid problems that may occur due to poor quality of work and project duration overruns. This diary may also play an important role in resolving legal disputes between the contractor and the Department of Transportation.

### **3.5.5 Incentive and Disincentive (I/D)**

Incentive and Disincentive (I/D) is a method of modification to help eliminate overruns and cut contract time. Projects that include I/D in the contract offer the contractor a bonus (incentive fee) if the project is completed early and charge the contractor a penalty (disincentive fee) if the project is completed after the contract time. Highway construction costs have increased significantly in recent years. One of the main reasons is the increase in project duration. Incentive and Disincentive (I/D) is one method of reducing the cost associated with time overrun. Such costs include (1) safety of the user, (2) loss of user time because of traffic, (3) increases in gasoline consumption, and (4) increases in administration costs. In order to use I/D in highway construction, the following factors need to be considered:

- the effectiveness of using I/D for a particular project
- the benefit as a result of the deviation between incentive cost and cost reduction as a result of a time reduction of the project
- the effects of time reduction on the quality of work as a result of an I/D project
- the potential for an increased number of legal disputes

Once it is decided that I/D will be used, the method and amount of I/D payment and a realistic time of project completion need to be established. Most transportation departments use the A+B Method. In this method, the I/D is calculated by using the daily road-user cost that is determined by the department combined with the initial bid price established by the contractor.

According to Herbsman and Ellis (1995), I/D significantly reduced the contract time in 14 projects in 7 states. Twelve of the projects were completed earlier than the time estimated by the engineer. The time saved varied from 2.9 to 68.4%. Two of the projects were completed later than the time estimated by the engineer. Although I/D contracts may look promising, the projects need to be analyzed for I/D before decisions are made to include I/D in the project documents, especially when the state may lose cases in court for projects that include disincentives. Therefore, the Department of Transportation and Federal Highway Administration need to sponsor research on the factors that affect project duration. Using this research, they will be better able to select the appropriate projects in which to include incentives and disincentives.

### **3.6 CONSTRUCTION SAFETY PROCEDURE**

Construction safety procedures are established by the Department of Transportation and the Federal Highway Administration to prevent personal injury or property damage. A construction safety program considers the safety of the traveling public, the contractor, state employees, and equipment.

#### **(1) The Traveling Public**

The traveling public must be protected from the dangers of construction operations. Adequate barricades, signs, and traffic control should be used properly and where needed. Traffic control should be done according to the

FHWA's "Manual on Uniform Traffic Control Devices for Streets and Highways," as specified in the contract.

## (2) Contractor Safety

The hazardous nature of the work involved in road construction requires all personnel to be constantly alert if injury is to be avoided. In both federally funded and state-funded projects, the contractor is required by law to comply with the safety regulations administered by the State Department of Labor and the Federal Occupational Safety and Health ACT (OSHA) administered by the U.S. Department of Labor.

Although contractors are ultimately responsible for the overall project, and the Department of Transportation deals only with contractors, the sub-contractor must also comply with the construction safety and health standards. Each contractor is required to provide construction safety procedures for their company.

## (3) State Employee Safety

All state employees are placed under the Occupational Safety and Health Act (OSHA) standards that a contractor is working under. Employees on construction projects should be especially careful of exposure to unnecessary danger. Project engineers are expected to ensure that employees are furnished with and use safety devices and equipment. Safety hard hats must be worn at all times at construction sites. Also, state vehicles must be well-maintained

and frequently inspected. The Department of Safety monitors safety procedures and programs by providing training and seminars. These procedures should reduce accidents in highway projects. In addition, time reduction should significantly reduce roadway hazards on many construction sites.

The Department of Transportation is one of the largest organizations in the state. Various divisions within the department interact with each other and work individually to achieve the common interest of providing an adequate transportation system capable of meeting the traffic needs of the public, to assure minimum safety requirements, to decrease the daily user's cost by eliminating time loss, and to decrease gasoline costs. The Department of Transportation works with all its divisions and with the FHWA to establish a transportation system that will fulfill the needs of the public with reasonable cost and duration.

## **CHAPTER 4**

### **THE AVERAGE AND DISTRIBUTION MODEL OF PRODUCTIVITY (ADMP) FOR CONSTRUCTION OPERATIONS**

#### **4.1 INTRODUCTION**

In the literature review, many methods of predicting construction productivity were discussed and evaluated, such as using labor productivity to represent total productivity; using the cost alone to evaluate task duration; using the productive and non-productive time demonstrated in a graphical method; and using the discrete method to evaluate task duration. Although these methods have contributed tremendously to a better understanding of productivity, they cannot be adequately applied to highway construction projects because variability in weather, job conditions, method of construction, resources allocation, and management is very difficult to evaluate and determine. Since every project is unique, variability can affect one project or site more than another. Although many studies explain the effect of only one factor such as weather or material delays, other factors that also may affect the project duration are ignored.

Due to the complicated effects of many factors on project duration, a method that combines the effects of all these variables is needed. The development of a new technique of analysis that relies on extensive data collection for several site conditions is essential for predicting and measuring highway construction

productivity. The Average and Distribution Model of Productivity (ADMP) tests, measures, evaluates, predicts, and analyzes highway construction productivity. The ADMP relies on extensive data collection to evaluate variability and determine task duration. The mean cycle times of the actual data are increased by considering the 95% confidence of completion. This chapter provides a detailed discussion of the ADMP and its procedures.

## **4.2 HISTORICAL DATA FOR PROJECT DURATION**

A study of the historical data on project time is an important procedure for evaluating the experience-based (discrete) method, which is currently used by most departments of transportation to determine contract time.

The historical data on highway projects that were let from 1989 through 1995 were studied for this research. The projects were divided according to the following Federal Highway Administration classifications:

- Small projects (0-\$500,000)
- Medium projects (\$500,000-\$2.5 million)
- Large projects (\$2.5 million and above)

Analyses were done on 451 small projects, 166 medium projects, and 69 large projects. The projects were analyzed to determine the following factors:

- The ratio of the actual time and the estimated time of completion
- The number of occurrences that fall into specified ratio ranges
- The mean ratio

- The standard deviation of the ratio
- The number of projects that were overestimated, underestimated, or completed exactly on time.

The statistical analyses of the ratio of project duration to estimated project duration for small, medium, and large projects are shown in Table 4-1. Histograms of the analyses are shown in Figures 4-1, 4-2, and 4-3.

Table 4-1. Statistical Analysis of Variability in Highway Construction Project Duration

| Small Projects<br>( \$ 0.00-\$ 500,000) |             | Medium Projects<br>( \$ 500,000-\$ 2,500,000) |             | Large Projects<br>(More than \$ 2,500,000) |             |
|-----------------------------------------|-------------|-----------------------------------------------|-------------|--------------------------------------------|-------------|
| <u>Act. Duration</u><br>Est. Duration   | Occurrences | <u>Act. Duration</u><br>Est. Duration         | Occurrences | <u>Act. Duration</u><br>Est. Duration      | Occurrences |
| 0                                       | 0           | 0                                             | 0           | 0                                          | 0           |
| 0.100-0.199                             | 1           | 0.200-0.299                                   | 1           | 0.500-0.599                                | 1           |
| 0.200-0.299                             | 16          | 0.300-0.399                                   | 2           | 0.600-0.699                                | 1           |
| 0.300-0.399                             | 29          | 0.400-0.499                                   | 2           | 0.700-0.799                                | 2           |
| 0.400-0.499                             | 38          | 0.500-0.599                                   | 10          | 0.800-0.899                                | 6           |
| 0.500-0.599                             | 46          | 0.600-0.699                                   | 13          | 0.900-0.999                                | 18          |
| 0.600-0.699                             | 47          | 0.700-0.799                                   | 16          | 1.000-1.099                                | 24          |
| 0.700-0.799                             | 54          | 0.800-0.899                                   | 28          | 1.100-1.199                                | 5           |
| 0.800-0.899                             | 56          | 0.900-0.999                                   | 39          | 1.200-1.299                                | 3           |
| 0.900-0.999                             | 74          | 1.000-1.099                                   | 29          | 1.300-1.399                                | 3           |
| 1.000-1.099                             | 55          | 1.100-1.199                                   | 9           | 1.400-1.499                                | 0           |
| 1.100-1.199                             | 10          | 1.200-1.299                                   | 8           | 1.500-1.599                                | 1           |
| 1.200-1.299                             | 7           | 1.300-1.399                                   | 3           | 1.600-1.699                                | 0           |
| 1.300-1.399                             | 5           | 1.400-1.499                                   | 3           | 1.700-1.799                                | 1           |
| 1.400-1.499                             | 2           | 1.500-1.599                                   | 0           | 1.800-1.899                                | 0           |
| 1.500-1.599                             | 1           | 1.600-1.699                                   | 0           | 1.900-1.999                                | 2           |
| 1.600-1.699                             | 2           | 1.700-1.799                                   | 2           | 2.000-2.099                                | 0           |
| 1.700-1.799                             | 2           | 1.800-1.899                                   | 0           | 2.100-2.199                                | 1           |
| 1.800-1.899                             | 2           | 1.900-1.999                                   | 0           |                                            |             |
| 1.900-1.999                             | 1           | 2.000-2.099                                   | 1           |                                            |             |
| 2.000-2.099                             | 3           |                                               |             |                                            |             |

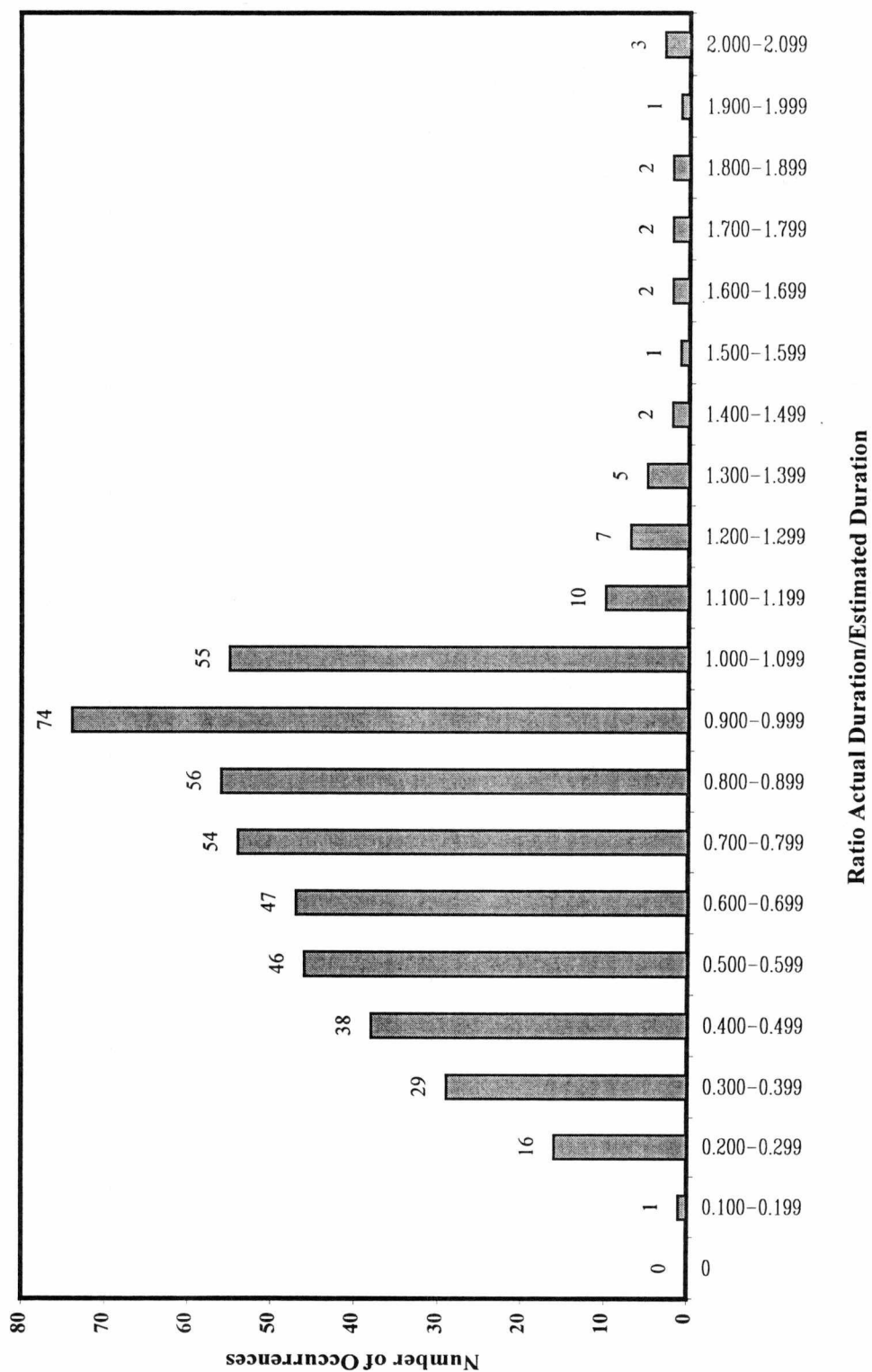


**Figure 4-1 Histogram Analysis for Small Projects**

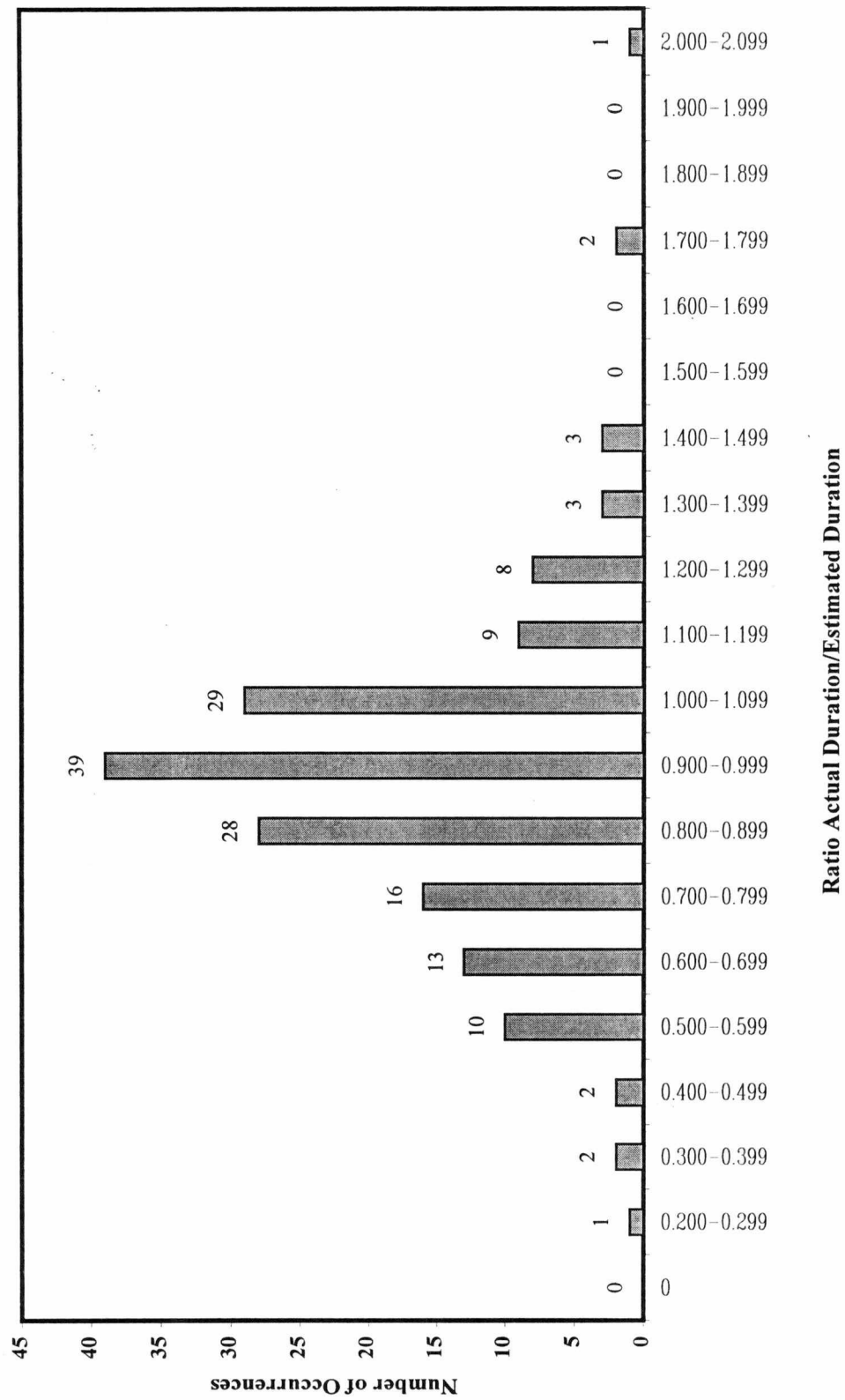


**Figure 4-2. Histogram Analysis for Medium Projects**

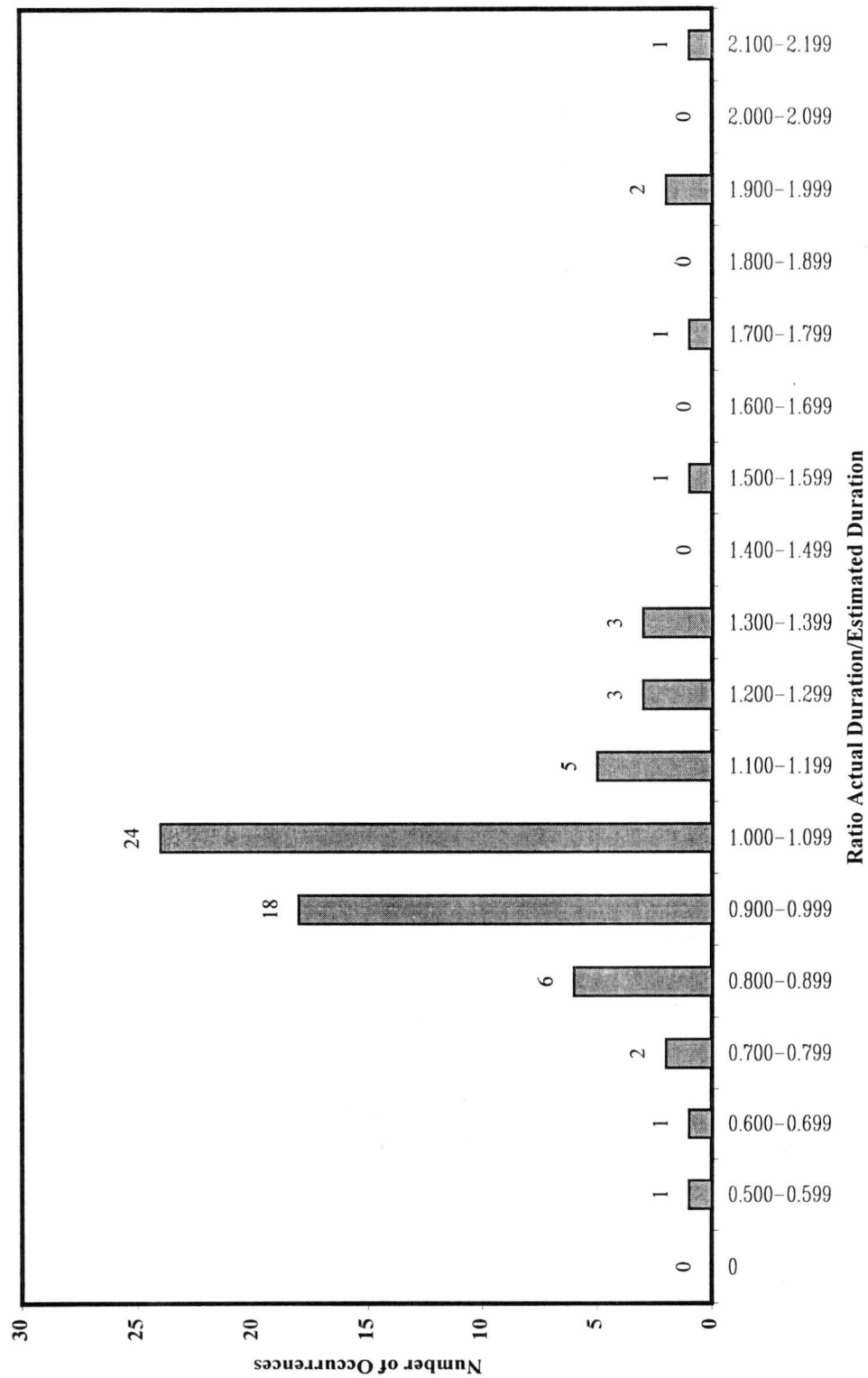


Figure 4-3 Histogram Analysis for Large Projects

Of the 451 small projects, the construction duration was overestimated for 361 projects and underestimated for 35 projects, while 55 projects were completed exactly on time. Of the 166 medium projects, 111 were overestimated, 26 were underestimated, and 29 were completed exactly on time. Of the 68 large projects, 28 were overestimated, 16 were underestimated, and 24 were completed exactly on time (Table 4-2).

Table 4-2. The Number of Highway Construction Projects Overestimated, Underestimated, and Completed Exactly on Time From 1989 Through 1995.

|                 | Total Number of Projects | Overestimated | Underestimated | Completed on Time |
|-----------------|--------------------------|---------------|----------------|-------------------|
| Small Projects  | 451                      | 361           | 35             | 55                |
| Medium Projects | 166                      | 111           | 26             | 29                |
| Large Projects  | 68                       | 28            | 16             | 24                |

From these results, the following conclusions can be made:

- TDOT, in most cases, overestimated project time.
- Many projects were completed exactly on time.
- The mean ratios showed that large projects on average were slightly underestimated (Table 4-3).

Table 4-3. Statistics of the Ratio of Actual Project Duration Versus Estimated Project Duration.

|                    | Small Projects | Medium Projects | Large Projects |
|--------------------|----------------|-----------------|----------------|
| Mean               | 0.774          | 0.913           | 1.123          |
| Standard Deviation | 0.305          | 0.202           | 0.517          |

## **4.3 DEVELOPMENT OF THE ADMP**

### **4.3.1 Data Collection**

Data on the cycle times of a task were collected to use as a basis for modeling and analyzing the nine tasks chosen for this study. Initially, highway construction projects that included the desired task were identified. This information was obtained by first determining locations of jobs from the state and then contacting the DOT official in charge of the project. After the location and date of the work were determined, the site was visited. At the beginning of the site visit, a general information sheet (shown in Appendix A) was prepared to describe the project and resources. This sheet included the following items: prime contractor, item number, contract number, county, region, environmental conditions, soil conditions if applicable, construction resources, date on which the data were collected, distance of haul, method of construction, cycle time, capacity of the cycle, and unit of measurement. Then, a data task form (also shown in Appendix A) was prepared specifically for each task. This form included information on task identification, start time of a cycle, end time of a cycle, and processor cycle time. Finally, changes in construction and unusual conditions and delays were documented by the data collector to better explain variation in the operations.

### **4.3.2 Statistical Summary of Observed Data**

Statistical analyses were applied to all nine tasks; however, the mineral aggregate task was chosen to demonstrate the ADMP methodology in this chapter. Cycle times for the placing of mineral aggregate were collected and evaluated to

demonstrate this technique. The cycle time of a mineral aggregate task is the time associated with loading the truck with the material, traveling to the construction site, dumping the material, and returning to the quarry. The observed number of cycles and the cycle time in minutes are listed in ascending order in Table 4-4. The mean and the standard deviation were calculated for the 34 observed cycle times. The frequency histograms were plotted as shown in Figure 4-4. Although the histograms resemble a normal distribution, they better fit a log-normal distribution.

Table 4-4. Statistical Summary of Sample Data for Mineral Aggregate Task

| Contract #: 4017                                      |                       | County: Davidson |                       |
|-------------------------------------------------------|-----------------------|------------------|-----------------------|
| Cycle Number                                          | Cycle Time<br>( min.) | Cycle Number     | Cycle Time<br>( min.) |
| 1                                                     | 34.00                 | 18               | 56.17                 |
| 2                                                     | 39.10                 | 19               | 56.50                 |
| 3                                                     | 43.20                 | 20               | 59.87                 |
| 4                                                     | 43.33                 | 21               | 60.25                 |
| 5                                                     | 44.11                 | 22               | 61.05                 |
| 6                                                     | 44.88                 | 23               | 61.07                 |
| 7                                                     | 46.47                 | 24               | 61.17                 |
| 8                                                     | 46.92                 | 25               | 62.25                 |
| 9                                                     | 47.20                 | 26               | 62.72                 |
| 10                                                    | 47.31                 | 27               | 62.72                 |
| 11                                                    | 49.00                 | 28               | 63.50                 |
| 12                                                    | 50.00                 | 29               | 65.75                 |
| 13                                                    | 50.77                 | 30               | 66.45                 |
| 14                                                    | 51.87                 | 31               | 69.92                 |
| 15                                                    | 52.17                 | 32               | 73.85                 |
| 16                                                    | 53.13                 | 33               | 75.82                 |
| 17                                                    | 54.83                 | 34               | 103.20                |
| Mean of cycle times of production units               |                       |                  | <b>56.49</b>          |
| Standard deviation of cycle times of production units |                       |                  | <b>12.87</b>          |

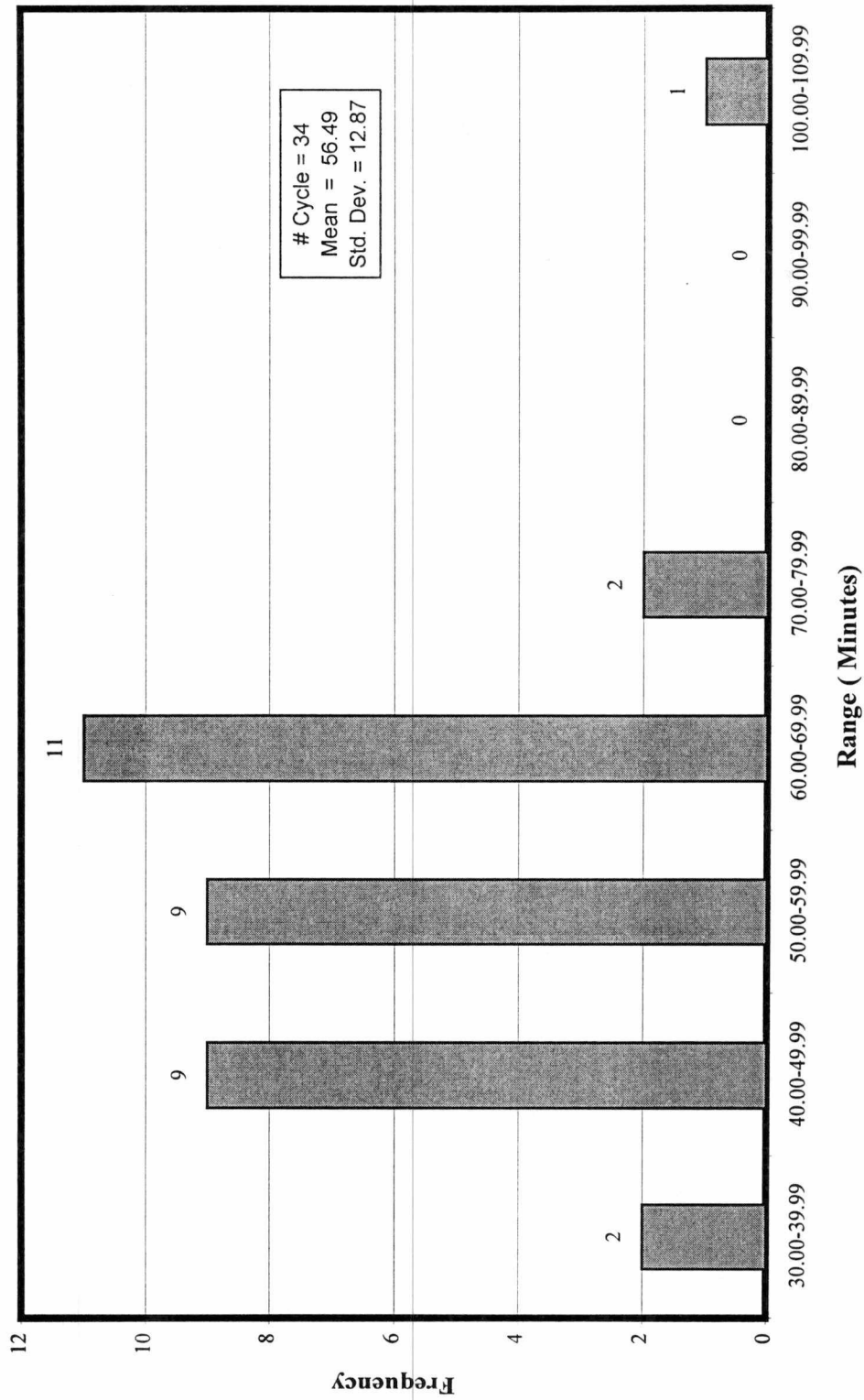


Figure 4-4. Frequency Histogram for Data Sample

### 4.3.3 Delay Versus Non-Delay Cycles

Determining the cut-off point of delay and non-delay cycles remains the most difficult aspect of the analysis. In determining the cut-off point between delay and non-delay cycles, several points were used and evaluated. These points were the median; the mean; the 1.1 mean; the mean plus one standard deviation; the mean plus 2,3,4, or 5 standard deviations; and finally considering no delays. Then, the mean of non-delay cycles, the mean of delay cycles, the standard deviation of non-delay cycles, and the standard deviation of delay cycles were calculated for each of the 10 sets of data points in the mineral aggregate task.

The result of the analysis for the mineral aggregate task showed the following:

- Using the cut-off point at the mean or below the mean resulted in about 50% of the cycles as delay cycles, which is not reasonable in highway construction.
- Using the mean of delay and non-delay cycles for the cut-off point based on experience is arbitrary and not realistic.
- The cut-off point should be above the mean since a cut-off point below the mean results in a high number of delay cycles, which is unrealistic for highway construction.
- Using only the mean or a percentage of the mean does not accurately represent the full distribution of the data, especially for data that contain a lot of variation in the cycle time.

Therefore, two approaches can be considered for determining the cut-off point between delay and non-delay cycles:

- 1) Consider all cycles with no delay. In this case, the data are taken as a whole indiscriminately. This is the most conservative approach for determining the production rate.
- 2) If it is necessary to determine the cut-off point, both the mean and standard deviation should be used for the following reasons:
  - For a particular data set, the mean of overall cycles is a constant value.
  - The effect of relatively long cycles on the data distribution can be minimized by considering the standard deviation.
  - Using the mean plus a standard deviation as a cut-off point results in the data for all 10 observed data sets consistently having 8 to 13% of delay cycles. This percentage can be lowered by using the mean plus 2,3,4, or 5 standard deviations until one reaches the point where there is no delay.

Finally, considering the cut-off point using these two approaches seemed to be very reasonable. Either approach can be used depending on the model of data distribution; however, testing the data for normal and log-normal distribution can determine if it is necessary to consider the cut-off point between delay and non-delay.

#### **4.3.4 Statistical Model to Verify Data Distribution**

Probabilistic models are verified by comparing actual observations with model predictions. The probability of data distribution must be verified using a statistical test. Two goodness-of-fit tests are commonly used to verify the data

distribution of a model: the Chi-Square ( $X^2$ ) and the Kolmogorov-Smirnov (K-S) tests.

Although the normal and log-normal distributions can be verified using these tests, the Kolmogorov-Smirnov test is more effective for evaluating the distribution of cycle times of construction operations than the  $X^2$  test because the K-S test was developed for continuous random variables, while the  $X^2$  test was developed for discrete random variables. Therefore, for evaluating the data distribution for this research, the K-S test was selected. The K-S test compares the deviation between the cumulative distribution and the observed cumulative frequency.

The basic concept of the K-S test is to measure the difference in cumulative probabilities between the proposed model and the observed data. If the maximum deviation in cumulative probabilities exceeds the allowable value, the proposed probability model will not adequately describe the random behavior of the samples. The allowable deviated value can be calculated as follows:

$$D_n \geq \max |F_X(x) - F_O(x)| \quad (4.1)$$

where  $D_n$  = the allowable deviated value

$F_X(x)$  = the cumulative probability

$F_O(x)$  = the cumulative frequency

The allowable deviated value ( $D_n$ ) is determined according to the number of samples collected ( $n$ ) and the confidence level ( $1 - \alpha$ ) desired. Note that as  $n$  increases,  $D_n$  decreases; and as  $\alpha$  decreases,  $D_n$  increases (Table 4-5).

Table 4.5. Critical Values of  $D_n$  in the Kolmogorov-Smirnov Test  
(Ang and Tang, 1975)

| $\alpha \backslash n$ | 0.20            | 0.10            | 0.05            | 0.01            |
|-----------------------|-----------------|-----------------|-----------------|-----------------|
| 5                     | 0.45            | 0.51            | 0.56            | 0.67            |
| 10                    | 0.32            | 0.37            | 0.41            | 0.49            |
| 15                    | 0.27            | 0.30            | 0.34            | 0.40            |
| 20                    | 0.23            | 0.26            | 0.29            | 0.36            |
| 25                    | 0.21            | 0.24            | 0.27            | 0.32            |
| 30                    | 0.19            | 0.22            | 0.24            | 0.29            |
| 35                    | 0.18            | 0.20            | 0.23            | 0.27            |
| 40                    | 0.17            | 0.19            | 0.21            | 0.25            |
| 45                    | 0.16            | 0.18            | 0.20            | 0.24            |
| 50                    | 0.15            | 0.17            | 0.19            | 0.23            |
| >50                   | $1.07/\sqrt{n}$ | $1.22/\sqrt{n}$ | $1.36/\sqrt{n}$ | $1.63/\sqrt{n}$ |

The following procedures were used to evaluate the data for log-normal and normal distributions of the mineral aggregate task:

- 1) Arrange the data in ascending order.
- 2) Calculate the cumulative frequency  $F_{O(x)}$ , which is the order divided by the number of observations ( $n$ ). The cumulative frequency can be listed as  $1/n, 2/n, 3/n, \dots, n/n$ , where  $n$  is the number of cycles.
- 3) Calculate the normal and log-normal cumulative probability function using the following probability density equations:

a. Normal Probability Density Function:

$$f_x(x) = \frac{1}{\sqrt{2\pi\sigma}} \exp\left(-\frac{1}{2}\left(\frac{(x-u)}{\sigma}\right)^2\right) \quad (4.2)$$

Where  $u$  and  $\sigma$  are the parameters

$$u = E(X) = \text{mean}$$

$$\sigma^2 = \text{Var}(x) = \text{variance}$$

$$X = \text{cycle time}$$

b. Log-normal Probability Density Function:

$$f_x(x) = \frac{1}{\sqrt{2\pi\zeta x}} \exp\left(-\frac{1}{2}\left(\frac{(\ln x - \gamma)}{\zeta}\right)^2\right) \quad (4.3)$$

Where  $\gamma$  and  $\zeta$  are the parameters

$$E(X) = \exp\left(\gamma + \frac{1}{2}\zeta^2\right) = \text{mean} \quad (4.4)$$

$$\text{Var} = E^2(X) [\exp(\zeta^2) - 1] = \text{variance} \quad (4.5)$$

Solve for  $\zeta$  first in the variance equation and then solve for  $\gamma$  in the mean equation.

$$\zeta = \sqrt{\ln\left(1 + \frac{S^2}{(\bar{X})^2}\right)} \quad (4.6)$$

$$\gamma = \ln(\bar{X}) - \frac{1}{2}\zeta^2 \quad (4.7)$$

The deviation is defined as the absolute difference between the cumulative frequency and the cumulative probability.

- 4) Determine the allowable deviation for any given confidence level ( $\alpha$ ) and number of observations ( $n$ ) from Table 4-5.
- 5) Compare the maximum deviation of each distribution to the allowable deviation.

In order for the data to pass the K-S test, the maximum deviation must be less than the allowable deviation. Table 4-6 shows numerically the procedures and results of the test for the mineral aggregate data. The maximum deviation observed for log-normal and normal distribution is 0.087 and 0.116, respectively, and the allowable deviation for this data using a 95% confidence level is 0.232. Therefore, this data overwhelmingly passes the test for both log-normal and normal distribution. The cumulative frequency and probability can also be graphically presented to visualize the deviation and the effects of statistical uncertainty. Figures 4-5 and 4-6 show the cumulative frequency and the cumulative log-normal and normal probability distribution, respectively. The allowable maximum deviation is also shown in the figures.

The data for the mineral aggregate task in the aforementioned example passes the K-S test for both normal and log-normal distributions. If the data fail the K-S test, the effect of delay cycles will be examined. The data will be reevaluated by dividing the cycles into delay and non-delay cycles using the cut-off point at the mean plus one standard deviation.

Table 4.7 Result of the Kolmogorov-Smirnov Test of the Mineral Aggregate Data for Log-Normal and Normal Distribution

|                  |               |                      |                         |                                |                      |             |
|------------------|---------------|----------------------|-------------------------|--------------------------------|----------------------|-------------|
| Contract #: 4017 |               | County: Davidson     |                         | Mineral Aggregate Mix (303-01) |                      |             |
| mean    56.49    |               | stand. dev=    12.87 |                         | # samples=    34               |                      |             |
|                  |               |                      |                         |                                |                      |             |
|                  |               | cum. freq.           | lognormal<br>cum. prob. | deviation                      | Normal<br>cum. prob. | deviation   |
| order            | Time          |                      |                         |                                |                      |             |
|                  | (min)         | Fo(x)                | Fx(x)                   | Fx(x)-Fo(x)                    | Fx(x)                | Fx(x)-Fo(x) |
| 1                | 34.000        | 0.029                | 0.017                   | 0.012                          | 0.040                | 0.011       |
| 2                | 39.100        | 0.059                | 0.067                   | 0.008                          | 0.088                | 0.030       |
| 3                | 43.200        | 0.088                | 0.144                   | 0.056                          | 0.151                | 0.063       |
| 4                | 43.330        | 0.118                | 0.147                   | 0.029                          | 0.153                | 0.036       |
| 5                | 44.110        | 0.147                | 0.166                   | 0.019                          | 0.168                | 0.021       |
| 6                | 44.880        | 0.176                | 0.185                   | 0.009                          | 0.184                | 0.007       |
| 7                | 46.470        | 0.206                | 0.229                   | 0.023                          | 0.218                | 0.012       |
| 8                | 46.920        | 0.235                | 0.242                   | 0.006                          | 0.229                | 0.007       |
| 9                | 47.200        | 0.265                | 0.250                   | 0.015                          | 0.235                | 0.029       |
| 10               | 47.310        | 0.294                | 0.253                   | 0.041                          | 0.238                | 0.056       |
| 11               | 49.000        | 0.324                | 0.305                   | 0.019                          | 0.280                | 0.043       |
| 12               | 50.000        | 0.353                | 0.337                   | 0.016                          | 0.307                | 0.046       |
| 13               | 50.770        | 0.382                | 0.362                   | 0.021                          | 0.328                | 0.054       |
| 14               | 51.870        | 0.412                | 0.397                   | 0.014                          | 0.360                | 0.052       |
| 15               | 52.170        | 0.441                | 0.407                   | 0.034                          | 0.369                | 0.073       |
| 16               | 53.130        | 0.471                | 0.438                   | 0.032                          | 0.397                | 0.073       |
| 17               | 54.830        | 0.500                | 0.493                   | 0.007                          | 0.449                | 0.051       |
| 18               | 56.170        | 0.529                | 0.536                   | 0.006                          | 0.490                | 0.039       |
| 19               | 56.500        | 0.559                | 0.546                   | 0.013                          | 0.500                | 0.058       |
| 20               | 59.870        | 0.588                | 0.644                   | 0.056                          | 0.604                | 0.015       |
| 21               | 60.250        | 0.618                | 0.654                   | 0.037                          | 0.615                | 0.003       |
| 22               | 61.050        | 0.647                | 0.675                   | 0.028                          | 0.639                | 0.009       |
| 23               | 61.070        | 0.676                | 0.676                   | 0.001                          | 0.639                | 0.037       |
| 24               | 61.170        | 0.706                | 0.679                   | 0.027                          | 0.642                | 0.064       |
| 25               | 62.250        | 0.735                | 0.706                   | 0.030                          | 0.673                | 0.062       |
| 26               | 62.720        | 0.765                | 0.717                   | 0.048                          | 0.686                | 0.079       |
| 27               | 62.720        | 0.794                | 0.717                   | 0.077                          | 0.686                | 0.108       |
| 28               | 63.500        | 0.824                | 0.735                   | 0.089                          | 0.707                | 0.116       |
| 29               | 65.750        | 0.853                | 0.782                   | 0.071                          | 0.764                | 0.089       |
| 30               | 66.450        | 0.882                | 0.796                   | 0.086                          | 0.781                | 0.102       |
| 31               | 69.920        | 0.912                | 0.853                   | 0.059                          | 0.852                | 0.060       |
| 32               | 73.850        | 0.941                | 0.902                   | 0.040                          | 0.911                | 0.030       |
| 33               | 75.820        | 0.971                | 0.920                   | 0.050                          | 0.933                | 0.037       |
| 34               | 103.200       | 1.000                | 0.997                   | 0.003                          | 1.000                | 0.000       |
| Zi<br>0.228      | Gama<br>4.008 | maximum deviation    |                         | 0.089                          |                      | 0.116       |
|                  |               | (95%) for            | N = 34                  | 0.232                          |                      |             |

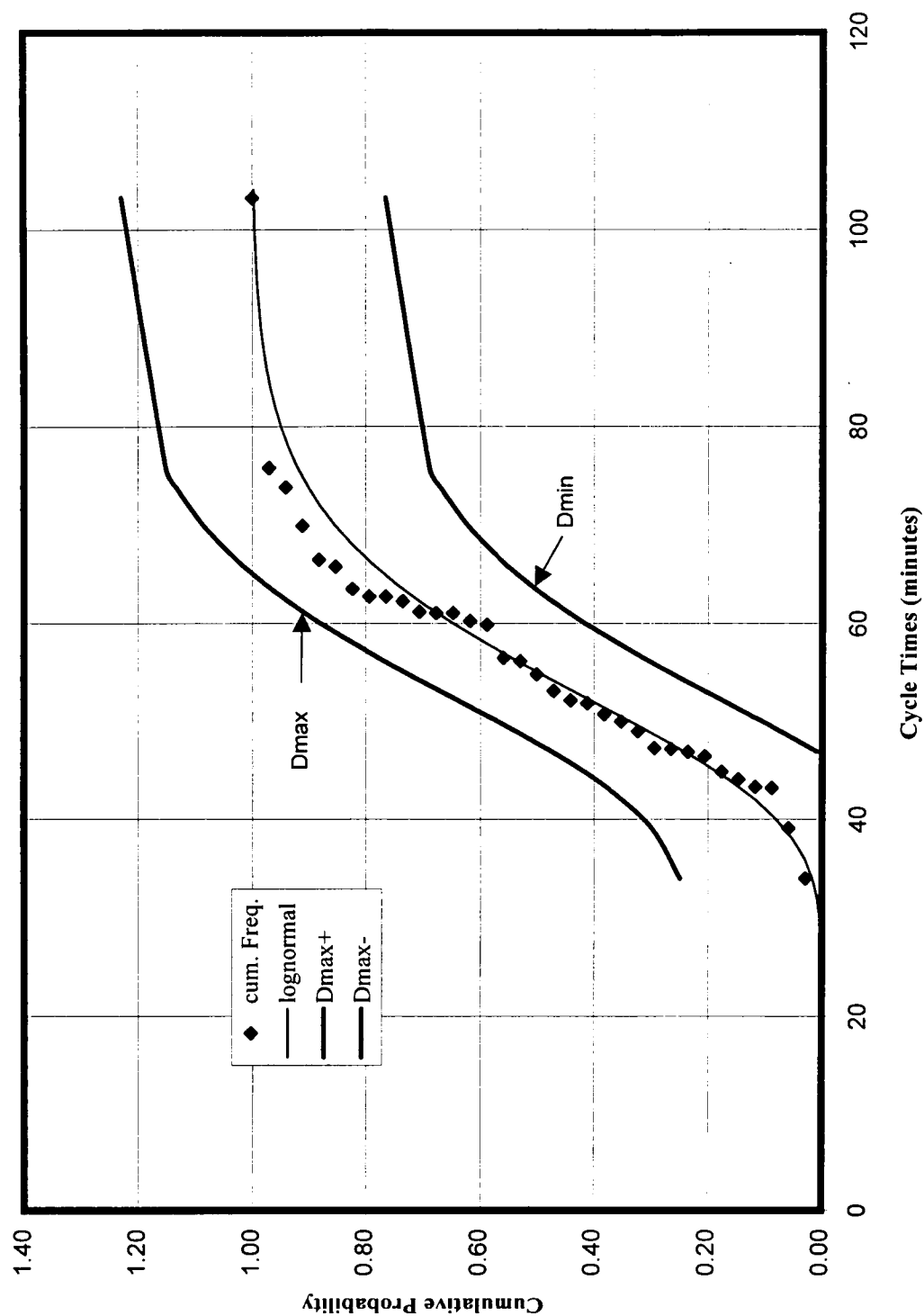


Figure 4-5. Cumulative Frequency for Log-normal Distribution

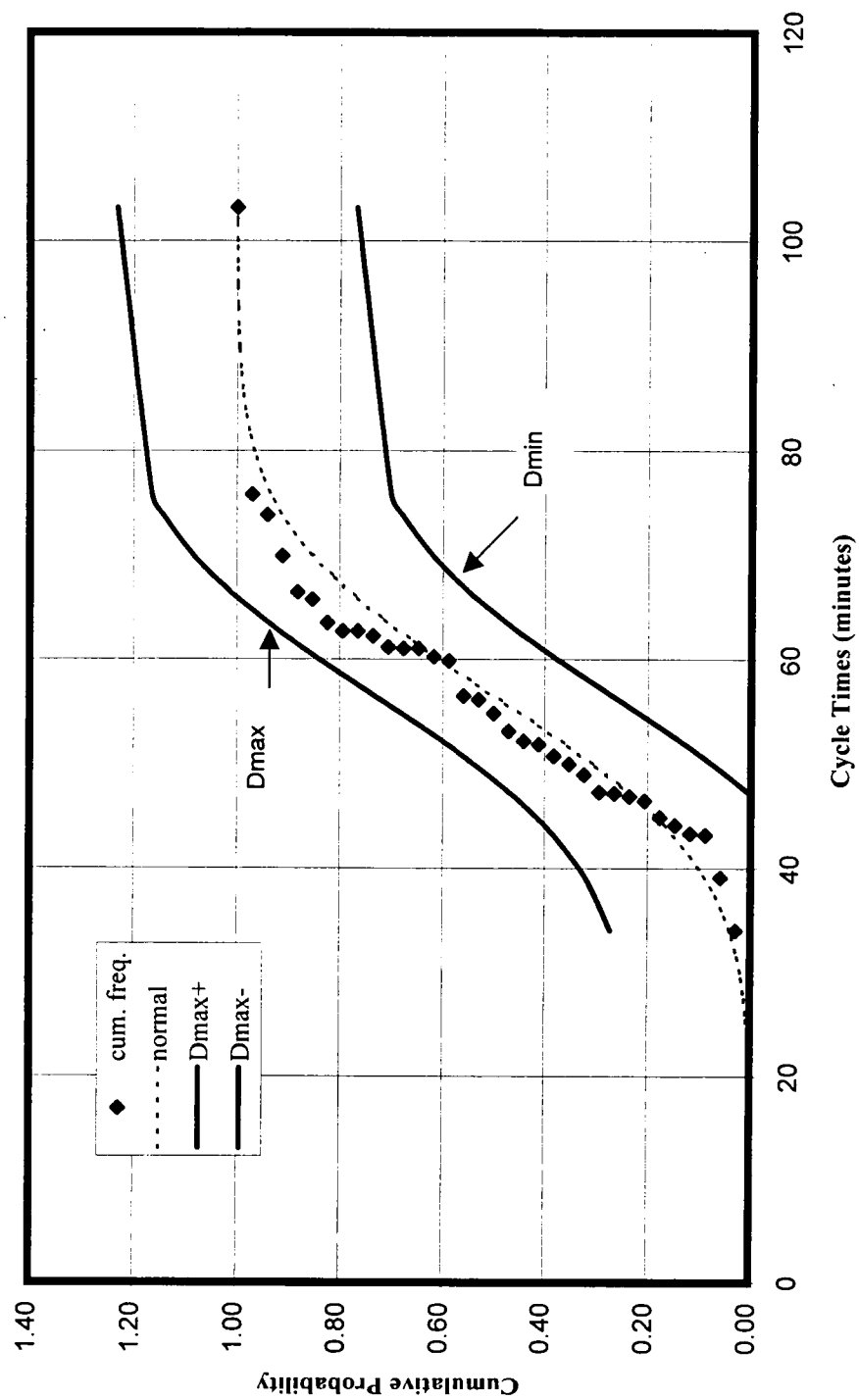


Figure4-6. Cumulative Frequency for Normal Distribution

Two conclusions were reached as a result of the analysis of all 10 data sets:

- The data of a repetitive cycle in the construction operation leaned more toward the log-normal than normal distributions.
- Excessive delay cycles can easily misrepresent the distribution. However, if the cut-off point between delay and non-delay cycles is considered for those data that fail the K-S test for log-normal distribution, the majority of the data will pass the test.

#### 4.3.5 Prediction of Cycle Time and the Application of $T_{0.95}$

The distribution of highway construction cycle times can be evaluated as a log-normal distribution. The log-normal distribution was shown to be acceptable for the majority of the data as shown in Chapter 5. The prediction of cycle times based on the collected data is computed using the 95% confidence level on the overall statistic (Figure 4-7).

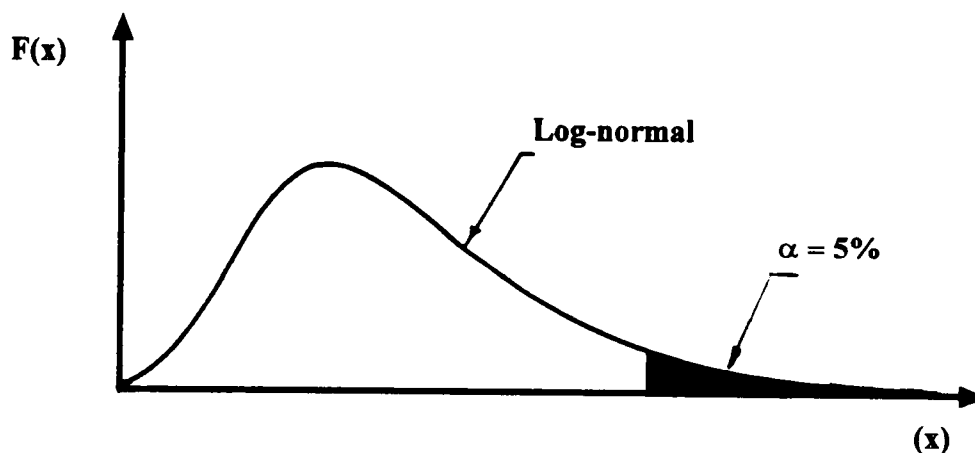


Figure 4-7. Typical Probability Model Corresponding to Prediction Value of  $\alpha$

The 95% confidence level was chosen because it offers a high degree of accuracy, while making allowances for uncertainty in extreme delay cycles, which occur in approximately 10 to 15% of highway construction operations. For  $\alpha=5\%$ , the 95% confidence level of predicting cycle time is  $(1 - \alpha)$ . The 95% confidence cycle time for a given data can be solved for log-normal and normal distribution as follows:

$$T_{0.95} = \%ND (\bar{X}_{ND} + K_{0.95}S_{ND}) + \%D (\bar{X}_D + K_{0.95}S_D) \quad (4.8)$$

When the data are considered as a whole without considering the effects of delay cycles on the productivity, only one part of the equation is computed using the following equation:

$$T_{0.95} = (\bar{X} + K_{0.95}S) \quad (4.9)$$

where  $T_{0.95}$  = 95% confidence of cycle time

$\%ND$  = fraction of the total data considered as non-delay

$\%D$  = fraction of the total data considered as delay

$\bar{X}_{ND}$  = Mean of non-delay cycles

$S_{ND}$  = Standard deviation of non-delay cycles

$\bar{X}_D$  = Mean of delay cycles

$S_D$  = Standard deviation of delay cycles

$\bar{X}$  = Mean of overall cycles

$S$  = Standard deviation of overall cycles

$k_{0.95}$  = Factor of standard deviation above the mean that will give a cumulative probability of 95%.

The relationship between the normal and log-normal variant can be calculated as follows:

$$X = \ln Y \quad (4.10)$$

Due to the logarithmic relationship between log-normal and normal variation, both log-normal and normal variables can be characterized by a standardized normal variate (U) when the mean of  $U = 0$  and the standard deviation of  $U = 1.0$ .

$$U = \frac{\ln X - \zeta}{\gamma} \quad \Leftrightarrow \quad X = \exp(U\gamma + \zeta) \quad (4.11)$$

$$\Phi(u) = 0.95 \Rightarrow P[u \leq 1.645] = 0.95 \quad (4.12)$$

where  $\Phi(\bullet)$  is the cumulative distribution function for U which is normal.

In the above expression,  $1 - \alpha = 0.95$

$$k_{0.95} = 1.645 = u$$

$$\text{Hence, } X = \exp(k_{0.95}\gamma + \zeta) \quad (4.13)$$

where  $X = 95$  percentile for log-normal distribution

$$u = k_{0.95} \text{ for normal distribution}$$

$\zeta$  and  $\gamma$  are the parameters of log-normal distribution and can be determined from Equations 4.6 and 4.7, respectively

The sample of the mineral aggregate task illustrated earlier passed the K-S test for log-normal distribution without using the cut-off point between delay and non-delay cycles. Therefore,  $T_{0.95}$  was determined using Equation 4.9. The results of the calculations showed that  $k_{0.95}$  for log-normal distribution = 1.92, and  $T_{0.95} = 81.20$  minutes.

#### 4.3.6 Task Duration and Productivity Analysis

Once  $T_{0.95}$  is calculated, it can be entered into the General Productivity Equation (4.14).

$$P = \frac{C * N_E (60) \text{ min / hr}}{T_{0.95} \text{ (min)}} \quad (4.14)$$

Also, task duration can be calculated as follows:.

$$T_{D(WT)}(HR) = \frac{TP \text{ (Production)}}{P \text{ (production/hour)}} \quad (4.15)$$

where  $P$  = Productivity (production/hour)

$C$  = Capacity of one cycle (production)

$N_E$  = Equivalent number of units (the sum of the ratios of the number of cycles to the maximum number of cycles for each production unit)

$T_{0.95}$  = 95% confidence of overall cycle times

$T_{D(WT)}$  = Total duration of a task in a working day

TP= Total production considered for determining duration

For the mineral aggregate task previously discussed in this chapter,

$C = 22$  tons

$T_{0.95} = 81.20$  min. (considering log-normal distribution)

Mean of overall cycle times = 56.49 min.

Mean of processor cycle times = 4.012 min. (Appendix C-10)

$N_E$  for processor = 1

$N_E$  for trucks can be determined as follows. From site observation, the maximum cycles accomplished by a single production unit (truck) = 7 cycles (Trucks 1 and 6 completed 4 cycles each, trucks 2, 3, and 4 completed 7 cycles each, and Truck 5 completed 5 cycles). In order to calculate the productivity of the system properly, the equivalent number of production units ( $N_E$ ) must be determined as shown in Equation 4.16 and entered into the General Productivity Equation (4.14).

$$N_E = \frac{\sum N_i}{N_{\max}} \quad (4.16)$$

$N_E = 4.86$

For each data set, three types of productivity can be calculated:

- 1) Productivity based on the ADMP ( $P_{ADMP}$ )
- 2) Productivity based on a one-day site visit ( $P_M$ )
- 3) The theoretical maximum productivity based on the average cycle times of the processor ( $P_{\max}$ ).

$$P_{ADMP} = \frac{22 \times 4.86 (60 \text{ min})}{81.20} = 79.0 \text{ tons/hour}$$

$$P_M = P_{ADMP} \frac{T_{0.95}}{\bar{X}} \quad (4.17)$$

$$P_M = 79 \text{ tons/hour} \times \frac{(81.20 \text{ min.})}{(56.49 \text{ min.})} = 114 \text{ tons/hour}$$

where  $T_{0.95}$  = The 95% level of confidence of cycle times based on log-normal distribution

$\bar{X}$  = The mean of overall cycles

$P_{ADMP}$  = Productivity based on the ADMP

$P_M$  = Productivity based on a one-day site visit.

The theoretical maximum productivity based on the processor is determined by entering the cycle times of the processor and the number of the processors into the General Productivity Equation (4.14). In this case,  $N_E$  for the processor =1.

$$P_{\max} = \frac{22 \text{ tons (1 processor) (60 min.)}}{(4.012 \text{ min})} = 329 \text{ tons/hour}$$

$P_{\max}$  = Maximum productivity based on the cycle time of the processor.

For any given production, time can also be calculated for working days by multiplying the productivity per hour by the number of hours worked per day.

The ADMP is a method to evaluate and determine productivity and task duration for highway construction tasks. The basic purpose of this method is to account for the effect of variables on construction productivity. In particular, it determines the effect of variables on productivity collectively rather than individually to arrive at a confidence level of predicting task duration.

## **CHAPTER 5**

### **APPLICATION OF THE ADMP IN HIGHWAY CONSTRUCTION**

#### **5.1 INTRODUCTION**

The following nine highway construction tasks were studied and analyzed using the Average and Distribution Model of Productivity (ADMP):

- Road and Drainage Excavation
- Borrow Excavation
- Mineral Aggregate Mix
- Bituminous Plant Mix Grade A-S
- Bituminous Plant Mix Grade A
- Bituminous Plant Mix Grade B-M
- Asphaltic Concrete Surface Grading D
- Portland Cement Concrete Pavement (RAMP)
- Steel Piles

At the beginning of each section in this chapter, a general description of each task's requirements, specifications, construction procedures, and resources, such as materials, labor, and equipment, is provided.

The cycle times of the production units and processors were measured and documented in minutes for the nine tasks. Appendix B shows these cycle times in

ascending order, along with the mean and the standard deviation, and Appendix C shows the mean of processor cycle times. Once the cycle times were determined for each site visit, they were evaluated for log-normal distribution using the Kolmogorov-Smirnov (K-S) test. The ADMP procedures were applied to determine the productivity for each data set.

Two summary calculation tables are provided for each of the nine tasks. The first table (the  $T_{0.95}$  calculation table) provides the location and contract number of the project and shows the summary calculations for  $\gamma$  and  $\zeta$ , the mean of overall cycles, and  $T_{0.95}$ . If the data did not pass the K-S test for log-normal distribution, the cut-off point between delay and non-delay was considered at the mean plus one standard deviation. For this information, the mean,  $\gamma$ ,  $\zeta$ , and the percentage of delay and non-delay cycles are also shown in the  $T_{0.95}$  calculation table. The  $T_{0.95}$  calculation tables are shown in Appendix D.

The second table (the productivity calculation table) provides the location, the contract number, the number of cycles, and the capacity of production cycles. In addition, it shows the summary calculations for the equivalent number of production units ( $N_E$ ), the mean,  $T_{0.95}$  in minutes, and the productivity ( $P_{ADMP}$ ,  $P_M$ ,  $P_{max}$ ) and the average productivity for all data sets for each task ( $\bar{P}_{ADMP}$ ,  $\bar{P}_M$ ,  $\bar{P}_{max}$ ) based on (1) the ADMP, (2) a measured one-day site visit, and (3) the theoretical maximum productivity. The mean of overall cycles of the processor for each task is used to determine the theoretical maximum productivity. The productivity calculation tables are shown at the end of each section.

## 5.2 EARTHMOVING

Although a variety of machines have been developed in the past forty years to improve earthmoving operations, there have been no significant annual increases in productivity. Equipment plays a very important role in the productivity and cost of earthmoving operations. However, despite the variety of machinery available, there are still many problems. The improper selection of equipment, limited training on the new equipment, and the contractor's poor evaluation of site conditions and poor planning have all contributed to stagnation in productivity.

Earthmoving projects in highway construction consist of many operations, including road and drainage excavation, borrow excavation, channel excavation, undercutting, and placing top soil.

The contractor for an earthmoving operation is required to provide adequate equipment to complete the project in the required time. The size, capacity, and variety of equipment must be suitable for the job condition and size of the project. Excavation is typically measured and computed by the cubic meter. The original position of the excavated area is measured using the cross-section, which is often determined by surveying methods. Additional excavation materials should be computed from the cross-section using the Average Areas Cross-section Method.

Although there are several excavation tasks in highway construction, the two main types that are used and that will be discussed in this study are Road and Drainage Excavation and Borrow Excavation. Both types will be evaluated to determine task duration and productivity.

### 5.2.1 Road and Drainage Excavation

Road and drainage excavation includes all types of excavation above the sub-grade elevation, except borrow excavation. Other road and drainage excavation tasks, such as channel excavation and undercutting, which are not included in the data collection for this study, are called unclassified road and drainage excavation. Channel excavation must be 14 feet or more in the bottom width of a channel, and undercutting deals with removing material below the grade in a cut-section.

The 12 data sets for road and drainage excavation were collected in the four regions of Tennessee (Appendix B-1 and C-1). The road and drainage excavations were mainly performed using two different types of equipment: (1) scrapers and dozers and 2) trucks and excavators. The choice between the two sets of equipment is mainly based on the distance of the haul. When the distance is less than 5000 feet, it is more economical to consider using scrapers and dozers (*Better Road*, October 1993). Other important factors are the type of soil and the slope. Scrapers and dozers work best in flat areas and soft soil, while excavators and trucks are required for sharp slopes and rocky soil. In severe job conditions when scrapers are used, a dozer is used to push several scrapers. In truck and excavator operations, two types of trucks -- mining trucks and triaxle trucks --- may be used. Because mining trucks are prohibited from using paved roadways, they are only used when the earthmoving is within the project limits. Triaxle trucks, on the other hand, can be used both within the project limits and when the truck must use paved roadways. Figure 5-1 shows a typical earthmoving operation.



A. MINING TRUCK AND EXCAVATOR



B. TRIAXLE TRUCK AND EXCAVATOR

Figure 5-1. Earthmoving Operation



C. SCRAPER



D. SCRAPER WITH A DOZER

Figure 5-1. Earthmoving Operation (Continued)

In the scraper and dozer operation, the cycle time of the production units (the scrapers) is the combined time of loading, travelling, dumping, returning, and maneuvering. The cycle time of the processors (dozers) is the combined time of pushing and maneuvering. In the truck and excavator operation, the cycle time of the production units (the trucks) is the combined time of loading, travelling, dumping, returning, and maneuvering. The cycle time of the processors (excavators) is the combined time of loading and maneuvering. In both types of operation, loading, dumping, and maneuvering are referred to as fixed times, while travelling, returning, and waiting in queue are referred to as variable times. The documentation of the cycle times of the production units is essential to determine the productivity rate when using the ADMP. All 12 data sets were evaluated for log-normal distribution. All data passed the K-S test without considering the cut-off point between delay and non-delay. Also, in evaluating the production rate of the operation, the cycle time of the processor is used to determine the theoretical maximum productivity of the system. The data for the road and drainage operation were analyzed using the ADMP. The summary calculations for  $T_{0.95}$  are shown in Appendix D-1. The productivity table (Table 5-1) shows the productivity and the average productivity for all 12 data sets,

where  $P_{ADMP}$  = Productivity based on the ADMP

$P_M$  = Productivity measured for a one-day site visit

$P_{max}$  = Maximum productivity based on the cycle times of the processor

$\bar{P}_{ADMP}$  = Average of all data sets' productivity based on the ADMP

**Table 5-1. Productivity Calculations for Road and Drainage Excavation**

|                      | Region # | Contract # | County     | Capacity of Unit (tons) | # of Non-Delay Cycles | # of Delay Cycles | # of Delay Cycles | Equivalent # of Units $N_E$ | *Mean Overall Cycle Time (minutes) | ** $T_{95}$ (minutes) | Productivity Based on $T_{95}$ (tons/hr) | Productivity Measured Day Site Visit (tons/hr) | Maximum Productivity Based on Capacity of Processor (tons/hr) |
|----------------------|----------|------------|------------|-------------------------|-----------------------|-------------------|-------------------|-----------------------------|------------------------------------|-----------------------|------------------------------------------|------------------------------------------------|---------------------------------------------------------------|
| 1                    | 1        | 3564       | Grainger   | 35                      | 40                    | -                 | -                 | 4                           | 22.82                              | 29.34                 | 286                                      | 368                                            | 368                                                           |
| 2                    | 1        | 3564-2     | Grainger   | 35                      | 100                   | -                 | -                 | 4                           | 9.35                               | 12.04                 | 698                                      | 898                                            | 933                                                           |
| 3                    | 1        | 4123       | Knox       | 12                      | 100                   | -                 | -                 | 11.11                       | 54.46                              | 83.54                 | 96                                       | 147                                            | 303                                                           |
| 4                    | 2        | 4384       | McMinn     | 13                      | 106                   | -                 | -                 | 1.93                        | 3.63                               | 5.54                  | 272                                      | 415                                            | 541                                                           |
| 5                    | 2        | 4410       | White      | 13 & 19                 | 72                    | -                 | -                 | 2.77                        | 11.05                              | 14.44                 | 157                                      | 205                                            | 384                                                           |
| 6                    | 2        | 3926       | Rhea       | 13                      | 91                    | -                 | -                 | 3.79                        | 11.32                              | 17.38                 | 170                                      | 261                                            | 476                                                           |
| 7                    | 3        | 3556       | Davidson   | 12                      | 42                    | -                 | -                 | 2.47                        | 25.07                              | 58.83                 | 30                                       | 71                                             | 188                                                           |
| 8                    | 3        | 4251       | Williamson | 12                      | 33                    | -                 | -                 | 3                           | 36.47                              | 65.53                 | 33                                       | 59                                             | 424                                                           |
| 9                    | 3        | 3948       | Davidson   | 24                      | 29                    | -                 | -                 | 1                           | 6.44                               | 7.74                  | 186                                      | 224                                            | 392                                                           |
| 10                   | 4        | 3915       | Henderson  | 12                      | 92                    | -                 | -                 | 4.6                         | 10.40                              | 16.91                 | 196                                      | 318                                            | 692                                                           |
| 11                   | 4        | 4572       | Weakley    | 12                      | 76                    | -                 | -                 | 5.85                        | 15.98                              | 20.91                 | 201                                      | 264                                            | 679                                                           |
| 12                   | 4        | 4696       | Fayette    | 13                      | 71                    | -                 | -                 | 1.97                        | 4.90                               | 9.22                  | 167                                      | 314                                            | 443                                                           |
| Average Productivity |          |            |            |                         |                       |                   |                   |                             |                                    |                       | $\overline{P_{ADMP}}=208$                | $\overline{P_M}=295$                           | $\overline{P_{max}}=485$                                      |

\* See Appendix B1 for Mean Cycle Times

\*\* See Appendix D1 for  $T_{0.95}$  Calculation

$\bar{P}_M$  = Average of all productivity measured for a one-day site visit

$P_{max}$  = Average of all productivity based on the mean cycle time of the processor

### 5.2.2 Borrow Excavation

In borrow excavation, the soil is brought to the project from another site, and, therefore, this task is performed using only trucks and excavators rather than scrapers and dozers as in road and drainage excavation. When the specifications require a different type of soil than that available in the project, borrow excavation is necessary to provide the project with the required soil. Because borrow excavation usually requires a longer haul and the use of paved roadways, triaxle trucks and excavators are generally used. Therefore, the unit cost associated with borrow excavation is usually more than that for road and drainage excavation.

The seven data sets for borrow excavation were collected in three regions of Tennessee (Appendices B-2 and C-2). The cycle time of a borrow excavation task is the time of the production unit (the truck). The seven data sets for borrow excavation were also evaluated for log-normal distribution. Five of these seven data sets failed the K-S test. Therefore, considering the cut-off point between delay and non-delay cycles was necessary for these five data sets. Once the cut-off point was considered, all five data sets passed the K-S test. The summary calculations for  $T_{0.95}$  are shown in Appendix D-2. The productivity table (Table 5.2) shows the productivity and the average productivity for all seven data sets.

Table 5-2. Productivity Calculations for Borrow Excavation

| #                    | Region # | Contract # | County    | Capacity of Unit (cy) | # of Non-Delay Cycles | # of Delay Cycles | Equivelant # of Units $N_E$ | *Mean Overall Cycle Time (minutes) | ** $T_{95}$ (minutes) | Productivity Based on $T_{95}$ (cy/hr) | Productivity Measured 1-Day Site Visit (cy/hr) | Maximum Productivity Based on Capacity of Processor (cy/hr) |
|----------------------|----------|------------|-----------|-----------------------|-----------------------|-------------------|-----------------------------|------------------------------------|-----------------------|----------------------------------------|------------------------------------------------|-------------------------------------------------------------|
| 1                    | 2        | 3866       | Marion    | 12                    | 37                    | 8                 | 3.83                        | 35.28                              | 42.69                 | 65                                     | 78                                             | 387                                                         |
| 2                    | 3        | 4017       | Davidson  | 12                    | 49                    |                   | 3.27                        | 41.83                              | 69.45                 | 34                                     | 56                                             | 348                                                         |
| 3                    | 3        | 3948       | Davidson  | 24                    | 25                    |                   | 1                           | 12.66                              | 37.19                 | 39                                     | 114                                            | 340                                                         |
| 4                    | 3        | 4723       | Robertson | 12                    | 94                    | 6                 | 3                           | 11.39                              | 13.41                 | 161                                    | 190                                            | 246                                                         |
| 5                    | 4        | 3502       | Carroll   | 12                    | 65                    |                   | 4.33                        | 23.40                              | 41.10                 | 86                                     | 151                                            | 390                                                         |
| 6                    | 4        | 3863       | McNairy   | 12                    | 60                    | 5                 | 5                           | 19.66                              | 24.02                 | 150                                    | 183                                            | 558                                                         |
| 7                    | 4        | 4224       | Fayette   | 12                    | 61                    | 7                 | 5.45                        | 20.37                              | 27.65                 | 142                                    | 193                                            | 719                                                         |
| Average Productivity |          |            |           |                       |                       |                   |                             |                                    |                       | $\overline{P_{ADMP}}=97$               | $\overline{P_M}=138$                           | $\overline{P_{max}}=427$                                    |

\* See Appendix B1 for Mean Cycle Times

\*\* See Appendix D1 for  $T_{0.95}$  Calculation

### 5.3 ROADWAY AND PAVEMENT

Six roadway and pavement tasks were observed and evaluated in this study. These tasks are the mineral aggregate base task, four asphalt tasks, and the concrete pavement (RAMP) task (Figure 5-2).

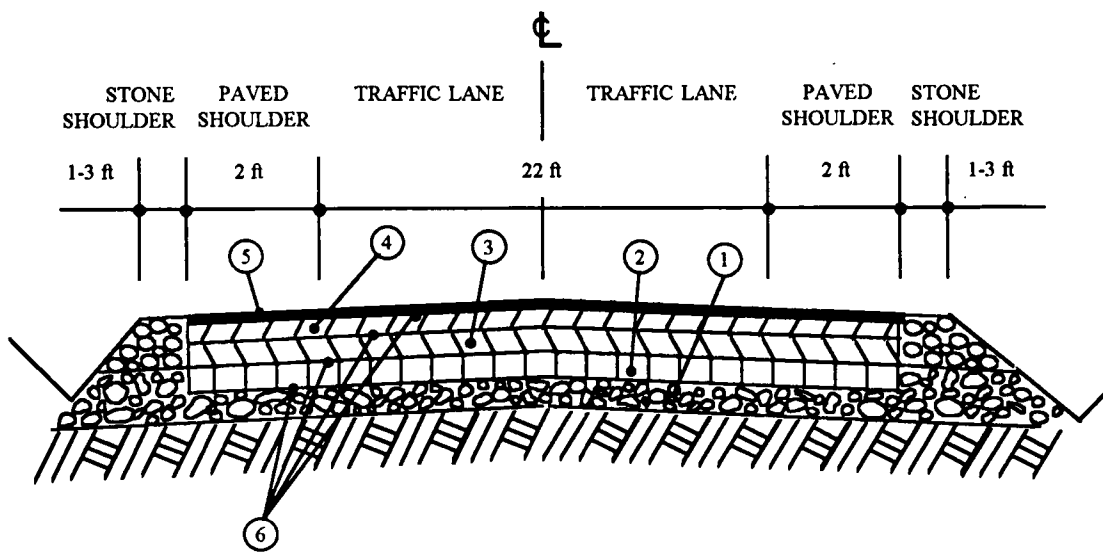


Figure 5-2. Typical Roadway Cross-Section

- 1- Mineral Aggregate Mix (one or more layers @ 6 inches each)
- 2- Bituminous Plant Mix Grade A-S (3.5 inches)
- 3- Bituminous Plant Mix Grade A (3 inches)
- 4- Bituminous Plant Mix Grade B-M (1.75 inches)
- 5- Asphaltic Concrete Surface Grading D (1.25 inches)
- 6- Tack Coat ( 0.09 gallons/sq. ft.)

### **5.3.1 Mineral Aggregate Mix**

The mineral aggregate mix task consists of furnishing and placing one or more courses of aggregate on a prepared sub-grade in accordance with DOT specifications and in reasonably close conformity with the line, grade, thickness, and typical cross-section shown in the plans. The mineral aggregate materials, which include the course aggregate, calcium chloride, sodium chloride, and water, must meet DOT grading requirements.

The Department of Transportation requires the contractor to have all of the equipment necessary for performing the operation on-site and approved before starting the work. This equipment includes a stationary mixing plant, which is equipped with a truck-loading hopper of sufficient size with a gate, which will prevent segregation of the material when dumped into the truck. On-site equipment includes a spreader with a hopper or bulldozer, a grader, a water tank, and a steel roller with sufficient weight to obtain the required density and seal the surface of the base course.

The following procedures are used for placing mineral aggregate:

- 1) The sub-grade is graded to the required level using a grader.
- 2) The mineral aggregate is dumped into the hopper spreader and is spread in the proper proportions.
- 3) With a grader the material is graded to an even level according to the plans and specifications.

- 4) The base course is compacted to the required depth and density using a steel roller.

The four major steps for placing mineral aggregate are shown in Figure 5-3.

The 10 data sets for the mineral aggregate task were collected in the four regions of Tennessee (Appendices B-3 and C-3). The cycle time of the production units (trucks) is the combined time of the following: loading, travelling, dumping into the hopper, maneuvering, and returning to the plant. The cycle time of the processor is the combined time of spreading, grading, and compacting. While collecting the data on the cycle times of the processor, the overlap of spreading, grading, and compacting activities as a result of simultaneous work was taken into consideration. All 10 data sets were analyzed using the ADMP. The data were tested for log-normal distribution. Five of these data failed the K-S test for log-normal distribution. Therefore, the cut-off point between delay and non-delay cycles was considered for these sets. As a result, nine of the data passed the test, and one failed by 1.5%. Since nine out of ten data sets passed the K-S test, it can be concluded that log-normal distribution is appropriate for the mineral aggregate task.

The summary calculations for  $T_{0.95}$  are shown in Appendix D-3. The productivity table (Table 5-3) shows the productivity and the average productivity for all 10 data sets.



A. SUB-GRADE PREPARATION USING SCRAPER



B. DUMPING AND SPREADING THE MATERIALS

Figure 5-3. Mineral Aggregate Operation



C. GRADING THE MATERIAL WITH A GRADER



D. COMPACTING USING A STEEL ROLLER

Figure 5-3. Mineral Aggregate Operation (Continued)

Table 5-3. Productivity Calculations for Mineral Aggregate

| #                    | Region # | Contract # | County     | Capacity of Unit (tons) | # of Non-Delay Cycles | # of Delay Cycles | Equivalent # of Units $N_E$ | *Mean Overall Cycle Time (minutes) | ** $T_{95}$ (minutes) | Productivity Based on $T_{95}$ (tons/hr) | Productivity Measured 1-Day Site Visit (tons/hr) | Maximum Productivity Based on Capacity of Processor (tons/hr) |
|----------------------|----------|------------|------------|-------------------------|-----------------------|-------------------|-----------------------------|------------------------------------|-----------------------|------------------------------------------|--------------------------------------------------|---------------------------------------------------------------|
| 1                    | 1        | 4044       | Roane      | 23                      | 44                    | -                 | 4.89                        | 45.67                              | 69.01                 | 98                                       | 148                                              | 224                                                           |
| 2                    | 1        | 3564       | Grainger   | 23                      | 93                    | 9                 | 6                           | 22.9                               | 29.28                 | 283                                      | 362                                              | 389                                                           |
| 3                    | 1        | 2440       | Knox       | 23                      | 47                    | 7                 | 6.75                        | 52.53                              | 66.39                 | 140                                      | 177                                              | 422                                                           |
| 4                    | 2        | 3707       | Rhea       | 23                      | 62                    | 16                | 16.6                        | 108.47                             | 146.77                | 156                                      | 211                                              | 409                                                           |
| 5                    | 2        | 4160       | White      | 23                      | 108                   | 15                | 12.6                        | 40.67                              | 50.57                 | 344                                      | 428                                              | 400                                                           |
| 6                    | 2        | 3866       | Marion     | 23                      | 41                    | -                 | 4.89                        | 44.13                              | 61.98                 | 109                                      | 153                                              | 364                                                           |
| 7                    | 3        | 4251       | Williamson | 23                      | 57                    | 10                | 22.33                       | 97.57                              | 119.77                | 257                                      | 316                                              | 440                                                           |
| 8                    | 3        | 4017       | Davidson   | 23                      | 34                    | -                 | 4.86                        | 56.49                              | 79.74                 | 79                                       | 114                                              | 329                                                           |
| 9                    | 4        | 3915       | Henderson  | 23                      | 45                    | -                 | 9                           | 69.32                              | 74.65                 | 166                                      | 179                                              | 386                                                           |
| 10                   | 4        | 4699       | Henderson  | 23                      | 52                    | -                 | 12.25                       | 112.62                             | 123.67                | 137                                      | 150                                              | 319                                                           |
| Average Productivity |          |            |            |                         |                       |                   |                             |                                    |                       | $\overline{P}_{ADMP}=177$                | $\overline{P}_M=224$                             | $\overline{P}_{max}=368$                                      |

\* See Appendix B1 for Mean Cycle Times

\*\* See Appendix D1 for  $T_{0.95}$  Calculation

### 5.3.2 Asphalt Operation

There are four main types of asphalt mix tasks: A-S Mix, A Mix, B-M Mix, and D Mix. These tasks are classified according to placement order, the size of the course materials, the proportion of the mixes, and the thickness of the layer.

The Department of Transportation requires the contractor to have all of the equipment necessary for performing the operation on-site and approved before starting the work. This equipment includes a paver with hopper for spreading the materials, two steel rollers, and a prime coat or tack coat truck. A rubber tire roller is sometimes required if specified in the plans. All types of mixes are measured in tons, and the contractor is paid for the finished units accordingly.

The procedures for most asphalt operations are similar. The following steps are the general procedure for placing asphalt:

- 1) Clean the surface and prepare it according to the plans and specifications or whether or not the sub-grade requires treatment
- 2) Apply the prime coat or tack coat at the rate of approximately 0.09 gallons per square foot. This rate may vary from one mix to another.
- 3) Dump the materials into the paver's hopper from the truck. Spread the materials to a certain thickness with the paver.
- 4) Compact first using a steel roller.
- 5) Using a second steel roller, compact the material to its required density.

If required, the intermediate rubber tire roller (pneumatic type) is used to increase the density of the asphalt. The pneumatic type is not used if the surface course contains latex or polymer material.

The procedures of the asphalt operation are shown in Figure 5-4.

Asphalt compaction is done according to the plans and specifications. Five density tests are applied for each 1000-square-yard lot. Two main tests are used for density: the back-scatter test and the core density test. The back-scatter test, which uses a nuclear density gage device, is used for asphalt that is less than 3" thick. The core density test, in which a hole is punched into the asphalt for measurement, is used for asphalt that is more than 3" thick.

The cycle time for asphalt operations consists of the cycle time of the production units (trucks). This time is the combined time of loading, travelling, dumping into the hopper, maneuvering, and returning. The cycle time of the processor is the combined time of spreading and compacting. When processor activities are performed simultaneously, the data collector must consider the overlap time. A list of all cycle times, the means, and the standard deviations is shown in Appendix B. The mean of processor cycle times is shown in Appendix C.

### **5.3.3 Bituminous Plant Mix Grade A-S**

This task is a combination of the mineral aggregate and the asphalt cement tasks. The proportions of this task are 96.3-97.7% for the combined mineral aggregate and 2.3-3.7% for the asphalt cement.



A. TACK COAT



B. DUMPING AND SPREADING THE MATERIAL

Figure 5-4. Asphalt Operation



C. COMPACTION (FIRST STEEL ROLLER)



D. COMPACTION (SECOND STEEL ROLLER)

Figure 5-4. Asphalt Operation (Continued)

The six data sets for the A-S Mix were collected in three regions of Tennessee (Appendices B-4 and C-4). These data were tested for log-normal distribution using the K-S test. Although one of these six data sets failed the first test, it passed when the cut-off point between delay and non-delay cycles was considered. The summary calculations for  $T_{0.95}$  are shown in Appendix D-4. The productivity table (Table 5-4) shows the productivity and the average productivity for all six data sets.

#### **5.3.4 Bituminous Plant Mix Grade A**

The proportions of mineral aggregate and asphalt cement for this mix are 95.8-96.7% for the aggregate and 3.3-4.2% for the asphalt cement. A maximum of 20% of recycled materials may be incorporated in the A Mix. The A Mix is placed immediately above the A-S mix with a thickness of 3".

The seven data sets of the A Mix were collected in the four regions of Tennessee (Appendices B-5 and C-5). Although one of the seven data sets failed the log-normal distribution test, this data set passed when the cut-off point between delay and non-delay cycles was considered.

The summary calculations for  $T_{0.95}$  are shown in Appendix D-5. The productivity table (Table 5-5) shows the productivity and the average productivity for all seven data sets.

#### **5.3.5 Bituminous Plant Mix Grade B-M**

The proportions of mineral aggregate and asphalt cement for this mix are 93.8-95.8% for the aggregate and 4.2-6.2% for the asphalt cement. Up to 20% of

Table 5-4. Productivity Calculations for Asphalt A-S Mix

|                      | Region # | Contract # | County     | Capacity of Unit (tons) | # of Non-Delay Cycles | # of Delay Cycles | Equivalant # of Units $N_E$ | *Mean Overall Cycle Time (minutes) | ** $T_{95}$ (minutes) | Productivity Based on $T_{95}$ (tons/hr) | Productivity Measured 1-Day Site Visit (tons/hr) | Maximum Productivity Based on Capacity of Processor (tons/hr) |
|----------------------|----------|------------|------------|-------------------------|-----------------------|-------------------|-----------------------------|------------------------------------|-----------------------|------------------------------------------|--------------------------------------------------|---------------------------------------------------------------|
| 1                    | 2        | 3707       | Rhea       | 22                      | 36                    | -                 | 12                          | 113.68                             | 138.39                | 114                                      | 139                                              | 406                                                           |
| 2                    | 3        | 3935       | Sumner     | 22                      | 87                    | 16                | 14.86                       | 70.5                               | 89.09                 | 220                                      | 278                                              | 490                                                           |
| 3                    | 3        | 4251       | Williamson | 22                      | 64                    | -                 | 16                          | 94.62                              | 107.15                | 197                                      | 223                                              | 478                                                           |
| 4                    | 4        | 3145       | Weakley    | 22                      | 52                    | -                 | 6.75                        | 56.64                              | 65.54                 | 136                                      | 157                                              | 295                                                           |
| 5                    | 4        | 3721       | McNairy    | 22                      | 38                    | -                 | 19                          | 119.75                             | 119.75                | 209                                      | 209                                              | 450                                                           |
| 6                    | 4        | 4224       | Fayette    | 22                      | 36                    | -                 | 9                           | 84.18                              | 84.18                 | 141                                      | 141                                              | 291                                                           |
| Average Productivity |          |            |            |                         |                       |                   |                             |                                    |                       | $\overline{P}_{ADM} = 170$               | $\overline{P}_M = 208$                           | $\overline{P}_{max} = 402$                                    |

\* See Appendix B1 for Mean Cycle Times

\*\* See Appendix D1 for  $T_{0.95}$  Calculation

**Table 5-5. Productivity Calculations for Asphalt A-Mix**

|                             | Region # | Contract # | County   | Capacity of Unit (tons) | # of Non-Delay Cycles | # of Delay Cycles | Equivalent # of Units $N_E$ | *Mean Overall Cycle Time (minutes) | ** $T_{95}$ (minutes) | Productivity Based on $T_{95}$ (tons/hr)   | Productivity Measured 1-Day Site Visit (tons/hr) | Maximum Productivity Based on Capacity of Processor (tons/hr) |
|-----------------------------|----------|------------|----------|-------------------------|-----------------------|-------------------|-----------------------------|------------------------------------|-----------------------|--------------------------------------------|--------------------------------------------------|---------------------------------------------------------------|
| 1                           | 1        | 4123       | Knox     | 22                      | 64                    | -                 | 12.8                        | 74.24                              | 98.95                 | 171                                        | 228                                              | 582                                                           |
| 2                           | 2        | 3707       | Rhea     | 22                      | 43                    | -                 | 16.67                       | 88.05                              | 107.75                | 204                                        | 250                                              | 529                                                           |
| 3                           | 2        | 4160       | White    | 22                      | 78                    | 4                 | 9.2                         | 48.79                              | 56.25                 | 216                                        | 249                                              | 428                                                           |
| 4                           | 3        | 3428       | Cheatham | 22                      | 95                    | -                 | 15.83                       | 92.58                              | 133.04                | 157                                        | 226                                              | 608                                                           |
| 5                           | 3        | 3935       | Sumner   | 22                      | 114                   | -                 | 14.25                       | 64.62                              | 81.02                 | 232                                        | 291                                              | 520                                                           |
| 6                           | 4        | 4729       | Shelby   | 22                      | 70                    | -                 | 23.33                       | 116.36                             | 143.09                | 215                                        | 265                                              | 482                                                           |
| 7                           | 4        | 3701       | Madison  | 22                      | 28                    | -                 | 7                           | 77.78                              | 99.68                 | 93                                         | 119                                              | 321                                                           |
| <b>Average Productivity</b> |          |            |          |                         |                       |                   |                             |                                    |                       | <b><math>\overline{P_{ADM}}=184</math></b> | <b><math>\overline{P_M}=232</math></b>           | <b><math>\overline{P_{max}}=496</math></b>                    |

\* See Appendix B1 for Mean Cycle Times

\*\* See Appendix D1 for  $T_{0.95}$  Calculation

recycled materials may be incorporated in the B-M Mix. This mix is placed immediately above the A Mix with a thickness of approximately 1.75”.

The eight data sets of the B-M Mix were collected in the four regions of Tennessee (Appendices B-6 and C-6). All data were tested for log-normal distribution and passed the K-S test.

The summary calculations for  $T_{0.95}$  are shown in Appendix D-6. The productivity table (Table 5-6) shows the productivity and the average productivity for all eight data sets.

#### **5.3.6 Asphaltic Concrete Surface Grading D**

This type of mix consists of an asphaltic concrete pavement composed of a mixture of course aggregate, fine aggregate, mineral filler (if required in the specifications), and asphalt concrete constructed on prepared roadbed in accordance with the specifications and plans. The specified mineral aggregate and asphalt concrete is combined in the following proportions: 93.0-94.7% combined mineral aggregate and 5.3-7.0% asphalt concrete.

The nine data sets for asphaltic concrete surface D-Mix were collected in the four regions of Tennessee (Appendices B-7 and C-7). The data were tested for log-normal distribution. Only two data sets failed the K-S test. After considering the cut-off point between delay and non-delay and re-testing, all the data passed the K-S test for log-normal distribution. The summary calculations for  $T_{0.95}$  are shown in Appendix D-7. The productivity table (Table 5-7) shows the productivity and the average productivity for all nine data sets.

**Table 5-6. Productivity Calculations for Asphalt B-M Mix**

| #                           | Region # | Contract # | County     | Capacity of Unit (tons) | # of Non-Delay Cycles | # of Delay Cycles | Equivelant # of Units N <sub>E</sub> | *Mean Overall Cycle Time (minutes) | **T <sub>95</sub> (minutes) | Productivity Based on T <sub>95</sub> (tons/hr) | Productivity Measured 1-Day Site Visit (tons/hr) | Maximum Productivity Based on Capacity of Processor (tons/hr) |
|-----------------------------|----------|------------|------------|-------------------------|-----------------------|-------------------|--------------------------------------|------------------------------------|-----------------------------|-------------------------------------------------|--------------------------------------------------|---------------------------------------------------------------|
| 1                           | 1        | 4298       | Hancock    | 22                      | 22                    | -                 | 11                                   | 155.24                             | 192.67                      | 75                                              | 94                                               | 298                                                           |
| 2                           | 2        | 4687       | McMinn     | 22                      | 53                    | -                 | 9                                    | 91.21                              | 119.85                      | 99                                              | 130                                              | 308                                                           |
| 3                           | 2        | 3707       | Rhea       | 22                      | 46                    | -                 | 11.5                                 | 92.45                              | 111.28                      | 136                                             | 164                                              | 258                                                           |
| 4                           | 3        | 4017       | Davidson   | 22                      | 68                    | -                 | 9.71                                 | 83.72                              | 120.88                      | 106                                             | 153                                              | 225                                                           |
| 5                           | 3        | 4251       | Williamson | 22                      | 27                    | -                 | 9                                    | 107.16                             | 133.04                      | 89                                              | 111                                              | 358                                                           |
| 6                           | 4        | 3366       | Weakley    | 22                      | 38                    | -                 | 7.6                                  | 68.42                              | 86.23                       | 116                                             | 147                                              | 184                                                           |
| 7                           | 4        | 4738       | Weakley    | 22                      | 42                    | -                 | 7                                    | 65.22                              | 83.47                       | 111                                             | 142                                              | 175                                                           |
| 8                           | 4        | 3701       | Madison    | 22                      | 24                    | -                 | 8                                    | 85.28                              | 127.14                      | 83                                              | 124                                              | 208                                                           |
| <b>Average Productivity</b> |          |            |            |                         |                       |                   |                                      |                                    |                             | <b>P<sub>ADMP</sub>=102</b>                     | <b>P<sub>M</sub>=133</b>                         | <b>P<sub>max</sub>=252</b>                                    |

\* See Appendix B1 for Mean Cycle Times

\*\* See Appendix D1 for T<sub>0.95</sub> Calculation

**Table 5-7. Productivity Calculations for D-Mix Asphalt**

| #                           | Region # | Contract # | County     | Capacity of Unit (tons) | # of Non-Delay Cycles | # of Delay Cycles | Equivelant # of Units NE | *Mean Overall Cycle Time (minutes) | **T95 (minutes) | Productivity Based on T95 (tons/hr) | Productivity Measured 1-Day Site Visit (tons/hr) | Maximum Productivity Based on Capacity of Processor (tons/hr) |
|-----------------------------|----------|------------|------------|-------------------------|-----------------------|-------------------|--------------------------|------------------------------------|-----------------|-------------------------------------|--------------------------------------------------|---------------------------------------------------------------|
| 1                           | 1        | 4180       | Gainger    | 22                      | 20                    | -                 | 10                       | 100.69                             | 129.47          | 102                                 | 131                                              | 336                                                           |
| 2                           | 1        | 4400       | Sevier     | 22                      | 50                    | -                 | 10                       | 68.25                              | 83.19           | 159                                 | 193                                              | 328                                                           |
| 3                           | 2        | 4687       | McMinn     | 22                      | 48                    | -                 | 9.6                      | 103.80                             | 134.40          | 94                                  | 122                                              | 339                                                           |
| 4                           | 2        | 3707       | Rhea       | 22                      | 63                    | -                 | 10.5                     | 79.78                              | 91.03           | 152                                 | 174                                              | 204                                                           |
| 5                           | 3        | 4815       | Cheatham   | 22                      | 60                    | 6                 | 11                       | 90.53                              | 109.09          | 133                                 | 160                                              | 365                                                           |
| 6                           | 3        | 4740       | Williamson | 22                      | 58                    | -                 | 5.8                      | 51.34                              | 74.49           | 103                                 | 149                                              | 201                                                           |
| 7                           | 3        | 4722       | Robertson  | 22                      | 68                    | 8                 | 12.67                    | 93.55                              | 118.78          | 141                                 | 179                                              | 287                                                           |
| 8                           | 4        | 4660       | Obion      | 22                      | 48                    | -                 | 8                        | 85.63                              | 118.20          | 89                                  | 123                                              | 151                                                           |
| 9                           | 4        | 4286       | Dyer       | 22                      | 48                    | -                 | 6                        | 52.47                              | 59.19           | 134                                 | 151                                              | 168                                                           |
| 10                          | 4        | 4355       | Gibson     | 22                      | 17                    | -                 | 9.5                      | 130.65                             | 185.88          | 67                                  | 96                                               | 162                                                           |
| <b>Average Productivity</b> |          |            |            |                         |                       |                   |                          |                                    |                 | <b>P<sub>ADM</sub>P=117</b>         | <b>P<sub>M</sub>=148</b>                         | <b>P<sub>max</sub>=254</b>                                    |

\* See Appendix B1 for Mean Cycle Times

\*\* See Appendix D1 for T0.95 Calculation

### **5.3.7 Portland Cement Concrete Pavement**

This task consists of the construction of a ramp pavement using Portland cement concrete with or without reinforcement on a prepared surface in accordance with the specifications and in reasonably close conformity with the line, grade, and typical cross-section shown in the plans. The Portland cement concrete mix consists of fine aggregate, coarse aggregate, Portland cement, water, curing materials, reinforcing steel, joint sealants, joint fillers, and chemical additives. The concrete is mixed either at the construction site or in a truck mixer, and the mixing must be supervised by a certified technician. The mix is tested for four properties: compressive strength, slump, air content, and temperature. The contractor must provide a certified technician to test the materials. The State Inspector documents the results of the slump, air content, and temperature tests, and a sample of the mix is sent to the state's laboratory for testing the compressive strength at 14 and 21 days.

The construction of the ramp pavement begins with setting a steel form to the correct grade and alignment. The steel reinforcements must be placed as specified in the plans. The base must be wet prior to placing the concrete. In most concrete ramp operations, the concrete is poured directly into the base area. The concrete must be thoroughly consolidated using a vibrator. Once the strike-off and consolidation are completed, the concrete is leveled using a straightedge, and the final surface is finished and cured. The steel form is removed after 24 hours, and the joints are sawed. A concrete placement operation for a ramp pavement is shown in Figure 5-5.



A. POURING CONCRETE



B. FINISHING CONCRETE

Figure 5-5. Portland Cement Concrete Pavement (RAMP)

The equipment for placing a concrete pavement consists of a concrete screed, a vibrator, a compressor, a fork lift, a joint saw, and small tools. The operation requires a crew of between seven and twelve people. The cycle time for this operation is the combined time of setting the steel form, placing the steel reinforcement, pouring the concrete, leveling, curing, removing the form, and sawing the concrete for one load. The simultaneous work of these activities must be taken into consideration when collecting data. Although the cycle time of a truck is not considered in the analysis of productivity, delays in the delivery of concrete to the site can significantly affect the overall productivity of the operation. The unit of measurement for concrete pavement is square yard for a required thickness.

Although concrete pavement provides greater strength, durability, and rolling resistance than asphalt, concrete pavement is also much more expensive. Ramps, however, require a high degree of strength, durability, and rolling resistance to slow down heavy vehicles, especially in case of severe weather. Therefore, concrete pavement is necessary for ramp construction.

The five data sets for the concrete pavement ramp were collected in three regions of Tennessee (Appendix B-8). The data were tested for log-normal distribution. All data passed the K-S test for log-normal distribution. The summary calculations for  $T_{0.95}$  are shown in Appendix D-8. The productivity table (Table 5-8) shows the productivity and the average productivity for all five data sets. The maximum productivity is based on the cycle times of those cycles whose times are

Table 5-8. Productivity Calculations for Concrete Pavement (Ramp)

| #                    | Region # | Contract # | County   | Capacity<br>of unit (sy) | # of Non-<br>Delay<br>Cycles | # of<br>Delay<br>Cycles | Mean<br>Overall<br>Cycle Time<br>(minutes) | **T95%<br>(minutes) | (P <sub>ADMP</sub> )<br>Productivity<br>Based on T95<br>(SY/hr) | (P <sub>M</sub> )<br>Productivity<br>Measured 1-<br>Day Site Visit<br>(sy/hr) | (P <sub>MAX</sub> )<br>Maximum<br>Productivity<br>Based on<br>Capacity of<br>Processor<br>(sy/hr) |
|----------------------|----------|------------|----------|--------------------------|------------------------------|-------------------------|--------------------------------------------|---------------------|-----------------------------------------------------------------|-------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| 1                    | 2        | 3701       | Madison  | 40                       | 6                            | -                       | 47.86                                      | 51.06               | 47.78                                                           | 50.97                                                                         | 53.1                                                                                              |
| 2                    | 3        | 4017       | Davidson | 40                       | 13                           | -                       | 42.67                                      | 53.6                | 45.52                                                           | 51.2                                                                          | 66.87                                                                                             |
| 3                    | 3        | 4017       | Davidson | 40                       | 9                            | -                       | 46.85                                      | 59.67               | 40.89                                                           | 52.07                                                                         | 61.53                                                                                             |
| 4                    | 3        | 3145       | Carroll  | 40                       | 9                            | -                       | 48.36                                      | 65.98               | 36.98                                                           | 50.45                                                                         | 63.08                                                                                             |
| 5                    | 4        | 4044       | roane    |                          | 11                           | -                       | 65.2                                       | 75.46               | 32.33                                                           | 37.42                                                                         | 41.18                                                                                             |
| Average Productivity |          |            |          |                          |                              |                         |                                            |                     | P <sub>ADMP</sub> =40.70                                        | P <sub>M</sub> =48.42                                                         | P <sub>MAX</sub> =57.15                                                                           |

\* See Appendix B1 for Mean cycle times

\*\* See Appendix D1 for T95 % Calculation

less than the mean minus the standard deviation. These cycles must not be less than 5% of the overall number of cycles.

## **5.4 STEEL PILES**

This work consists of driving steel piles in accordance with the specifications and in reasonably close conformity with the plans. The steel piles are either 8, 10, 12, or 14-inch H-type steel piles. The steel piles are driven into the soil no less than 10-feet deep until they either hit rock or develop sufficient resistance to support the foundations for bridge structures. These foundations ultimately support the load of the bridge.

Equipment for driving steel piles consists of a driver and a crane to carry the pile and balance it in the driver. Most drivers are steam, air, or diesel driven, but when approved by the engineer, gravity hammers may be used as long as the weight of the pile is no more than the weight of the hammer. The hammer must weigh at least 3,000 pounds and not more than 5,000 pounds. The hammer fall distance must not be more than 10 feet. The clearing and preparation of the foundation and the excavation of the embankment in the driving area must be completed before the driving of piles begins.

The cycle time for pile driving is the combined time of the following four steps:

- 1) Preparing the place where the piles are to be driven. This includes moving the crane to the end of the bridge.

- 2) Driving. This consists of the crane's hooking up the pile, carrying it to the driver or hammer, balancing the pile, driving it, un-hooking it, and repositioning for the next pile.
- 3) Cutting the driven pile using a torch.
- 4) Cleaning up before casting the foundation.

Figure 5-6 shows the pile driving task.

The unit of measurement is the linear foot. The four data sets for the steel pile task were collected in Regions 1 and 3 (Appendix B-9). Data were tested for log-normal distribution. All data passed the K-S test for log-normal distribution. The summary calculations for  $T_{0.95}$  are shown in Appendix D-9. The productivity table (Table 5-9) shows the productivity for all four data sets. The maximum productivity is based on the cycle times of those cycles whose times are less than the mean minus the standard deviation. These cycles must not be less than 5% of the overall number of cycles.



Figure 5-6. Steel Pile Driving

Table 5-9. Productivity Calculations for Driving Steel Piles

| #                    | Region # | Contract # | County   | Capacity<br>of unit (lf) | # of Non-<br>Delay<br>Cycles | # of<br>Delay<br>Cycles | Mean<br>Overall<br>Cycle Time<br>(minutes) | **T95%<br>(minutes) | (P <sub>ADMP</sub> )<br>Productivity<br>Based on T95<br>(lf/hr) | (P <sub>M</sub> )<br>Productivity<br>Measured 1-<br>Day Site Visit<br>(lf/hr) | (P <sub>MAX</sub> )<br>Maximum<br>Productivity<br>Based on<br>Capacity of<br>Processor<br>(lf/hr) |
|----------------------|----------|------------|----------|--------------------------|------------------------------|-------------------------|--------------------------------------------|---------------------|-----------------------------------------------------------------|-------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| 1                    | 1        | 3564       | Grainger | 20.35                    | -                            | -                       | 39.72                                      | 54.52               | 22.38                                                           | 30.74                                                                         | 36.94                                                                                             |
| 2                    | 1        | 4214       | Knox     | 21.1                     | -                            | -                       | 36.98                                      | 38.48               | 32.81                                                           | 34.22                                                                         | 35.07                                                                                             |
| 3                    | 1        | 3571       | Knox     | 32.82                    | -                            | -                       | 46.94                                      | 58.47               | 33.66                                                           | 41.93                                                                         | 48.75                                                                                             |
| 4                    | 3        | 4334       | Wayne    | 38.33                    | -                            | -                       | 54.15                                      | 34.78               | 34.78                                                           | 42.45                                                                         | 48.59                                                                                             |
| Average Productivity |          |            |          |                          |                              |                         |                                            |                     | P <sub>ADMP</sub> =30.91                                        | P <sub>M</sub> =37.34                                                         | P <sub>MAX</sub> =42.34                                                                           |

\* See Appendix B1 for Mean cycle times

\*\* See Appendix D1 for T95 % Calculation

## **CHAPTER 6**

### **VALIDATION OF THE DATA AND THE APPLICATION OF THE ADMP FOR EVALUATING CLAIMS**

#### **6.1 INTRODUCTION**

The purpose of this study was to evaluate and measure the productivity of highway construction operations; maximizing production and efficiency was not considered. The productivity was calculated using the ADMP with the data collected on-site. The ADMP measures, calculates, and evaluates productivity for a site condition regardless of the method of construction. The method of construction, however, has a significant impact on the efficiency of the operation. Although the efficiency of the operation is one measurement tool for evaluating the production of the operation, many other factors must be considered as well. It was noticed in a lot of the observed data that one of the reasons for low production was the lack of management skills. Poor management skills may result in (1) the use of inefficient or inadequate equipment for the size of the operation, (2) the late arrival of materials, (3) the failure to train the crew adequately to maximize its production, and (4) the selection of an improper method of construction. These factors have contributed to low production in highway construction and as a result have led to an increase in the number of claims associated with project duration.

This chapter discusses the validity of the data, evaluates the effectiveness of using the ADMP to determine highway construction productivity, and introduces the use of the ADMP to resolve claims.

## 6.2 DATA VALIDATION

In the beginning of this study, it was proposed that three data sets be collected for each of the four regions of Tennessee, a total of 12 data sets for each task. However, in order to validate this methodology, the number of data sets required for properly analyzing the productivity using the ADMP methodology must be determined. The average variation of productivity approach was used to answer this question. Statistically, it is well-known that the more the data sets the more reliable the evaluation of the statistical model. This assessment is fair, but rather undefined. The average variation of productivity approach evaluates the ADMP analysis using the variation between the productivity for one data set and the average overall productivity from the ADMP. The average variation can be calculated as follows:

$$AV. = \frac{P_{ADMP} - \bar{P}_{ADMP}}{\bar{P}_{ADMP}} \times 100 \% \quad (6.1)$$

where AV. = Average Variation (%)

$P_{ADMP}$  = The productivity of one observation using the ADMP

$\bar{P}_{ADMP}$  = The mean productivity from the ADMP

This variation indicates how many data sets should be considered for each task (Table 6-1).

**Table 6-1. The Average Variation Analysis for Productivity**

| #                                                                                                                                           | Contract # | Region # | County     | P <sub>ADMP</sub><br>(cy/hour) | Average Variation % |       |
|---------------------------------------------------------------------------------------------------------------------------------------------|------------|----------|------------|--------------------------------|---------------------|-------|
|                                                                                                                                             |            |          |            |                                | -                   | +     |
| a. The Variation Between the P <sub>ADMP</sub> for Each Observation and the Average Productivity (P <sub>ADMP</sub> ) for Road and Drainage |            |          |            |                                |                     |       |
| 1                                                                                                                                           | 3564       | 1        | Grainger   | 286                            | -                   | 37.5  |
| 2                                                                                                                                           | 3564-2     | 1        | Grainger   | 698                            | -                   | 235.6 |
| 3                                                                                                                                           | 4123       | 1        | Knox       | 96                             | 53.8                | -     |
| 4                                                                                                                                           | 4384       | 2        | McMinn     | 272                            | -                   | 30.8  |
| 5                                                                                                                                           | 4410       | 2        | White      | 157                            | 24.5                | -     |
| 6                                                                                                                                           | 3926       | 2        | Rhea       | 170                            | 18.3                | -     |
| 7                                                                                                                                           | 3556       | 3        | Davidson   | 30                             | 85.6                | -     |
| 8                                                                                                                                           | 4251       | 3        | Williamson | 33                             | 84.1                | -     |
| 9                                                                                                                                           | 3948       | 3        | Davidson   | 186                            | 10.6                | -     |
| 10                                                                                                                                          | 3915       | 4        | Henderson  | 196                            | 5.8                 | -     |
| 11                                                                                                                                          | 4572       | 4        | Weakley    | 201                            | 3.4                 | -     |
| 12                                                                                                                                          | 4696       | 4        | Fayette    | 167                            | 19.7                | -     |
| Average Productivity ( $\bar{P}_{ADMP}$ )                                                                                                   |            |          |            | 208                            |                     |       |

|                                                                                                                                             |      |   |           |     |      |      |
|---------------------------------------------------------------------------------------------------------------------------------------------|------|---|-----------|-----|------|------|
| b. The Variation Between the P <sub>ADMP</sub> for Each Observation and the Average Productivity ( $\bar{P}_{ADMP}$ ) for Borrow Excavation |      |   |           |     |      |      |
| 1                                                                                                                                           | 3866 | 2 | Marion    | 65  | 33   | -    |
| 2                                                                                                                                           | 4017 | 3 | Davidson  | 39  | 59.8 | -    |
| 3                                                                                                                                           | 3948 | 3 | Davidson  | 39  | 59.8 | -    |
| 4                                                                                                                                           | 4723 | 3 | Robertson | 161 | -    | 66   |
| 5                                                                                                                                           | 3502 | 4 | Carroll   | 86  | 11.3 | -    |
| 6                                                                                                                                           | 3863 | 4 | McNairy   | 150 | -    | 54.6 |
| 7                                                                                                                                           | 4224 | 4 | Fayette   | 142 | -    | 46.4 |
| Average Productivity ( $\bar{P}_{ADMP}$ )                                                                                                   |      |   |           | 97  |      |      |

Table 6-1. (Continued)

| #                                                                                                                                           | Contract # | Region # | County     | P <sub>ADMP</sub><br>(tons/hour) | Average Variation |      |
|---------------------------------------------------------------------------------------------------------------------------------------------|------------|----------|------------|----------------------------------|-------------------|------|
|                                                                                                                                             |            |          |            |                                  | -                 | +    |
| c. The Variation Between the P <sub>ADMP</sub> for Each Observation and the Average Productivity ( $\bar{P}_{ADMP}$ ) for Mineral Aggregate |            |          |            |                                  |                   |      |
| 1                                                                                                                                           | 4044       | 1        | Roane      | 98                               | 44.6              | -    |
| 2                                                                                                                                           | 3564       | 1        | Grainger   | 283                              | -                 | 60   |
| 3                                                                                                                                           | 2440       | 1        | Knox       | 140                              | 20.9              | -    |
| 4                                                                                                                                           | 3707       | 2        | Rhea       | 156                              | 11.8              | -    |
| 5                                                                                                                                           | 4160       | 2        | White      | 344                              | -                 | 94.4 |
| 6                                                                                                                                           | 3866       | 2        | Marion     | 109                              | 38.4              | -    |
| 7                                                                                                                                           | 4251       | 3        | Williamson | 257                              | -                 | 45.2 |
| 8                                                                                                                                           | 4017       | 3        | Davidson   | 79                               | 55.4              | -    |
| 9                                                                                                                                           | 3915       | 4        | Henderson  | 166                              | 6.2               | -    |
| 10                                                                                                                                          | 4699       | 4        | Henderson  | 137                              | 22.6              | -    |
| Average Productivity ( $\bar{P}_{ADMP}$ )                                                                                                   |            |          |            | 177                              |                   |      |

|                                                                                                                                           |      |   |            |     |      |      |
|-------------------------------------------------------------------------------------------------------------------------------------------|------|---|------------|-----|------|------|
| d. The Variation Between the P <sub>ADMP</sub> for Each Observation and the Average Productivity ( $\bar{P}_{ADMP}$ ) for Asphalt A-S Mix |      |   |            |     |      |      |
| 1                                                                                                                                         | 3707 | 2 | Rhea       | 114 | 32.9 | -    |
| 2                                                                                                                                         | 3935 | 3 | Sumner     | 220 | -    | 29.4 |
| 3                                                                                                                                         | 4251 | 3 | Williamson | 197 | -    | 15.9 |
| 4                                                                                                                                         | 3145 | 4 | Weakley    | 136 | 20   | -    |
| 5                                                                                                                                         | 2721 | 4 | McNairy    | 209 | -    | 22.9 |
| 6                                                                                                                                         | 4224 | 4 | Fayette    | 141 | 17.1 | -    |
| Average Productivity ( $\bar{P}_{ADMP}$ )                                                                                                 |      |   |            | 170 |      |      |

Table 6-1. (Continued)

| #                                                                                                                                        | Contract # | Region # | County   | P <sub>ADMP</sub><br>(tons/hour) | Average Variation |      |
|------------------------------------------------------------------------------------------------------------------------------------------|------------|----------|----------|----------------------------------|-------------------|------|
|                                                                                                                                          |            |          |          |                                  | -                 | +    |
| e. The Variation Between the P <sub>ADMP</sub> for Each Observation and the Average Productivity ( $\bar{P}_{ADMP}$ ) for Asphalt A Mix. |            |          |          |                                  |                   |      |
| 1                                                                                                                                        | 4123       | 1        | Knox     | 171                              | 7.1               | -    |
| 2                                                                                                                                        | 3707       | 2        | Rhea     | 204                              | -                 | 10.9 |
| 3                                                                                                                                        | 4160       | 2        | White    | 216                              | -                 | 17.4 |
| 4                                                                                                                                        | 3428       | 3        | Cheatham | 157                              | 14.7              | -    |
| 5                                                                                                                                        | 3935       | 3        | Sumner   | 232                              | -                 | 26.1 |
| 6                                                                                                                                        | 4729       | 4        | Shelby   | 215                              | -                 | 16.8 |
| 7                                                                                                                                        | 3701       | 4        | Madison  | 93                               | 49.5              | -    |
| Average Productivity ( $\bar{P}_{ADMP}$ )                                                                                                |            |          |          | 184                              |                   |      |

|                                                                                                                                    |      |   |            |     |      |      |
|------------------------------------------------------------------------------------------------------------------------------------|------|---|------------|-----|------|------|
| f. The Variation Between the $P_{ADMP}$ for Each Observation and the Average Productivity ( $\bar{P}_{ADMP}$ ) for Asphalt B-M Mix |      |   |            |     |      |      |
| 1                                                                                                                                  | 4298 | 1 | Hancock    | 75  | 26.5 | -    |
| 2                                                                                                                                  | 4687 | 2 | McMinn     | 99  | 2.9  | -    |
| 3                                                                                                                                  | 3707 | 2 | Rhea       | 136 | -    | 33.3 |
| 4                                                                                                                                  | 4017 | 3 | Davidson   | 106 | -    | 3.9  |
| 5                                                                                                                                  | 4251 | 3 | Williamson | 89  | 12.7 | -    |
| 6                                                                                                                                  | 3366 | 4 | Weakley    | 116 | -    | 13.7 |
| 7                                                                                                                                  | 4738 | 4 | Weakley    | 111 | -    | 8.8  |
| 8                                                                                                                                  | 3701 | 4 | Madison    | 83  | 18.6 | -    |
| Average Productivity ( $\bar{P}_{ADMP}$ )                                                                                          |      |   |            | 102 |      |      |

Table 6-1. (Continued)

| #                                                                                                                                       | Contract # | Region # | County     | P <sub>ADMP</sub><br>(tons/hour) | Average Variation |      |
|-----------------------------------------------------------------------------------------------------------------------------------------|------------|----------|------------|----------------------------------|-------------------|------|
|                                                                                                                                         |            |          |            |                                  | -                 | +    |
| g. The Variation Between the P <sub>ADMP</sub> for Each Observation and the Average Productivity ( $\bar{P}_{ADMP}$ ) for Asphalt D Mix |            |          |            |                                  |                   |      |
| 1                                                                                                                                       | 4180       | 1        | Grainger   | 102                              | 12.8              | -    |
| 2                                                                                                                                       | 4400       | 1        | Sevier     | 159                              | -                 | 35.9 |
| 3                                                                                                                                       | 4687       | 2        | McMinn     | 94                               | 19.7              | -    |
| 4                                                                                                                                       | 3707       | 2        | Rhea       | 152                              | -                 | 29.9 |
| 5                                                                                                                                       | 4815       | 3        | Cheatham   | 133                              | -                 | 13.7 |
| 6                                                                                                                                       | 4740       | 3        | Williamson | 103                              | 11.9              | -    |
| 7                                                                                                                                       | 4722       | 3        | Robertson  | 141                              | -                 | 20.5 |
| 8                                                                                                                                       | 4660       | 4        | Obion      | 89                               | 23.9              | -    |
| 9                                                                                                                                       | 4286       | 4        | Dyer       | 134                              | -                 | 14.5 |
| 10                                                                                                                                      | 4355       | 4        | Gibson     | 67                               | 42.7              | -    |
| Average Productivity ( $\bar{P}_{ADMP}$ )                                                                                               |            |          |            | 117                              |                   |      |

|                                                                                                                                                  |      |   |          |       |      |      |
|--------------------------------------------------------------------------------------------------------------------------------------------------|------|---|----------|-------|------|------|
| h. The Variation Between the P <sub>ADMP</sub> for Each Observation and the Average Productivity ( $\bar{P}_{ADMP}$ ) for Concrete Pavement Ramp |      |   |          |       |      |      |
| 1                                                                                                                                                | 3701 | 4 | Madison  | 47.78 | -    | 17   |
| 2                                                                                                                                                | 4017 | 3 | Davidson | 45.52 | -    | 12.3 |
| 3                                                                                                                                                | 4017 | 3 | Davidson | 40.89 | -    | 2.6  |
| 4                                                                                                                                                | 3145 | 4 | Carroll  | 36.98 | 5.6  | -    |
| 5                                                                                                                                                | 4044 | 1 | Roane    | 27.03 | 26.4 | -    |
| Average Productivity ( $\bar{P}_{ADMP}$ )                                                                                                        |      |   |          | 39.64 |      |      |

Table 6-1. (Continued)

| #                                                                                                                                           | Contract # | Region # | County   | P <sub>ADMP</sub><br>(ft/hour) | Average Variation |      |
|---------------------------------------------------------------------------------------------------------------------------------------------|------------|----------|----------|--------------------------------|-------------------|------|
|                                                                                                                                             |            |          |          |                                | -                 | +    |
| i. The Variation <u>Between</u> the P <sub>ADMP</sub> for Each Observation and the Average Productivity (P <sub>ADMP</sub> ) for Steel Pile |            |          |          |                                |                   |      |
| 1                                                                                                                                           | 3564       | 1        | Grainger | 22.38                          | 27.6              | -    |
| 2                                                                                                                                           | 4214       | 1        | Knox     | 32.81                          | -                 | 6.1  |
| 3                                                                                                                                           | 3571       | 1        | Knox     | 33.66                          | -                 | 8.9  |
| 4                                                                                                                                           | 4334       | 3        | Wayne    | 34.78                          | -                 | 12.5 |
| Average Productivity ( $\bar{P}_{ADMP}$ )                                                                                                   |            |          |          | 30.91                          |                   |      |

Although there is some variation in productivity from one observation to another for the mineral aggregate, asphalt, concrete pavement ramp, and driving steel pile tasks, these variations are typical because of the dynamic nature and variability of highway construction. However, these variations can be minimized by using a minimum of four data sets, and the model can be adequately applied to determine the productivity of the operation (Tables 6-1c through 6-1i). On the other hand, variability increased for the road and drainage excavation and the borrow excavation. The two data sets for the road and drainage excavation that were collected at the same site (Grainger County) showed a 144% variation in productivity as a result of the change in the processors' capacity for this operation (Table 6-1a). The data collection and analysis show that the production for road and drainage excavation is greatly affected by the size of the equipment, especially the processors. Therefore, to properly validate the

data for the road and drainage excavation, the operation must be classified based on the type of equipment used, and a minimum of four data sets must be collected for each type of equipment operation. These classifications include the following:

- Massive excavation using two or more processors
- Massive excavation using four or more scrapers
- Small size excavation using one processor
- Small size excavation using fewer than four scrapers

For road and drainage excavations that require the use of triaxle trucks, the operations can be classified as either a one-processor or two-processor operation.

The seven data sets for the borrow excavation showed significant variation as a result of using a different number of processors and production units (Table 6-1b). Therefore, to properly validate the data for the borrow excavation, the operation must be classified based on the number of processors used. The following classifications may be used:

- Excavation using one processor
- Excavation using two or more processors

The number of production units must be determined based on the traffic and the haul distance.

### 6.3 EVALUATION OF THE ADMP FOR HIGHWAY CONSTRUCTION

Although the effect of variation in highway construction increases the difficulty of evaluating productivity, the ADMP accounts for most of the factors that affect variability by using the 95% confidence level of task completion. In Chapter 5, productivity was explained in three ways:

- 1)  $P_{\max}$ : the maximum productivity based on the processor's production rate
- 2)  $P_M$ : the measured productivity based on one-day data collection
- 3)  $P_{\text{ADMP}}$ : the productivity based on the 95% confidence of task completion

Maximum production can not be considered for the overall production because it assumes that there is no variation in the production and that production mainly depends on the theoretical maximum production of the processor. The measured productivity based on a one-day site visit can be considered a good rate of the overall operation but is not necessarily realistic because the production is based on the data for only one day. These data may not be representative of the overall productivity and all of the variability because the data collector may stop collecting data if the operation stops for any reason such as rain or breakdowns in important equipment.

In evaluating the  $P_{\text{ADMP}}$  for the road and drainage excavation, the historical production rate of the Grainger County site based on 319 working days was 5,912 cy/day, and the productivity based on the ADMP was 5,584 cy/day (Table 6-2). This result also indicates that the use of the ADMP is adequate for evaluating the overall productivity of an operation with a 95% confidence of completion time.

Table 6-2. Comparison of the Actual Productivity of the Grainger County Site With the Result of the ADMP Analysis

| Date       | Working Days | Quantity<br>(cy/month) | Quantity<br>(cy/day) |
|------------|--------------|------------------------|----------------------|
| Sept. 1995 | 19           | 54794                  | 2884                 |
| Oct. 1995  | 12           | 10387                  | 866                  |
| Nov. 1995  | 9            | 6277                   | 697                  |
| Dec. 1995  | 12           | 7475                   | 623                  |
| Jan. 1996  | 6            | 307                    | 51                   |
| March 1996 | 14           | 81515                  | 5823                 |
| Apr. 1996  | 8            | 89562                  | 11195                |
| May 1996   | 12           | 153033                 | 12753                |
| June 1996  | 10           | 153342                 | 15334                |
| July 1996  | 18           | 142251                 | 7903                 |
| Aug. 1996  | 15           | 79404                  | 5294                 |
| Sept. 1996 | 18           | 122262                 | 6792                 |
| Oct. 1996  | 16           | 300780                 | 18799                |
| Nov. 1996  | 13           | 57131                  | 4395                 |
| Dec. 1996  | 13           | 157407                 | 12108                |
| Jan. 1997  | 1            | 86909                  | 86909                |
| Feb. 1997  | 13           | 67562                  | 5197                 |
| March 1997 | 9            | 109088                 | 12121                |
| Apr. 1997  | 17           | 55250                  | 3250                 |
| May 1997   | 13           | 67266                  | 5174                 |
| June 1997  | 10           | 14350                  | 1435                 |
| July 1997  | 21           | 27709                  | 1319                 |
| Aug. 1997  | 23           | 22878                  | 995                  |
| Sept. 1997 | 17           | 19025                  | 1119                 |
| <b>Σ</b>   | <b>319</b>   | <b>1885964</b>         |                      |

|                                                        |              |
|--------------------------------------------------------|--------------|
| <b>Monthly Average (cy/month)</b>                      | <b>78582</b> |
| <b>Project Average (cy/day)</b>                        | <b>5912</b>  |
| <b>Productivity Based on 1-Day Site Visit (cy/day)</b> | <b>7184</b>  |
| <b>Productivity Based on the ADMP (cy/day)</b>         | <b>5584</b>  |

## **6.4 EFFICIENCY ANALYSIS AND EVALUATION OF CLAIMS**

Productivity in highway construction is mainly controlled by the processor rate since the processor production rate determines the maximum production rate of the operation. Efficiency of the operation, on the other hand, considers not only the production rate of the processor but also the production rate of production units. The overall production can be maximized by using the optimum number of production units and the proper processor.

The earthmoving operation in Figure 6-1 shows how two equipment selection decisions can affect the productivity of an operation. In the first example (a), the contractor used more production units (trucks) than the processor (excavator) could serve. As a result of this decision, the production of the processor was maximized, but the trucks were not used efficiently. Each truck had to wait in the queue to be served. This idle time is considered non-productive time for the trucks (Figure 6-1a). In the second example (b), the contractor used a large processor with only two production units. As a result of this decision, the processor did not work efficiently, and the productivity of the operation was decreased (Figure 6-1b).

Two other case studies of an earthmoving operation from the observed site in Grainger County on two different days provide more detailed examples for understanding the productivity and efficiency of a construction operation. The operation was to excavate, move, and dump soil in the waste area within the project limit using four mining trucks as production units. The two cases had identical site conditions, with the only exception being that in Case 1, one excavator was used to



A. TRUCK IN THE QUEUE WAITING TO BE SERVED



B. IDLE FRONT-END LOADER WAITING FOR TRUCKS

Figure 6-1. Two Conditions that Influence the Productivity of Earthmoving Operations

excavate, pile, and load the soil into the four trucks, while in Case 2, the contractor increased the capacity of the processor by using two excavators to excavate and pile and a front-end loader to load the soil into the four trucks. While the time associated with the trucks (traveling, dumping, returning, and maneuvering) remained the same for both cases, the processor cycle times for Case 2 dropped significantly because of the use of massive processing equipment.

The change in the processor in Case 2 not only increased the productivity, but also affected the efficiency of the operation. The mean cycle times of the processor in Case 1 were 5.7 minutes, and the mean cycle times of the processor in Case 2 were 2.25 minutes. The mean time for traveling, dumping, returning, and maneuvering for both cases was 7.1 minutes. The optimum number of trucks that give the maximum productivity for the operation (the balance point) can be determined using a deterministic model. The balance point can be calculated as follows:

$$n = \frac{T_P + T_T + T_D + T_M}{T_P} \quad (6.2)$$

where  $n$  = Balance Point (the optimum number of trucks that gives the maximum productivity)

$T_P$  = Processor Time

$T_T$  = Travel Time

$T_D$  = Dump Time

$T_M$  = Maneuver Time

The balance point was determined to be 2.25 and 4.15 for Cases 1 and 2, respectively. The productivity was determined to be 368 cubic yards and 897 cubic yards for Cases 1 and 2, respectively.

The efficiency of the processors can be determined using Eq. 6-3, and the efficiency of the production units can be determined using Eq. 6-4 as follows:

$$E_p = \frac{i}{n}, \quad 0 = i \leq n \quad (6.3)$$

$$E_c = \frac{n}{n+i}, \quad 0 = i \leq \infty \quad (6.4)$$

where  $E_p$  = Efficiency of the processors

$n$  = Balance Point (optimum number of trucks)

$E_c$  = Efficiency of production units (calling units)

Although the processor in Case 1 worked at its maximum capacity, the overall productivity was low because the processor's maximum capacity was not enough to serve the four trucks. This resulted in high cycle times for the processor and caused increased idle time for trucks beyond the balance point (Figure 6-2a). Another problem with this operation was that the contractor used four trucks, which kept the productivity beyond the balance point (2.25) steady, while the efficiency of the trucks decreased (Figure 6-2b).

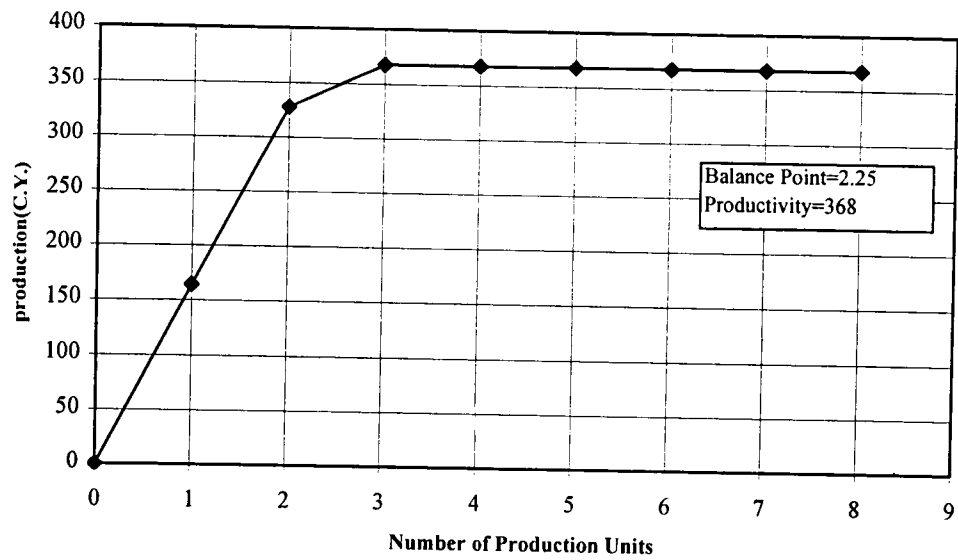


**Figure 6-2a. Productivity Curve for Earthmoving Operation  
(Grainger County Case # 1)**

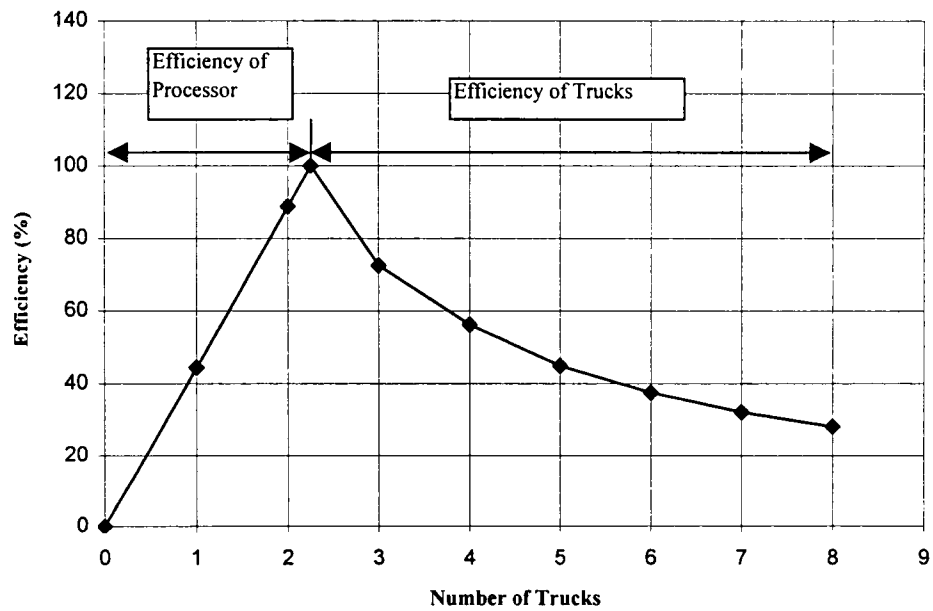


**Figure 6-2b. Efficiency Analysis for Earthmoving Operation  
(Grainger County Case # 1)**

In Case 2, the change in the processor capacity decreased both the cycle times of the processor and the idle time of the trucks. As a result, the productivity was 144% more than that of Case 1 (Figure 6-3a). Also, the balance point of this case was determined to be 4.15. The efficiency of the four trucks was 100%, and the efficiency of the processor was 96% (Figure 6-3b).

The selection of the number of production units and the number and type of processors not only affects the productivity but also the unit cost and duration of projects. Increases in project cost and duration increase the chance of claims in highway construction. Claims based on duration have increased significantly in the last 20 years.

In order to properly analyze claims for time, some of the factors that cause delay in highway construction need to be explained:

- Delay can occur as a result of the contractor's lack of management skills, such as the improper use of resources.
- Delay can occur as a result of environmental factors, such as inclement weather.
- Delay can occur as a result of the contractor's underestimation of the scope of the operation, which often occurs in incentive/disincentive projects.
- Delay can occur as a result of the late arrival of materials.
- Delay can occur as a result of having to redo work.

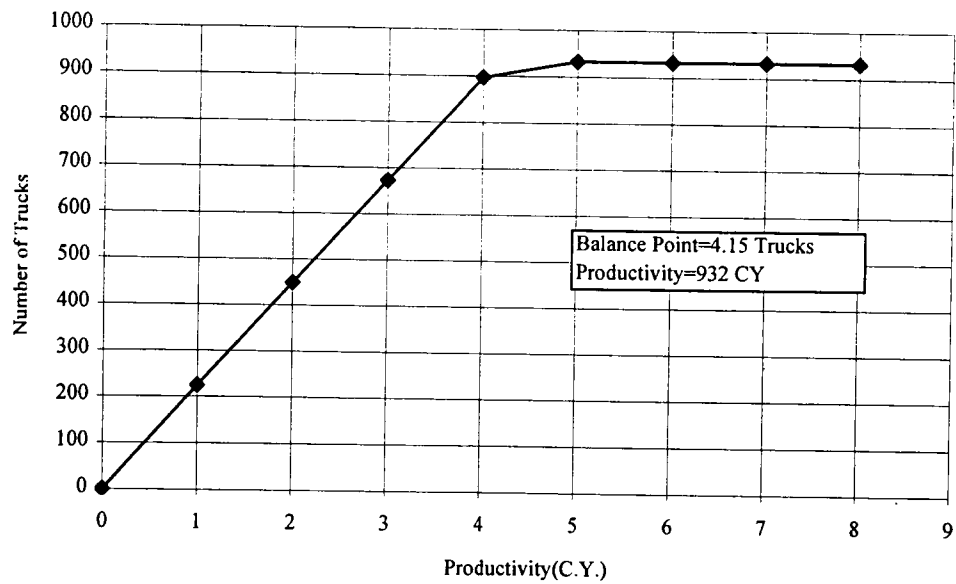


**Figure 6-3a productivity Curve for Earthmoving Operation  
(Grainger County Case#2)**

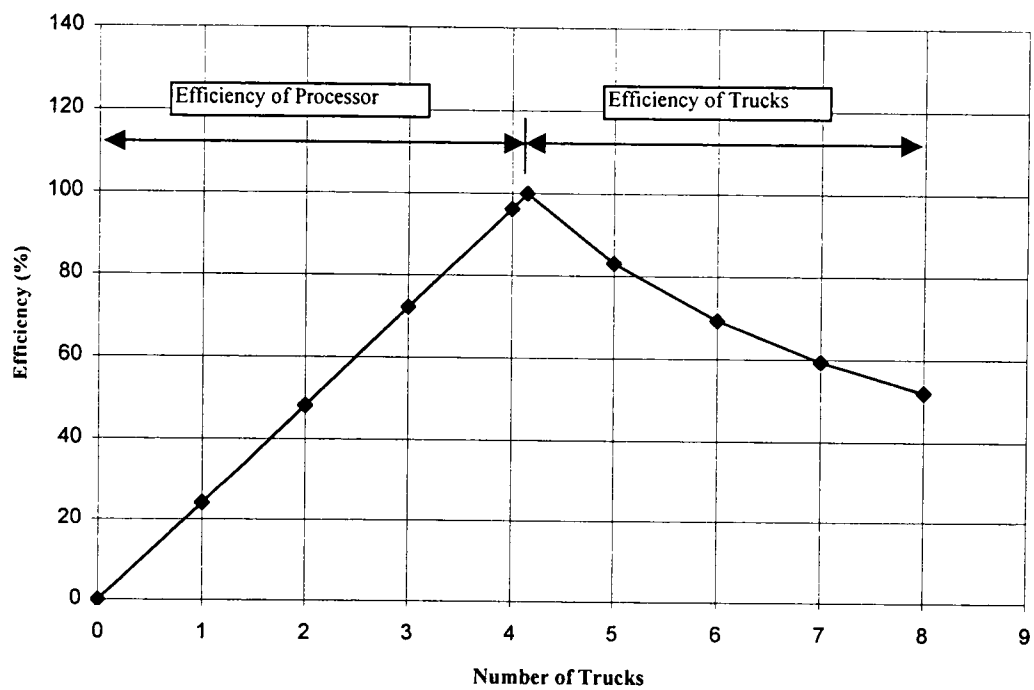


**Figure 6-3b. Efficiency Analysis for Earthmoving Operation  
(Grainger County Case #2)**

Some of the reasons that can cause delay and are attributable to the Department of Transportation include the following:

- Errors in the plans
- Changes in the scope of the work
- Changes in the sequence of operations

These delays cause the project not to be completed in the time required, which may cause cost increases and lead to penalties (costs for delay). The contractor may file a claim requesting the following:

- No- cost time extension
- Additional cost without time extension
- Extended cost and time
- Extended overhead cost

The contractor may take the case to the Department of Transportation. If a settlement is not reached, the matter is settled in court. In court, the contractor tries to show that the reasons for the delay are the fault of the DOT and to establish the cost associated with these delays. The two main advantages that the contractor often has are his/her documentation of the daily operation and cause of delays and legal counsel specialized in resolving construction-related cases.

The ADMP is an effective tool for resolving claims and protecting the rights of both DOTs and contractors. In order to properly apply the ADMP, documentation of the delay operation is required, including all the resources, the size and amount of the equipment, the size of the crew, and the availability of materials. Completion of

the form shown in Appendix A is essential for evaluating a claim. The data must be collected and calculated using a minimum of four data sets for each site. Once the data have been collected, productivity can be calculated based on the ADMP and the measured and maximum productivity. Figure 6-4 shows the three productivity rates for an Asphalt A-Mix task. The data were collected in White County in Region 2.

In evaluating any claim with regard to productivity and time completion, the productivity of the project must first be determined from the Inspector's diary. The site productivity will be evaluated using at least four working days. Documentation from the Inspector's diary is essential for determining the productivity for the particular site. Forms in Appendix A must be filled out by the Inspector. Once the data have been evaluated, the three types of productivity (PADMP, the PM, and the PMAX) are calculated. Once the productivity is calculated, the claim can be evaluated.

If the result of the analysis shows that the overall production of the operation is between the maximum production and the daily production, the contractor is doing well, and the claim is valid. If the productivity falls between the measured productivity and the ADMP rate, the reason for the delay might not be the contractor's fault. However, if the overall productivity of the operation falls below the ADMP rate, the analysis shows that 95% of the time the contractor is not utilizing his resources and management skills properly to perform the job within the required time. In this case, the contractor has a greater chance to lose the claim.

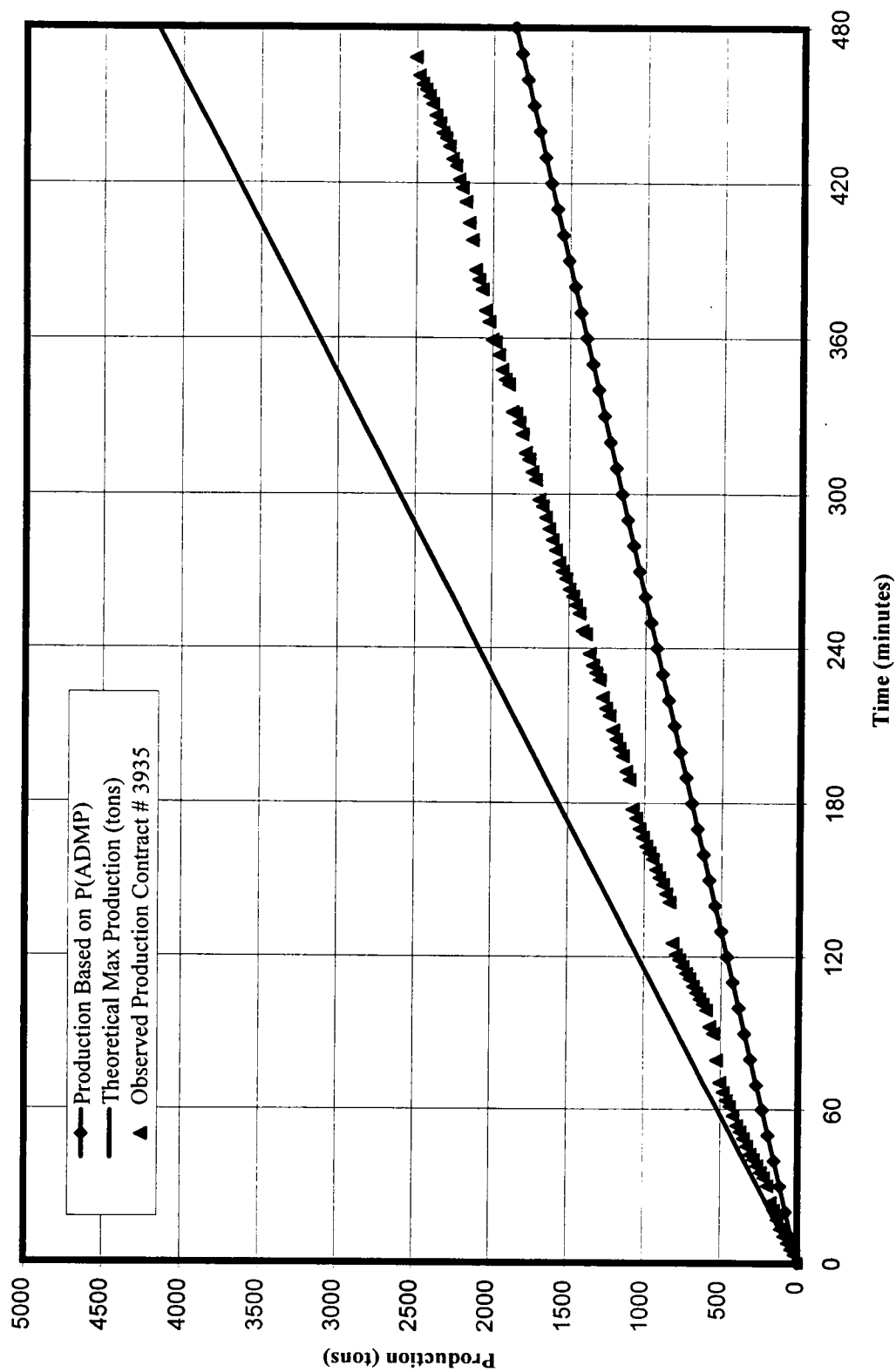


Figure 6-4. Productivity Graph of Asphalt( A- Mix) Task for Claim Evaluation

## **6.4 BENEFITS OF THE ADMP**

The benefits of using the ADMP include the following:

- 1) It calculates, measures, and evaluates productivity for highway construction operations.
- 2) It calculates task duration which can be used in project scheduling and in estimating the cost of the project.
- 3) It evaluates and resolves claims with respect to time and productivity.
- 4) It evaluates the operation for efficiency and determines the effect of management skills on production.
- 5) It explains the importance of documenting the operation.
- 6) It simplifies the effect of many variables on productivity and project duration.
- 7) It explains the distribution of time in highway construction.
- 8) It evaluates productivity and can assist in evaluating incentive and disincentive contracts by determining the feasibility of project completion time.
- 9) It can be applied to any repetitive cycle operation task, which is typical for highway construction.

## **CHAPTER 7**

### **INFLUENCE OF TASK DURATION ON CONSTRUCTION COST**

#### **7.1 INTRODUCTION TO BIDDING AND ESTIMATING**

This chapter discusses bidding and estimating, bid proposals, types of construction contracts, cost estimates, evaluating cost for highway tasks, and the influence of task duration on project cost.

A bid is a quote submitted by contractors containing a proposed price on a project or part of a project. In general, a bid proposal includes the cost of materials, labor, equipment, sub-contractors, overhead, and profit. An estimate, on the other hand, is a calculation of the probable cost of a project, and it is made through the use of measurement and price determinations. These measurement and price determinations are approximated rather than fixed. Although the fundamentals of estimating are the same, the procedure for estimating may vary from one individual to another because estimation is based not only on the collection of information, but also on the experience of the estimator. Although it would seem that there are many variations in the cost of a project, in reality most variations occur in the areas of evaluating duration and the productivity of labor and equipment. Obviously, the variation in the cost estimate of materials is small compared to the variation in the cost estimate of labor and equipment because of the variability in estimating the productivity of equipment and labor.

The estimator of a company must evaluate a project before the contractor decides whether or not to bid on it. The estimator must evaluate the company for the following points:

- a. It must have the financial capability to maintain adequate cash flow.
- b. It must have the technical expertise to perform the work.
- c. It must have the resources, including manpower, machines, and access to materials.
- d. It must have the management skills to complete the project within a required time.
- e. It must have a good safety program.

After the contractor receives a contract document including a bid proposal form, plans, and specifications, the estimator begins gathering information and considering many factors such as location, site conditions, the type of construction, the probable competition, the labor market, the quality of the drawings and specifications, the risks, the proposed completion time and penalties for delay, the company's need for work, and the estimating and bidding deadline. Once the information is gathered and the site is evaluated, the company prepares a bid proposal. A typical bid proposal should contain the following:

- 1) Legal documents
- 2) Project references, such as the name and address of the contractor and the type of project (i.e., highway)
- 3) Description of the work in accordance with the plans and specifications

- 4) Price, which includes labor, materials, equipment, taxes and burden on labor, overhead cost, time adjustment fees, and profit
- 5) Special conditions, such as the time required for certain work to be done; work that must be done before the contract is completed; and federal, state, and local regulations (i.e., equal opportunity and the Davis Bacon Act)  
Work done by those other than the prime contractor, such as sub-contractors, must be in accordance with the plans and specifications, and the contractor may be required to provide their name and addresses.
- 6) Time and scheduling information, including the time from mobilization to completion expressed in working or calendar days, the date of the proposal, and the acceptance time
- 7) The signature of the contractor or contractor's representative, along with the company name, address, and job title.

Once the bid proposal is turned in, all bids are opened at a specific time on the basis of competition, and the lowest reliable bid is ultimately awarded the project.

## **7.2 TYPES OF CONSTRUCTION CONTRACTS**

There are five main types of construction contracts:

- 1) Stipulated Sum Contract, sometimes called a lump-sum or fixed price contract. This type of contract specifies the amount of payment to be made by the owner to the contractor for the proposed work. This amount is first stipulated by the contractor in his offer to the owner in the following

manner: "We offer to perform all the work shown on the drawings and described in the specifications for the sum of \_\_\_\_ dollars." Contractors take most of the risk in this type of contract.

- 2) Cost Plus Contract. This type of contract specifies the total cost of the project plus a specific mark-up proposed by the contractor. It is usually written in the following manner: "We offer to perform all the work for all costs as defined in the agreement for a fixed fee of \_\_\_\_ dollars or a percent of all costs." Owners take most of the risk in this type of contract. This type of contract is preferred by contractors when a large portion of the project design is incomplete or where uncertain conditions exist.

Contractors in this type of contract have no desire to keep the construction cost down since their fee is respectively high with high cost. To control this problem, the owner often allocates a maximum price for protection from overflow cost. Furthermore, the owner can establish a fixed percentage mark-up fee.

- 3) Target Figure Contract. This type of contract is a combination of the Stipulated Sum Contract and the Cost Plus Contract. In this type of contract, the contractor and owner both share the risk to a certain degree.

- 4) Unit Price Contract. This type of contract is more familiar in heavy construction and highway construction. A project contains many tasks,

which are estimated individually for cost. The sum of the cost for all the individual tasks determines the overall project bid price.

- 5) Construction Management Contract. In this type of contract, the owner manages the job and divides the tasks among many specialty contractors. Two agents represent the owner: (1) the designer who is responsible for the design and (2) the construction manager who is primarily responsible for translating the design into reality. There is no single contractor responsible for all the work, but rather several specialty contractors who each have separate contracts with the owner for parts of the required work.

### **7.3 BIDDING STRATEGY**

Bidding strategy contains three main stages that determine and evaluate a particular company's strength in bidding and estimating.

- 1) Stage 1. Before contractors bid on a job, they must consider the following:
  - a. The kind of a job or specialty they are going to bid on and the risk involved
  - b. The size job they are capable of handling in respect to finances, manpower, and equipment capacity
  - c. The distance of the job from the contractor's office
  - d. The site conditions, including type of soil, topography, and sub-contractors involved in the project

- e. The proposed duration of the project
  - f. The amount of time allocated for each task. Also, the contractors must consider the time of the year, especially for short-term projects. In the winter, weather conditions cause slow performance of work, while in the summer, a faster pace is expected
  - g. Availability of other work
  - h. Contractors who may be competing for the same job
- 2) Stage 2. During preparation of the bids, the contractor has a cost estimate prepared by a well-trained estimator. The estimator must collect all relevant data to determine material cost, equipment cost, and labor cost. As part of the labor cost, the estimator must determine the burden on labor cost, which includes Workers Compensation, public liability, property damage insurance, fringe benefits, FICA, Medicare, unemployment benefits, and subsistence. Indirect costs such as overhead, time adjustment cost, and bond must also be determined. Finally, the contractor establishes the percentage of profit. In addition, the estimator must determine the productivity of labor and equipment. This determination will contain most of the variability in estimating and is the most difficult part of the estimation.
- 3) Stage 3. After the contract has been awarded, if the company does not get the bid, the contractor should go back and re-evaluate the bid for future reference and evaluate some of the reasons the contract was not awarded.

If the company is awarded the job, the contractor should go back and review the estimate for ways to minimize cost and maximize profit. The following strategies may be considered:

- Reducing the cost of materials by calling other suppliers
- Reducing the overhead cost
- Establishing a good management system, including office management, financial management and interest, and site construction management and scheduling
- Increasing productivity
- Reducing overtime hours
- Motivating, training, and retaining long-term skilled labor and maintaining good labor relations
- Controlling on-site safety

The contractor must perform the work according to the plans and specifications and the time allocated for the project to avoid legal fees in case of a dispute and to avoid redoing work that may be expensive.

## **7.4 ESTIMATING DIRECT COST**

Estimations of the direct cost include the cost of the materials, labor, equipment, taxes, and burden on labor.

### 7.4.1 Material Cost

The price of materials is subject to supply and demand and is affected by many other things including the quality, the quantity, the time needed, the location of the project, the buyer, the seller, the list price, discounts, delivery, and storage. Although there are few variations in estimating material cost, determining the quantity of the materials needed may require some knowledge of construction mathematics, such as arithmetic, geometry, and trigonometry.

Estimations of the quantity of material (soil) for an earthmoving task must take into consideration changes in the volume of the materials. There are three volume conditions of soil: bank, loose, and compacted. The undisturbed soil, also called the Bank Volume (BV), is the condition of the borrow pit. When the soil is excavated and loaded into trucks, it swells and is changed to the loose condition, often called the Loose Volume (LV). Finally, when the soil is dumped and compacted, it shrinks to the Compacted Volume (CV) (Figure 7-1).

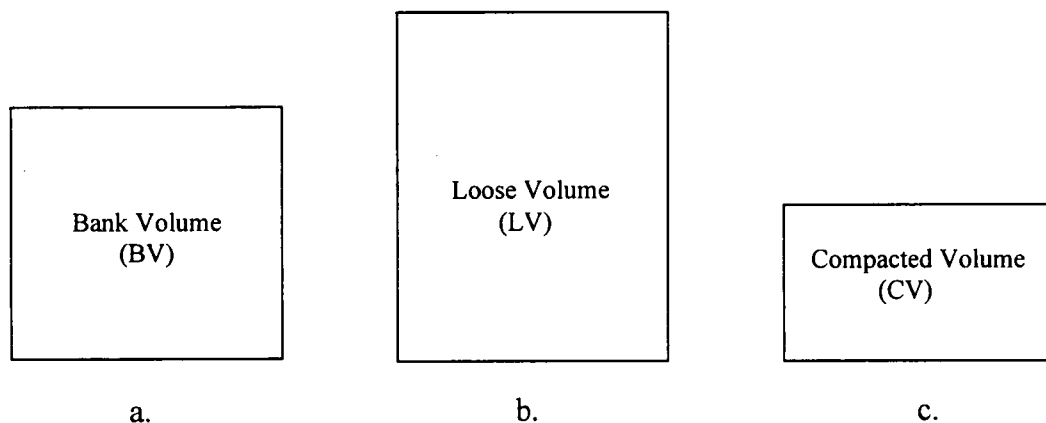


Figure 7-1. Three Types of Soil Volume

Swelling and shrinking factors, which vary depending on the type of soil, affect the cost and productivity of an earthmoving operation. The following equation can be used to calculate the volume of loose and compacted volumes of soil:

$$LV = BV (1 + LF) \quad (7.1)$$

$$CV = LV (1 - SF) \quad (7.2)$$

where LV = Loose Volume

BV = Bank Volume

CV = Compacted Volume

LF = Swelling Factor

SF = Shrinkage Factor

The cost of earthmoving materials is included in the borrow site or the dump waste area that the contractor may purchase. These costs can be divided into the quantity to be excavated and moved in order to determine the unit price of the materials. The cost of asphalt materials delivered to the site usually includes the truck cost, and these costs vary depending on the type of mix and the distance of the haul. The cost of concrete materials also includes the cost of delivery to the project site, and the cost depends mainly on the type of concrete and the distance of the haul. Steel pile cost includes the price for delivery, or the contractor adds it on separately. The piles are usually standard 40-foot long piles.

The cost of the material in general is the number of production units required to perform the task multiplied by the cost for one unit. In a unit price contract, which is typical for highway construction projects, it is helpful to determine the hourly cost of material using the hourly cost of production as shown in Equation 7.3:

$$\text{HMC} = \text{PR (unit/hour)} \times \text{CPU} \quad (7.3)$$

where HMC = hourly material cost

PR = production rate (unit/hour)

CPU = cost per unit

#### **7.4.2 Labor Cost**

The construction industry has been witnessing the continuing increase of labor wages and a very low annual increase in labor productivity. Construction labor wages have been rising at the rate of 3.5 % to 4.0 % annually, depending on the craft; and this percentage keeps rising every year. On the other hand, construction productivity has only been increasing about 0.8% annually, and this percentage does not seem to be increasing.

Along with these higher wages, the contractor must pay an additional amount above the cost of his labor payroll. This additional cost, which is called burden, includes fringe benefits, insurance, social security, and unemployment that the contractor must pay for each employee. These additional costs to the contractor can vary depending on the amount of overtime worked. Burden cost is often confused

with overhead cost. However, burden applies to labor only, while overhead applies to the direct cost of the overall project.

Contractors have three main methods of paying their site workers. The most common method is the hourly rate. With this payment method, the contractor sacrifices high productivity. The second method is based on the worker's production. The more the worker produces, the more the worker is paid. With this method, the contractor receives high productivity, but sacrifices quality. The last method is a combination of the first two. It combines an hourly rate with production incentives. With this method, the contractor can better control both quality and quantity.

Crew selection for a particular activity depends largely on the experience of the contractor or superintendent. It is important to have a reasonable number of crew members on site. Too many workers will cause disturbances and increase the cost. On the other hand, too few workers might cause an accident and decrease productivity.

Labor cost can be determined by multiplying the average hourly wage of the crew by the total man hours. The average hourly wage of the crew is the total wages of the crew per hour multiplied by the ratio time for each member.

#### **7.4.3 Equipment Cost**

Equipment resources play an important role in the construction industry, and equipment cost in highway construction is a significant portion of the total cost of a project. Thus, it is important that the contractor or manager select the best equipment to maximize the production of the operation.

There are two major types of construction equipment: (1) production equipment (the units that do the actual work) and (2) support equipment (the units that help to move equipment, labor, tools, and supplies to the site and from one location to another). The cost of equipment can be classified into three categories: owner cost, rent cost, and lease-to-buy cost. The decision to own, rent, or lease a piece of equipment is determined by the contractor, depending on the cost for buying, renting, or leasing; the type of job; the financial situation of the contractor; the value of the equipment; and the usage of the equipment (whether it will be continually used or only for a specific job). The equipment cost, which includes owner cost, rental cost, and lease cost, is also determined by the method of using the equipment.

- Owner Cost

There are three types of cost involved in owning equipment:

- 1) depreciation cost
- 2) ownership cost, which includes insurance, interest, taxes, and storage
- 3) operational cost, which includes tire replacement; fuel, oil, and grease; and repair and maintenance

Depreciation and ownership costs are fixed costs, while operational cost is variable.

- Rental Cost

The rental cost to the contractor mainly includes the rental rate and the operational cost. The cost for mobilization of the rental equipment depends on the agreement between the contractor and the rental company.

- Lease Cost:

This type of equipment resource is often not the most economical solution. Contractors use it in cases when the need for the equipment is continuous throughout long periods of time, and they are unable to purchase it. The cost of leasing includes the cost of owning the equipment, except the depreciation is replaced by the lease rate. In essence, the contractor has all the ownership cost, but does not own the equipment.

Before the contractor makes the decision to buy, rent, or lease equipment, a cost analysis should be done on all three options to determine the most economical method. Solutions may vary from contractor to contractor and from one type of job to another. Selecting the method of equipment cost can significantly affect the estimate of a highway construction project because equipment cost is a major portion of the overall cost for many tasks. This estimate plays an important role in determining whether or not the contractor is awarded the bid.

The direct cost of a highway task includes the cost of materials, labor, equipment, taxes, and burden on labor. The cost of materials can be easily determined. Determining the cost of labor and equipment, however, is difficult because the productivity of a task is difficult to calculate. However, once the productivity is determined, the cost estimate is easily calculated. The rental cost

method was used to estimate equipment cost for the nine highway tasks in this study. An example of estimating direct cost is shown in Table 7-1.

## **7.5 ESTIMATING INDIRECT COST**

The indirect cost of a project includes overhead, time adjustment cost, and bond. Because the calculation of indirect cost varies from one contractor to another, it is not considered for the nine highway tasks in this study. However, an explanation of indirect cost is important for a proper understanding of the procedures for estimating highway construction projects.

### **7.5.1 Overhead Cost**

Overhead cost is an indirect cost of a project, which can be attributed to a specific job site or to other operational cost. Overhead cost can be classified into two main categories: job overhead cost and operating overhead cost. Job overhead cost is the cost of work related to direct cost. This type of overhead is related to a specific project; therefore, estimating this cost can only be done based on the condition of a particular project. This estimate of overhead cost must include such costs as the following (if applicable): legal fees, consulting fees, personnel expenses, accommodations for site workers, and short-term financing for specific projects.

Operational overhead cost is the cost that cannot be attributed to any particular job, often called office overhead. The construction firm's accountant should provide the estimator with this information so that it can be considered in the estimate for the project.

**Table 7-1. Sample Calculation of Direct Cost ( Road & Drainage operation)**

|                                    |                          |                   |                      |                          |                      |
|------------------------------------|--------------------------|-------------------|----------------------|--------------------------|----------------------|
| Item #                             | 203-01                   |                   |                      |                          |                      |
| Description                        | Road&Drainage Excavation |                   |                      |                          |                      |
| Contract #                         | 3564                     |                   |                      |                          |                      |
| County                             | Grainger                 |                   |                      |                          |                      |
| Region                             | I                        |                   |                      |                          |                      |
|                                    |                          |                   |                      |                          |                      |
| Materials Cost                     |                          |                   |                      |                          |                      |
|                                    |                          |                   |                      |                          | Total Cost/Hour (\$) |
| Type of Mterials                   | Quantity Used (CY /hour) |                   |                      | Cost/Unit                |                      |
| Soil                               |                          | 898               |                      | 0.00                     | 0.00                 |
| Total Materals Cost                |                          |                   |                      |                          | 0.00                 |
| Equipment:                         |                          |                   |                      |                          |                      |
|                                    |                          |                   |                      |                          | Total Cost/Hour (\$) |
| Model                              | Quantity                 | Rate/Month (\$)   | Rate/Hour (\$)       | Operation Cost/Hour (\$) |                      |
| Cat 375 Excavator                  | 1                        | 20,000            | 113.64               | 21.64                    | 135.28               |
| Cat 350 Excavator                  | 1                        | 16,500            | 93.75                | 14.81                    | 108.56               |
| Cat 777 Haul Truck                 | 4                        | 25,000            | 142.05               | 25.52                    | 670.26               |
| Cat 140G Grader                    | 1                        | 6,600             | 37.50                | 8.01                     | 45.51                |
| Cat D8R Bulldozer                  | 1                        | 13,000            | 73.86                | 13.03                    | 86.89                |
| Cat 992 Front End Loader           | 1                        | 25,000            | 142.05               | 30.32                    | 172.37               |
| Total Cost of Equipment /hour      |                          |                   |                      |                          | 1218.87              |
| Labor:                             |                          |                   |                      |                          |                      |
|                                    |                          |                   |                      |                          |                      |
| Classification                     | Quantity                 | Rate/Hour (\$/hr) | Crew Hour Worked/Hr. | Crew Rate (\$/hr)        | Total Cost (\$/hr)   |
| Foreman                            | 1                        | 12.80             | 0.25                 |                          | 3.2                  |
| Class A Operator                   | 2                        | 11.80             | 2.0                  |                          | 23.6                 |
| Class B Operator                   | 2                        | 10.04             | 2.0                  |                          | 20.08                |
| Truck Driver                       | 4                        | 8.89              | 4.0                  |                          | 35.56                |
|                                    |                          |                   | 8.25                 | 9.99                     | 82.44                |
| Base Rate Wages of Labor           |                          |                   |                      |                          | 82.44                |
| Burden                             |                          |                   |                      |                          | 32.98                |
| Total Labor Cost                   |                          |                   |                      |                          | 115.42               |
|                                    |                          |                   |                      |                          |                      |
| Total Direct Cost                  |                          |                   |                      |                          | 1334.28              |
| Observed Production Rate(cy/hr)    |                          |                   |                      |                          | 898                  |
| Unit Cost for Road & Drainage Task |                          |                   |                      |                          | 1.49                 |

The following are examples of operational overhead:

- Management and staff costs, which include salaries, fringe benefits, and expenses
- Business office costs, which include rent, utilities, office furniture, computers, and office supplies
- Communications costs, which include telephone, fax, mail, and advertising

Calculation of the operational overhead cost for forecasting a project can be estimated as a percentage of the direct cost using the historical operational overhead cost of a company. The cost may be adjusted for cost of living and project duration.

#### **7.5.2 Time Adjustment Cost (TAC)**

The Time Adjustment Cost is additional cost as a result of increases in the cost of living over a period of time and inflation. This cost includes higher wages for labor; higher prices for purchasing, renting, and maintaining equipment; higher overhead expenses; and adjustments for profit corresponding to the cost of living and inflation rate. Estimators usually determine TAC as a percentage of the total cost of a project, considering the following factors: project duration, economy (market and inflation), and the historical increase in the cost of materials, labor, equipment, fuel, and overhead.

The TAC must be considered when preparing the estimate for a project.

### **7.5.3 Bond**

Bond is a three-party agreement that protects one party from defaulting on the part of a second party. Contractors pay a fee to a bonding company to ensure that they will not default on their contract.

There are three main types of bond:

- 1) Bid Bond is issued to the contractor to guarantee that the contractor will complete the job with the total bid amount.
- 2) Performance Bond is issued to the contractor to guarantee that the contractor will perform the work with respect to agreement and specification.
- 3) Payment Bond is issued to the contractor to guarantee that the contractor will pay the sub-contractors, laborers, and suppliers. The surety bond must protect the owner from the sub-contractors, laborers, and suppliers in case the contractor defaults in paying them.

The bond cost varies from one project to another, depending on the project size.

However, it is a cost to the contractor which must be considered when preparing the total estimate.

## **7.6 PROFIT**

Profit is the main motivation of almost every business and is an important measurement of the efficiency and success of a company. Profit is the positive difference between total income and total expenditure. Loss occurs when the total

expenditures exceed the total income. The break-even-point is the point in the project when income is equal to expenditures.

Profit is usually determined as a percentage of the overall cost of the project. The percentage of profit for projects varies based on the many factors that affect profit, such as the accuracy of the cost estimate, the determination of the percentage of profit, management skills, the availability of a skilled crew, the allocation of equipment, and, most importantly, the duration of the project and the amount of risk involved in it. When determining the percentage of profit, the contractor must also consider the market, the availability of jobs, and the possibility of competition for the bid.

## **7.7 ESTIMATING HIGHWAY CONSTRUCTION TASKS AND EVALUATING COST ANALYSIS**

Most of the variability in estimating is related to the variability in calculating productivity, which influences cost. The completion time of a construction task varies depending on the productivity. Generally, higher productivity results in lower cost per unit. Cost analysis can be used to evaluate the productivity of a task.

Based on the measured productivity and the project resources shown in Appendix E for each data set, an estimate of the direct cost was prepared for the nine tasks. This includes the cost of the materials, labor, equipment, taxes, and burden on labor.

The direct cost of a task based on site observation, the cost of resources, and the measured productivity is compared to the historical annual average bid price and

the contractor's bid price (Tables 7-2 through 7-10). When comparing these three costs, the measured cost of a task does not include overhead and profit.

Proper productivity calculations are the key factor in estimating because of the variability involved in productivity as demonstrated by the two case studies of road and drainage excavation from the data collected in Grainger County, Tennessee. Equipment allocation decisions greatly affected the productivity of the operation. The productivity increased from 368 cy/hour to 898 cy/hour (a 144% increase) when the method of construction was changed. This increase in the efficiency of the operation decreased the unit cost from \$2.74 to \$1.49 (Table 7-2). This shows that utilizing resources efficiently can dramatically affect the duration of the operation and ultimately affect the cost of a production unit. The borrow excavation also showed some variation in the cost. These variations were mainly caused by differences in the type of soil, the distance of the haul, and the type of equipment used (Table 7-3).

The unit cost for the mineral aggregate task was almost the same for all 10 data sets. The variation in the cost was based mainly on the haul distance (Table 7-4). There was little variation in the average cost of the asphalt operation because the asphalt operation is mainly material cost-oriented, and the variation of the material cost depends mainly on the distance between the asphalt plant and the project site (Table 7-5 through Table 7-8). The unit cost of the concrete ramp task remained consistent with little variation (Table 7-9). Finally, the unit cost for driving steel pile increased somewhat for the Grainger County site (Table 7-10) because the contractor used an unusual method of construction (Figure 7-2).

**Table 7-2. Cost Estimate for Road and Drainage Excavation**

| No. | Contract # | Region | County     | Method             | Production Rate (cy/hr) | Production (cy) | Material Cost (\$/hr) | Equipment Cost (\$/hr) | Labor Cost (\$/hr) | * Total Cost (\$/hr) | Unit Cost (\$/cy) | Actual Unit Bid Price (\$/cy) |
|-----|------------|--------|------------|--------------------|-------------------------|-----------------|-----------------------|------------------------|--------------------|----------------------|-------------------|-------------------------------|
| 1   | 3564       | I      | Grainger   | Excavator          | 368                     | 1369            | -                     | 921.82                 | 60.60              | 1006.66              | 2.74              | 3.53                          |
| 2   | 3564-2     | I      | Grainger   | Loader & Excavator | 898                     | 2455            | -                     | 1,218.87               | 82.44              | 1334.29              | 1.49              | 3.53                          |
| 3   | 4123       | I      | Knox       | Excavator          | 147                     | 1131            | -                     | 563.43                 | 15.00              | 584.43               | 3.98              | 5.25                          |
| 4   | 4384       | II     | McMinn     | Scraper            | 415                     | 1625            | -                     | 279.54                 | 36.52              | 330.67               | 0.80              | 1.64                          |
| 5   | 4410       | II     | White      | Scraper            | 205                     | 1137            | -                     | 442.89                 | 53.40              | 517.65               | 2.53              | 2.50                          |
| 6   | 3926       | II     | Rhea       | Scraper            | 261                     | 1396            | -                     | 680.34                 | 52.96              | 754.48               | 2.89              | 1.58                          |
| 7   | 3948       | III    | Davidson   | Excavator          | 224                     | 845             | -                     | 258.21                 | 33.93              | 305.71               | 1.36              | 3.50                          |
| 8   | 4251       | III    | Williamson | Excavator          | 59                      | 367             | -                     | 320.46                 | 35.08              | 369.57               | 6.26              | 5.50                          |
| 9   | 3556       | III    | Davidson   | Excavator          | 71                      | 466             | -                     | 246.21                 | 25.04              | 281.27               | 3.96              | 5.15                          |
| 10  | 4572       | IV     | Weakley    | Excavator          | 264                     | 839             | -                     | 435.65                 | 31.88              | 480.28               | 1.82              | 2.24                          |
| 11  | 3915       | IV     | Henderson  | Excavator          | 318                     | 1318            | -                     | 417.48                 | 74.30              | 521.50               | 1.64              | 2.00                          |
| 12  | 4696       | IV     | Fayette    | Scraper            | 314                     | 985             | -                     | 282.38                 | 30.12              | 324.55               | 1.03              | 2.45                          |

**BASED ON 1-DAY SITE VISIT**

Region I Weighted Average Unit Cost = **2.40**  
Region II Weighted Average Unit Cost = **1.97**  
Region III Weighted Average Unit Cost = **3.15**  
Region IV Weighted Average Unit Cost = **1.49**

Weighted Average Unit Cost = **2.16**

**Production**

4954.97  
4156.92  
1678.81  
3142.56  
**13933.26**

**1996 TDOT AVG. UNIT PRICE**

Region I = **2.98**  
Region II = **2.77**  
Region III = **2.20**  
Region IV = **1.94**

Weighted Average Unit Price = **2.31**

**\* NOTE:** 40% Labor Burden has been added to the Labor Cost to arrive at Total Cost.  
Unit Cost do not contain Mark-Up and Overhead.

**Table 7-3. Cost Estimate for Borrow Excavation**

| No. | Contract # | Region | County    | Production Rate (cy/hr) | Production (cy) | Material Cost (\$/hr) | Equipment Cost (\$/hr) | Labor Cost (\$/hr) | * Total Cost (\$/hr) | Unit Cost (\$/cy) | Actual Unit Bid Price (\$/cy) |
|-----|------------|--------|-----------|-------------------------|-----------------|-----------------------|------------------------|--------------------|----------------------|-------------------|-------------------------------|
| 1   | 3866       | II     | Marion    | 78                      | 459             | -                     | 222.37                 | 15.00              | 243.37               | 3.12              | 4.40                          |
| 2   | 3948       | III    | Davidson  | 114                     | 589             | **                    | 258.21                 | 33.93              | 305.71               | 2.68              | 7.50                          |
| 3   | 4723       | III    | Robertson | 190                     | 2011            | -                     | 330.91                 | 45.13              | 394.09               | 2.07              | 8.45                          |
| 4   | 4017       | III    | Davidson  | 56                      | 456             | **                    | 311.66                 | 44.68              | 374.21               | 6.68              | 6.50                          |
| 5   | 3502       | IV     | Carroll   | 151                     | 752             | -                     | 406.20                 | 35.08              | 455.32               | 3.02              | 3.00                          |
| 6   | 3863       | IV     | McNairy   | 183                     | 766             | -                     | 328.19                 | 35.08              | 377.30               | 2.06              | 5.00                          |
| 7   | 4224       | IV     | Fayette   | 193                     | 676             | -                     | 402.09                 | 44.68              | 464.64               | 2.41              | 2.80                          |

**BASED ON 1-DAY SITE VISIT**

|                                         |             |                   |
|-----------------------------------------|-------------|-------------------|
| Region I Weighted Average Unit Cost =   | <b>0.00</b> | <b>Production</b> |
| Region II Weighted Average Unit Cost =  | <b>3.12</b> | 0.00              |
| Region III Weighted Average Unit Cost = | <b>2.87</b> | 458.9             |
| Region IV Weighted Average Unit Cost =  | <b>2.50</b> | 3056.23           |
|                                         |             | 2193.53           |
|                                         |             | <b>570.67</b>     |
| Weighted Average Unit Cost =            | <b>2.75</b> |                   |

**1996 TDOT AVG. UNIT PRICE**

|                               |             |
|-------------------------------|-------------|
| Region I =                    | <b>4.47</b> |
| Region II =                   | <b>4.28</b> |
| Region III =                  | <b>2.54</b> |
| Region IV =                   | <b>3.4</b>  |
| Weighted Average Unit Price = | <b>3.16</b> |

\* **NOTE:** 40% Labor Burden has been added to the Labor Cost to arrive at Total Cost.

Unit Cost do not contain Mark-Up and Overhead.

\*\* **NOTE:** This Data was taken on Rock Excavation.

**Table 7-4. Cost Estimate for Mineral Aggregate Task**

| No. | Contract # | Region | County     | Time Observed (hours) | Total Production (tons) | Production Rate (tons/hr) | Material Cost (\$/ton) | Equipment Cost (\$/hr) | Labor Cost (\$/hr) | * Unit Cost (\$/ton) | Actual Unit Bid Price (\$/ton) |
|-----|------------|--------|------------|-----------------------|-------------------------|---------------------------|------------------------|------------------------|--------------------|----------------------|--------------------------------|
| 1   | 2440       | I      | Knox       | 7                     | 1242                    | 177                       | 5.50                   | 123.48                 | 43.73              | 6.54                 |                                |
| 2   | 3564       | I      | Grainger   | 6.55                  | 2369                    | 362                       | 4.80                   | 131.54                 | 62.13              | 5.40                 | 8.36                           |
| 3   | 4044       | I      | Roane      | 6.85                  | 1012                    | 148                       | 5.20                   | 112.50                 | 53.91              | 6.47                 | 10.00                          |
| 4   | 3707       | II     | Rhea       | 9.05                  | 1909                    | 211                       | 6.50                   | 145.06                 | 60.24              | 7.59                 | 8.00                           |
| 5   | 4160       | II     | White      | 6.6                   | 2829                    | 429                       | 5.30                   | 114.07                 | 69.04              | 5.79                 |                                |
| 6   | 3866       | II     | Marion     | 6.6                   | 1012                    | 153                       | 5.70                   | 122.28                 | 43.84              | 6.90                 | 11.70                          |
| 7   | 4017       | III    | Davidson   | 6.55                  | 782                     | 119                       | 5.70                   | 126.99                 | 23.02              | 7.03                 | 8.65                           |
| 8   | 4251       | III    | Williamson | 4.87                  | 1541                    | 316                       | 7.50                   | 139.08                 | 34.24              | 8.09                 | 8.25                           |
| 10  | 3915       | IV     | Henderson  | 5.78                  | 1035                    | 179                       | 6.50                   | 81.48                  | 41.53              | 7.28                 | 7.25                           |
| 11  | 4699       | IV     | Henderson  | 7.5                   | 1127                    | 150                       | 6.70                   | 103.93                 | 53.91              | 7.89                 | 9.50                           |

**BASED ON 1-DAY SITE VISIT**

Region I Average Unit Cost = **5.94**  
Region II Average Unit Cost = **6.58**  
Region III Average Unit Cost = **7.74**  
Region IV Average Unit Cost = **7.60**

Weighted Average Unit Cost = **6.71**

**Production**

4623  
5750  
2323  
2162  
**14858**

**TDOT AVG. UNIT PRICE**

Region I = **9.76**  
Region II = **9.33**  
Region III = **8.15**  
Region IV = **10.37**

Weighted Average Unit Price = **9.06**

**\* NOTE:** 40% Labor Burden has been added to the Labor Cost to Arrive at the Unit Cost.  
Unit Cost do not contain Mark-Up and Overhead.

**Table 7-5 Cost Estimate for Asphalt Grade A-S Mix**

| No. | Contract # | Region | County     | Time Observed (hours) | Total Production (tons) | Production Rate (tons/hr) | Material Cost (\$/ton) | Equipment Cost (\$/hr) | Labor Cost (\$/hr) | * Unit Cost (\$/ton) | Actual Unit Bid Price (\$/ton) |
|-----|------------|--------|------------|-----------------------|-------------------------|---------------------------|------------------------|------------------------|--------------------|----------------------|--------------------------------|
| 1   | 3707       | II     | Rhea       | 5.8                   | 814                     | 140                       | 17.67                  | 148.40                 | 68.12              | 19.41                | 19.06                          |
| 2   | 4251       | III    | Williamson | 6.3                   | 1408                    | 223                       | 20.00                  | 193.52                 | 86.36              | 21.41                | 16.22                          |
| 3   | 3935       | III    | Sumner     | 8.25                  | 2288                    | 277                       | 19.00                  | 251.35                 | 79.29              | 20.31                |                                |
| 4   | 4224       | IV     | Fayette    | 4.75                  | 792                     | 167                       | 18.63                  | 129.91                 | 64.11              | 19.95                | 26.52                          |
| 5   | 2721       | IV     | McNairy    | 3                     | 836                     | 279                       | 18.63                  | 197.21                 | 101.76             | 19.85                |                                |
| 6   | 3145       | IV     | Weakley    | 7.1                   | 1188                    | 167                       | 18.63                  | 155.36                 | 86.78              | 20.28                | 26.33                          |

**BASED ON 1-DAY SITE VISIT**

|                                |              |                   |
|--------------------------------|--------------|-------------------|
| Region I Average Unit Cost =   | <b>0.00</b>  | <b>Production</b> |
| Region II Average Unit Cost =  | <b>19.41</b> | 814               |
| Region III Average Unit Cost = | <b>20.73</b> | 3696              |
| Region IV Average Unit Cost =  | <b>20.06</b> | 2816              |
| Weighted Average Unit Cost =   | <b>20.32</b> | <b>7326</b>       |

**TDOT AVG. UNIT PRICE**

|              |              |                               |              |
|--------------|--------------|-------------------------------|--------------|
| Region I =   | <b>19.34</b> | Weighted Average Unit Price = | <b>19.67</b> |
| Region II =  | <b>22.02</b> |                               |              |
| Region III = | <b>16.94</b> |                               |              |
| Region IV =  | <b>23.85</b> |                               |              |

**\* NOTE:** 40% Labor Burden has been added to the Labor Cost to arrive at Total Cost.  
Unit Cost do not contain Mark-Up and Overhead.

**Table 7-6. Cost Estimate for Asphalt Grade A Mix**

| No. | Contract # | Region | County   | Time Observed (hours) | Total Production (tons) | Production Rate (tons/hr) | Material Cost (\$/ton) | Equipment Cost (\$/hr) | Labor Cost (\$/hr) | * Unit Cost (\$/ton) | Actual Unit Bid Price (\$/ton) |
|-----|------------|--------|----------|-----------------------|-------------------------|---------------------------|------------------------|------------------------|--------------------|----------------------|--------------------------------|
| 1   | 4123       | I      | Knox     | 6.15                  | 1408                    | 229                       | 18.00                  | 141.25                 | 100.18             | 19.23                | 25.50                          |
| 2   | 3707       | II     | Rhea     | 4.4                   | 1100                    | 250                       | 18.48                  | 167.83                 | 68.12              | 19.53                | 20.00                          |
| 3   | 4160       | II     | White    | 8.15                  | 2024                    | 248                       | 18.48                  | 165.58                 | 85.94              | 19.63                | 37.50                          |
| 4   | 3428       | III    | Cheatham | 9.25                  | 2090                    | 226                       | 19.50                  | 212.06                 | 96.85              | 21.04                | 20.50                          |
| 5   | 3935       | III    | Sumner   | 8.6                   | 2508                    | 292                       | 19.50                  | 281.98                 | 97.69              | 20.94                |                                |
| 6   | 4729       | IV     | Shelby   | 5.8                   | 1540                    | 266                       | 19.45                  | 167.31                 | 117.58             | 20.70                | 29.50                          |
| 7   | 3701       | IV     | Madison  | 5.15                  | 616                     | 120                       | 19.45                  | 183.06                 | 101.76             | 22.17                | 23.50                          |

**BASED ON 1-DAY SITE VISIT**

Region I Average Unit Cost = **19.23**  
Region II Average Unit Cost = **19.60**  
Region III Average Unit Cost = **20.98**  
Region IV Average Unit Cost = **21.12**

Weighted Average Unit Cost = **20.41**

**Production**

1408  
3124  
4598  
2156  
**11286**

**TDOT AVG. UNIT PRICE**

Region I = **25.52**  
Region II = **23.82**  
Region III = **23.22**  
Region IV = **34.87**

Weighted Average Unit Price = **25.55**

**\*NOTE:** 40% Labor Burden has been added to the Labor Cost to the Labor Cost to arrive at Total Cost.  
Unit Cost do not contain Mark-Up and Overhead.

**Table 7-7. Cost Estimate for Asphalt Mix Base Grade B-M**

| No. | Contract # | Region | County     | Time Observed (hours) | Total Production (tons) | Production Rate (tons/hr) | Material Cost (\$/ton) | Equipment Cost (\$/hr) | Labor Cost (\$/hr) | * Unit Cost (\$/ton) | Actual Unit Bid Price (\$/ton) |
|-----|------------|--------|------------|-----------------------|-------------------------|---------------------------|------------------------|------------------------|--------------------|----------------------|--------------------------------|
| 1   | 4298       | I      | Hancock    | 5.15                  | 484                     | 94                        | 16.71                  | 208.04                 | 92.81              | 20.31                | 28.16                          |
| 2   | 4687       | II     | Bradley    | 9.15                  | 1188                    | 130                       | 21.07                  | 232.81                 | 87.34              | 23.80                | 26.72                          |
| 3   | 3707       | II     | Rhea       | 6.15                  | 1012                    | 165                       | 21.07                  | 170.24                 | 77.03              | 22.76                | 24.00                          |
| 4   | 4251       | III    | Williamson | 5.3                   | 594                     | 112                       | 22.00                  | 224.33                 | 122.42             | 25.53                |                                |
| 5   | 4017       | III    | Davidson   | 9.8                   | 1496                    | 153                       | 21.00                  | 151.40                 | 70.42              | 22.64                | 27.00                          |
| 6   | 3701       | IV     | Madison    | 4.25                  | 528                     | 124                       | 20.41                  | 152.15                 | 101.14             | 22.77                | 24.00                          |
| 7   | 3366       | IV     | Weakley    | 5.7                   | 836                     | 147                       | 20.41                  | 187.39                 | 85.94              | 22.51                | 31.00                          |
| 8   | 4738       | IV     | Weakley    | 7.5                   | 1056                    | 141                       | 20.41                  | 154.02                 | 101.76             | 22.52                | 33.00                          |

**BASED ON 1-DAY SITE VISIT**

|                                |              |            |             |
|--------------------------------|--------------|------------|-------------|
| Region I Average Unit Cost =   | <b>20.31</b> | Production | 484         |
| Region II Average Unit Cost =  | <b>23.32</b> |            | 2200        |
| Region III Average Unit Cost = | <b>23.46</b> |            | 2090        |
| Region IV Average Unit Cost =  | <b>22.57</b> |            | 2420        |
|                                |              |            | <u>7194</u> |
| Weighted Average Unit Cost =   | <b>22.91</b> |            |             |

**TDOT AVG. UNIT PRICE**

|                               |              |
|-------------------------------|--------------|
| Region I =                    | <b>27.57</b> |
| Region II =                   | <b>21.55</b> |
| Region III =                  | <b>25.88</b> |
| Region IV =                   | <b>32.97</b> |
| Weighted Average Unit Price = | <b>26.24</b> |

\* **NOTE:** 40% Labor Burden has been added to the Labor Cost to arrive at Total Cost.

Unit Cost do not contain Mark-Up and Overhead.

**Table 7-8 Cost Estimate for Asphalt Cement and Aggregate Grade D**

| No. | Contract # | Region | County     | Time Observed (hours) | Total Production (tons) | Production Rate (tons/hr) | Material Cost (\$/ton) | Equipment Cost (\$/hr) | Labor Cost (\$/hr) | * Unit Cost (\$/ton) | Actual Unit Bid Price (\$/ton) |
|-----|------------|--------|------------|-----------------------|-------------------------|---------------------------|------------------------|------------------------|--------------------|----------------------|--------------------------------|
| 1   | 4180       | I      | Grainger   | 3.3                   | 440                     | 133                       | 22.75                  | 208.04                 | 92.81              | 25.28                | 31.72                          |
| 2   | 4400       | I      | Sevier     | 5.7                   | 1100                    | 193                       | 22.75                  | 202.70                 | 120.73             | 24.68                | 43.32                          |
| 3   | 4687       | II     | McMinn     | 8.6                   | 1056                    | 123                       | 25.39                  | 228.14                 | 84.36              | 28.21                | 45.93                          |
| 4   | 3707       | II     | Rhea       | 8                     | 1386                    | 173                       | 24.39                  | 183.39                 | 77.03              | 26.07                | 25.51                          |
| 5   | 4722       | III    | Robertson  | 9.3                   | 1672                    | 180                       | 21.50                  | 181.17                 | 109.65             | 23.36                | 22.18                          |
| 6   | 4740       | III    | Williamson | 8.5                   | 1276                    | 150                       | 21.50                  | 231.17                 | 100.76             | 23.98                | 34.39                          |
| 7   | 4815       | III    | Cheatham   | 9                     | 1452                    | 161                       | 21.50                  | 244.86                 | 97.43              | 23.86                | 38.27                          |
| 8   | 4355       | IV     | Gibson     | 3.9                   | 374                     | 96                        | 22.81                  | 174.23                 | 92.85              | 25.98                | 56.70                          |
| 9   | 4660       | IV     | Obion      | 8.6                   | 1056                    | 123                       | 22.81                  | 162.58                 | 101.76             | 25.29                | 46.45                          |
| 10  | 4286       | IV     | Dyer       | 7                     | 1056                    | 151                       | 22.81                  | 176.24                 | 101.76             | 24.92                | 47.21                          |

**BASED ON 1-DAY SITE VISIT**

|                                |              |                   |              |
|--------------------------------|--------------|-------------------|--------------|
| Region I Average Unit Cost =   | <b>24.85</b> | <b>Production</b> | <b>1540</b>  |
| Region II Average Unit Cost =  | <b>27.00</b> |                   | <b>2442</b>  |
| Region III Average Unit Cost = | <b>23.71</b> |                   | <b>4400</b>  |
| Region IV Average Unit Cost =  | <b>25.24</b> |                   | <b>2486</b>  |
|                                |              |                   | <b>10868</b> |

Weighted Average Unit Cost = **24.96**

**TDOT AVG. UNIT PRICE**

|              |              |
|--------------|--------------|
| Region I =   | <b>28.24</b> |
| Region II =  | <b>28.40</b> |
| Region III = | <b>24.58</b> |
| Region IV =  | <b>28.90</b> |

Weighted Average Unit Price = **26.91**

**\* NOTE:** 40% Labor Burden has been added to the Labor Cost to arrive at Total Cost.  
Unit Cost do not contain Mark-Up and Overhead.

**Table 7-9. Cost Estimate for Concrete Pavement (Ramp) Task**

| No. | Contract # | Region | County   | Production<br>Rate (sy/hr) | Production<br>(sy) | Material<br>Cost<br>(\$/hr) | Equipment<br>Cost<br>(\$/hr) | Labor<br>Cost<br>(\$/hr) | *<br>Total Cost<br>(\$/hr) | Unit Cost<br>(\$/sy) | Actual Unit<br>Bid Price<br>(\$/sy) |
|-----|------------|--------|----------|----------------------------|--------------------|-----------------------------|------------------------------|--------------------------|----------------------------|----------------------|-------------------------------------|
| 1   | 4044       | 1      | Roane    | 50                         | 240                | 815                         | 200.00                       | 155.00                   | 1170                       | 23.33                | 29.30                               |
| 2   | 4017       | 3      | Davidson | 56                         | 520                | 900                         | 175.00                       | 190.00                   | 1265                       | 22.50                | 29.00                               |
| 3   | 4017       | 3      | Davidson | 51                         | 360                | 834                         | 167.00                       | 130.00                   | 1131                       | 22.08                | 29.00                               |
| 4   | 3707       | 4      | Madison  | 50                         | 360                | 806                         | 261.00                       | 174.00                   | 1241                       | 25.01                | 29.00                               |
| 5   | 3145       | 4      | Carroll  | 37                         | 440                | 599                         | 204.00                       | 164.00                   | 967                        | 26.27                | 34.00                               |

**BASED ON 1-DAY SITE VISIT**

|                                         |              |                   |                |
|-----------------------------------------|--------------|-------------------|----------------|
| Region I Weighted Average Unit Cost =   | <b>23.33</b> | <b>Production</b> | 240.00         |
| Region II Weighted Average Unit Cost =  | <b>0.00</b>  |                   | 0.00           |
| Region III Weighted Average Unit Cost = | <b>22.33</b> |                   | 880.00         |
| Region IV Weighted Average Unit Cost =  | <b>25.70</b> |                   | 800.00         |
|                                         |              |                   | <b>1920.00</b> |

Weighted Average Unit Cost = **23.86**

**1996 TDOT AVG. UNIT PRICE**

|              |              |
|--------------|--------------|
| Region I =   | <b>35.18</b> |
| Region II =  | <b>125</b>   |
| Region III = | <b>27.87</b> |
| Region IV =  | <b>23.07</b> |

Weighted Average Unit Price = **23.95**

**\* NOTE:** 40% Labor Burden has been added to the Labor Cost to arrive at Total Cost.

Unit Cost do not contain Mark-Up and Overhead.

**Table 7-10. Cost Estimate for Driving Steel Piles Task**

| No. | Contract # | Region | County   | Production Rate (lf/hr) | Production (lf) | Material Cost (\$/hr) | Equipment Cost (\$/hr) | Labor Cost (\$/hr) | * Total Cost (\$/hr) | Unit Cost (\$/lf) | Actual Unit Bid Price (\$/lf) |
|-----|------------|--------|----------|-------------------------|-----------------|-----------------------|------------------------|--------------------|----------------------|-------------------|-------------------------------|
| 1   | 3564       | 1      | Grainger | 31                      | 407             | 199.81                | 389.00                 | 185.00             | 773.81               | 25.17             | 21.14                         |
| 2   | 4124       | 1      | Knox     | 37                      | 274             | 240                   | 271.00                 | 139.00             | 650.00               | 17.58             | 19.00                         |
| 3   | 3571       | 1      | Knox     | 42                      | 558             | 272.35                | 241.00                 | 134.00             | 647.35               | 15.45             | 17.00                         |
| 4   | 4334       | 3      | Wayne    | 42                      | 919             | 371.62                | 418.00                 | 144.00             | 933.62               | 21.98             | 23.25                         |

**BASED ON 1-DAY SITE VISIT**

Region I Weighted Average Unit Cost =  
Region II Weighted Average Unit Cost =  
Region III Weighted Average Unit Cost =  
Region IV Weighted Average Unit Cost =

**Production**  
1239.00  
0.00  
919.00  
0.00

**2158.00**

Weighted Average Unit Cost =

**20.33**

**1996 TDOT AVG. UNIT PRICE**

Region I =  
Region II =  
Region III =  
Region IV =

**21.35**  
**25.4**  
**18.45**  
**22.89**

Weighted Average Unit Price =

**21.06**

\* **NOTE:** 40% Labor Burden has been added to the Labor Cost to arrive at Total Cost.

Unit Cost do not contain Mark-Up and Overhead.

\*\* **NOTE:** This Data was taken on Rock Excavation.



A. EXCAVATOR LIFTING A PILE TO THE CRANE



B. WELDING AN EXTENSION TO A PILE

Figure 7-2. Methods of Construction that Caused Delay in a Steel Pile Task

The pile cycle increased because the contractor used an excavator to load the steel piles to the crane, while typically the crane picks up the pile. He also attempted to drive a shorter-than-normal pile that caused some delay in the cycle time when an additional pile had to be welded to the original pile because it was too short. This method of construction not only increased the cycle time, but also added additional cost to the task.

The direct cost of all tasks is based on the measured productivity. The estimated cost of a task must be based on a given condition and operation. The ADMP measures productivity based on a 95% confidence level of task completion. For cost purposes, the contractor is being conservative if he or she bases an estimate on the 95% confidence level. Although the risk involved in such an estimate may be low, the estimate may not be competitive. Because of the competition involved in bidding, overestimating the cost may prevent the contractor from being awarded the project, while underestimating the cost, on the other hand, may decrease the profits or cause the company to lose money. Therefore, performing a job with higher productivity decreases the cost and maximizes profit. However, if the productivity reaches a level below the 95% confidence level of completion, the contractor will start losing money.

## **CHAPTER 8**

### **SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS**

#### **8.1 SUMMARY**

This study served three purposes that are relevant to highway construction operations. The first purpose was to model highway construction to determine task duration for the purpose of scheduling. Although scheduling requires a proper determination of task duration and productivity, productivity is difficult to determine because of the collective effect of many variables, such as weather, site conditions, method of construction, equipment, labor, the arrival of materials, and management decisions. Previous research that evaluated the effect of only one variable such as labor production to determine productivity is not adequate, since task duration is influenced by many variables at once. Likewise, research that determined the productivity based on the cost of the project is also insufficient because project duration is not the only factor that affects cost. The Average and Distribution Model of Productivity (ADMP) combines the effects of many variables on the productivity of a daily highway construction task and measures these effects with a 95% confidence level of task completion. Unlike other models, the ADMP relies on extensive data collection to evaluate variability and determine task duration. This study considered nine major highway construction tasks, and data were collected on up to 12 data sets for each task. The summary of data collection charts showing dates, locations, and

contract numbers of projects can be seen in Appendix F. The data were mainly collected on the cycle times of the production units, the cycle times of the processors, the allocation of resources, and the occurrences of delay. The cycle times were also investigated for delay and non-delay cycles. Delay cycles were defined as those cycles whose completion times exceeded the mean plus the standard deviation of the overall cycle times. The overall cycle time of actual data was increased to the 95% confidence of completion time to consider the effect of variables on the task duration of a working day, considering not only the mean of overall cycle time but also the distribution of the cycle times. The data were verified for log-normal distribution using the Kolmogorov-Smirnov (K-S) test. The results of the test showed that the cyclic operations of highway construction best fit a log-normal distribution. Data that did not pass the test were re-tested after considering the delay and non-delay cycles, and all data then passed the test. Once the 95% confidence level of cycle time completion was determined, productivity and task duration were calculated using the productivity of the Average and Distribution Model of Productivity based on the  $T_{95\%}$  confidence level of cycle time completion ( $P_{ADMP}$ ), the measured productivity based on a one-day site visit ( $P_M$ ), and the maximum productivity based on the measured mean cycle time of the processor ( $P_{MAX}$ ).

The second purpose of this study was to use the ADMP and efficiency analysis to evaluate the validity of claims for time-related disputes in highway construction projects. Management problems and poor resource allocation are the cause of most delays on the part of the contractor. Efficiency analysis is a useful tool for evaluating

productivity and claims for highway construction projects because it measures the performance of the operation and compares the actual productivity to the measured productivity ( $P_M$ ), the  $P_{ADMP}$ , and the maximum productivity ( $P_{MAX}$ ).

The third purpose of this study was to calculate the cost of a task based on observed site conditions and to define the influence of task duration on cost. The results of this study showed that the duration of highway construction projects affected cost in general. Highway construction tasks, however, differ with regard to the degree of these effects. The cost of some tasks was affected more than the cost of others. Earthmoving operations, for example, are equipment-oriented tasks, and the cost of equipment accounts for a large percentage of the direct cost of the task. Asphalt operations are material-oriented and concrete work is labor-oriented as far as cost is concerned. Although duration significantly influences the cost of equipment and labor, it insignificantly affects the cost of materials. Therefore, duration can affect the cost of one highway construction task more than another. In addition, the effect of duration on the cost of overhead and inflation costs can significantly affect the overall cost of the project.

When bidding on a job, contractors must prepare a cost estimate based on the availability of resources and the performance of the company. The ADMP can assist the contractor in estimating the cost of the project and evaluating his cost and profit. However, if the contractor bases his or her cost estimate on the 95% confidence level of completion, the cost estimate will be conservative and may not be competitive.

The determination of task duration and productivity is essential for project scheduling , estimating the cost of a project, and evaluating claims. The experience-based method has shown significant shortcomings in determining task duration properly. The ADMP is an excellent method for evaluating, determining, and predicting task duration and evaluating cost estimates and claims in highway construction. The simplicity of combining the effects of the many variables that influence highway construction is the most important contribution of this method.

## **8.2 CONCLUSIONS**

The results of the productivity and cost analysis for nine major tasks in highway construction lead to a number of conclusions, the most important of which are listed below:

- 1) The ADMP is useful for determining task duration and productivity for highway construction projects. By considering the collective effect of the many variables that affect productivity, the ADMP can simplify the determination of variability in highway construction tasks.
- 2) The experience-based method of evaluating task duration and productivity lacks accuracy and is inconsistent.
- 3) Determining task duration and productivity based on the productivity of only one factor, such as labor, equipment, or weather, is not adequate for highway construction because a single factor cannot represent the overall productivity of a highway construction task.

- 4) Highway construction operations tend to be either cyclic or semi-cyclic in nature.
- 5) Scheduling techniques are inadequate unless task duration has been calculated properly.
- 6) Cyclic highway operations are considered to fit the log-normal distribution. The distribution of cycles are affected by location and whether or not the cycles perform within or outside the project limit. Cycles outside the project limit, which are subject to more variation and delay, such as traffic, may fail the log-normal distribution. Cycles within the system, on the other hand, which are subject to less delay, generally pass both normal and log-normal distribution.
- 7) The more data collected, the more accurate the analysis of the ADMP. Tasks, such as mineral aggregate, asphalt, concrete ramp, and driving a steel pile, showed little variation beyond the four data sets. An earthmoving task, on the other hand, showed considerable variation because of differences in equipment use and the type of soil.
- 8) The ADMP can evaluate time-related claims in highway construction by determining the actual productivity of the operation and comparing it to the  $P_M$ , the  $P_{ADMP}$ , and the  $P_{max}$ .
- 9) In a cyclic operation of a production unit, the haul distance should not affect productivity because the distance should be controlled by the amount of equipment used for the operation.

- 10) Changes in the method of construction and the allocation of equipment in an earthmoving operation resulted in a 144% increase in productivity and a 54% reduction in direct cost.
- 11) The cost of highway construction projects in general is affected by duration. However, while task duration has a significant influence on the cost of labor, equipment, and overhead, it has an insignificant influence on the cost of materials.

### **8.3 RECOMMENDATIONS**

This study exposed several deficiencies in the available methods of measuring construction productivity and task duration. These deficiencies provide important subjects for further research in the field of construction productivity. To address the many questions that arose during the course of this study, the following recommendations for future research are suggested:

- 1) A modification of the ADMP to determine task duration and productivity for non-cyclic operations in highway construction
- 2) A study to improve the effectiveness of the ADMP for resolving claims by establishing better documentation and training procedures
- 3) A detailed study of the factors that cause claims
- 4) A study of the ratio between calendar days and working days for highway construction project duration
- 5) A study of the use of the ADMP integrated with a scheduling method

- 6) A study of the factors that influence variability in highway construction duration
- 7) A study to maximize productivity for highway construction
- 8) A study of the effects of traffic on roadway task duration
- 9) A study of the efficiency and productivity of highway construction tasks and the influence of this on the cost of the overall project
- 10) A study of project delay as a result of utilities

Each one of these topics would constitute an interesting and potentially useful research effort. Collectively, a thorough study of these topics would make a major contribution to the body of knowledge in the area of construction productivity and scheduling.

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## **APPENDICES**

**APPENDIX A**  
**DATA COLLECTION FORMS**

# Data Collection Form For:

## General Information

Contract #: \_\_\_\_\_

County: \_\_\_\_\_

Region: \_\_\_\_\_

Item #: \_\_\_\_\_

Description:

\_\_\_\_\_

Date of Data Collection:

\_\_\_\_\_

Contractor:

\_\_\_\_\_

Subcontractor:

\_\_\_\_\_

Superintendent: \_\_\_\_\_

TDOT Engineer: \_\_\_\_\_

TDOT Inspector: \_\_\_\_\_

Environmental Conditions:

\_\_\_\_\_

Soil / Moisture Content:

\_\_\_\_\_

**Temperature:**

\_\_\_\_\_

**Humidity:**

\_\_\_\_\_

**Rainfall:**

\_\_\_\_\_

**Start Date of Project:** \_\_\_\_\_

**Total Number of Working Days:**

\_\_\_\_\_

**General Information**

**Resources:**

**Equipment:**

\_\_\_\_\_

\_\_\_\_\_

**Labor:**

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

**Material:**

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

**Distance of Haul:** \_\_\_\_\_

**Method of Construction:**

\_\_\_\_\_

### Cycle Times:

**Capacity of the Cycle:** \_\_\_\_\_

**Unit of Measurement:** \_\_\_\_\_

# **Data Collection Forms For:**

## **Earth Moving**

**Item #:**

**Description:**

**203 - 01**

**Road and Drainage Excavation**

**203 - 03.01**

**Borrow Excavation**

Note: Method # 1 is the use of an excavator and trucks.

Method # 2 is the use of a dozer and scrapers.

## Earth Moving Method # 1:

### Cycle of the Truck

|                      |  |  |  |  |  |  |
|----------------------|--|--|--|--|--|--|
| <b>Truck #</b>       |  |  |  |  |  |  |
| <b>Arrival Time</b>  |  |  |  |  |  |  |
| <b>Start Loading</b> |  |  |  |  |  |  |
| <b>End Loading</b>   |  |  |  |  |  |  |

|                      |  |  |  |  |  |  |
|----------------------|--|--|--|--|--|--|
| <b>Truck #</b>       |  |  |  |  |  |  |
| <b>Arrival Time</b>  |  |  |  |  |  |  |
| <b>Start Loading</b> |  |  |  |  |  |  |
| <b>End Loading</b>   |  |  |  |  |  |  |

|                      |  |  |  |  |  |  |
|----------------------|--|--|--|--|--|--|
| <b>Truck #</b>       |  |  |  |  |  |  |
| <b>Arrival Time</b>  |  |  |  |  |  |  |
| <b>Start Loading</b> |  |  |  |  |  |  |
| <b>End Loading</b>   |  |  |  |  |  |  |

|                      |  |  |  |  |  |  |
|----------------------|--|--|--|--|--|--|
| <b>Truck #</b>       |  |  |  |  |  |  |
| <b>Arrival Time</b>  |  |  |  |  |  |  |
| <b>Start Loading</b> |  |  |  |  |  |  |
| <b>End Loading</b>   |  |  |  |  |  |  |

|                      |  |  |  |  |  |  |
|----------------------|--|--|--|--|--|--|
| <b>Truck #</b>       |  |  |  |  |  |  |
| <b>Arrival Time</b>  |  |  |  |  |  |  |
| <b>Start Loading</b> |  |  |  |  |  |  |
| <b>End Loading</b>   |  |  |  |  |  |  |

## Earth Moving Method # 2:

### Cycle of the Scraper

|               |  |  |  |  |  |  |
|---------------|--|--|--|--|--|--|
| Scraper #     |  |  |  |  |  |  |
| Arrival Time  |  |  |  |  |  |  |
| Start Loading |  |  |  |  |  |  |
| End Loading   |  |  |  |  |  |  |

|               |  |  |  |  |  |  |
|---------------|--|--|--|--|--|--|
| Scraper #     |  |  |  |  |  |  |
| Arrival Time  |  |  |  |  |  |  |
| Start Loading |  |  |  |  |  |  |
| End Loading   |  |  |  |  |  |  |

|               |  |  |  |  |  |  |
|---------------|--|--|--|--|--|--|
| Scraper #     |  |  |  |  |  |  |
| Arrival Time  |  |  |  |  |  |  |
| Start Loading |  |  |  |  |  |  |
| End Loading   |  |  |  |  |  |  |

|               |  |  |  |  |  |  |
|---------------|--|--|--|--|--|--|
| Scraper #     |  |  |  |  |  |  |
| Arrival Time  |  |  |  |  |  |  |
| Start Loading |  |  |  |  |  |  |
| End Loading   |  |  |  |  |  |  |

|               |  |  |  |  |  |  |
|---------------|--|--|--|--|--|--|
| Scraper #     |  |  |  |  |  |  |
| Arrival Time  |  |  |  |  |  |  |
| Start Loading |  |  |  |  |  |  |
| End Loading   |  |  |  |  |  |  |

## Earth Moving Method # 2: Continued

### Cycle of the Dozer

|                      |  |  |  |  |  |  |
|----------------------|--|--|--|--|--|--|
| <b>Dozer #</b>       |  |  |  |  |  |  |
| <b>Arrival Time</b>  |  |  |  |  |  |  |
| <b>Start Loading</b> |  |  |  |  |  |  |
| <b>End Loading</b>   |  |  |  |  |  |  |

|                      |  |  |  |  |  |  |
|----------------------|--|--|--|--|--|--|
| <b>Dozer #</b>       |  |  |  |  |  |  |
| <b>Arrival Time</b>  |  |  |  |  |  |  |
| <b>Start Loading</b> |  |  |  |  |  |  |
| <b>End Loading</b>   |  |  |  |  |  |  |

|                      |  |  |  |  |  |  |
|----------------------|--|--|--|--|--|--|
| <b>Dozer #</b>       |  |  |  |  |  |  |
| <b>Arrival Time</b>  |  |  |  |  |  |  |
| <b>Start Loading</b> |  |  |  |  |  |  |
| <b>End Loading</b>   |  |  |  |  |  |  |

|                      |  |  |  |  |  |  |
|----------------------|--|--|--|--|--|--|
| <b>Dozer #</b>       |  |  |  |  |  |  |
| <b>Arrival Time</b>  |  |  |  |  |  |  |
| <b>Start Loading</b> |  |  |  |  |  |  |
| <b>End Loading</b>   |  |  |  |  |  |  |

# **Data Collection Forms For:**

## **Asphalt Operations**

| <b><u>Item #:</u></b> | <b><u>Description:</u></b>                    |
|-----------------------|-----------------------------------------------|
| <b>307 - 01.03</b>    | <b>Aggregate Grade A.S. Mix</b>               |
| <b>307 - 03.09</b>    | <b>Bituminous Plant Mix (hot mix) Grade A</b> |
| <b>307 - 03.15</b>    | <b>Bituminous Plant Mix Base Grade B - M</b>  |
| <b>411 - 01.01</b>    | <b>Mineral Aggregate (ACS) Grading D</b>      |
| <b>411 - 01.02</b>    | <b>Asphalt Cement (ACS) Grading D</b>         |

Note: Method of trucks, paver, and roller.

## Asphalt Operations

### the Truck Cycle of

|                     |  |  |  |  |  |  |
|---------------------|--|--|--|--|--|--|
| <b>Truck #</b>      |  |  |  |  |  |  |
| <b>Arrival Time</b> |  |  |  |  |  |  |
| <b>Start Dump</b>   |  |  |  |  |  |  |
| <b>End Dump</b>     |  |  |  |  |  |  |

|                     |  |  |  |  |  |  |
|---------------------|--|--|--|--|--|--|
| <b>Truck #</b>      |  |  |  |  |  |  |
| <b>Arrival Time</b> |  |  |  |  |  |  |
| <b>Start Dump</b>   |  |  |  |  |  |  |
| <b>End Dump</b>     |  |  |  |  |  |  |

|                     |  |  |  |  |  |  |
|---------------------|--|--|--|--|--|--|
| <b>Truck #</b>      |  |  |  |  |  |  |
| <b>Arrival Time</b> |  |  |  |  |  |  |
| <b>Start Dump</b>   |  |  |  |  |  |  |
| <b>End Dump</b>     |  |  |  |  |  |  |

|                     |  |  |  |  |  |  |
|---------------------|--|--|--|--|--|--|
| <b>Truck #</b>      |  |  |  |  |  |  |
| <b>Arrival Time</b> |  |  |  |  |  |  |
| <b>Start Dump</b>   |  |  |  |  |  |  |
| <b>End Dump</b>     |  |  |  |  |  |  |

|                     |  |  |  |  |  |  |
|---------------------|--|--|--|--|--|--|
| <b>Truck #</b>      |  |  |  |  |  |  |
| <b>Arrival Time</b> |  |  |  |  |  |  |
| <b>Start Dump</b>   |  |  |  |  |  |  |
| <b>End Dump</b>     |  |  |  |  |  |  |

## Cycle of the Processor

186

# **Data Collection Forms For:**

## **Mineral Aggregate**

**Item #:**

**Description:**

**303 - 01**

**Mineral Aggregate Mix**

## Mineral Aggregate Mix

### Cycle of the Truck

|                     |  |  |  |  |  |  |
|---------------------|--|--|--|--|--|--|
| <b>Truck #</b>      |  |  |  |  |  |  |
| <b>Arrival Time</b> |  |  |  |  |  |  |
| <b>Start Dump</b>   |  |  |  |  |  |  |
| <b>End Dump</b>     |  |  |  |  |  |  |

|                     |  |  |  |  |  |  |
|---------------------|--|--|--|--|--|--|
| <b>Truck #</b>      |  |  |  |  |  |  |
| <b>Arrival Time</b> |  |  |  |  |  |  |
| <b>Start Dump</b>   |  |  |  |  |  |  |
| <b>End Dump</b>     |  |  |  |  |  |  |

|                     |  |  |  |  |  |  |
|---------------------|--|--|--|--|--|--|
| <b>Truck #</b>      |  |  |  |  |  |  |
| <b>Arrival Time</b> |  |  |  |  |  |  |
| <b>Start Dump</b>   |  |  |  |  |  |  |
| <b>End Dump</b>     |  |  |  |  |  |  |

|                     |  |  |  |  |  |  |
|---------------------|--|--|--|--|--|--|
| <b>Truck #</b>      |  |  |  |  |  |  |
| <b>Arrival Time</b> |  |  |  |  |  |  |
| <b>Start Dump</b>   |  |  |  |  |  |  |
| <b>End Dump</b>     |  |  |  |  |  |  |

|                     |  |  |  |  |  |  |
|---------------------|--|--|--|--|--|--|
| <b>Truck #</b>      |  |  |  |  |  |  |
| <b>Arrival Time</b> |  |  |  |  |  |  |
| <b>Start Dump</b>   |  |  |  |  |  |  |
| <b>End Dump</b>     |  |  |  |  |  |  |

## Mineral Aggregate Mix

## Cycle of the Processor

[illegible]

# **Data Collection Forms For:**

## **Concrete RAMP**

**Item #:**

**Description:**

**501 - 01      Portland Cement Concrete Pavement (RAMP)**

## Concrete RAMP

Depth of the Pour: \_\_\_\_\_

Time to Form: \_\_\_\_\_

Time to Place Rebar: \_\_\_\_\_

Time to Remove Forms: \_\_\_\_\_

## Cycle of the Truck

|              |  |  |  |  |  |  |
|--------------|--|--|--|--|--|--|
| Truck #      |  |  |  |  |  |  |
| Arrival Time |  |  |  |  |  |  |
| Start Pour   |  |  |  |  |  |  |
| End Pour     |  |  |  |  |  |  |
| Leaving Time |  |  |  |  |  |  |

|              |  |  |  |  |  |  |
|--------------|--|--|--|--|--|--|
| Truck #      |  |  |  |  |  |  |
| Arrival Time |  |  |  |  |  |  |
| Start Pour   |  |  |  |  |  |  |
| End Pour     |  |  |  |  |  |  |
| Leaving Time |  |  |  |  |  |  |

|              |  |  |  |  |  |  |
|--------------|--|--|--|--|--|--|
| Truck #      |  |  |  |  |  |  |
| Arrival Time |  |  |  |  |  |  |
| Start Pour   |  |  |  |  |  |  |
| End Pour     |  |  |  |  |  |  |
| Leaving Time |  |  |  |  |  |  |

## Concrete RAMP

### Cycle of the Finishers

| Cycle # | Start Pour | Stop Finishing |
|---------|------------|----------------|
|         |            |                |
|         |            |                |
|         |            |                |
|         |            |                |
|         |            |                |
|         |            |                |
|         |            |                |
|         |            |                |
|         |            |                |
|         |            |                |

# **Data Collection Forms For:**

## **Pile Driving Operations**

**Item #:**

**Description:**

**606 - 02.03**

**Steel Piles 10"**

**606 - 09.03**

**Precast Concrete Plies**

## Pile Driving Operations

## Time to Mobilize and

**Grade:**

## Time to Cut and

**Clean:**

## Cycle of the Pile Driving

[illegible]

## Pile Driving Operations

### Documentation of Delays

| Cycle # | Time | Material | Labor | Equipment | Management | Other | Remarks |
|---------|------|----------|-------|-----------|------------|-------|---------|
|         |      |          |       |           |            |       |         |
|         |      |          |       |           |            |       |         |
|         |      |          |       |           |            |       |         |
|         |      |          |       |           |            |       |         |
|         |      |          |       |           |            |       |         |
|         |      |          |       |           |            |       |         |
|         |      |          |       |           |            |       |         |
|         |      |          |       |           |            |       |         |
|         |      |          |       |           |            |       |         |
|         |      |          |       |           |            |       |         |
|         |      |          |       |           |            |       |         |
|         |      |          |       |           |            |       |         |
|         |      |          |       |           |            |       |         |
|         |      |          |       |           |            |       |         |
|         |      |          |       |           |            |       |         |
|         |      |          |       |           |            |       |         |

**APPENDIX B**

**CYCLE TIMES, MEANS, AND STANDARD  
DEVIATIONS FOR NINE HIGHWAY CONSTRUCTION TASKS**

## APPENDIX B

### Cycle Times, Means, and Standard Deviations of Nine Highway Tasks

Table B-1 Road and Drainage Excavation

| Contract # | 3556                 | 3948                 | 4410                 | 4572                 | 4696                 | 3564                 | 3915                 | 4123                 | 4251                 | 4384                 | 3926                 | 3564                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Davidson             | Davidson             | White                | Weakley              | Fayette              | Grainger             | Henderson            | Knox                 | Williamson           | McMinn               | Rhea                 | Grainger             |
| Region     | 3                    | 3                    | 2                    | 4                    | 4                    | 1                    | 4                    | 1                    | 3                    | 2                    | 2                    | 1                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 1          | 6.45                 | 5.57                 | 8.12                 | 11.83                | 1.65                 | 13.07                | 4.50                 | 31.40                | 19.02                | 2.13                 | 4.13                 | 5.17                 |
| 2          | 7.75                 | 5.60                 | 8.32                 | 12.52                | 1.82                 | 14.25                | 6.12                 | 34.62                | 22.07                | 2.20                 | 4.42                 | 5.25                 |
| 3          | 8.38                 | 5.70                 | 8.33                 | 12.78                | 2.77                 | 17.00                | 6.73                 | 35.08                | 22.77                | 2.23                 | 4.62                 | 5.25                 |
| 4          | 9.57                 | 5.72                 | 8.50                 | 12.93                | 2.92                 | 17.10                | 7.02                 | 38.63                | 23.65                | 2.25                 | 4.93                 | 6.75                 |
| 5          | 9.83                 | 5.78                 | 8.72                 | 13.03                | 3.07                 | 18.50                | 7.28                 | 39.25                | 24.70                | 2.27                 | 6.50                 | 7.67                 |
| 6          | 10.05                | 5.87                 | 8.85                 | 13.33                | 3.07                 | 19.58                | 7.32                 | 39.58                | 24.72                | 2.28                 | 6.67                 | 7.75                 |
| 7          | 10.22                | 5.92                 | 8.87                 | 13.42                | 3.23                 | 19.83                | 7.33                 | 40.30                | 25.12                | 2.33                 | 7.13                 | 7.80                 |
| 8          | 10.53                | 6.00                 | 8.88                 | 13.55                | 3.25                 | 20.25                | 7.35                 | 41.12                | 26.30                | 2.38                 | 7.82                 | 7.83                 |
| 9          | 11.08                | 6.08                 | 8.97                 | 13.67                | 3.28                 | 20.33                | 7.47                 | 41.45                | 27.15                | 2.42                 | 7.97                 | 7.88                 |
| 10         | 11.37                | 6.15                 | 9.13                 | 13.72                | 3.32                 | 21.02                | 7.50                 | 42.25                | 29.25                | 2.48                 | 8.92                 | 7.95                 |
| 11         | 11.45                | 6.17                 | 9.22                 | 13.95                | 3.33                 | 21.08                | 7.50                 | 42.30                | 29.42                | 2.50                 | 9.02                 | 8.00                 |
| 12         | 11.5                 | 6.18                 | 9.25                 | 14.00                | 3.33                 | 21.33                | 7.60                 | 42.52                | 30.23                | 2.52                 | 9.03                 | 8.00                 |
| 13         | 11.58                | 6.22                 | 9.27                 | 14.03                | 3.38                 | 21.33                | 7.65                 | 43.02                | 30.35                | 2.53                 | 9.15                 | 8.08                 |
| 14         | 12.18                | 6.27                 | 9.28                 | 14.03                | 3.43                 | 21.33                | 7.68                 | 43.03                | 31.33                | 2.60                 | 9.22                 | 8.12                 |
| 15         | 12.43                | 6.27                 | 9.30                 | 14.05                | 3.47                 | 22.17                | 7.70                 | 43.12                | 31.87                | 2.62                 | 9.33                 | 8.17                 |
| 16         | 12.53                | 6.28                 | 9.40                 | 14.08                | 3.48                 | 22.33                | 7.87                 | 43.17                | 32.23                | 2.63                 | 9.35                 | 8.18                 |
| 17         | 12.77                | 6.42                 | 9.42                 | 14.1                 | 3.53                 | 22.42                | 7.93                 | 43.72                | 32.68                | 2.65                 | 9.45                 | 8.25                 |
| 18         | 13.08                | 6.43                 | 9.45                 | 14.1                 | 3.53                 | 22.77                | 8.08                 | 44.00                | 32.70                | 2.65                 | 9.48                 | 8.25                 |

Table B-1 Road and Drainage Excavation Cont.

| Contract # | 3556                 | 3948                 | 4410                 | 4572                 | 4696                 | 3564                 | 3915                 | 4123                 | 4251                 | 4384                 | 3926                 | 3564                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Davidson             | Davidson             | White                | Weakley              | Fayette              | Grainger             | Henderson            | Knox                 | Williamson           | McMinn               | Rhea                 | Grainger             |
| Region     | 3                    | 3                    | 2                    | 4                    | 4                    | 1                    | 4                    | 1                    | 3                    | 2                    | 2                    | 1                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 19         | 13.25                | 6.48                 | 9.60                 | 14.17                | 3.53                 | 22.83                | 8.12                 | 44.02                | 33.72                | 2.67                 | 9.57                 | 8.32                 |
| 20         | 14.5                 | 6.50                 | 9.60                 | 14.22                | 3.62                 | 22.85                | 8.22                 | 44.03                | 33.73                | 2.68                 | 9.62                 | 8.37                 |
| 21         | 15.3                 | 6.55                 | 9.60                 | 14.33                | 3.65                 | 22.92                | 8.24                 | 44.08                | 34.73                | 2.77                 | 9.65                 | 8.40                 |
| 22         | 16                   | 6.58                 | 9.70                 | 14.35                | 3.67                 | 23.00                | 8.28                 | 44.13                | 37.12                | 2.80                 | 9.68                 | 8.42                 |
| 23         | 16.18                | 6.58                 | 9.73                 | 14.37                | 3.70                 | 23.08                | 8.42                 | 44.50                | 38.53                | 2.82                 | 9.75                 | 8.48                 |
| 24         | 22.98                | 6.70                 | 9.82                 | 14.4                 | 3.73                 | 23.17                | 8.47                 | 44.50                | 38.78                | 2.83                 | 9.75                 | 8.50                 |
| 25         | 23.45                | 7.02                 | 9.85                 | 14.42                | 3.73                 | 23.33                | 8.52                 | 44.75                | 39.12                | 2.85                 | 9.78                 | 8.50                 |
| 26         | 23.88                | 7.17                 | 10.00                | 14.55                | 3.80                 | 23.67                | 8.67                 | 44.80                | 39.42                | 2.87                 | 9.82                 | 8.50                 |
| 27         | 26.30                | 7.30                 | 10.07                | 14.62                | 3.80                 | 24.33                | 8.68                 | 45.00                | 45.35                | 2.87                 | 9.87                 | 8.50                 |
| 28         | 33.65                | 8.25                 | 10.15                | 14.75                | 3.82                 | 24.83                | 8.70                 | 45.58                | 46.75                | 2.92                 | 9.98                 | 8.65                 |
| 29         | 33.8                 | 9.02                 | 10.15                | 14.75                | 3.83                 | 25.00                | 8.77                 | 45.63                | 47.97                | 2.93                 | 10.00                | 8.67                 |
| 30         | 34.15                |                      | 10.18                | 14.75                | 3.87                 | 25.33                | 8.83                 | 45.65                | 52.68                | 2.98                 | 10.02                | 8.68                 |
| 31         | 34.38                |                      | 10.33                | 14.77                | 3.88                 | 25.40                | 8.85                 | 45.83                | 58.42                | 3.00                 | 10.15                | 8.68                 |
| 32         | 35.53                |                      | 10.72                | 14.82                | 3.90                 | 25.83                | 8.85                 | 45.83                | 59.80                | 3.00                 | 10.18                | 8.70                 |
| 33         | 35.65                |                      | 10.75                | 14.82                | 3.97                 | 26.33                | 9.00                 | 46.10                | 101.78               | 3.08                 | 10.18                | 8.73                 |
| 34         | 35.78                |                      | 11.02                | 14.88                | 4.03                 | 26.48                | 9.13                 | 46.32                |                      | 3.17                 | 10.22                | 8.73                 |
| 35         | 37.08                |                      | 11.03                | 15                   | 4.05                 | 27.00                | 9.15                 | 46.62                |                      | 3.18                 | 10.23                | 8.77                 |
| 36         | 38.96                |                      | 11.07                | 15                   | 4.07                 | 27.50                | 9.20                 | 46.80                |                      | 3.22                 | 10.27                | 8.82                 |
| 37         | 39.52                |                      | 11.12                | 15.13                | 4.10                 | 28.00                | 9.30                 | 47.00                |                      | 3.25                 | 10.27                | 8.83                 |
| 38         | 51.16                |                      | 11.25                | 15.2                 | 4.20                 | 28.17                | 9.32                 | 47.00                |                      | 3.25                 | 10.28                | 8.83                 |
| 39         | 57.67                |                      | 11.35                | 15.22                | 4.27                 | 28.48                | 9.33                 | 47.42                |                      | 3.30                 | 10.33                | 8.83                 |
| 40         | 63.98                |                      | 11.45                | 15.27                | 4.38                 | 29.50                | 9.40                 | 47.45                |                      | 3.30                 | 10.40                | 8.85                 |

Table B-1 Road and Drainage Excavation Cont.

| Contract # | 3556                 | 3948                 | 4410                 | 4572                 | 4696                 | 3564                 | 3915                 | 4123                 | 4251                 | 4384                 | 3926                 | 3564                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Davidson             | Davidson             | White                | Weakley              | Fayette              | Grainger             | Henderson            | Knox                 | Williamson           | McMinn               | Rhea                 | Grainger             |
| Region     | 3                    | 3                    | 2                    | 4                    | 4                    | 1                    | 4                    | 1                    | 3                    | 2                    | 2                    | 1                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 41         | 65.53                |                      | 11.45                | 15.33                | 4.50                 |                      | 9.48                 | 47.50                |                      | 3.30                 | 10.43                | 8.87                 |
| 42         | 79.17                |                      | 11.57                | 15.35                | 4.50                 |                      | 9.60                 | 47.73                |                      | 3.32                 | 10.47                | 8.90                 |
| 43         |                      |                      | 11.65                | 15.6                 | 4.53                 |                      | 9.60                 | 47.97                |                      | 3.32                 | 10.55                | 9.00                 |
| 44         |                      |                      | 11.70                | 15.7                 | 4.58                 |                      | 9.73                 | 48.00                |                      | 3.33                 | 10.65                | 9.00                 |
| 45         |                      |                      | 11.73                | 15.78                | 4.58                 |                      | 9.75                 | 48.00                |                      | 3.37                 | 10.65                | 9.05                 |
| 46         |                      |                      | 11.75                | 15.8                 | 4.60                 |                      | 9.77                 | 48.07                |                      | 3.37                 | 10.70                | 9.08                 |
| 47         |                      |                      | 11.82                | 15.93                | 4.67                 |                      | 9.83                 | 48.30                |                      | 3.40                 | 10.78                | 9.17                 |
| 48         |                      |                      | 11.95                | 15.95                | 4.72                 |                      | 9.93                 | 48.75                |                      | 3.40                 | 10.80                | 9.18                 |
| 49         |                      |                      | 12.33                | 16.03                | 4.73                 |                      | 10.12                | 48.83                |                      | 3.43                 | 10.83                | 9.22                 |
| 50         |                      |                      | 12.38                | 16.03                | 4.78                 |                      | 10.25                | 49.00                |                      | 3.47                 | 10.87                | 9.25                 |
| 51         |                      |                      | 12.45                | 16.28                | 4.87                 |                      | 10.28                | 49.05                |                      | 3.48                 | 10.87                | 9.32                 |
| 52         |                      |                      | 12.52                | 16.3                 | 4.97                 |                      | 10.28                | 49.22                |                      | 3.48                 | 10.92                | 9.33                 |
| 53         |                      |                      | 12.60                | 16.53                | 5.07                 |                      | 10.33                | 49.52                |                      | 3.48                 | 11.00                | 9.35                 |
| 54         |                      |                      | 12.70                | 16.57                | 5.15                 |                      | 10.35                | 50.20                |                      | 3.50                 | 11.05                | 9.35                 |
| 55         |                      |                      | 12.75                | 16.62                | 5.47                 |                      | 10.35                | 50.33                |                      | 3.52                 | 11.10                | 9.48                 |
| 56         |                      |                      | 12.75                | 16.62                | 5.78                 |                      | 10.41                | 50.45                |                      | 3.57                 | 11.18                | 9.50                 |
| 57         |                      |                      | 13.03                | 16.63                | 5.97                 |                      | 10.43                | 51.00                |                      | 3.60                 | 11.27                | 9.50                 |
| 58         |                      |                      | 13.03                | 16.67                | 6.00                 |                      | 10.47                | 52.10                |                      | 3.63                 | 11.35                | 9.50                 |
| 59         |                      |                      | 13.53                | 17.32                | 6.02                 |                      | 10.58                | 52.28                |                      | 3.63                 | 11.43                | 9.52                 |
| 60         |                      |                      | 14.08                | 17.48                | 6.08                 |                      | 10.62                | 52.73                |                      | 3.63                 | 11.48                | 9.57                 |
| 61         |                      |                      | 14.45                | 17.7                 | 6.50                 |                      | 10.73                | 53.00                |                      | 3.63                 | 11.55                | 9.65                 |
| 62         |                      |                      | 14.45                | 17.9                 | 6.92                 |                      | 10.87                | 53.40                |                      | 3.65                 | 11.57                | 9.65                 |

Table B-1 Road and Drainage Excavation Cont.

| Contract # | 3556                 | 3948                 | 4410                 | 4572                 | 4696                 | 3564                 | 3915                 | 4123                 | 4251                 | 4384                 | 3926                 | 3564                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Davidson             | Davidson             | White                | Weakley              | Fayette              | Grainger             | Henderson            | Knox                 | Willimson            | McMinn               | Rhea                 | Grainger             |
| Region     | 3                    | 3                    | 2                    | 4                    | 4                    | 1                    | 4                    | 1                    | 3                    | 2                    | 2                    | 1                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 63         |                      |                      | 14.52                | 17.92                | 7.23                 |                      | 10.87                | 53.58                |                      | 3.67                 | 11.70                | 9.67                 |
| 64         |                      |                      | 14.53                | 18.22                | 8.92                 |                      | 10.88                | 53.92                |                      | 3.67                 | 11.77                | 9.67                 |
| 65         |                      |                      | 14.73                | 18.42                | 9.20                 |                      | 10.88                | 54.00                |                      | 3.68                 | 11.83                | 9.68                 |
| 66         |                      |                      | 14.75                | 18.73                | 9.20                 |                      | 11.08                | 54.25                |                      | 3.70                 | 11.97                | 9.73                 |
| 67         |                      |                      | 15.65                | 18.77                | 10.67                |                      | 11.28                | 54.37                |                      | 3.72                 | 12.03                | 9.75                 |
| 68         |                      |                      |                      | 18.83                | 10.82                |                      | 11.33                | 54.77                |                      | 3.73                 | 12.32                | 9.80                 |
| 69         |                      |                      |                      | 19.18                | 11.50                |                      | 11.37                | 55.00                |                      | 3.73                 | 12.35                | 9.83                 |
| 70         |                      |                      |                      | 19.55                | 11.57                |                      | 11.42                | 55.83                |                      | 3.78                 | 12.68                | 9.95                 |
| 71         |                      |                      |                      | 19.83                | 12.17                |                      | 11.57                | 55.87                |                      | 3.80                 | 12.83                | 10.13                |
| 72         |                      |                      |                      | 20.6                 |                      |                      | 11.70                | 56.00                |                      | 3.80                 | 13.32                | 10.13                |
| 73         |                      |                      |                      | 21.23                |                      |                      | 11.73                | 56.15                |                      | 3.82                 | 13.40                | 10.17                |
| 74         |                      |                      |                      | 23.02                |                      |                      | 11.92                | 56.73                |                      | 3.83                 | 13.68                | 10.26                |
| 75         |                      |                      |                      | 23.22                |                      |                      | 11.95                | 57.47                |                      | 3.85                 | 13.80                | 10.28                |
| 76         |                      |                      |                      | 29.57                |                      |                      | 11.95                | 57.62                |                      | 3.87                 | 13.88                | 10.30                |
| 77         |                      |                      |                      |                      |                      |                      | 12.30                | 58.98                |                      | 3.88                 | 13.90                | 10.40                |
| 78         |                      |                      |                      |                      |                      |                      | 12.33                | 59.08                |                      | 3.92                 | 14.10                | 10.47                |
| 79         |                      |                      |                      |                      |                      |                      | 12.50                | 59.30                |                      | 3.98                 | 14.13                | 10.47                |
| 80         |                      |                      |                      |                      |                      |                      | 12.57                | 59.72                |                      | 4.00                 | 14.15                | 10.50                |
| 81         |                      |                      |                      |                      |                      |                      | 12.65                | 60.10                |                      | 4.00                 | 14.87                | 10.52                |
| 82         |                      |                      |                      |                      |                      |                      | 12.93                | 61.25                |                      | 4.03                 | 15.17                | 10.54                |
| 83         |                      |                      |                      |                      |                      |                      | 12.95                | 62.62                |                      | 4.10                 | 15.68                | 10.6                 |
| 84         |                      |                      |                      |                      |                      |                      | 13.00                | 67.97                |                      | 4.18                 | 16.45                | 10.71                |

Table B-1 Road and Drainage Excavation Cont.

| Contract # | 3556                 | 3948                 | 4410                 | 4572                 | 4696                 | 3564                 | 3915                 | 4123                 | 4251                 | 4384                 | 3926                 | 3564                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Davidson             | Davidson             | White                | Weakley              | Fayette              | Grainger             | Henderson            | Knox                 | Williamson           | McMinn               | Rhea                 | Grainger             |
| Region     | 3                    | 3                    | 2                    | 4                    | 4                    | 1                    | 4                    | 1                    | 3                    | 2                    | 2                    | 1                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 85         |                      |                      |                      |                      |                      |                      | 13.00                | 68.00                |                      | 4.28                 | 17.10                | 10.75                |
| 86         |                      |                      |                      |                      |                      |                      | 13.43                | 68.92                |                      | 4.30                 | 17.32                | 10.75                |
| 87         |                      |                      |                      |                      |                      |                      | 14.13                | 69.30                |                      | 4.33                 | 17.87                | 10.78                |
| 88         |                      |                      |                      |                      |                      |                      | 16.38                | 70.45                |                      | 4.43                 | 18.52                | 10.85                |
| 89         |                      |                      |                      |                      |                      |                      | 16.50                | 73.35                |                      | 4.47                 | 20.38                | 11.03                |
| 90         |                      |                      |                      |                      |                      |                      | 17.25                | 74.63                |                      | 4.48                 | 21.82                | 11.08                |
| 91         |                      |                      |                      |                      |                      |                      | 27.55                | 75.00                |                      | 4.55                 | 22.83                | 11.30                |
| 92         |                      |                      |                      |                      |                      |                      | 29.58                | 75.90                |                      | 4.58                 |                      | 11.33                |
| 93         |                      |                      |                      |                      |                      |                      |                      | 81.48                |                      | 4.60                 |                      | 11.97                |
| 94         |                      |                      |                      |                      |                      |                      |                      | 81.93                |                      | 4.70                 |                      | 12.00                |
| 95         |                      |                      |                      |                      |                      |                      |                      | 97.00                |                      | 4.82                 |                      | 12.00                |
| 96         |                      |                      |                      |                      |                      |                      |                      | 97.58                |                      | 5.00                 |                      | 12.50                |
| 97         |                      |                      |                      |                      |                      |                      |                      | 100.55               |                      | 5.18                 |                      | 12.97                |
| 98         |                      |                      |                      |                      |                      |                      |                      | 102.27               |                      | 5.18                 |                      | 13.25                |
| 99         |                      |                      |                      |                      |                      |                      |                      | 104.67               |                      | 5.23                 |                      | 13.52                |
| 100        |                      |                      |                      |                      |                      |                      |                      | 113.42               |                      | 5.27                 |                      | 114.12               |
| 101        |                      |                      |                      |                      |                      |                      |                      |                      |                      | 5.35                 |                      |                      |
| 102        |                      |                      |                      |                      |                      |                      |                      |                      |                      | 5.38                 |                      |                      |
| 103        |                      |                      |                      |                      |                      |                      |                      |                      |                      | 6.08                 |                      |                      |
| 104        |                      |                      |                      |                      |                      |                      |                      |                      |                      | 6.17                 |                      |                      |
| 105        |                      |                      |                      |                      |                      |                      |                      |                      |                      | 7.23                 |                      |                      |
| 106        |                      |                      |                      |                      |                      |                      |                      |                      |                      | 8.28                 |                      |                      |
| Count      | 42                   | 29                   | 67                   | 76                   | 71                   | 40                   | 92                   | 100                  | 33                   | 106                  | 91                   | 100                  |
| Mean       | 24.78                | 6.44                 | 11.05                | 15.98                | 4.90                 | 22.82                | 10.40                | 54.46                | 36.47                | 3.63                 | 11.32                | 9.35                 |
| Std.Dev.   | 18.01                | 0.75                 | 1.91                 | 2.78                 | 2.29                 | 3.69                 | 3.51                 | 15.75                | 15.46                | 1.04                 | 3.30                 | 1.52                 |

Table B-2 Borrow Excavation

| Contract # | 3948                 | 3866                 | 4224                 | 3863                 | 3502                 | 4017                 | 4723                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Davidson             | Marion               | Fayette              | McNairy              | Carroll              | Davidson             | Robertson            |
| Region     | 3                    | 2                    | 4                    | 4                    | 4                    | 3                    | 3                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 1          | 7.95                 | 22.17                | 8.83                 | 11.17                | 7.45                 | 23.42                | 8.83                 |
| 2          | 8.35                 | 23.95                | 10.67                | 11.60                | 7.93                 | 23.72                | 8.97                 |
| 3          | 8.63                 | 24.42                | 11.47                | 11.68                | 15.52                | 23.75                | 9.02                 |
| 4          | 8.63                 | 24.78                | 11.98                | 12.87                | 15.87                | 23.80                | 9.08                 |
| 5          | 8.92                 | 25.07                | 12.02                | 13.32                | 15.93                | 24.93                | 9.18                 |
| 6          | 9.02                 | 25.10                | 12.33                | 13.60                | 15.93                | 25.07                | 9.28                 |
| 7          | 9.12                 | 25.32                | 12.38                | 14.10                | 16.03                | 25.27                | 9.47                 |
| 8          | 9.17                 | 25.70                | 12.38                | 14.40                | 16.13                | 25.32                | 9.47                 |
| 9          | 9.28                 | 25.83                | 12.42                | 14.58                | 16.15                | 25.33                | 9.50                 |
| 10         | 9.33                 | 25.97                | 12.42                | 14.83                | 16.17                | 25.58                | 9.50                 |
| 11         | 9.40                 | 26.65                | 12.70                | 14.87                | 16.17                | 26.93                | 9.50                 |
| 12         | 9.65                 | 26.77                | 12.75                | 15.00                | 16.23                | 27.43                | 9.70                 |
| 13         | 9.70                 | 26.87                | 12.82                | 15.00                | 16.30                | 29.83                | 9.73                 |
| 14         | 9.82                 | 27.05                | 12.90                | 15.02                | 16.32                | 31.50                | 9.77                 |
| 15         | 9.85                 | 27.08                | 13.00                | 15.23                | 16.52                | 33.38                | 9.78                 |
| 16         | 10.05                | 27.33                | 13.65                | 15.30                | 16.65                | 34.08                | 9.78                 |
| 17         | 10.08                | 27.92                | 14.12                | 15.38                | 16.83                | 34.33                | 9.78                 |
| 18         | 10.20                | 27.95                | 14.23                | 15.52                | 16.90                | 36.65                | 9.90                 |
| 19         | 10.30                | 27.95                | 14.42                | 15.57                | 17.12                | 37.60                | 10.07                |
| 20         | 11.17                | 28.07                | 15.02                | 15.60                | 17.25                | 38.75                | 10.08                |
| 21         | 11.50                | 28.15                | 15.18                | 15.70                | 17.27                | 39.00                | 10.08                |
| 22         | 11.58                | 28.48                | 15.18                | 15.72                | 17.80                | 39.27                | 10.10                |
| 23         | 11.62                | 28.53                | 15.32                | 15.83                | 17.82                | 39.43                | 10.13                |
| 24         | 12.55                | 28.62                | 16.22                | 15.90                | 18.00                | 39.50                | 10.17                |
| 25         | 80.63                | 28.83                | 16.25                | 15.97                | 18.17                | 41.55                | 10.17                |
| 26         |                      | 28.92                | 16.27                | 15.98                | 18.28                | 41.55                | 10.18                |
| 27         |                      | 28.92                | 16.42                | 16.07                | 18.37                | 41.93                | 10.20                |
| 28         |                      | 29.03                | 16.43                | 16.07                | 18.40                | 43.55                | 10.20                |

Table B-2 Borrow Excavation Cont.

| Contract # | 3948                 | 3866                 | 4224                 | 3863                 | 3502                 | 4017                 | 4723                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Davidson             | Marion               | Fayette              | McNairy              | Carroll              | Davidson             | Robertson            |
| Region     | 3                    | 2                    | 4                    | 4                    | 4                    | 3                    | 3                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 29         |                      | 29.07                | 16.43                | 16.28                | 18.55                | 43.72                | 10.22                |
| 30         |                      | 29.12                | 16.47                | 16.60                | 18.67                | 44.20                | 10.23                |
| 31         |                      | 30.52                | 16.50                | 16.63                | 18.90                | 44.32                | 10.23                |
| 32         |                      | 30.80                | 16.58                | 16.72                | 19.25                | 46.63                | 10.25                |
| 33         |                      | 30.93                | 16.87                | 16.88                | 20.42                | 47.60                | 10.25                |
| 34         |                      | 31.10                | 16.92                | 16.97                | 20.70                | 49.60                | 10.27                |
| 35         |                      | 31.25                | 16.93                | 17.07                | 20.78                | 52.33                | 10.32                |
| 36         |                      | 35.43                | 17.02                | 17.08                | 21.75                | 52.83                | 10.33                |
| 37         |                      | 38.63                | 17.12                | 17.15                | 23.50                | 55.58                | 10.33                |
| 38         |                      | 51.80                | 17.22                | 17.17                | 23.93                | 56.17                | 10.33                |
| 39         |                      | 60.85                | 17.25                | 17.18                | 24.00                | 57.67                | 10.33                |
| 40         |                      | 63.67                | 17.33                | 17.30                | 24.35                | 58.03                | 10.33                |
| 41         |                      | 70.75                | 17.35                | 17.47                | 24.52                | 58.62                | 10.33                |
| 42         |                      | 70.83                | 17.47                | 17.50                | 24.67                | 59.02                | 10.33                |
| 43         |                      | 72.10                | 17.73                | 17.50                | 25.33                | 59.32                | 10.35                |
| 44         |                      | 75.60                | 17.75                | 17.77                | 25.33                | 64.25                | 10.37                |
| 45         |                      | 83.82                | 17.78                | 17.82                | 25.45                | 67.07                | 10.40                |
| 46         |                      |                      | 17.78                | 18.02                | 26.32                | 70.22                | 10.40                |
| 47         |                      |                      | 18.30                | 18.03                | 26.80                | 76.18                | 10.42                |
| 48         |                      |                      | 18.47                | 18.28                | 26.83                | 83.67                | 10.42                |
| 49         |                      |                      | 18.47                | 18.30                | 26.83                |                      | 10.43                |
| 50         |                      |                      | 18.53                | 18.32                | 27.08                |                      | 10.47                |
| 51         |                      |                      | 18.72                | 18.38                | 27.50                |                      | 10.48                |
| 52         |                      |                      | 18.75                | 18.70                | 28.13                |                      | 10.48                |
| 53         |                      |                      | 18.80                | 18.82                | 30.40                |                      | 10.55                |

Table B-2 Borrow Excavation Cont.

| Contract # | 3948                 | 3866                 | 4224                 | 3863                 | 3502                 | 4017                 | 4723                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Davidson             | Marion               | Fayette              | McNairy              | Carroll              | Davidson             | Robertson            |
| Region     | 3                    | 2                    | 4                    | 4                    | 4                    | 3                    | 3                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 54         |                      |                      | 19.47                | 18.82                | 30.57                |                      | 10.58                |
| 55         |                      |                      | 20.90                | 18.82                | 30.63                |                      | 10.65                |
| 56         |                      |                      | 21.47                | 18.90                | 31.15                |                      | 10.67                |
| 57         |                      |                      | 22.50                | 19.08                | 31.25                |                      | 10.67                |
| 58         |                      |                      | 23.77                | 20.08                | 32.08                |                      | 10.68                |
| 59         |                      |                      | 23.87                | 22.68                | 35.58                |                      | 10.72                |
| 60         |                      |                      | 24.15                | 23.13                | 39.75                |                      | 10.80                |
| 61         |                      |                      | 24.52                | 50.43                | 39.78                |                      | 10.82                |
| 62         |                      |                      | 44.68                | 55.92                | 40.22                |                      | 10.90                |
| 63         |                      |                      | 45.73                | 56.05                | 47.72                |                      | 11.05                |
| 64         |                      |                      | 49.73                | 59.17                | 51.50                |                      | 11.07                |
| 65         |                      |                      | 52.22                | 65.23                | 57.45                |                      | 11.13                |
| 66         |                      |                      | 58.05                |                      |                      |                      | 11.13                |
| 67         |                      |                      | 66.35                |                      |                      |                      | 11.17                |
| 68         |                      |                      | 69.17                |                      |                      |                      | 11.17                |
| 69         |                      |                      |                      |                      |                      |                      | 11.22                |
| 70         |                      |                      |                      |                      |                      |                      | 11.27                |
| 71         |                      |                      |                      |                      |                      |                      | 11.33                |
| 72         |                      |                      |                      |                      |                      |                      | 11.33                |
| 73         |                      |                      |                      |                      |                      |                      | 11.48                |
| 74         |                      |                      |                      |                      |                      |                      | 11.65                |
| 75         |                      |                      |                      |                      |                      |                      | 11.67                |

Table B-2 Borrow Excavation Cont.

| Contract # | 3948                 | 3866                 | 4224                 | 3863                 | 3502                 | 4017                 | 4723                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Davidson             | Marion               | Fayette              | McNairy              | Carrol               | Davidson             | Robertson            |
| Region     | 3                    | 2                    | 4                    | 4                    | 4                    | 3                    | 3                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 76         |                      |                      |                      |                      |                      |                      | 11.72                |
| 77         |                      |                      |                      |                      |                      |                      | 11.83                |
| 78         |                      |                      |                      |                      |                      |                      | 11.92                |
| 79         |                      |                      |                      |                      |                      |                      | 12.03                |
| 80         |                      |                      |                      |                      |                      |                      | 12.13                |
| 81         |                      |                      |                      |                      |                      |                      | 12.17                |
| 82         |                      |                      |                      |                      |                      |                      | 12.17                |
| 83         |                      |                      |                      |                      |                      |                      | 12.22                |
| 84         |                      |                      |                      |                      |                      |                      | 12.33                |
| 85         |                      |                      |                      |                      |                      |                      | 12.58                |
| 86         |                      |                      |                      |                      |                      |                      | 12.70                |
| 87         |                      |                      |                      |                      |                      |                      | 12.80                |
| 88         |                      |                      |                      |                      |                      |                      | 12.92                |
| 89         |                      |                      |                      |                      |                      |                      | 13.12                |
| 90         |                      |                      |                      |                      |                      |                      | 13.13                |
| 91         |                      |                      |                      |                      |                      |                      | 13.15                |
| 92         |                      |                      |                      |                      |                      |                      | 13.57                |
| 93         |                      |                      |                      |                      |                      |                      | 13.83                |
| 94         |                      |                      |                      |                      |                      |                      | 14.28                |
| 95         |                      |                      |                      |                      |                      |                      | 14.38                |
| 96         |                      |                      |                      |                      |                      |                      | 15.65                |
| 97         |                      |                      |                      |                      |                      |                      | 16.68                |
| 98         |                      |                      |                      |                      |                      |                      | 24.95                |

Table B-2 Borrow Excavation Cont.

| Contract # | 3948       | 3866       | 4224       | 3863       | 3502       | 4017       | 4723       |
|------------|------------|------------|------------|------------|------------|------------|------------|
| County     | Davidson   | Marion     | Fayette    | McNairy    | Carrol     | Davidson   | Robertson  |
| Region     | 3          | 2          | 4          | 4          | 4          | 3          | 3          |
|            | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time |
|            | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     |
| 99         |            |            |            |            |            |            | 26.50      |
| 100        |            |            |            |            |            |            | 26.58      |
| Count      | 25         | 45         | 68         | 65         | 65         | 48         | 100        |
| Mean       | 12.66      | 35.28      | 20.37      | 19.66      | 23.40      | 42.70      | 11.39      |
| Std.Dev.   | 14.21      | 16.42      | 12.64      | 11.26      | 9.44       | 15.24      | 2.94       |
| X+S        | 26.87      | 51.70      | 33.00      | 30.92      |            |            | 14.33      |
| XND        | 9.83       | 28.06      | 16.38      | 16.52      |            |            | 10.63      |
| SND        | 1.15       | 3.06       | 3.42       | 2.25       |            |            | 0.95       |

Table B-3 Mineral Aggregate

| Contract # | 2440                 | 3564                 | 3707                 | 3866                 | 3915                 | 4017                 | 4044                 | 4251                 | 4699                 | 4160                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Knox                 | Grainger             | Rhea                 | Marion               | Henderson            | Davidson             | Roane                | Williamson           | Henderson            | White                |
| Region     | 1                    | 1                    | 2                    | 2                    | 4                    | 3                    | 1                    | 3                    | 4                    | 2                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 1          | 37.67                | 15.33                | 62.00                | 30.97                | 61.22                | 34.00                | 30.75                | 70.45                | 98.28                | 26.15                |
| 2          | 38.38                | 16.11                | 63.77                | 32.30                | 64.62                | 39.10                | 33.00                | 71.83                | 100.13               | 28.43                |
| 3          | 38.93                | 16.20                | 64.27                | 33.50                | 64.63                | 43.20                | 33.73                | 74.35                | 101.81               | 29.15                |
| 4          | 39.27                | 16.67                | 65.08                | 33.80                | 65.39                | 43.33                | 33.75                | 74.50                | 102.08               | 30.59                |
| 5          | 39.58                | 16.75                | 65.85                | 33.97                | 65.48                | 44.11                | 34.00                | 74.50                | 103.98               | 30.60                |
| 6          | 39.90                | 17.67                | 66.23                | 35.57                | 66.40                | 44.88                | 35.00                | 75.03                | 104.07               | 30.78                |
| 7          | 41.30                | 17.95                | 66.30                | 37.40                | 66.50                | 46.47                | 35.75                | 75.50                | 104.23               | 31.00                |
| 8          | 42.10                | 18.00                | 67.17                | 37.92                | 67.02                | 46.92                | 36.00                | 75.50                | 104.70               | 31.12                |
| 9          | 43.12                | 18.36                | 67.20                | 38.05                | 67.04                | 47.20                | 36.80                | 75.85                | 106.47               | 31.47                |
| 10         | 43.17                | 18.48                | 68.13                | 38.65                | 67.10                | 47.31                | 37.10                | 77.55                | 107.75               | 31.50                |
| 11         | 43.43                | 18.53                | 68.22                | 38.90                | 67.24                | 49.00                | 38.15                | 77.60                | 108.17               | 31.52                |
| 12         | 43.47                | 18.77                | 68.28                | 39.18                | 67.52                | 50.00                | 38.60                | 77.93                | 108.20               | 31.57                |
| 13         | 43.48                | 18.80                | 68.57                | 39.20                | 67.75                | 50.77                | 39.00                | 77.97                | 108.32               | 31.67                |
| 14         | 43.50                | 19.00                | 68.71                | 39.97                | 68.02                | 51.87                | 39.00                | 78.08                | 108.64               | 32.03                |
| 15         | 43.50                | 19.00                | 69.07                | 40.43                | 68.03                | 52.17                | 39.00                | 78.18                | 108.72               | 32.07                |
| 16         | 43.50                | 19.00                | 69.66                | 41.48                | 68.25                | 53.13                | 39.50                | 79.85                | 109.08               | 32.23                |
| 17         | 44.62                | 19.00                | 71.65                | 41.68                | 68.45                | 54.83                | 40.00                | 80.00                | 109.38               | 32.23                |
| 18         | 44.72                | 19.06                | 71.83                | 42.50                | 68.50                | 56.17                | 40.00                | 80.00                | 110.12               | 32.26                |
| 19         | 45.00                | 19.07                | 71.83                | 42.62                | 68.70                | 56.50                | 40.17                | 80.07                | 110.60               | 32.30                |
| 20         | 45.17                | 19.15                | 72.31                | 43.18                | 68.82                | 59.87                | 40.30                | 80.17                | 110.67               | 32.69                |
| 21         | 45.43                | 19.35                | 72.90                | 43.30                | 69.07                | 60.25                | 41.00                | 80.43                | 111.28               | 33.05                |
| 22         | 45.67                | 19.51                | 73.60                | 43.38                | 69.17                | 61.05                | 41.50                | 80.59                | 111.52               | 33.35                |

Table B-3 Mineral Aggregate Cont.

| Contract # | 2440                 | 3564                 | 3707                 | 3866                 | 3915                 | 4017                 | 4044                 | 4251                 | 4699                 | 4160                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Knox                 | Grainger             | Rhea                 | Marion               | Henderson            | Davidson             | Roane                | Williamson           | Henderson            | White                |
| Region     | 1                    | 1                    | 2                    | 2                    | 4                    | 3                    | 1                    | 3                    | 4                    | 2                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 23         | 45.67                | 19.60                | 74.47                | 43.92                | 69.25                | 61.07                | 42.00                | 81.00                | 111.87               | 33.40                |
| 24         | 45.70                | 19.70                | 74.47                | 44.10                | 69.46                | 61.17                | 42.33                | 82.38                | 111.93               | 33.48                |
| 25         | 45.70                | 19.78                | 74.68                | 44.21                | 69.48                | 62.25                | 42.50                | 83.10                | 112.03               | 33.50                |
| 26         | 45.83                | 19.79                | 74.90                | 44.38                | 69.48                | 62.72                | 42.70                | 84.72                | 112.15               | 33.53                |
| 27         | 45.98                | 19.79                | 75.47                | 44.60                | 69.50                | 62.72                | 43.00                | 84.83                | 112.87               | 33.55                |
| 28         | 46.02                | 19.90                | 75.58                | 44.87                | 69.93                | 63.50                | 44.00                | 84.88                | 112.90               | 33.55                |
| 29         | 46.23                | 19.92                | 75.73                | 46.97                | 70.00                | 65.75                | 44.00                | 85.65                | 113.16               | 33.70                |
| 30         | 46.25                | 19.93                | 75.89                | 47.20                | 70.00                | 66.45                | 45.00                | 85.83                | 113.87               | 34.05                |
| 31         | 46.25                | 20.00                | 77.00                | 47.50                | 70.07                | 69.92                | 47.00                | 86.00                | 114.65               | 34.13                |
| 32         | 46.55                | 20.00                | 77.87                | 47.52                | 70.10                | 73.85                | 50.10                | 86.60                | 115.06               | 34.16                |
| 33         | 46.68                | 20.00                | 78.18                | 47.70                | 70.25                | 75.82                | 51.00                | 86.75                | 115.10               | 34.37                |
| 34         | 46.82                | 20.00                | 78.60                | 47.81                | 70.40                | 103.20               | 53.00                | 86.75                | 115.24               | 34.45                |
| 35         | 46.87                | 20.00                | 79.02                | 48.62                | 70.50                |                      | 53.00                | 87.50                | 115.56               | 34.53                |
| 36         | 47.17                | 20.00                | 80.62                | 48.80                | 71.17                |                      | 54.00                | 87.50                | 115.87               | 34.64                |
| 37         | 47.17                | 20.00                | 82.27                | 50.95                | 71.50                |                      | 54.00                | 87.82                | 116.15               | 34.82                |
| 38         | 47.23                | 20.00                | 82.62                | 51.47                | 71.58                |                      | 55.25                | 88.67                | 116.17               | 34.95                |
| 39         | 47.58                | 20.00                | 83.78                | 58.48                | 71.67                |                      | 58.00                | 88.83                | 116.24               | 34.99                |
| 40         | 50.00                | 20.00                | 83.80                | 61.10                | 72.55                |                      | 58.00                | 89.57                | 116.75               | 35.00                |
| 41         | 52.67                | 20.00                | 83.93                | 91.23                | 73.40                |                      | 60.50                | 89.62                | 117.48               | 35.11                |
| 42         | 53.00                | 20.07                | 86.37                |                      | 73.72                |                      | 74.75                | 90.07                | 118.53               | 35.17                |
| 43         | 54.50                | 20.16                | 86.73                |                      | 74.05                |                      | 79.25                | 92.00                | 118.67               | 35.39                |
| 44         | 61.82                | 20.20                | 88.59                |                      | 77.04                |                      | 94.00                | 94.70                | 118.70               | 35.54                |
| 45         | 62.17                | 20.33                | 88.65                |                      | 79.41                |                      |                      | 94.75                | 118.73               | 35.95                |

Table B-3 Mineral Aggregate Cont.

| Contract # | 2440                 | 3564                 | 3707                 | 3866                 | 3915                 | 4017                 | 4044                 | 4251                 | 4699                 | 4160                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Knox                 | Grainger             | Rhea                 | Marion               | Henderson            | Davidson             | Roane                | Williamson           | Henderson            | White                |
| Region     | 1                    | 1                    | 2                    | 2                    | 4                    | 3                    | 1                    | 3                    | 4                    | 2                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 46         | 62.17                | 20.50                | 88.83                |                      |                      |                      |                      | 98.00                | 118.75               | 36.05                |
| 47         | 63.55                | 20.60                | 89.11                |                      |                      |                      |                      | 98.33                | 119.39               | 36.10                |
| 48         | 78.58                | 20.60                | 90.28                |                      |                      |                      |                      | 99.25                | 119.48               | 36.12                |
| 49         | 78.98                | 20.65                | 92.27                |                      |                      |                      |                      | 99.90                | 120.67               | 36.15                |
| 50         | 79.50                | 20.67                | 92.30                |                      |                      |                      |                      | 100.73               | 122.02               | 36.16                |
| 51         | 92.55                | 20.75                | 92.30                |                      |                      |                      |                      | 101.37               | 126.00               | 36.20                |
| 52         | 92.73                | 20.79                | 94.12                |                      |                      |                      |                      | 102.10               | 132.08               | 36.28                |
| 53         | 93.50                | 20.91                | 94.22                |                      |                      |                      |                      | 108.15               |                      | 36.28                |
| 54         | 136.37               | 20.98                | 97.30                |                      |                      |                      |                      | 110.62               |                      | 36.46                |
| 55         |                      | 21.00                | 106.43               |                      |                      |                      |                      | 112.85               |                      | 36.47                |
| 56         |                      | 21.00                | 106.65               |                      |                      |                      |                      | 113.20               |                      | 36.98                |
| 57         |                      | 21.07                | 123.76               |                      |                      |                      |                      | 114.47               |                      | 37.08                |
| 58         |                      | 21.17                | 124.78               |                      |                      |                      |                      | 126.83               |                      | 37.18                |
| 59         |                      | 21.30                | 125.63               |                      |                      |                      |                      | 131.42               |                      | 37.28                |
| 60         |                      | 21.34                | 140.65               |                      |                      |                      |                      | 151.12               |                      | 38.05                |
| 61         |                      | 21.93                | 153.63               |                      |                      |                      |                      | 151.85               |                      | 38.28                |
| 62         |                      | 22.02                | 153.78               |                      |                      |                      |                      | 153.17               |                      | 38.30                |
| 63         |                      | 22.20                | 166.28               |                      |                      |                      |                      | 155.95               |                      | 38.38                |
| 64         |                      | 22.25                | 171.78               |                      |                      |                      |                      | 157.17               |                      | 38.93                |
| 65         |                      | 22.60                | 171.90               |                      |                      |                      |                      | 158.53               |                      | 39.06                |
| 66         |                      | 22.75                | 181.47               |                      |                      |                      |                      | 189.05               |                      | 39.18                |
| 67         |                      | 22.79                | 185.98               |                      |                      |                      |                      | 197.50               |                      | 39.30                |

Table B-3 Mineral Aggregate Cont.

| Contract # | 2440                 | 3564                 | 3707                 | 3866                 | 3915                 | 4017                 | 4044                 | 4251                 | 4699                 | 4160                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Knox                 | Grainger             | Rhea                 | Marion               | Henderson            | Davidson             | Roane                | Williamson           | Henderson            | White                |
| Region     | 1                    | 1                    | 2                    | 2                    | 4                    | 3                    | 1                    | 3                    | 4                    | 2                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 68         |                      | 22.80                | 192.83               |                      |                      |                      |                      |                      |                      | 39.35                |
| 69         |                      | 22.81                | 196.33               |                      |                      |                      |                      |                      |                      | 39.57                |
| 70         |                      | 22.90                | 201.93               |                      |                      |                      |                      |                      |                      | 39.72                |
| 71         |                      | 22.90                | 207.42               |                      |                      |                      |                      |                      |                      | 39.78                |
| 72         |                      | 23.00                | 209.18               |                      |                      |                      |                      |                      |                      | 39.87                |
| 73         |                      | 23.05                | 212.13               |                      |                      |                      |                      |                      |                      | 39.97                |
| 74         |                      | 23.17                | 225.52               |                      |                      |                      |                      |                      |                      | 40.15                |
| 75         |                      | 23.83                | 226.37               |                      |                      |                      |                      |                      |                      | 40.26                |
| 76         |                      | 24.00                | 231.95               |                      |                      |                      |                      |                      |                      | 40.45                |
| 77         |                      | 24.10                | 233.37               |                      |                      |                      |                      |                      |                      | 40.60                |
| 78         |                      | 24.33                | 238.28               |                      |                      |                      |                      |                      |                      | 41.00                |
| 79         |                      | 24.36                |                      |                      |                      |                      |                      |                      |                      | 41.10                |
| 80         |                      | 24.60                |                      |                      |                      |                      |                      |                      |                      | 41.15                |
| 81         |                      | 25.07                |                      |                      |                      |                      |                      |                      |                      | 41.17                |
| 82         |                      | 25.19                |                      |                      |                      |                      |                      |                      |                      | 41.21                |
| 83         |                      | 25.61                |                      |                      |                      |                      |                      |                      |                      | 41.34                |
| 84         |                      | 26.00                |                      |                      |                      |                      |                      |                      |                      | 41.43                |
| 85         |                      | 26.50                |                      |                      |                      |                      |                      |                      |                      | 41.46                |
| 86         |                      | 26.66                |                      |                      |                      |                      |                      |                      |                      | 41.52                |
| 87         |                      | 26.93                |                      |                      |                      |                      |                      |                      |                      | 41.68                |
| 88         |                      | 27.06                |                      |                      |                      |                      |                      |                      |                      | 41.70                |
| 89         |                      | 27.12                |                      |                      |                      |                      |                      |                      |                      | 41.71                |

Table B-3 Mineral Aggregate Cont.

| Contract # | 2440                 | 3564                 | 3707                 | 3866                 | 3915                 | 4017                 | 4044                 | 4251                 | 4699                 | 4160                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Knox                 | Grainger             | Rhea                 | Marion               | Henderson            | Davidson             | Roane                | Williamson           | Henderson            | White                |
| Region     | 1                    | 1                    | 2                    | 2                    | 4                    | 3                    | 1                    | 3                    | 4                    | 2                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 90         |                      | 27.40                |                      |                      |                      |                      |                      |                      |                      | 41.72                |
| 91         |                      | 27.62                |                      |                      |                      |                      |                      |                      |                      | 72.05                |
| 92         |                      | 28.47                |                      |                      |                      |                      |                      |                      |                      | 42.16                |
| 93         |                      | 29.18                |                      |                      |                      |                      |                      |                      |                      | 72.22                |
| 94         |                      | 29.71                |                      |                      |                      |                      |                      |                      |                      | 42.36                |
| 95         |                      | 29.81                |                      |                      |                      |                      |                      |                      |                      | 42.42                |
| 96         |                      | 30.93                |                      |                      |                      |                      |                      |                      |                      | 43.05                |
| 97         |                      | 32.17                |                      |                      |                      |                      |                      |                      |                      | 43.48                |
| 98         |                      | 33.93                |                      |                      |                      |                      |                      |                      |                      | 44.07                |
| 99         |                      | 39.18                |                      |                      |                      |                      |                      |                      |                      | 44.10                |
| 100        |                      | 44.53                |                      |                      |                      |                      |                      |                      |                      | 45.40                |
| 101        |                      | 55.72                |                      |                      |                      |                      |                      |                      |                      | 46.18                |
| 102        |                      | 56.03                |                      |                      |                      |                      |                      |                      |                      | 46.72                |
| 103        |                      |                      |                      |                      |                      |                      |                      |                      |                      | 46.77                |
| 104        |                      |                      |                      |                      |                      |                      |                      |                      |                      | 46.99                |
| 105        |                      |                      |                      |                      |                      |                      |                      |                      |                      | 47.02                |
| 106        |                      |                      |                      |                      |                      |                      |                      |                      |                      | 47.50                |
| 107        |                      |                      |                      |                      |                      |                      |                      |                      |                      | 48.12                |
| 108        |                      |                      |                      |                      |                      |                      |                      |                      |                      | 49.43                |
| 109        |                      |                      |                      |                      |                      |                      |                      |                      |                      | 49.83                |
| 110        |                      |                      |                      |                      |                      |                      |                      |                      |                      | 49.90                |
| 111        |                      |                      |                      |                      |                      |                      |                      |                      |                      | 50.97                |

Table B-3 Mineral Aggregate Cont.

| Contract # | 2440       | 3564       | 3707       | 3866       | 3915       | 4017       | 4044       | 4251       | 4699       | 4160       |
|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| County     | Knox       | Grainger   | Rhea       | Marion     | Henderson  | Davidson   | Roane      | Williamson | Henderson  | White      |
| Region     | 1          | 1          | 2          | 2          | 4          | 3          | 1          | 3          | 4          | 2          |
|            | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time |
|            | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     |
| 112        |            |            |            |            |            |            |            |            |            | 51.10      |
| 113        |            |            |            |            |            |            |            |            |            | 51.32      |
| 114        |            |            |            |            |            |            |            |            |            | 52.13      |
| 115        |            |            |            |            |            |            |            |            |            | 57.31      |
| 116        |            |            |            |            |            |            |            |            |            | 60.20      |
| 117        |            |            |            |            |            |            |            |            |            | 60.31      |
| 118        |            |            |            |            |            |            |            |            |            | 63.98      |
| 119        |            |            |            |            |            |            |            |            |            | 67.63      |
| 120        |            |            |            |            |            |            |            |            |            | 68.26      |
| 121        |            |            |            |            |            |            |            |            |            | 68.49      |
| 122        |            |            |            |            |            |            |            |            |            | 73.83      |
| 123        |            |            |            |            |            |            |            |            |            | 87.02      |
|            |            |            |            |            |            |            |            |            |            |            |
| Count      | 58         | 102        | 78         | 41         | 45         | 36         | 44         | 67         | 52         | 123        |
| Mean       | 52.53      | 22.68      | 108.47     | 44.13      | 69.32      | 56.49      | 45.67      | 97.57      | 112.62     | 40.06      |
| Std.Dev.   | 18.13      | 6.83       | 52.90      | 9.89       | 3.17       | 12.87      | 12.74      | 28.36      | 6.53       | 10.99      |
| X+S        | 70.66      | 29.52      | 161.37     | 45.02      | 72.49      | 69.36      | 58.31      | 125.93     |            | 51.05      |
| XND        |            |            | 84.00      |            | 69.32      | 56.49      |            | 87.10      |            |            |
| SND        |            |            | 20.69      |            | 3.17       | 12.87      |            | 11.10      |            |            |

**Table B-4 Asphalt A-S Mix**

| Contract # | 3145                 | 3721                 | 3935                 | 4224                 | 4251                 | 3707                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Weakley              | McNairy              | Sumner               | Fayette              | Williamson           | Rhea                 |
| Region     | 4                    | 4                    | 3                    | 4                    | 3                    | 2                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 1          | 44.57                | 50.02                | 42.92                | 58.05                | 79.58                | 62.00                |
| 2          | 45.95                | 62.80                | 44.75                | 63.12                | 82.47                | 63.77                |
| 3          | 46.58                | 65.05                | 46.22                | 63.25                | 83.00                | 64.27                |
| 4          | 49.32                | 65.40                | 48.67                | 63.38                | 83.80                | 65.08                |
| 5          | 50.02                | 73.00                | 49.33                | 63.47                | 83.85                | 65.85                |
| 6          | 50.22                | 74.40                | 51.92                | 63.73                | 84.00                | 66.23                |
| 7          | 50.38                | 74.98                | 52.37                | 64.22                | 84.23                | 66.30                |
| 8          | 50.40                | 75.00                | 52.67                | 64.87                | 84.93                | 67.20                |
| 9          | 50.72                | 75.17                | 52.87                | 65.20                | 85.40                | 68.13                |
| 10         | 51.28                | 75.75                | 53.50                | 65.43                | 85.50                | 68.22                |
| 11         | 51.40                | 77.00                | 53.67                | 65.80                | 85.92                | 68.28                |
| 12         | 52.62                | 77.07                | 54.33                | 66.26                | 86.20                | 68.57                |
| 13         | 52.72                | 78.00                | 55.28                | 66.47                | 87.84                | 68.71                |
| 14         | 52.72                | 81.70                | 55.92                | 66.88                | 87.85                | 69.07                |
| 15         | 52.75                | 82.83                | 56.10                | 66.97                | 87.85                | 69.66                |
| 16         | 52.85                | 83.90                | 56.33                | 66.98                | 88.62                | 71.65                |
| 17         | 52.92                | 85.00                | 56.43                | 67.02                | 89.33                | 71.83                |
| 18         | 53.77                | 88.90                | 56.80                | 67.35                | 90.00                | 72.31                |
| 19         | 54.32                | 89.00                | 57.08                | 67.42                | 90.92                | 72.90                |
| 20         | 54.50                | 89.00                | 57.13                | 68.17                | 91.05                | 73.60                |
| 21         | 55.13                | 91.00                | 57.23                | 68.73                | 91.50                | 74.46                |

Table B-4 Asphalt A-S Mix Cont.

| Contract # | 3145       | 3721       | 3935       | 4224       | 4251       | 3707       |
|------------|------------|------------|------------|------------|------------|------------|
| County     | Weakley    | McNairy    | Sumner     | Fayette    | Williamson | Rhea       |
| Region     | 4          | 4          | 3          | 4          | 3          | 2          |
|            | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time |
|            | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     |
| 22         | 55.15      | 94.00      | 57.50      | 69.22      | 91.63      | 74.47      |
| 23         | 55.98      | 95.00      | 57.50      | 70.37      | 92.00      | 74.68      |
| 24         | 57.37      | 96.08      | 57.62      | 72.93      | 92.07      | 74.90      |
| 25         | 57.48      | 97.93      | 57.92      | 74.18      | 93.57      | 75.47      |
| 26         | 58.13      | 98.00      | 58.07      | 74.37      | 93.83      | 75.58      |
| 27         | 58.15      | 99.57      | 58.08      | 76.63      | 93.83      | 75.73      |
| 28         | 58.52      | 101.55     | 58.10      | 77.53      | 94.23      | 75.89      |
| 29         | 58.57      | 102.72     | 58.33      | 78.73      | 94.43      | 77.00      |
| 30         | 58.60      | 103.07     | 58.47      | 79.82      | 94.50      | 77.87      |
| 31         | 59.20      | 104.88     | 58.53      | 79.88      | 94.65      | 78.18      |
| 32         | 59.45      | 105.15     | 58.67      | 80.38      | 94.67      | 78.60      |
| 33         | 59.58      | 107.17     | 58.83      | 83.75      | 94.72      | 79.02      |
| 34         | 59.65      | 107.67     | 58.97      | 84.62      | 94.77      | 80.62      |
| 35         | 59.82      | 110.67     | 59.08      | 85.72      | 95.13      | 82.27      |
| 36         | 60.25      | 113.82     | 59.13      | 89.12      | 95.45      | 82.62      |
| 37         | 60.37      | 121.37     | 59.57      |            | 95.70      | 83.78      |
| 38         | 60.58      | 125.15     | 59.85      |            | 96.17      | 83.80      |
| 39         | 60.87      |            | 59.92      |            | 96.52      | 83.93      |
| 40         | 61.03      |            | 60.00      |            | 96.57      | 86.37      |
| 41         | 61.28      |            | 60.15      |            | 96.67      | 86.73      |
| 42         | 61.37      |            | 60.33      |            | 96.67      | 88.59      |
| 43         | 61.72      |            | 60.52      |            | 97.92      | 88.65      |
| 44         | 62.00      |            | 60.72      |            | 97.95      | 88.83      |
| 45         | 62.18      |            | 61.25      |            | 98.83      | 89.11      |
| 46         | 62.28      |            | 61.58      |            | 100.10     | 90.28      |
| 47         | 62.58      |            | 61.63      |            | 100.60     | 92.27      |

Table B-4 Asphalt A-S Mix Cont.

| Contract # | 3145                 | 3721                 | 3935                 | 4224                 | 4251                 | 3707                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Weakley              | McNairy              | Sumner               | Fayette              | Williamson           | Rhea                 |
| Region     | 4                    | 4                    | 3                    | 4                    | 3                    | 2                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 48         | 62.73                |                      | 62.65                |                      | 100.87               | 92.30                |
| 49         | 62.92                |                      | 62.77                |                      | 100.92               | 92.30                |
| 50         | 63.07                |                      | 62.78                |                      | 100.97               | 94.12                |
| 51         | 64.28                |                      | 63.45                |                      | 101.03               | 94.22                |
| 52         | 65.23                |                      | 64.28                |                      | 101.12               | 97.30                |
| 53         | 68.12                |                      | 64.42                |                      | 101.40               | 106.65               |
| 54         | 118.27               |                      | 64.50                |                      | 101.48               | 106.00               |
| 55         |                      |                      | 64.52                |                      | 101.52               | 65.00                |
| 56         |                      |                      | 64.92                |                      | 101.87               | 123.76               |
| 57         |                      |                      | 65.17                |                      | 101.87               | 124.78               |
| 58         |                      |                      | 65.25                |                      | 101.88               | 125.63               |
| 59         |                      |                      | 65.50                |                      | 102.67               | 140.65               |
| 60         |                      |                      | 65.58                |                      | 102.97               | 163.63               |
| 61         |                      |                      | 65.67                |                      | 104.33               | 153.78               |
| 62         |                      |                      | 65.92                |                      | 107.15               | 166.28               |
| 63         |                      |                      | 66.10                |                      | 110.22               | 171.90               |
| 64         |                      |                      | 66.23                |                      | 116.67               | 171.91               |
| 65         |                      |                      | 66.42                |                      |                      | 181.47               |
| 66         |                      |                      | 67.10                |                      |                      | 185.95               |
| 67         |                      |                      | 68.17                |                      |                      | 192.83               |
| 68         |                      |                      | 68.78                |                      |                      | 192.91               |
| 69         |                      |                      | 69.08                |                      |                      | 196.33               |
| 70         |                      |                      | 69.62                |                      |                      | 201.93               |
| 71         |                      |                      | 71.33                |                      |                      | 207.42               |
| 72         |                      |                      | 72.17                |                      |                      | 209.18               |
| 73         |                      |                      | 73.22                |                      |                      | 212.13               |
| 74         |                      |                      | 73.28                |                      |                      | 225.52               |

Table B-4 Asphalt A-S Mix Cont.

| Contract # | 3145                 | 3721                 | 3935                 | 4224                 | 4251                 | 3707                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Weakley              | McNairy              | Sumner               | Fayette              | Williamson           | Rhea                 |
| Region     | 4                    | 4                    | 3                    | 4                    | 3                    | 2                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 75         |                      |                      | 73.53                |                      |                      | 226.37               |
| 76         |                      |                      | 73.58                |                      |                      | 231.95               |
| 77         |                      |                      | 73.87                |                      |                      | 233.37               |
| 78         |                      |                      | 74.33                |                      |                      | 238.28               |
| 79         |                      |                      | 76.00                |                      |                      |                      |
| 80         |                      |                      | 76.58                |                      |                      |                      |
| 81         |                      |                      | 78.25                |                      |                      |                      |
| 82         |                      |                      | 78.72                |                      |                      |                      |
| 83         |                      |                      | 80.08                |                      |                      |                      |
| 84         |                      |                      | 80.17                |                      |                      |                      |
| 85         |                      |                      | 80.92                |                      |                      |                      |
| 86         |                      |                      | 87.92                |                      |                      |                      |
| 87         |                      |                      | 89.42                |                      |                      |                      |
| 88         |                      |                      | 92.75                |                      |                      |                      |
| 89         |                      |                      | 94.22                |                      |                      |                      |
| 90         |                      |                      | 94.58                |                      |                      |                      |
| 91         |                      |                      | 95.53                |                      |                      |                      |
| 92         |                      |                      | 96.58                |                      |                      |                      |
| 93         |                      |                      | 100.67               |                      |                      |                      |
| 94         |                      |                      | 101.10               |                      |                      |                      |
| 95         |                      |                      | 101.67               |                      |                      |                      |
| 96         |                      |                      | 102.05               |                      |                      |                      |
| 97         |                      |                      | 105.77               |                      |                      |                      |
| 98         |                      |                      | 121.05               |                      |                      |                      |
| 99         |                      |                      | 122.25               |                      |                      |                      |
| 100        |                      |                      | 137.17               |                      |                      |                      |
| 101        |                      |                      | 137.33               |                      |                      |                      |

Table B-4 Asphalt A-S Mix Cont.

| Contract # | 3145       | 3721       | 3935       | 4224       | 4251       | 3707       |
|------------|------------|------------|------------|------------|------------|------------|
| County     | Weakley    | McNairy    | Sumner     | Fayette    | Williamson | Rhea       |
| Region     | 4          | 4          | 3          | 4          | 3          | 2          |
|            | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time |
|            | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     |
| 102        |            |            | 141.50     |            |            |            |
| 103        |            |            | 143.58     |            |            |            |
|            |            |            |            |            |            |            |
| Count      | 54         | 38         | 103        | 36         | 64         | 78         |
| Mean       | 58.00      | 89.44      | 70.50      | 70.83      | 94.62      | 108.47     |
| Std.Dev.   | 9.90       | 16.98      | 20.90      | 7.71       | 7.34       | 52.90      |
| X+S        | 67.90      | 106.42     | 91.40      | 78.43      | 111.96     | 161.37     |
| XND        | 56.64      |            | 62.92      |            |            | 84.00      |
| SND        | 5.18       |            | 9.04       |            |            | 20.69      |

**Table B-5 Asphalt A Mix**

| Contract # | 3428                 | 3701                 | 3707                 | 3935                 | 4123                 | 4160                 | 4729                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Cheatham             | Madison              | Rhea                 | Sumner               | Knox                 | White                | Shelby               |
| Region     | 3                    | 4                    | 2                    | 3                    | 1                    | 2                    | 4                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 1          | 60.00                | 61.83                | 70.47                | 40.67                | 43.98                | 36.55                | 90.45                |
| 2          | 60.42                | 61.92                | 73.58                | 45.52                | 46.33                | 41.85                | 92.67                |
| 3          | 60.45                | 63.90                | 74.42                | 47.00                | 48.50                | 41.85                | 94.30                |
| 4          | 60.50                | 64.85                | 75.00                | 47.55                | 56.53                | 41.88                | 97.25                |
| 5          | 60.50                | 65.03                | 75.18                | 49.53                | 62.17                | 42.25                | 99.68                |
| 6          | 60.55                | 66.25                | 76.97                | 49.90                | 63.10                | 42.37                | 101.67               |
| 7          | 60.57                | 66.83                | 77.60                | 51.25                | 63.10                | 43.32                | 101.82               |
| 8          | 60.77                | 67.35                | 79.80                | 52.17                | 63.33                | 43.53                | 102.80               |
| 9          | 60.88                | 67.55                | 80.02                | 53.05                | 64.22                | 43.58                | 103.17               |
| 10         | 61.08                | 67.97                | 80.03                | 54.08                | 64.43                | 43.62                | 103.42               |
| 11         | 61.25                | 69.88                | 80.45                | 54.27                | 64.43                | 43.72                | 104.53               |
| 12         | 65.00                | 70.05                | 81.51                | 54.82                | 64.47                | 43.90                | 104.72               |
| 13         | 65.08                | 70.22                | 82.20                | 55.17                | 64.57                | 43.92                | 105.03               |
| 14         | 65.62                | 76.90                | 83.17                | 55.42                | 64.63                | 44.58                | 106.83               |
| 15         | 67.08                | 78.50                | 83.90                | 55.68                | 64.72                | 44.80                | 107.75               |
| 16         | 69.92                | 78.77                | 84.65                | 56.13                | 66.38                | 44.97                | 107.83               |
| 17         | 70.20                | 78.90                | 84.67                | 56.18                | 66.57                | 45.02                | 108.00               |
| 18         | 70.20                | 80.00                | 85.88                | 56.37                | 68.22                | 45.20                | 108.00               |
| 19         | 70.72                | 82.92                | 86.42                | 56.68                | 68.87                | 45.23                | 108.07               |
| 20         | 71.42                | 85.30                | 87.30                | 56.72                | 69.78                | 45.30                | 109.00               |
| 21         | 72.50                | 86.83                | 87.50                | 56.80                | 69.80                | 45.38                | 109.25               |
| 22         | 72.90                | 90.10                | 88.03                | 57.33                | 69.87                | 45.38                | 109.47               |
| 23         | 74.02                | 91.62                | 88.57                | 57.42                | 70.52                | 45.42                | 109.50               |
| 24         | 75.83                | 93.37                | 88.92                | 57.75                | 70.53                | 45.43                | 109.80               |

Table B-5 Asphalt A Mix Cont.

| Contract # | 3428       | 3701       | 3707       | 3935       | 4123       | 4160       | 4729       |
|------------|------------|------------|------------|------------|------------|------------|------------|
| County     | Cheatham   | Madison    | Rhea       | Sumner     | Knox       | White      | Shelby     |
| Region     | 3          | 4          | 2          | 3          | 1          | 2          | 4          |
|            | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time |
|            | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     |
| 25         | 75.87      | 93.72      | 89.17      | 58.03      | 70.70      | 45.48      | 110.75     |
| 26         | 75.90      | 97.42      | 89.32      | 58.23      | 70.73      | 45.53      | 111.93     |
| 27         | 76.02      | 98.58      | 89.72      | 58.42      | 70.85      | 45.53      | 112.12     |
| 28         | 82.42      | 101.15     | 90.52      | 58.82      | 70.93      | 46.45      | 112.65     |
| 29         | 84.18      |            | 90.80      | 58.98      | 70.97      | 46.45      | 113.18     |
| 30         | 85.00      |            | 91.10      | 59.00      | 71.73      | 46.65      | 113.50     |
| 31         | 85.50      |            | 91.42      | 59.00      | 71.93      | 46.68      | 114.00     |
| 32         | 85.50      |            | 91.52      | 59.03      | 72.03      | 46.70      | 114.00     |
| 33         | 85.58      |            | 91.93      | 59.25      | 73.21      | 46.77      | 114.23     |
| 34         | 85.70      |            | 92.77      | 59.42      | 74.20      | 46.78      | 114.55     |
| 35         | 85.75      |            | 93.03      | 59.42      | 74.35      | 47.00      | 114.60     |
| 36         | 85.97      |            | 93.62      | 59.48      | 74.37      | 47.08      | 114.83     |
| 37         | 87.40      |            | 94.40      | 59.70      | 74.75      | 47.12      | 115.00     |
| 38         | 88.15      |            | 94.67      | 59.88      | 74.80      | 47.25      | 115.00     |
| 39         | 88.50      |            | 95.55      | 60.25      | 74.87      | 47.25      | 115.12     |
| 40         | 90.00      |            | 96.38      | 60.45      | 75.18      | 47.40      | 115.50     |
| 41         | 90.23      |            | 106.13     | 60.83      | 75.65      | 47.42      | 115.55     |
| 42         | 90.25      |            | 109.10     | 60.92      | 76.83      | 47.65      | 115.67     |
| 43         | 90.25      |            | 138.57     | 61.08      | 77.98      | 47.67      | 116.25     |
| 44         | 90.37      |            |            | 61.62      | 78.32      | 47.68      | 116.28     |
| 45         | 90.50      |            |            | 61.75      | 78.75      | 47.77      | 116.67     |
| 46         | 90.50      |            |            | 61.83      | 78.87      | 47.80      | 117.05     |
| 47         | 90.50      |            |            | 62.02      | 78.88      | 47.88      | 117.80     |

Table B-5 Asphalt A Mix Cont.

| Contract # | 3428                 | 3701                 | 3707                 | 3935                 | 4123                 | 4160                 | 4729                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Cheatham             | Madison              | Rhea                 | Sumner               | Knox                 | White                | Shelby               |
| Region     | 3                    | 4                    | 2                    | 3                    | 1                    | 2                    | 4                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 48         | 90.75                |                      |                      | 62.42                | 79.17                | 47.90                | 117.83               |
| 49         | 90.75                |                      |                      | 62.42                | 80.57                | 47.93                | 118.17               |
| 50         | 90.78                |                      |                      | 62.42                | 80.82                | 48.15                | 118.33               |
| 51         | 90.83                |                      |                      | 62.82                | 81.08                | 48.20                | 118.33               |
| 52         | 90.87                |                      |                      | 62.88                | 82.00                | 48.30                | 119.58               |
| 53         | 93.62                |                      |                      | 63.18                | 82.15                | 48.32                | 121.00               |
| 54         | 93.63                |                      |                      | 63.33                | 82.17                | 48.38                | 121.05               |
| 55         | 94.93                |                      |                      | 63.42                | 82.28                | 48.77                | 122.23               |
| 56         | 95.08                |                      |                      | 63.90                | 82.38                | 49.07                | 124.50               |
| 57         | 95.50                |                      |                      | 64.00                | 82.95                | 49.12                | 125.00               |
| 58         | 97.12                |                      |                      | 64.32                | 84.68                | 49.22                | 125.22               |
| 59         | 97.17                |                      |                      | 64.47                | 87.85                | 49.25                | 128.45               |
| 60         | 98.50                |                      |                      | 64.62                | 91.35                | 49.52                | 130.00               |
| 61         | 98.92                |                      |                      | 65.03                | 92.58                | 49.85                | 130.55               |
| 62         | 99.42                |                      |                      | 65.32                | 103.62               | 50.00                | 131.95               |
| 63         | 100.00               |                      |                      | 65.50                | 103.98               | 50.22                | 132.10               |
| 64         | 100.83               |                      |                      | 65.52                | 141.95               | 50.42                | 133.62               |
| 65         | 102.47               |                      |                      | 66.42                |                      | 50.53                | 136.37               |
| 66         | 103.42               |                      |                      | 66.75                |                      | 51.35                | 137.25               |
| 67         | 103.67               |                      |                      | 66.82                |                      | 51.55                | 138.55               |
| 68         | 104.00               |                      |                      | 66.92                |                      | 51.63                | 139.17               |
| 69         | 105.25               |                      |                      | 67.23                |                      | 51.70                | 142.15               |

Table B-5 Asphalt A Mix Cont.

| Contract # | 3428                 | 3701                 | 3707                 | 3935                 | 4123                 | 4160                 | 4729                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Cheatham             | Madison              | Rhea                 | Sumner               | Knox                 | White                | Shelby               |
| Region     | 3                    | 4                    | 2                    | 3                    | 1                    | 2                    | 4                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 70         | 105.65               |                      |                      | 67.25                |                      | 51.85                | 202.73               |
| 71         | 105.70               |                      |                      | 67.30                |                      | 52.45                |                      |
| 72         | 105.87               |                      |                      | 67.32                |                      | 52.83                |                      |
| 73         | 105.92               |                      |                      | 67.42                |                      | 53.08                |                      |
| 74         | 106.75               |                      |                      | 67.47                |                      | 53.35                |                      |
| 75         | 107.73               |                      |                      | 67.50                |                      | 53.45                |                      |
| 76         | 110.00               |                      |                      | 67.52                |                      | 54.97                |                      |
| 77         | 110.17               |                      |                      | 67.58                |                      | 55.32                |                      |
| 78         | 110.42               |                      |                      | 67.62                |                      | 56.30                |                      |
| 79         | 110.50               |                      |                      | 67.77                |                      | 57.38                |                      |
| 80         | 112.55               |                      |                      | 68.08                |                      | 57.62                |                      |
| 81         | 112.63               |                      |                      | 68.13                |                      | 87.82                |                      |
| 82         | 112.67               |                      |                      | 68.17                |                      | 95.72                |                      |
| 83         | 113.47               |                      |                      | 69.27                |                      |                      |                      |
| 84         | 114.27               |                      |                      | 69.30                |                      |                      |                      |
| 85         | 114.58               |                      |                      | 69.42                |                      |                      |                      |
| 86         | 115.50               |                      |                      | 69.47                |                      |                      |                      |
| 87         | 115.83               |                      |                      | 69.62                |                      |                      |                      |
| 88         | 116.42               |                      |                      | 69.88                |                      |                      |                      |
| 89         | 118.95               |                      |                      | 70.13                |                      |                      |                      |
| 90         | 125.17               |                      |                      | 70.17                |                      |                      |                      |
| 91         | 125.50               |                      |                      | 70.38                |                      |                      |                      |

Table B-5 Asphalt A Mix Cont.

| Contract # | 3428       | 3701       | 3707       | 3935       | 4123       | 4160       | 4729       |
|------------|------------|------------|------------|------------|------------|------------|------------|
| County     | Cheatham   | Madison    | Rhea       | Sumner     | Knox       | White      | Shelby     |
| Region     | 3          | 4          | 2          | 3          | 1          | 2          | 4          |
|            | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time |
|            | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     |
| 92         | 135.00     |            |            | 70.48      |            |            |            |
| 93         | 150.08     |            |            | 70.50      |            |            |            |
| 94         | 162.72     |            |            | 70.67      |            |            |            |
| 95         | 175.75     |            |            | 70.82      |            |            |            |
| 96         |            |            |            | 71.10      |            |            |            |
| 97         |            |            |            | 71.35      |            |            |            |
| 98         |            |            |            | 71.92      |            |            |            |
| 99         |            |            |            | 72.00      |            |            |            |
| 100        |            |            |            | 72.27      |            |            |            |
| 101        |            |            |            | 72.92      |            |            |            |
| 102        |            |            |            | 73.50      |            |            |            |
| 103        |            |            |            | 73.98      |            |            |            |
| 104        |            |            |            | 74.32      |            |            |            |
| 105        |            |            |            | 77.05      |            |            |            |
| 106        |            |            |            | 78.17      |            |            |            |
| 107        |            |            |            | 78.30      |            |            |            |
| 108        |            |            |            | 79.43      |            |            |            |
| 109        |            |            |            | 80.80      |            |            |            |
| 110        |            |            |            | 87.37      |            |            |            |
| 111        |            |            |            | 88.60      |            |            |            |
| 112        |            |            |            | 91.27      |            |            |            |
| 113        |            |            |            | 93.08      |            |            |            |

Table B-5 Asphalt A Mix Cont.

|            |            |            |            |            |            |            |            |
|------------|------------|------------|------------|------------|------------|------------|------------|
| Contract # | 3428       | 3701       | 3707       | 3935       | 4123       | 4160       | 4729       |
| County     | Cheatham   | Madison    | Rhea       | Sumner     | Knox       | White      | Shelby     |
| Region     | 3          | 4          | 2          | 3          | 1          | 2          | 4          |
|            | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time |
|            | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     |
| 114        |            |            |            | 95.95      |            |            |            |
|            |            |            |            |            |            |            |            |
| Count      | 95         | 28         | 43         | 114        | 64         | 82         | 70         |
| Mean       | 92.58      | 77.78      | 88.05      | 64.62      | 74.24      | 48.79      | 116.36     |
| Std.Dev.   | 22.31      | 12.40      | 11.29      | 9.40       | 13.86      | 7.82       | 15.30      |
| X+S        | 114.89     | 90.18      | 99.34      | 73.96      | 88.1       | 56.61      | 121.66     |
| XND        |            |            |            |            |            | 47.46      |            |
| SND        |            |            |            |            |            | 3.50       |            |

Table B-6 Asphalt B-M Mix

| Contract # | 3366                 | 3701                 | 3707                 | 3717                 | 4251                 | 4298                 | 4687                 | 4738                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Weakley              | Madison              | Rhea                 | Davidson             | Williamson           | Hancock              | Bradley              | Weakley              |
| Region     | 4                    | 4                    | 2                    | 3                    | 3                    | 1                    | 2                    | 4                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 1          | 53.43                | 49.67                | 73.62                | 38.75                | 86.50                | 114.20               | 63.65                | 51.97                |
| 2          | 56.00                | 50.02                | 74.50                | 45.70                | 89.83                | 120.10               | 70.13                | 53.92                |
| 3          | 57.60                | 56.88                | 81.23                | 46.15                | 92.53                | 130.07               | 70.33                | 54.13                |
| 4          | 57.63                | 65.10                | 81.38                | 47.18                | 95.37                | 139.03               | 71.73                | 54.25                |
| 5          | 59.02                | 68.73                | 81.63                | 47.18                | 97.40                | 140.42               | 73.73                | 55.13                |
| 6          | 59.60                | 69.65                | 82.12                | 51.72                | 97.70                | 140.60               | 74.23                | 55.32                |
| 7          | 59.72                | 70.65                | 82.28                | 55.35                | 98.20                | 141.17               | 75.57                | 55.55                |
| 8          | 60.10                | 70.90                | 82.37                | 55.77                | 98.35                | 142.00               | 76.05                | 55.57                |
| 9          | 60.13                | 72.93                | 83.02                | 56.88                | 99.75                | 142.47               | 76.75                | 55.63                |
| 10         | 60.30                | 75.93                | 85.45                | 58.17                | 100.83               | 144.80               | 77.32                | 55.65                |
| 11         | 61.23                | 76.18                | 85.52                | 59.00                | 100.88               | 149.87               | 77.77                | 57.62                |
| 12         | 62.02                | 79.50                | 86.97                | 59.65                | 101.17               | 161.93               | 78.97                | 57.78                |
| 13         | 62.03                | 80.77                | 87.47                | 59.87                | 101.92               | 166.68               | 79.33                | 57.83                |
| 14         | 62.50                | 87.35                | 87.78                | 60.17                | 102.37               | 167.57               | 80.42                | 57.98                |
| 15         | 62.57                | 92.43                | 88.24                | 62.48                | 102.42               | 170.80               | 80.63                | 59.03                |
| 16         | 62.95                | 92.43                | 88.68                | 63.58                | 106.05               | 171.02               | 80.70                | 59.38                |
| 17         | 63.58                | 93.13                | 88.84                | 73.00                | 108.58               | 171.23               | 80.85                | 61.17                |
| 18         | 64.20                | 93.32                | 89.00                | 75.37                | 109.05               | 172.60               | 81.50                | 61.28                |
| 19         | 64.28                | 95.87                | 89.28                | 75.90                | 109.75               | 173.28               | 81.92                | 61.63                |
| 20         | 64.37                | 110.03               | 89.52                | 76.50                | 110.57               | 178.03               | 81.92                | 61.97                |
| 21         | 65.73                | 119.97               | 90.22                | 76.86                | 112.92               | 178.77               | 82.25                | 62.05                |
| 22         | 67.30                | 120.38               | 90.23                | 77.15                | 115.05               | 198.73               | 82.83                | 62.57                |
| 23         | 69.88                | 120.67               | 90.62                | 77.15                | 116.42               |                      | 83.40                | 62.63                |

**Table B-6 Asphalt B-M Mix Cont.**

| Contract # | 3366                 | 3701                 | 3707                 | 3717                 | 4251                 | 4298                 | 4687                 | 4738                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Weakley              | Madison              | Rhea                 | Davidson             | Williamson           | Hancock              | Bradley              | Weakley              |
| Region     | 4                    | 4                    | 2                    | 3                    | 3                    | 1                    | 2                    | 4                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 24         | 70.13                | 134.13               | 90.65                | 77.33                | 119.62               |                      | 84.17                | 63.83                |
| 25         | 72.23                |                      | 91.78                | 77.55                | 123.65               |                      | 86.07                | 63.92                |
| 26         | 74.37                |                      | 92.03                | 80.65                | 148.05               |                      | 87.97                | 64.23                |
| 27         | 75.33                |                      | 92.51                | 80.97                | 148.43               |                      | 87.98                | 64.33                |
| 28         | 75.58                |                      | 92.97                | 81.13                |                      |                      | 89.77                | 66.55                |
| 29         | 75.80                |                      | 93.05                | 81.17                |                      |                      | 89.93                | 66.67                |
| 30         | 76.10                |                      | 93.57                | 82.40                |                      |                      | 90.72                | 68.08                |
| 31         | 76.97                |                      | 94.08                | 82.75                |                      |                      | 91.46                | 69.05                |
| 32         | 76.98                |                      | 94.60                | 83.19                |                      |                      | 93.23                | 69.27                |
| 33         | 77.55                |                      | 95.00                | 84.11                |                      |                      | 93.95                | 69.57                |
| 34         | 81.17                |                      | 96.23                | 84.65                |                      |                      | 94.56                | 77.32                |
| 35         | 82.37                |                      | 96.83                | 85.45                |                      |                      | 95.08                | 77.93                |
| 36         | 83.50                |                      | 96.92                | 85.82                |                      |                      | 95.58                | 81.02                |
| 37         | 84.13                |                      | 98.18                | 85.97                |                      |                      | 96.93                | 81.50                |
| 38         | 101.52               |                      | 99.52                | 86.78                |                      |                      | 97.22                | 83.65                |
| 39         |                      |                      | 100.53               | 86.83                |                      |                      | 99.24                | 84.48                |
| 40         |                      |                      | 101.87               | 89.03                |                      |                      | 99.45                | 85.37                |
| 41         |                      |                      | 103.50               | 89.42                |                      |                      | 100.82               | 86.22                |
| 42         |                      |                      | 103.86               | 89.73                |                      |                      | 101.05               | 86.37                |
| 43         |                      |                      | 104.38               | 90.33                |                      |                      | 101.20               |                      |
| 44         |                      |                      | 104.67               | 90.62                |                      |                      | 104.20               |                      |
| 45         |                      |                      | 117.56               | 91.67                |                      |                      | 106.37               |                      |
| 46         |                      |                      | 138.28               | 94.17                |                      |                      | 108.78               |                      |

**Table B-6 Asphalt B-M Mix Cont.**

| Contract # | 3366                 | 3701                 | 3707                 | 3717                 | 4251                 | 4298                 | 4687                 | 4738                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Weakley              | Madison              | Rhea                 | Davidson             | Williamson           | Hancock              | Bradley              | Weakley              |
| Region     | 4                    | 4                    | 2                    | 3                    | 3                    | 1                    | 2                    | 4                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 47         |                      |                      |                      | 94.40                |                      |                      | 113.97               |                      |
| 48         |                      |                      |                      | 95.53                |                      |                      | 114.18               |                      |
| 49         |                      |                      |                      | 96.65                |                      |                      | 118.43               |                      |
| 50         |                      |                      |                      | 97.05                |                      |                      | 118.85               |                      |
| 51         |                      |                      |                      | 97.88                |                      |                      | 123.23               |                      |
| 52         |                      |                      |                      | 100.42               |                      |                      | 129.37               |                      |
| 53         |                      |                      |                      | 102.87               |                      |                      | 138.48               |                      |
| 54         |                      |                      |                      | 103.42               |                      |                      |                      |                      |
| 55         |                      |                      |                      | 104.33               |                      |                      |                      |                      |
| 56         |                      |                      |                      | 104.53               |                      |                      |                      |                      |
| 57         |                      |                      |                      | 104.68               |                      |                      |                      |                      |
| 58         |                      |                      |                      | 105.67               |                      |                      |                      |                      |
| 59         |                      |                      |                      | 106.12               |                      |                      |                      |                      |
| 60         |                      |                      |                      | 106.27               |                      |                      |                      |                      |
| 61         |                      |                      |                      | 106.40               |                      |                      |                      |                      |
| 62         |                      |                      |                      | 108.05               |                      |                      |                      |                      |
| 63         |                      |                      |                      | 110.28               |                      |                      |                      |                      |
| 64         |                      |                      |                      | 111.37               |                      |                      |                      |                      |
| 65         |                      |                      |                      | 113.20               |                      |                      |                      |                      |
| 66         |                      |                      |                      | 114.67               |                      |                      |                      |                      |
| 67         |                      |                      |                      | 115.43               |                      |                      |                      |                      |
| 68         |                      |                      |                      | 132.68               |                      |                      |                      |                      |

**Table B-6 Asphalt B-M Mix Cont.**

|            |            |            |            |            |            |            |            |            |
|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Contract # | 3366       | 3701       | 3707       | 3717       | 4251       | 4298       | 4687       | 4738       |
| County     | Weakley    | Madison    | Rhea       | Davidson   | Williamson | Hancock    | Bradley    | Weakley    |
| Region     | 4          | 4          | 2          | 3          | 3          | 1          | 2          | 4          |
|            | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time |
|            | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     |
|            |            |            |            |            |            |            |            |            |
| Count      | 38         | 24         | 46         | 68         | 27         | 22         | 53         | 42         |
| Mean       | 68.42      | 85.28      | 92.45      | 83.72      | 107.16     | 155.24     | 91.21      | 65.22      |
| Std.Dev.   | 10.13      | 22.91      | 10.84      | 20.47      | 14.77      | 21.37      | 16.12      | 10.34      |
| X+S        | 78.55      | 108.19     | 103.29     | 104.19     | 111.93     | 126.61     | 107.33     | 75.56      |
| XND        | 68.42      | 85.28      | 92.45      | 83.72      | 107.16     | 155.24     | 91.21      | 60.97      |
| SND        | 10.13      | 22.91      | 10.84      | 20.47      | 14.77      | 21.37      | 16.12      | 5.74       |

**Table B-7 Asphalt D Mix**

| Contract # | 3707                 | 4180                 | 4286                 | 4355                 | 4400                 | 4660                 | 4687                 | 4722                 | 4740                 | 4815                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Rhea                 | Grainger             | Dyer                 | Gibson               | Sevier               | Obion                | McMinn               | Robertson            | Williamson           | Cheatham             |
| Region     | 2                    | 1                    | 4                    | 4                    | 1                    | 4                    | 2                    | 3                    | 3                    | 3                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 1          | 70.50                | 82.67                | 41.45                | 110.28               | 55.05                | 54.35                | 68.67                | 64.88                | 35.37                | 64.47                |
| 2          | 70.80                | 85.70                | 43.65                | 124.03               | 55.83                | 55.88                | 71.03                | 65.83                | 35.45                | 67.08                |
| 3          | 70.95                | 85.93                | 46.10                | 126.73               | 56.18                | 57.88                | 72.45                | 66.8                 | 36.25                | 69.68                |
| 4          | 71.18                | 87.33                | 46.52                | 128.18               | 56.33                | 60.58                | 78.77                | 71.27                | 37.33                | 72.33                |
| 5          | 72.13                | 87.50                | 47.03                | 130.77               | 57.03                | 62.07                | 82.30                | 71.68                | 37.70                | 72.50                |
| 6          | 72.15                | 87.50                | 47.05                | 133.00               | 58.43                | 65.75                | 82.60                | 73.82                | 37.85                | 73.10                |
| 7          | 72.47                | 88.95                | 49.37                | 136.07               | 59.00                | 66.90                | 82.82                | 75.33                | 38.02                | 74.40                |
| 8          | 72.58                | 89.33                | 49.50                | 136.82               | 59.87                | 73.40                | 83.35                | 75.75                | 38.38                | 74.75                |
| 9          | 73.22                | 92.50                | 50.28                | 139.13               | 60.00                | 74.87                | 86.67                | 78.65                | 38.97                | 74.82                |
| 10         | 73.90                | 92.83                | 50.32                | 139.83               | 60.00                | 75.00                | 87.90                | 79.07                | 39.45                | 76.17                |
| 11         | 73.92                | 95.65                | 50.43                | 139.85               | 60.95                | 75.22                | 88.02                | 79.35                | 39.95                | 76.47                |
| 12         | 74.28                | 95.67                | 50.58                | 140.33               | 60.97                | 75.25                | 92.78                | 79.53                | 40.37                | 76.52                |
| 13         | 74.93                | 102.82               | 51.13                | 140.93               | 60.97                | 75.38                | 93.13                | 79.72                | 41.00                | 76.53                |
| 14         | 75.10                | 109.97               | 51.25                | 148.07               | 61.18                | 76.17                | 94.13                | 81.38                | 41.17                | 76.83                |
| 15         | 75.20                | 111.67               | 51.25                | 148.82               | 61.43                | 76.22                | 96.05                | 82                   | 41.72                | 77.83                |
| 16         | 75.72                | 113.67               | 51.43                | 151.48               | 62.83                | 76.73                | 96.62                | 82.15                | 42.17                | 78.37                |
| 17         | 76.10                | 117.70               | 51.68                | 160.32               | 63.13                | 77.53                | 98.03                | 82.2                 | 42.17                | 78.67                |
| 18         | 76.15                | 120.67               | 51.88                |                      | 64.50                | 77.98                | 98.22                | 82.3                 | 42.95                | 79.40                |
| 19         | 76.48                | 123.68               | 51.97                |                      | 65.32                | 79.58                | 98.55                | 83.05                | 43.50                | 79.53                |
| 20         | 76.52                | 141.97               | 51.98                |                      | 65.50                | 79.70                | 98.88                | 83.43                | 44.63                | 80.05                |
| 21         | 76.65                |                      | 52.20                |                      | 65.58                | 80.23                | 100.85               | 83.45                | 44.75                | 80.67                |
| 22         | 77.05                |                      | 52.27                |                      | 66.97                | 80.82                | 102.17               | 83.55                | 44.88                | 81.20                |
| 23         | 77.17                |                      | 52.33                |                      | 67.67                | 81.93                | 102.33               | 83.63                | 44.92                | 81.42                |

Table B-7 Asphalt D Mix Cont.

| Contract # | 3707                 | 4180                 | 4286                 | 4355                 | 4400                 | 4660                 | 4687                 | 4722                 | 4740                 | 4815                 |
|------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|----------------------|
| County     | Rhea                 | Grainger             | Dyer                 | Gibson               | Sevier               | Obion                | McMinn               | Robertson            | Williamson           | Cheatham             |
| Region     | 2                    | 1                    | 4                    | 4                    | 1                    | 4                    | 2                    | 3                    | 3                    | 3                    |
|            | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) | Cycle Time<br>(Min.) |
| 24         | 77.23                |                      | 52.58                |                      | 68.50                | 82.03                | 104.15               | 83.97                | 45.17                | 81.48                |
| 25         | 77.62                |                      | 52.60                |                      | 69.18                | 82.42                | 104.77               | 84.38                | 45.22                | 82.05                |
| 26         | 78.03                |                      | 52.70                |                      | 69.37                | 83.25                | 105.40               | 84.48                | 45.27                | 82.55                |
| 27         | 78.15                |                      | 52.70                |                      | 69.95                | 83.38                | 106.20               | 84.97                | 46.00                | 82.93                |
| 28         | 78.55                |                      | 52.93                |                      | 69.97                | 83.75                | 108.67               | 86.5                 | 46.33                | 83.32                |
| 29         | 78.85                |                      | 53.08                |                      | 70.00                | 83.92                | 111.12               | 87.22                | 47.57                | 83.38                |
| 30         | 78.97                |                      | 53.20                |                      | 70.18                | 85.33                | 111.15               | 87.6                 | 47.83                | 83.50                |
| 31         | 79.10                |                      | 53.25                |                      | 71.53                | 85.33                | 112.62               | 88                   | 47.87                | 83.67                |
| 32         | 79.12                |                      | 53.33                |                      | 72.33                | 86.77                | 113.33               | 88.03                | 48.80                | 84.80                |
| 33         | 79.17                |                      | 53.72                |                      | 72.47                | 88.25                | 113.47               | 88.13                | 48.92                | 84.83                |
| 34         | 79.33                |                      | 53.78                |                      | 73.18                | 89.40                | 114.78               | 88.45                | 48.95                | 85.27                |
| 35         | 79.70                |                      | 53.80                |                      | 73.33                | 91.38                | 114.80               | 88.78                | 49.83                | 86.37                |
| 36         | 80.22                |                      | 54.27                |                      | 73.67                | 91.60                | 116.55               | 88.95                | 50.22                | 86.58                |
| 37         | 81.55                |                      | 54.43                |                      | 75.18                | 92.93                | 117.25               | 89.15                | 50.75                | 86.62                |
| 38         | 81.62                |                      | 54.58                |                      | 76.00                | 96.18                | 117.47               | 89.3                 | 52.25                | 86.65                |
| 39         | 82.03                |                      | 54.60                |                      | 76.58                | 96.65                | 117.50               | 89.52                | 54.00                | 87.08                |
| 40         | 82.50                |                      | 55.07                |                      | 76.75                | 99.75                | 117.85               | 89.57                | 54.50                | 87.12                |
| 41         | 82.50                |                      | 55.58                |                      | 77.00                | 109.13               | 117.90               | 89.65                | 55.50                | 87.92                |
| 42         | 83.22                |                      | 55.78                |                      | 77.60                | 111.92               | 118.45               | 90.07                | 56.65                | 88.03                |
| 43         | 83.62                |                      | 56.12                |                      | 77.63                | 114.25               | 120.07               | 90.77                | 57.00                | 88.75                |
| 44         | 83.72                |                      | 56.82                |                      | 77.80                | 115.65               | 122.55               | 90.78                | 59.38                | 88.83                |
| 45         | 83.72                |                      | 58.12                |                      | 78.15                | 120.28               | 124.95               | 90.8                 | 60.85                | 89.25                |

Table B-7 Asphalt D Mix Cont.

| Contract # | 3707       | 4180       | 4286       | 4355       | 4400       | 4660       | 4687       | 4722       | 4740       | 4815       |
|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| County     | Rhea       | Grainger   | Dyer       | Gibson     | Sevier     | Obion      | McMinn     | Robertson  | Williamson | Cheatham   |
| Region     | 2          | 1          | 4          | 4          | 1          | 4          | 2          | 3          | 3          | 3          |
|            | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time | Cycle Time |
|            | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     | (Min.)     |
| 46         | 84.08      |            | 59.63      |            | 78.33      | 121.33     | 127.45     | 90.87      | 62.67      | 89.27      |
| 47         | 85.12      |            | 60.72      |            | 80.03      | 125.72     | 134.25     | 91.59      | 63.25      | 89.42      |
| 48         | 85.32      |            | 63.37      |            | 80.07      | 130.20     | 153.43     | 91.63      | 63.57      | 89.53      |
| 49         | 85.53      |            |            |            | 80.40      |            |            | 92.88      | 66.03      | 89.58      |
| 50         | 85.75      |            |            |            | 90.67      |            |            | 93.02      | 68.83      | 90.17      |
| 51         | 85.82      |            |            |            |            |            |            | 94.37      | 69.75      | 90.63      |
| 52         | 85.90      |            |            |            |            |            |            | 94.58      | 70.08      | 90.90      |
| 53         | 88.72      |            |            |            |            |            |            | 94.92      | 74.87      | 91.83      |
| 54         | 90.33      |            |            |            |            |            |            | 95         | 75.78      | 93.35      |
| 55         | 90.40      |            |            |            |            |            |            | 95.48      | 76.20      | 95.57      |
| 56         | 92.38      |            |            |            |            |            |            | 97.17      | 78.95      | 97.88      |
| 57         | 95.22      |            |            |            |            |            |            | 97.22      | 79.57      | 101.48     |
| 58         | 95.22      |            |            |            |            |            |            | 97.48      | 80.47      | 115.67     |
| 59         | 100.62     |            |            |            |            |            |            | 97.98      |            | 119.25     |
| 60         |            |            |            |            |            |            |            | 98.85      |            | 119.35     |
| 61         |            |            |            |            |            |            |            | 98.92      |            |            |
| 62         |            |            |            |            |            |            |            | 100.82     |            |            |
| 63         |            |            |            |            |            |            |            | 103.93     |            |            |
| 64         |            |            |            |            |            |            |            | 104.05     |            |            |
| 65         |            |            |            |            |            |            |            | 105.44     |            |            |
| 66         |            |            |            |            |            |            |            | 106.02     |            |            |
| 67         |            |            |            |            |            |            |            | 106.38     |            |            |



**Table B-8. Cycle Times ,Mean,Standard Deviation for  
Concrete Pavement( Ramp)**

| <b>Contract#</b>     | 3701                  | 4017                  | 4017                  | 3145                  | 4044                  |
|----------------------|-----------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| <b>County</b>        | Madison               | Davidson              | Davidson              | Carrol                | Roane                 |
| <b>Region</b>        | IV                    | III                   | III                   | IV                    | I                     |
| <b>Cycle #</b>       | Cycle Times<br>(Min.) | Cycle Times<br>(Min.) | Cycle Times<br>(Min.) | Cycle Times<br>(Min.) | Cycle Times<br>(Min.) |
| 1                    | 45.91                 | 40.32                 | 39.45                 | 45.42                 | 62.08                 |
| 2                    | 50.42                 | 41.14                 | 42.15                 | 48.32                 | 59.33                 |
| 3                    | 47.14                 | 51.62                 | 39.40                 | 52.10                 | 68.14                 |
| 4                    | 46.32                 | 43.19                 | 41.08                 | 70.12                 | 64.43                 |
| 5                    | 50.06                 | 36.31                 | 49.13                 | 43.16                 | 68.93                 |
| 6                    | 47.32                 | 39.44                 | 55.91                 | 38.08                 | 54.44                 |
| 7                    |                       | 38.44                 | 44.09                 | 44.24                 | 69.06                 |
| 8                    |                       | 37.09                 | 52.30                 | 38.81                 | 58.14                 |
| 9                    |                       | 39.02                 | 58.14                 | 42.10                 | 68.44                 |
| 10                   |                       | 40.00                 |                       |                       | 71.14                 |
| 11                   |                       | 44.66                 |                       |                       | 73.08                 |
| 12                   |                       | 45.38                 |                       |                       |                       |
| 13                   |                       | 58.14                 |                       |                       |                       |
|                      |                       |                       |                       |                       |                       |
| <b>Mean</b>          | 47.86                 | 42.67                 | 46.85                 | 48.36                 | 65.20                 |
| <b>standard dev.</b> | 1.92                  | 6.19                  | 7.23                  | 9.73                  | 5.96                  |
| <b>Mean-stdev.</b>   | 45.94                 | 36.49                 | 39.62                 | 38.63                 | 59.24                 |

\* Use the 5% lowest cycle times for determining P<sub>max</sub>

**Table B-9. Cycle Times ,Mean,Standerd Deviation for driving steel piles**

| <b>Contract#</b>   | 3564                  | 4214                  | 3571                  | 4334                  |
|--------------------|-----------------------|-----------------------|-----------------------|-----------------------|
| <b>County</b>      | Grainger              | Knox                  | Knox                  | Wayne                 |
| <b>Region</b>      | I                     | I                     | I                     | III                   |
| <b>Cycle #</b>     | Cycle Times<br>(Min.) | Cycle Times<br>(Min.) | Cycle Times<br>(Min.) | Cycle Times<br>(Min.) |
| 1                  | 38.11                 | 38.75                 | 41.06                 | 55.16                 |
| 2                  | 37.26                 | 37.53                 | 44.10                 | 52.33                 |
| 3                  | 35.83                 | 36.07                 | 41.14                 | 56.24                 |
| 4                  | 33.06                 | 37.83                 | 42.50                 | 62.10                 |
| 5                  | 37.33                 | 37.83                 | 56.11                 | 59.34                 |
| 6                  | 40.50                 | 37.60                 | 51.30                 | 54.38                 |
| 7                  | 40.33                 | 35.75                 | 57.11                 | 61.08                 |
| 8                  | 40.08                 | 36.65                 | 45.33                 | 61.10                 |
| 9                  | 38.02                 | 36.43                 | 42.07                 | 49.38                 |
| 10                 | 42.88                 | 36.28                 | 43.51                 | 48.41                 |
| 11                 | 36.30                 | 37.25                 | 52.30                 | 55.11                 |
| 12                 | 72.87                 | 35.90                 | 60.10                 | 61.71                 |
| 13                 | 38.80                 | 36.91                 | 36.19                 | 64.08                 |
| 14                 | 37.70                 |                       | 49.21                 | 44.81                 |
| 15                 | 41.63                 |                       | 44.34                 | 48.52                 |
| 16                 | 34.87                 |                       | 48.47                 | 63.10                 |
| 17                 | 35.68                 |                       | 43.06                 | 41.06                 |
| 18                 | 36.00                 |                       |                       | 49.71                 |
| 19                 | 37.60                 |                       |                       | 45.75                 |
| 20                 | 39.55                 |                       |                       | 49.71                 |
| 21                 |                       |                       |                       | 42.10                 |
| 22                 |                       |                       |                       | 46.13                 |
| 23                 |                       |                       |                       | 61.44                 |
| 24                 |                       |                       |                       | 52.08                 |
|                    |                       |                       |                       |                       |
| <b>Mean</b>        | 39.72                 | 36.98                 | 46.94                 | 54.15                 |
| <b>stdev.</b>      | 8.16                  | 0.90                  | 6.55                  | 6.84                  |
| <b>Mean-stdev.</b> | 31.56 (33.06)*        | 36.08                 | 40.38                 | 47.32                 |

\* Use the 5% lowest cycle times for determining P<sub>max</sub>

**APPENDIX C**

**MEAN OF PROCESSOR CYCLE TIMES  
FOR NINE HIGHWAY CONSTRUCTION TASKS**

## APPENDIX C

### Mean of Processor Cycle Times for Nine Highway Construction Tasks

Table C-1. Mean Processor Cycle Times for Road and Drainage Excavation

|         | Region # | Contract # | County     | Mean Processor Cycle Times |
|---------|----------|------------|------------|----------------------------|
| 1       | 1        | 3564       | Grainger   | 5.70                       |
| 2       | 1        | 3564-2     | Grainger   | 2.25                       |
| 3       | 1        | 4123       | Knox       | 2.38                       |
| 4       | 2        | 4384       | McMinn     | 1.44                       |
| 5       | 2        | 4410       | White      | 2.34                       |
| 6       | 2        | 3926       | Rhea       | 1.64                       |
| 7       | 3        | 3556       | Davidson   | 3.83                       |
| 8       | 3        | 4251       | Williamson | 1.70                       |
| 9       | 3        | 3948       | Davidson   | 3.67                       |
| 10      | 4        | 3915       | Henderson  | 1.04                       |
| 11      | 4        | 4572       | Weakley    | 1.06                       |
| 12      | 4        | 4696       | Fayette    | 1.76                       |
| Average |          |            |            | 2.40                       |

Table C-2. Mean Processor Cycle Times for Borrow Excavation

| #       | Region # | Contract # | County    | Mean Processor Cycle Times |
|---------|----------|------------|-----------|----------------------------|
| 1       | 2        | 3866       | Marion    | 1.86                       |
| 2       | 3        | 4017       | Davidson  | 2.07                       |
| 3       | 3        | 3948       | Davidson  | 4.24                       |
| 4       | 3        | 4723       | Robertson | 2.93                       |
| 5       | 4        | 3502       | Carroll   | 1.85                       |
| 6       | 4        | 3863       | McNairy   | 1.29                       |
| 7       | 4        | 4224       | Fayette   | 1                          |
| Average |          |            |           | 2.18                       |

Table C-3. Mean Processor Cycle Times for Mineral Aggregate

| #              | Region # | Contract # | County     | Mean Processor Cycle Times |
|----------------|----------|------------|------------|----------------------------|
| 1              | 1        | 4044       | Roane      | 6.16                       |
| 2              | 1        | 3564       | Grainger   | 3.54                       |
| 3              | 1        | 2440       | Knox       | 3.27                       |
| 4              | 2        | 3707       | Rhea       | 3.37                       |
| 5              | 2        | 4160       | White      | 3.45                       |
| 6              | 2        | 3866       | Marion     | 3.79                       |
| 7              | 3        | 4251       | Williamson | 3.14                       |
| 8              | 3        | 4017       | Davidson   | 4.01                       |
| 9              | 4        | 3915       | Henderson  | 3.58                       |
| 10             | 4        | 4699       | Henderson  | 3.75                       |
| <b>Average</b> |          |            |            | <b>3.81</b>                |

Table C-4. Mean Processor Cycle Times for Asphalt A-S Mix

|                | Region # | Contract # | County     | Mean Processor Cycle Times |
|----------------|----------|------------|------------|----------------------------|
| 1              | 2        | 3707       | Rhea       | 3.25                       |
| 2              | 3        | 3935       | Sumner     | 2.69                       |
| 3              | 3        | 4251       | Williamson | 2.76                       |
| 4              | 4        | 3145       | Weakley    | 4.47                       |
| 5              | 4        | 3721       | McNairy    | 2.93                       |
| 6              | 4        | 4224       | Fayette    | 4.74                       |
| <b>Average</b> |          |            |            | <b>3.47</b>                |

Table C-5. Mean Processor Cycle Times for Asphalt A Mix

|         | Region # | Contract # | County   | Mean Processor Cycle Times |
|---------|----------|------------|----------|----------------------------|
| 1       | 1        | 4123       | Knox     | 2.27                       |
| 2       | 2        | 3707       | Rhea     | 2.5                        |
| 3       | 2        | 4160       | White    | 3.08                       |
| 4       | 3        | 3428       | Cheatham | 2.17                       |
| 5       | 3        | 3935       | Sumner   | 2.54                       |
| 6       | 4        | 4729       | Shelby   | 2.74                       |
| 7       | 4        | 3701       | Madison  | 4.11                       |
| Average |          |            |          | 2.77                       |

Table C-6. Mean Processor Cycle Times for Asphalt B-M Mix

|         | Region # | Contract # | County     | Mean Processor Cycle Times |
|---------|----------|------------|------------|----------------------------|
| 1       | 1        | 4298       | Hancock    | 4.43                       |
| 2       | 2        | 4687       | McMinn     | 4.28                       |
| 3       | 2        | 3707       | Rhea       | 5.11                       |
| 4       | 3        | 4017       | Davidson   | 5.87                       |
| 5       | 3        | 4251       | Williamson | 3.69                       |
| 6       | 4        | 3366       | Weakley    | 7.17                       |
| 7       | 4        | 4738       | Weakley    | 7.54                       |
| 8       | 4        | 3701       | Madison    | 6.35                       |
| Average |          |            |            | 5.56                       |

Table C-7. Mean Processor Cycle Times for Asphalt D Mix

|         | Region # | Contract # | County     | Mean Processor Cycle Times |
|---------|----------|------------|------------|----------------------------|
| 1       | 1        | 4180       | Gainger    | 3.92                       |
| 2       | 1        | 4400       | Sevier     | 4.02                       |
| 3       | 2        | 4687       | McMinn     | 3.89                       |
| 4       | 2        | 3707       | Rhea       | 6.47                       |
| 5       | 3        | 4815       | Cheatham   | 3.62                       |
| 6       | 3        | 4740       | Williamson | 6.57                       |
| 7       | 3        | 4722       | Robertson  | 4.6                        |
| 8       | 4        | 4660       | Obion      | 8.74                       |
| 9       | 4        | 4286       | Dyer       | 7.86                       |
| 10      | 4        | 4355       | Gibson     | 8.15                       |
| Average |          |            |            | 5.78                       |

Table C-8. Mean Processor Cycle Times for Concrete Pavement (Ramp)

|         | Region # | Contract # | County   | Mean Processor Cycle Times |
|---------|----------|------------|----------|----------------------------|
| 1       | 4        | 3701       | Madison  | 45.94                      |
| 2       | 3        | 4017       | Davidson | 36.49                      |
| 3       | 3        | 4017       | Davidson | 39.62                      |
| 4       | 4        | 3145       | Carroll  | 38.63                      |
| 5       | 1        | 4044       | Rooane   | 59.24                      |
| Average |          |            |          | 43.98                      |

Table C-9. Mean Processor Cycle Times for Driving Steel Piles

|         | Region # | Contract # | County   | Mean Processor Cycle Times |
|---------|----------|------------|----------|----------------------------|
| 1       | 1        | 3564       | Grainger | 33.06                      |
| 2       | 1        | 4214       | Knox     | 36.08                      |
| 3       | 1        | 3571       | Knox     | 40.38                      |
| 4       | 3        | 4334       | Wayne    | 47.32                      |
| Average |          |            |          | 39.21                      |

Table C-10 Statistical Summary of Data Sample for A  
Processor Cycle Times for Mineral Aggregate Task

| Contract # 4017                  |                  | County Davidson |                  |
|----------------------------------|------------------|-----------------|------------------|
| Cycle Number                     | Cycle Time (min) | Cycle Number    | Cycle Time (min) |
| 1                                | 4.30             | 18              | 3.42             |
| 2                                | 4.25             | 19              | 3.43             |
| 3                                | 3.02             | 20              | 3.85             |
| 4                                | 2.85             | 21              | 3.22             |
| 5                                | 3.15             | 22              | 2.93             |
| 6                                | 3.07             | 23              | 3.02             |
| 7                                | 2.98             | 24              | 5.75             |
| 8                                | 2.92             | 25              | 5.53             |
| 9                                | 3.05             | 26              | 4.43             |
| 10                               | 2.85             | 27              | 6.75             |
| 11                               | 2.95             | 28              | 5.43             |
| 12                               | 2.98             | 29              | 6.75             |
| 13                               | 2.97             | 30              | 6.30             |
| 14                               | 3.30             | 31              | 6.93             |
| 15                               | 3.68             | 32              | 4.77             |
| 16                               | 3.57             | 33              | 6.60             |
| 17                               | 4.30             | 34              | 4.60             |
|                                  |                  |                 |                  |
| Mean of Cycle Times of Processor |                  |                 | <b>4.01</b>      |
| Standard Deviation               |                  |                 | <b>1.28</b>      |

**APPENDIX D**

**SUMMARY CALCULATIONS FOR  $T_{0.95}$  FOR NINE HIGHWAY  
CONSTRUCTION TASKS**

## APPENDIX D

### T95% Calculation for Nine Tasks

Table D-1. T95 % Calculations for Road and Drainage Excavation

| #  | Region # | Contract # | County     | $\gamma$ Non-Delay | $\zeta$ Non-Delay | $\gamma$ Delay | $\zeta$ Delay | Mean Non-Delay Cycle Time (minutes) | Mean Delay Cycle Time (minutes) | Fraction Non-Delay | Fraction Delay | T <sub>95</sub> (Minutes) |
|----|----------|------------|------------|--------------------|-------------------|----------------|---------------|-------------------------------------|---------------------------------|--------------------|----------------|---------------------------|
| 1  | 1        | 3564       | Grainger   | 3.115              | 0.161             | -              | -             | 22.82                               | -                               | 1.00               | -              | 29.34                     |
| 2  | 1        | 3564-2     | Grainger   | 2.222              | 0.162             | -              | -             | 9.35                                | -                               | 1.00               | -              | 12.04                     |
| 3  | 1        | 4123       | Knox       | 3.959              | 0.283             | -              | -             | 54.46                               | -                               | 1.00               | -              | 83.54                     |
| 4  | 2        | 4384       | McMinn     | 1.250              | 0.281             | -              | -             | 3.63                                | -                               | 1.00               | -              | 5.54                      |
| 5  | 2        | 4410       | White      | 2.388              | 0.172             | -              | -             | 11.05                               | -                               | 1.00               | -              | 14.44                     |
| 6  | 2        | 3926       | Rhea       | 2.386              | 0.286             | -              | -             | 11.32                               | -                               | 1.00               | -              | 17.38                     |
| 7  | 3        | 3556       | Davidson   | 3.014              | 0.645             | -              | -             | 25.07                               | -                               | 1.00               | -              | 58.83                     |
| 8  | 3        | 4251       | Williamson | 3.514              | 0.407             | -              | -             | 36.47                               | -                               | 1.00               | -              | 65.53                     |
| 9  | 3        | 3948       | Davidson   | 1.856              | 0.116             | -              | -             | 6.44                                | -                               | 1.00               | -              | 7.74                      |
| 10 | 4        | 3915       | Henderson  | 2.288              | 0.328             | -              | -             | 10.40                               | -                               | 1.00               | -              | 16.91                     |
| 11 | 4        | 4572       | Weakley    | 2.756              | 0.173             | -              | -             | 15.98                               | -                               | 1.00               | -              | 20.91                     |
| 12 | 4        | 4696       | Fayette    | 1.490              | 0.444             | -              | -             | 4.90                                | -                               | 1.00               | -              | 9.22                      |

Table D-2. T95 % Calculations for Borrow Excavation

| # | Region # | Contract # | County    | $\gamma$ Non-Delay | $\zeta$ Non-Delay | $\gamma$ Delay | $\zeta$ Delay | Mean Non-Delay Cycle Time (minutes) | Mean Delay Cycle Time (minutes) | Fraction Non-Delay | Fraction Delay | T <sub>95</sub> (Minutes) |
|---|----------|------------|-----------|--------------------|-------------------|----------------|---------------|-------------------------------------|---------------------------------|--------------------|----------------|---------------------------|
| 1 | 2        | 3866       | Marion    | 3.328              | 0.109             | 4.219          | 0.142         | 28.06                               | 68.68                           | 0.82               | 0.18           | 42.69                     |
| 2 | 3        | 4017       | Davidson  | 3.674              | 0.344             |                |               | 41.83                               |                                 | 1.00               |                | 69.45                     |
| 3 | 3        | 3948       | Davidson  | 2.131              | 0.903             |                |               | 12.66                               |                                 | 1.00               |                | 37.19                     |
| 4 | 3        | 4723       | Robertson | 2.360              | 0.089             | 2.997          | 0.273         | 10.63                               | 20.79                           | 0.94               | 0.06           | 13.41                     |
| 5 | 4        | 3502       | Carroll   | 3.077              | 0.388             |                |               | 23.40                               |                                 |                    |                | 41.10                     |
| 6 | 4        | 3863       | McNairy   | 2.795              | 0.136             | 4.045          | 0.094         | 16.52                               | 57.36                           | 0.92               | 0.08           | 24.02                     |
| 7 | 4        | 4224       | Fayette   | 2.775              | 0.206             | 3.994          | 0.175         | 20.37                               | 55.13                           | 0.90               | 0.10           | 27.65                     |

Table D-3. T95 % Calculations for Mineral Aggregate

| #  | Region # | Contract # | County     | $\gamma$ Non-Delay | $\zeta$ Non-Delay | $\gamma$ Delay | $\zeta$ Delay | Mean Non-Delay Cycle Time (minutes) | Mean Delay Cycle Time (minutes) | Fraction Non-Delay | Fraction Delay | T <sub>95</sub> (Minutes) |
|----|----------|------------|------------|--------------------|-------------------|----------------|---------------|-------------------------------------|---------------------------------|--------------------|----------------|---------------------------|
| 1  | 1        | 4044       | Roane      | 3.7839726          | 0.274             | -              | -             | 45.67                               | -                               | 1.00               | -              | 69.01                     |
| 2  | 1        | 3564       | Grainger   | 3.051              | 0.136             | 3.631          | 0.268         | 21.33                               | 39.11                           | 0.91               | 0.09           | 29.28                     |
| 3  | 1        | 2440       | Knox       | 3.831              | 0.129             | 4.511          | 0.215         | 46.48                               | 93.17                           | 0.87               | 0.13           | 66.39                     |
| 4  | 2        | 3866       | Marion     | 3.763              | 0.221             | -              | -             | 44.13                               | -                               | 1.00               | -              | 61.98                     |
| 5  | 2        | 3707       | Rhea       | 4.401              | 0.243             | 5.308          | 0.116         | 84.00                               | 203.30                          | 0.79               | 0.21           | 146.77                    |
| 6  | 2        | 4160       | White      | 3.620              | 0.134             | 4.119          | 0.157         | 37.67                               | 62.29                           | 0.88               | 0.12           | 50.57                     |
| 7  | 3        | 4017       | Davidson   | 4.009              | 0.2249519         | -              | -             | 56.49                               | -                               | 1.00               | -              | 79.74                     |
| 8  | 3        | 4251       | Williamson | 4.459              | 0.127             | 5.048          | 0.139         | 87.1                                | 157.26                          | 0.85               | 0.15           | 119.77                    |
| 9  | 4        | 4699       | Henderson  | 4.722              | 0.058             | -              | -             | 112.62                              | -                               | 1.00               | -              | 123.67                    |
| 10 | 4        | 3915       | Henderson  | 4.2376889          | 0.0457061         | -              | -             | 69.32                               | -                               | 1.00               | -              | 74.65                     |

Table D-4. T<sub>95</sub> % Calculation for Asphalt A-S Mix

| # | Region # | Contract # | County     | $\gamma$ Non-Delay | $\zeta$ Non-Delay | $\gamma$ Delay | $\zeta$ Delay | Mean Non-Delay Cycle Time (minutes) | Mean Delay Cycle Time (minutes) | Fraction of Non-Delay | Fraction Delay | T <sub>95</sub> (Minutes) |
|---|----------|------------|------------|--------------------|-------------------|----------------|---------------|-------------------------------------|---------------------------------|-----------------------|----------------|---------------------------|
| 1 | 2        | 3707       | Rhea       | 4.726              | 0.124             | -              | -             | 113.68                              | -                               | 1.00                  | -              | 138.39                    |
| 2 | 3        | 3935       | Sumner     | 4.132              | 0.143             | 4.702          | 0.167         | 62.92                               | 111.74                          | 0.84                  | 0.16           | 89.09                     |
| 3 | 3        | 4251       | Williamson | 4.547              | 0.077             | -              | -             | 94.62                               | -                               | 1.00                  | -              | 107.15                    |
| 4 | 4        | 3145       | Weakley    | 4.033              | 0.091             | -              | -             | 56.64                               | -                               | 1.00                  | -              | 65.54                     |
| 5 | 4        | 3721       | McNairy    | 4.476              | 0.188             | -              | -             | 89.44                               | -                               | 1.00                  | -              | 119.75                    |
| 6 | 4        | 4224       | Fayette    | 4.254              | 0.109             | -              | -             | 70.83                               | -                               | 1.00                  | -              | 84.18                     |

Table D-5. T95 % Calculations for Asphalt A-Mix

| # | Region # | Contract # | County   | $\gamma$ Non-Delay | $\zeta$ Non-Delay | $\gamma$ Delay | $\zeta$ Delay | Mean Non-Delay Cycle Time (minutes) | Mean Delay Cycle Time (minutes) | Fraction Non-Delay | Fraction Delay | T <sub>95</sub> (Minutes) |
|---|----------|------------|----------|--------------------|-------------------|----------------|---------------|-------------------------------------|---------------------------------|--------------------|----------------|---------------------------|
| 1 | 1        | 4123       | Knox     | 4.290              | 0.185             | -              | -             | 74.24                               | -                               | 1.00               | -              | 98.95                     |
| 2 | 2        | 3707       | Rhea     | 4.470              | 0.128             | -              | -             | 88.05                               | -                               | 1.00               | -              | 107.75                    |
| 3 | 2        | 4160       | White    | 3.857              | 0.074             | 4.278          | 0.264         | 47.46                               | 74.64                           | 0.95               | 0.05           | 56.25                     |
| 4 | 3        | 3428       | Cheatham | 4.500              | 0.238             | -              | -             | 92.58                               | -                               | 1.00               | -              | 133.04                    |
| 5 | 3        | 3935       | Sumner   | 4.158              | 0.144             | -              | -             | 64.62                               | -                               | 1.00               | -              | 81.02                     |
| 6 | 4        | 4729       | Shelby   | 4.748              | 0.131             | -              | -             | 116.36                              | -                               | 1.00               | -              | 143.09                    |
| 7 | 4        | 3701       | Madison  | 4.341              | 0.158             | -              | -             | 77.78                               | -                               | 1.00               | -              | 99.68                     |

Table D-6. T95 % Calculations for Asphalt B-M Mix

| # | Region # | Contract # | County     | $\gamma$ Non-Delay | $\zeta$ Non-Delay | $\gamma$ Delay | $\zeta$ Delay | Mean Non-Delay Cycle Time (minutes) | Mean Delay Cycle Time (minutes) | Fraction Non-Delay | Fraction Delay | T <sub>95</sub> (Minutes) |
|---|----------|------------|------------|--------------------|-------------------|----------------|---------------|-------------------------------------|---------------------------------|--------------------|----------------|---------------------------|
| 1 | 1        | 4298       | Hancock    | 5.036              | 0.137             | -              | -             | 155.24                              | -                               | 1.00               | -              | 192.67                    |
| 2 | 2        | 4687       | McMinn     | 4.498              | 0.175             | -              | -             | 91.21                               | -                               | 1.00               | -              | 119.85                    |
| 3 | 2        | 3707       | Rhea       | 4.520              | 0.117             | -              | -             | 92.45                               | -                               | 1.00               | -              | 111.28                    |
| 4 | 3        | 4017       | Davidson   | 4.398              | 0.241             | -              | -             | 83.72                               | -                               | 1.00               | -              | 120.88                    |
| 5 | 3        | 4251       | Williamson | 4.665              | 0.137             | -              | -             | 107.16                              | -                               | 1.00               | -              | 133.04                    |
| 6 | 4        | 3366       | Weakley    | 4.215              | 0.147             | -              | -             | 68.42                               | -                               | 1.00               | -              | 86.23                     |
| 7 | 4        | 4738       | Weakley    | 4.165              | 0.158             | -              | -             | 65.22                               | -                               | 1.00               | -              | 83.47                     |
| 8 | 4        | 3701       | Madison    | 4.411              | 0.264             | -              | -             | 85.28                               | -                               | 1.00               | -              | 127.14                    |

Table D-7. T95 % Calculations for Asphalt D-Mix

| #  | Region # | Contract # | County     | $\gamma$ Non-Delay | $\zeta$ Non-Delay | $\gamma$ Delay | $\zeta$ Delay | Mean Non-Delay Cycle Time (minutes) | Mean Delay Cycle Time (minutes) | Fraction Non-Delay | Fraction Delay | T <sub>95</sub> (Minutes) |
|----|----------|------------|------------|--------------------|-------------------|----------------|---------------|-------------------------------------|---------------------------------|--------------------|----------------|---------------------------|
| 1  | 1        | 4180       | Gainger    | 4.599              | 0.161             | -              | -             | 100.69                              | -                               | 1.00               | -              | 129.47                    |
| 2  | 1        | 4400       | Sevier     | 4.215              | 0.125             | -              | -             | 68.25                               | -                               | 1.00               | -              | 83.19                     |
| 3  | 2        | 4687       | McMinn     | 4.629              | 0.165             | -              | -             | 103.80                              | -                               | 1.00               | -              | 134.40                    |
| 4  | 2        | 3707       | Rhea       | 4.376              | 0.082             | -              | -             | 79.78                               | -                               | 1.00               | -              | 91.03                     |
| 5  | 3        | 4815       | Cheatham   | 4.432              | 0.125             | 4.994          | 0.077         | 84.79                               | 147.89                          | 0.91               | 0.09           | 109.09                    |
| 6  | 3        | 4740       | Williamson | 3.909              | 0.244             | -              | -             | 51.34                               | -                               | 1.00               | -              | 74.49                     |
| 7  | 3        | 4722       | Robertson  | 4.471              | 0.109             | 4.882          | 0.361         | 87.99                               | 140.82                          | 0.89               | 0.11           | 118.78                    |
| 8  | 4        | 4660       | Obion      | 4.428              | 0.209             | -              | -             | 85.63                               | -                               | 1.00               | -              | 118.20                    |
| 9  | 4        | 4286       | Dyer       | 3.957              | 0.075             | -              | -             | 52.47                               | -                               | 1.00               | -              | 59.19                     |
| 10 | 4        | 4355       | Gibson     | 4.846              | 0.231             | -              | -             | 130.65                              | -                               | 1.00               | -              | 185.88                    |

Table D-8. T95 % Calculations for Concrete Pavement (Ramp)

| # | Region # | Contract # | County   | $\gamma$ Non-Delay | $\zeta$ Non-Delay | $\gamma$ Delay | $\zeta$ Delay | Mean Non-Delay Cycle Time (minutes) | Mean Delay Cycle Time (minutes) | Fraction Non-Delay | Fraction Delay | T <sub>95%</sub> (Minutes) |
|---|----------|------------|----------|--------------------|-------------------|----------------|---------------|-------------------------------------|---------------------------------|--------------------|----------------|----------------------------|
| 1 | 4        | 3701       | Madison  | 3.867              | 0.0401            | -              | -             | 47.86                               | -                               | -                  | -              | 51.06                      |
| 2 | 3        | 4017       | Davidson | 3.743              | 0.1451            | -              | -             | 42.67                               | -                               | -                  | -              | 53.60                      |
| 3 | 3        | 4017       | Davidson | 3.835              | 0.1543            | -              | -             | 46.85                               | -                               | -                  | -              | 59.67                      |
| 4 | 4        | 3145       | Carroll  | 4.173              | 0.2012            | -              | -             | 48.36                               | -                               | -                  | -              | 65.98                      |
| 5 | 1        | 4044       | roane    |                    | 0.0914            | -              | -             | 65.20                               | -                               | -                  | -              | 75.46                      |

Table D-9. T95 % Calculations for Driving Steel Piles

| # | Region # | Contract # | County   | $\gamma$ Non-Delay | $\zeta$ Non-Delay | $\gamma$ Delay | $\zeta$ Delay | Mean Non-Delay Cycle Time (minutes) | Mean Delay Cycle Time (minutes) | Fraction Non-Delay | Fraction Delay | T <sub>95%</sub> (Minutes) |
|---|----------|------------|----------|--------------------|-------------------|----------------|---------------|-------------------------------------|---------------------------------|--------------------|----------------|----------------------------|
| 1 | 1        | 3564       | Grainger | 3.661              | 0.2054            | -              | -             | 39.72                               | -                               | -                  | -              | 54.52                      |
| 2 | 1        | 4214       | Knox     | 3.610              | 0.0243            | -              | -             | 36.98                               | -                               | -                  | -              | 38.48                      |
| 3 | 1        | 3571       | Knox     | 3.839              | 0.1395            | -              | -             | 46.40                               | -                               | -                  | -              | 58.47                      |
| 4 | 3        | 4334       | Wayne    | 3.984              | 0.1263            | -              | -             | 54.15                               | -                               | -                  | -              | 66.12                      |

**APPENDIX E**

**LIST OF RESOURCES FOR NINE  
HIGHWAY CONSTRUCTION TASKS**

## APPENDIX E

### List of Resources for Nine Highway Construction Tasks

**Table E-1 Project Resources**

| <b>TASK ONE</b>            | <b>ITEM # : 203-01</b>                                                  |                                                                |
|----------------------------|-------------------------------------------------------------------------|----------------------------------------------------------------|
|                            | <b>Description: Road and Drainage Excavation</b>                        |                                                                |
| <b>Contract # : 3564</b>   | <b>County : Grainger</b>                                                | <b>Date : 7-26-96</b>                                          |
| <b>Materials</b>           | <b>Labor</b>                                                            | <b>Equipment</b>                                               |
| Clay, 10% moisture content | 1 Excavator operator<br>4 Truck drivers<br>1 Dozer operator<br>1 Forman | Excavator - Hitachi<br>4 Road trucks -777 caterpillar<br>Dozer |
| <b>Contract # : 3564</b>   | <b>County : Grainger</b>                                                | <b>Date : 8-6-96</b>                                           |
| <b>Materials</b>           | <b>Labor</b>                                                            | <b>Equipment</b>                                               |
| Clay, 10% moisture content | 1 Excavator operator<br>4 Truck drivers<br>1 Dozer operator<br>1 Forman | Excavator - Hitachi<br>4 Road trucks -777 caterpillar<br>Dozer |
| <b>Contract # :4123</b>    | <b>County : Knox</b>                                                    | <b>Date : 11-04-96</b>                                         |
| <b>Materials</b>           | <b>Labor</b>                                                            | <b>Equipment</b>                                               |
| Soil clay                  | 1 Excavator operator<br>12 Trucks drivers<br>1 Forman                   | Excavator PC 300 LC<br>12 Road trucks                          |
| <b>Contract # : 3556</b>   | <b>County : Davidson</b>                                                | <b>Date : 5-20-97</b>                                          |
| <b>Materials</b>           | <b>Labor</b>                                                            | <b>Equipment</b>                                               |
| Topsoil - Rock             | 2 Loader operators<br>4 Truck drivers<br>1 Forman                       | Loader CAT. 963<br>Dozer CAT. D8R<br>4 Dump trucks MACK.       |

**Table E-1 Project Resources (Con,t)**

| <b>TASK ONE</b>          |                                                                        | <b>ITEM # : 203-01</b>                                                                           |  |
|--------------------------|------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------|--|
|                          |                                                                        | <b>Description: Road and Drainage Excavation</b>                                                 |  |
| <b>Contract # : 4384</b> | <b>County : McMinn</b>                                                 | <b>Date : 5-23-97</b>                                                                            |  |
| <b>Materials</b>         | <b>Labor</b>                                                           | <b>Equipment</b>                                                                                 |  |
| Topsoil                  | 1 Dozer operator<br>2 Scraper operators<br>1 Forman                    | 1 Dozer CAT. D8L<br>2 Scrapers CAT. 621F                                                         |  |
| <b>Contract # : 4251</b> | <b>County : Williamson</b>                                             | <b>Date : 5-29-97</b>                                                                            |  |
| <b>Materials</b>         | <b>Labor</b>                                                           | <b>Equipment</b>                                                                                 |  |
| Wet clay and top soil    | 3 Excavator operators<br>4 Truck drivers                               | Excavator Kobelco SK300 LC                                                                       |  |
| <b>Contract # :3915</b>  | <b>County : Henderson</b>                                              | <b>Date : 6-19-97</b>                                                                            |  |
| <b>Materials</b>         | <b>Labor</b>                                                           | <b>Equipment</b>                                                                                 |  |
| Soil                     | 4 Excavator operators<br>2 Laborers<br>6 Truck drivers<br>1 Forman     | Excavator PC 400 LC, 3.5CY<br>Dozer Caterpillar D8R<br>2-Dozer Caterpillar D3<br>5-6 Road Trucks |  |
| <b>Contract # : 3948</b> | <b>County : Davidson</b>                                               | <b>Date : 6-24-97</b>                                                                            |  |
| <b>Materials</b>         | <b>Labor</b>                                                           | <b>Equipment</b>                                                                                 |  |
| Rock and Dirt            | 1 Excavator operator<br>1 Dozer operator<br>1 Truck driver<br>1 Forman | Excavator Caterpillar 325BL<br>Dozer Caterpillar D8N<br>Truck Caterpillar                        |  |

**Table E-1 Project Resources (Con,t)**

|                          |                                                                                 |                                                                                      |
|--------------------------|---------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|
| <b>TASK ONE</b>          | <b>ITEM # : 203-01</b>                                                          |                                                                                      |
|                          | <b>Description: Road and Drainage Excavation</b>                                |                                                                                      |
| <b>Contract # : 3926</b> | <b>County : Rhea</b>                                                            | <b>Date : 7-7-97</b>                                                                 |
| <b>Materials</b>         | <b>Labor</b>                                                                    | <b>Equipment</b>                                                                     |
| Common earth             | 1 Dozer operator<br>4 Scraper operators<br>1 Forman                             | 1 Dozer CAT.D-9<br>3 Scraper CAT. 641B<br>1 Scraper CAT. 651B                        |
| <b>Contract # : 4410</b> | <b>County : White</b>                                                           | <b>Date : 7-8-97</b>                                                                 |
| <b>Materials</b>         | <b>Labor</b>                                                                    | <b>Equipment</b>                                                                     |
| Common earth             | 2 Dozer operators<br>3 Scraper operators<br>1 Forman                            | 1 Dozer CAT. D8L<br>1 Dozer CAT. D6RXL<br>2 Scrapers CAT.621E<br>1 Scraper CAT. 631E |
| <b>Contract # : 4572</b> | <b>County : Weakly</b>                                                          | <b>Date : 7-8-97</b>                                                                 |
| <b>Materials</b>         | <b>Labor</b>                                                                    | <b>Equipment</b>                                                                     |
| Soil                     | 1Excavator operator<br>1 Grader operator<br>1 Dozer operator<br>7 Truck drivers | Excavator CAT. 330L<br>Grader CAT. 140G<br>Dozer CAT. D6E<br>7 Dump trucks           |
| <b>Contract # : 4696</b> | <b>County : Fayette</b>                                                         | <b>Date : 8-4-97</b>                                                                 |
| <b>Materials</b>         | <b>Labor</b>                                                                    | <b>Equipment</b>                                                                     |
| Top soil                 | 1 Dozer operator<br>2 Scraper operators<br>1 Forman                             | 1 Dozer CAT. D8R<br>2 Scraper CAT. 621F                                              |

**Table E-2 Project Resources**

|                        |                                                                                                |                                                                                     |
|------------------------|------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| <b>TASK TWO</b>        | <b>ITEM # : 203 03.01</b>                                                                      |                                                                                     |
|                        | <b>Description: Borrow Excavation</b>                                                          |                                                                                     |
| <b>Contract # 3948</b> | <b>County : Davidson</b>                                                                       | <b>Date : 6-16-97</b>                                                               |
| <b>Material</b>        | <b>Labor</b>                                                                                   | <b>Equipment</b>                                                                    |
| Shot Rock              | 1 Excavator operator<br>1 Dossier operator<br>1 Truck driver<br>1 Forman                       | 1 Excavator CAT. 325BL<br>1 Dossier CAT. D8N<br>1 Dump truck CAT. (30 ton)          |
| <b>Contract # 4017</b> | <b>County : Davidson</b>                                                                       | <b>Date : 6-18-97</b>                                                               |
| <b>Material</b>        | <b>Labor</b>                                                                                   | <b>Equipment</b>                                                                    |
| Rock borrow material   | 1 Excavator operator<br>1 Dossier operator<br>4 Truck drivers<br>1 Forman                      | 1 Excavator Hitachi 400<br>1 Dossier CAT. D8N<br>4 Dump trucks (rented)             |
| <b>Contract # 3866</b> | <b>County Marion</b>                                                                           | <b>Date : 6-20-97</b>                                                               |
| <b>Material</b>        | <b>Labor</b>                                                                                   | <b>Equipment</b>                                                                    |
| Common earth           | 1 Loader operator<br>5 Truck drivers<br>1 Forman                                               | 1 Loader CAT. -963<br>5 Trifle Dump Trucks                                          |
| <b>Contract # 4224</b> | <b>County Fayette</b>                                                                          | <b>Date : 6-27-97</b>                                                               |
| <b>Material</b>        | <b>Labor</b>                                                                                   | <b>Equipment</b>                                                                    |
| Borrow soil            | 1 Excavator operator<br>1 Dozer operator<br>1 Grader operator<br>6-9 Truck drivers<br>1 Forman | 1 Excavator Komatsu PC400LC<br>1 Dozer CAT. -D5<br>1 Grader CAT. -12G<br>6-9 Trucks |

**Table E-2 Project Resources (Con,t)**

| <b>TASK TWO</b>        |                                                                                             | <b>ITEM # : 203 03.01</b>                                                       |  |
|------------------------|---------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------|--|
|                        |                                                                                             | <b>Description: Borrow Excavation</b>                                           |  |
| <b>Contract # 3863</b> | <b>County McNairy</b>                                                                       | <b>Date : 7-2-97</b>                                                            |  |
| <b>Material</b>        | <b>Labor</b>                                                                                | <b>Equipment</b>                                                                |  |
| Sandy borrow soil      | 1 Excavator operator<br>1 Dozer operator<br>5 Truck drivers<br>1 Forman                     | 1 Excavator<br>1 Dozer<br>5 Trucks                                              |  |
| <b>Contract # 4723</b> | <b>County Robertson</b>                                                                     | <b>Date : 7-16-97</b>                                                           |  |
| <b>Material</b>        | <b>Labor</b>                                                                                | <b>Equipment</b>                                                                |  |
| Clay borrow material   | 1 Excavator operator (class D)<br>1 Dozer operator (class B)<br>3 Truck drivers<br>2 Forman | 1 Excavator Komatsu PC-400LC<br>1 Grader CAT.-120G<br>3 Dump trucks MACK.       |  |
| <b>Contract # 3502</b> | <b>County Carroll</b>                                                                       | <b>Date : 8-7-97</b>                                                            |  |
| <b>Material</b>        | <b>Labor</b>                                                                                | <b>Equipment</b>                                                                |  |
| Borrow soil            | 1 Excavator operator<br>2 Dozer operator<br>6 Truck drivers                                 | 1 Excavator Hitachi EX-400LC<br>1 Dozer CAT.-D8N<br>1 Dozer CAT.-D4<br>6 Trucks |  |

**Table E-3 Project Resources**

|                          |                                                                                                                  |                                                                                               |
|--------------------------|------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------|
| <b>TASK THREE</b>        |                                                                                                                  | <b>ITEM # : 303-01</b>                                                                        |
|                          |                                                                                                                  | <b>Description: Mineral Aggregate Mix</b>                                                     |
| <b>Contract # :2440</b>  | <b>County :Knox</b>                                                                                              | <b>Date : 10/25/96</b>                                                                        |
| <b>Materials</b>         | <b>Labor</b>                                                                                                     | <b>Equipment</b>                                                                              |
| Mineral Aggregate Mix    | 1 Foreman<br>1 Class A Operator<br>1 Class C Operator<br>1 Class D Operator<br>1 Skilled Labor                   | 1 Cat D7 Bulldozer<br>1 Cat 140H Grader<br>1 Ingersoll-Rand DA-50 Roller                      |
| <b>Contract # :3564</b>  | <b>County : Grainger</b>                                                                                         | <b>Date : 5/22/97</b>                                                                         |
| <b>Materials</b>         | <b>Labor</b>                                                                                                     | <b>Equipment</b>                                                                              |
| Mineral Aggregate Mix    | 1 Foreman<br>1 Class A Operator<br>1 Class C Operator<br>1 Class D Operator<br>1 Truck Driver<br>1 Skilled Labor | 1 Cat D7 Bulldozer<br>1 Cat 140H Grader<br>1 Bomag BM2130                                     |
| <b>Contract # : 4044</b> | <b>County : Roane</b>                                                                                            | <b>Date : 5/21/97</b>                                                                         |
| <b>Materials</b>         | <b>Labor</b>                                                                                                     | <b>Equipment</b>                                                                              |
| Mineral Aggregate Mix    | 1 Foreman<br>1 Class A Operator<br>1 Class C Operator<br>2 Class D Operator                                      | 1 Blaw Knox RW-100 Hopper<br>1 Cat 12G Grader<br>1 CC422 Dynapac Roller<br>1 Ford Sweeper2810 |
| <b>Contract # : 3707</b> | <b>County : Rhea</b>                                                                                             | <b>Date : 6/19/97</b>                                                                         |
| <b>Materials</b>         | <b>Labor</b>                                                                                                     | <b>Equipment</b>                                                                              |
| Mineral Aggregate Mix    | 1 Foreman<br>1 Class A Operator<br>1 Class C Operator<br>1 Class D Operator<br>2 Unskilled Labor                 | 1 Cat D8 Bulldozer<br>1 Cat 12G Grader<br>1 Cat CP553 Steel Roller                            |

**Table E-3 Project Resources (Con,t)**

| <b>TASK THREE</b>        |                                                                                                                    | <b>ITEM # : 303-01</b>                                                                                |  |
|--------------------------|--------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------|--|
|                          |                                                                                                                    | <b>Description: Mineral Aggregate Mix</b>                                                             |  |
| <b>Contract # : 4160</b> | <b>County : White</b>                                                                                              | <b>Date : 6/10/97</b>                                                                                 |  |
| <b>Materials</b>         | <b>Labor</b>                                                                                                       | <b>Equipment</b>                                                                                      |  |
| Mineral Aggregate Mix    | 1 Foreman<br>1 Class A Operator<br>1 Class C Operator<br>1 Class D Operator<br>1 Truck Driver<br>2 Unskilled Labor | 1 Cat D6D Bulldozer<br>1 Cat 12G Grader<br>1 Bomag BM2130                                             |  |
| <b>Contract # : 3866</b> | <b>County : Marion</b>                                                                                             | <b>Date : 7/28/97</b>                                                                                 |  |
| <b>Materials</b>         | <b>Labor</b>                                                                                                       | <b>Equipment</b>                                                                                      |  |
| Mineral Aggregate Mix    | 1 Foreman<br>1 Class A Operator<br>1 Class D Operator<br>1 Skilled Labor                                           | 1 Cat D6D Bulldozer<br>1 Cat 12G Grader<br>1 John Deere Backhoe 210C<br>1 Ingersoll-Rand DA-50 Roller |  |
| <b>Contract # : 4017</b> | <b>County : Davidson</b>                                                                                           | <b>Date : 7/2/97</b>                                                                                  |  |
| <b>Materials</b>         | <b>Labor</b>                                                                                                       | <b>Equipment</b>                                                                                      |  |
| Mineral Aggregate Mix    | 1 Foreman<br>1 Class C Operator<br>1 Class D Operator                                                              | 1 Cat D7 Bulldozer<br>1 Cat 140G Grader<br>1 CA 251 Dynapac Roller                                    |  |
| <b>Contract # : 4251</b> | <b>County : Williamson</b>                                                                                         | <b>Date : 7/1/97</b>                                                                                  |  |
| <b>Materials</b>         | <b>Labor</b>                                                                                                       | <b>Equipment</b>                                                                                      |  |
| Mineral Aggregate Mix    | 1 Foreman<br>1 Class A Operator<br>1 Class C Operator<br>1 Skilled Labor                                           | 1 Cat D8H Bulldozer<br>1 Cat 140G Grader<br>1 Bomag BW201 AD                                          |  |

**Table E-3 Project Resources (Con,t)**

|                          |                                                                            |                                                                                  |
|--------------------------|----------------------------------------------------------------------------|----------------------------------------------------------------------------------|
| <b>TASK THREE</b>        | <b>ITEM # : 303-01</b>                                                     |                                                                                  |
|                          | <b>Description: Mineral Aggregate Mix</b>                                  |                                                                                  |
| <b>Contract # : 3915</b> | <b>County : Henderson</b>                                                  | <b>Date : 6/20/97</b>                                                            |
| <b>Materials</b>         | <b>Labor</b>                                                               | <b>Equipment</b>                                                                 |
| Mineral Aggregate Mix    | 1 Foreman<br>1 Class C Operator<br>1 Class D Operator<br>1 Skilled Labor   | 1 Cat D7 Bulldozer<br>1 Bomag BM2130                                             |
| <b>Contract # :4699</b>  | <b>County : Henderson</b>                                                  | <b>Date : 8/21/97</b>                                                            |
| <b>Materials</b>         | <b>Labor</b>                                                               | <b>Equipment</b>                                                                 |
| Mineral Aggregate Mix    | 1 Forman<br>1 Class A Operator<br>1 Class C Operator<br>2 Class D Operator | 1 Barber-Greene BG-730 Spreader<br>1 Cat 140H Grader<br>1 Raygo Vibratory Roller |

**Table E-4 Project Resources**

|                          |                                                                                                    |                                                                                                                                                              |
|--------------------------|----------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>TASK FOUR</b>         | <b>ITEM # : 307-01.03</b>                                                                          |                                                                                                                                                              |
|                          | <b>Discription: Aggregate Grade A.S. Mix</b>                                                       |                                                                                                                                                              |
| <b>Contract # : 3707</b> | <b>County : Rhea</b>                                                                               | <b>Date : 6/10/97</b>                                                                                                                                        |
| <b>Materials</b>         | <b>Labor</b>                                                                                       | <b>Equipment</b>                                                                                                                                             |
| Asphalt Grade A.S. Mix   | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>2 Skilled Laborers                        | 1 CedarRapids CR551 (Paver)<br>1 Ingersoll-Rand DD-110 Steel Roller                                                                                          |
| <b>Contract # : 4251</b> | <b>County : Williamson</b>                                                                         | <b>Date : 7/8/97</b>                                                                                                                                         |
| <b>Materials</b>         | <b>Labor</b>                                                                                       | <b>Equipment</b>                                                                                                                                             |
| Asphalt Grade A.S. Mix   | 1 Foreman<br>2 Class C Operator<br>3 Class D Operator<br>2 Skilled Laborers<br>1 Unskilled Laborer | 1 Blaw-Knox PF3200<br>1 Roadtec SB2500(MTV) Shuttle Buggy<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Ferguson Pneumatic Tired Roller<br>1 Ford Water Truck |
| <b>Contract # : 3935</b> | <b>County : Sumner</b>                                                                             | <b>Date : 8/20/97</b>                                                                                                                                        |
| <b>Materials</b>         | <b>Labor</b>                                                                                       | <b>Equipment</b>                                                                                                                                             |
| Asphalt Grade A.S. Mix   | 1 Foreman<br>3 Class C Operator<br>2 Class D Operator<br>2 Skilled Laborers                        | 2 Blaw-Knox PF3200<br>1 Roadtec SB2500(MTV) Shuttle Buggy<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Ferguson Pneumatic Tired Roller<br>1 Ford Water Truck |
| <b>Contract # : 4224</b> | <b>County : Fayette</b>                                                                            | <b>Date : 6/30/97</b>                                                                                                                                        |
| <b>Materials</b>         | <b>Labor</b>                                                                                       | <b>Equipment</b>                                                                                                                                             |
| Asphalt Grade A.S. Mix   | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>4 Skilled Laborers                        | 1 CedarRapids CR461 (Paver)<br>1 Galion 710 Street Roller<br>1 Bomag BW10AS Steel Roller<br>1 Ingram Rubber Tire Roller                                      |

**Table E-4 Project Resources (Con,t)**

|                          |                                                                                                   |                                                                                                                                                                                            |
|--------------------------|---------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>TASK FOUR</b>         | <b>ITEM # : 307-01.03</b>                                                                         |                                                                                                                                                                                            |
|                          | <b>Description: Aggregate Grade A.S. Mix</b>                                                      |                                                                                                                                                                                            |
| <b>Contract # : 3721</b> | <b>County : McNairy</b>                                                                           | <b>Date : 11/23/96</b>                                                                                                                                                                     |
| <b>Materials</b>         | <b>Labor</b>                                                                                      | <b>Equipment</b>                                                                                                                                                                           |
| Asphalt Grade A.S. Mix   | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>4 Skilled Laborers<br>2 Skilled Laborers | 1 Cat AP1000C Paver<br>1 Ingersoll-Rand DD-90 Steel Roller<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Ingram Rubber Tire Roller<br>1 Ford Water Truck<br>1 Service Truck<br>1 Tack Truck |
| <b>Contract # : 3145</b> | <b>County : Weakley</b>                                                                           | <b>Date : 7/16/97</b>                                                                                                                                                                      |
| <b>Materials</b>         | <b>Labor</b>                                                                                      | <b>Equipment</b>                                                                                                                                                                           |
| Asphalt Grade A.S. Mix   | 1 Foreman<br>2 Class C Operator<br>2 Class D Operator<br>4 Skilled Laborers                       | 1 Blaw-Knox PF180H<br>1 Bomag BW 160 AD (Steel roller)<br>1 Cat 534C Steel Roller<br>1 Farguson SP-912 Pneumatic Tired Roller<br>1 Huber M-850-A Grader                                    |

**Table E-5 Project Resources**

|                          |                                                                                                     |                                                                                                                                                                            |
|--------------------------|-----------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>TASK FIVE</b>         | <b>ITEM # : 307-03.09</b>                                                                           |                                                                                                                                                                            |
|                          | <b>Description: Bituminous Plant Mix Grade A</b>                                                    |                                                                                                                                                                            |
| <b>Contract # : 4123</b> | <b>County : Knox</b>                                                                                | <b>Date : 7/31/97</b>                                                                                                                                                      |
| <b>Materials</b>         | <b>Labor</b>                                                                                        | <b>Equipment</b>                                                                                                                                                           |
| Asphalt Grade A          | 1 Foreman<br>1 Class C Operator<br>2 Class D Operator<br>4 Skilled Laborers<br>3 Unskilled Laborers | 1 Roadtec RP230 Paver<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Ingersoll-Rand DA-50 Steel Roller<br>1 Water Truck<br>1 Tack Truck                                      |
| <b>Contract # : 3707</b> | <b>County : Rhea</b>                                                                                | <b>Date : 6/17/97</b>                                                                                                                                                      |
| <b>Materials</b>         | <b>Labor</b>                                                                                        | <b>Equipment</b>                                                                                                                                                           |
| Asphalt Grade A          | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>2 Skilled Laborers                         | 1 CedarRapids CR551 (Paver)<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Hypac C778A Steel Roller<br>1 Ingram Rubber Tire Rollers SP-1118<br>1 Water Truck<br>1 Tack Truck |
| <b>Contract # : 4160</b> | <b>County : White</b>                                                                               | <b>Date : 5/30/97</b>                                                                                                                                                      |
| <b>Materials</b>         | <b>Labor</b>                                                                                        | <b>Equipment</b>                                                                                                                                                           |
| Asphalt Grade A          | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>4 Skilled Laborers                         | 1 Barber-Greene BG-260B Paver<br>2 Ingersoll-Rand DD90 Steel Roller<br>1 Ingram Rubber Tire Rollers<br>1 Water Truck<br>1 Tack Truck                                       |
| <b>Contract # : 3428</b> | <b>County : Cheatham</b>                                                                            | <b>Date : 8/6/97</b>                                                                                                                                                       |
| <b>Materials</b>         | <b>Labor</b>                                                                                        | <b>Equipment</b>                                                                                                                                                           |
| Asphalt Grade A          | 1 Foreman<br>2 Class C Operator<br>4 Class D Operator<br>3 Skilled Operator                         | 1 Cat AP800C Paver<br>1 BlawKnox MTV MC-30<br>1 Ingersoll-Rand DD-90 Steel Roller<br>1 Ingersoll -Rand DA-50 Steel Roller<br>1 Bomag BW12-A<br>1 Tack Truck                |

**Table E-5 Project Resources (Con,t)**

|                          |                                                                                                     |                                                                                                                                                                                       |
|--------------------------|-----------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>TASK FIVE</b>         | <b>ITEM # : 307-03.09</b>                                                                           |                                                                                                                                                                                       |
|                          | <b>Description: Bituminous Plant Mix Grade A</b>                                                    |                                                                                                                                                                                       |
| <b>Contract # : 3935</b> | <b>County : Sumner</b>                                                                              | <b>Date : 8/21/97</b>                                                                                                                                                                 |
| <b>Materials</b>         | <b>Labor</b>                                                                                        | <b>Equipment</b>                                                                                                                                                                      |
| Asphalt Grade A          | 1 Foreman<br>3 Class C Operator<br>3 Class D Operator<br>3 Skilled Laborers                         | 2 Blaw-Knox PF3200<br>1 Roadtec SB2500(MTV)Shuttle<br>1 Ferguson B-128 Steel Roller<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Ferguson Pneumatic Tire Roller<br>1 Ford Water Truck |
| <b>Contract # : 4729</b> | <b>County : Shelby</b>                                                                              | <b>Date : 8/22/97</b>                                                                                                                                                                 |
| <b>Materials</b>         | <b>Labor</b>                                                                                        | <b>Equipment</b>                                                                                                                                                                      |
| Asphalt Grade A          | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>4 Skilled Laborers<br>4 Unskilled Laborers | 1 CedarRapids CR451 (Paver)<br>1 Galion 2-66B Steel Roller<br>1 Hypac C778A Steel Roller<br>1 Case 580D Backhoe<br>1 RJ 300 Sweeper                                                   |
| <b>Contract # : 3701</b> | <b>County : Madison</b>                                                                             | <b>Date : 11/20/96</b>                                                                                                                                                                |
| <b>Materials</b>         | <b>Labor</b>                                                                                        | <b>Equipment</b>                                                                                                                                                                      |
| Asphalt Grade A          | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>4 Skilled Laborers<br>2 Unskilled Laborers | 1 Cat AP1000C Paver<br>2 Cat 534C Steel Rollers<br>1 Ingersoll-Rand ST-105<br>1 Water Truck<br>1 Tack Truck                                                                           |

**Table E-6 Project Resources**

|                          |                                                                                                                       |                                                                                                                                                                                                                  |
|--------------------------|-----------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>TASK SIX</b>          | <b>ITEM # : 307-03.15</b>                                                                                             |                                                                                                                                                                                                                  |
|                          | <b>Description: Bituminous Plant Mix Base Grade B-M</b>                                                               |                                                                                                                                                                                                                  |
| <b>Contract # : 4298</b> | <b>County : Hancock</b>                                                                                               | <b>Date : 8/19/96</b>                                                                                                                                                                                            |
| <b>Materials</b>         | <b>Labor</b>                                                                                                          | <b>Equipment</b>                                                                                                                                                                                                 |
| Asphalt Grade B-M        | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>1 Skilled Laborer<br>2 Unskilled Laborers<br>2 Truck Drivers | 1 Blaw-Knox PF180H<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Ingersoll-Rand DD-90 Steel Roller<br>1 Ingersoll-Rand ST-105 Steel Roller<br>1 Cat 14G Grader<br>1 Ford Service Truck<br>1 Cheverolet Tack Truck |
| <b>Contract # : 4687</b> | <b>County : Bradley/McMinn</b>                                                                                        | <b>Date : 6/17/97</b>                                                                                                                                                                                            |
| <b>Materials</b>         | <b>Labor</b>                                                                                                          | <b>Equipment</b>                                                                                                                                                                                                 |
| Asphalt Grade B-M        | 1 Foreman<br>2 Class C Operator<br>3 Class D Operator<br>2 Skilled Laborers<br>1 Truck Driver                         | 1 Blaw-Knox PF3200<br>1 Roadtec SB2500(MTV) Shuttle Buggy<br>1 Dynapac Steel Roller<br>1 Ferguson Steel Roller<br>1 Ingram Rubber Tire Roller<br>1 Tack Truck<br>1 Water Truck                                   |
| <b>Contract # : 3707</b> | <b>County : Rhea</b>                                                                                                  | <b>Date : 6/26/97</b>                                                                                                                                                                                            |
| <b>Materials</b>         | <b>Labor</b>                                                                                                          | <b>Equipment</b>                                                                                                                                                                                                 |
| Asphalt Grade B-M        | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>3 Skilled Laborers                                           | 1 CedarRapids CR551 (Paver)<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Hypac C778A Steel Roller<br>1 Ingram Rubber Tire Roller<br>1 Tack Truck<br>1 Water Truck                                                |
| <b>Contract # : 4395</b> | <b>County : Robertson</b>                                                                                             | <b>Date : 5/22/97</b>                                                                                                                                                                                            |
| <b>Materials</b>         | <b>Labor</b>                                                                                                          | <b>Equipment</b>                                                                                                                                                                                                 |
| Asphalt Grade B-M        | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>4 Skilled Laborers                                           | 1 Cat AP800C Paver<br>1 Dresser 708 Steel Roller<br>1 Ingersoll-Rand DD-90 Steel Roller<br>1 Bomag BW12A<br>1 Mack Tack Truck                                                                                    |

**Table E-6 Project Resources (Con,t)**

| <b>TASK SIX</b>          | <b>ITEM # : 307-03.15</b>                                                                                              |                                                                                                                                                                                      |
|--------------------------|------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                          | <b>Description: Bituminous Plant Mix Base Grade B-M</b>                                                                |                                                                                                                                                                                      |
| <b>Contract # : 4251</b> | <b>County : Williamson</b>                                                                                             | <b>Date : 5/28/97</b>                                                                                                                                                                |
| <b>Materials</b>         | <b>Labor</b>                                                                                                           | <b>Equipment</b>                                                                                                                                                                     |
| Asphalt Grade B-M        | 1 Foreman<br>2 Class C Operator<br>2 Class D Operator<br>8 Skilled Laborers                                            | 1 Blaw-Knox PF3180H<br>1 Roadtec SB2500(MTV) Shuttle Buggy<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Ingersoll-Rand DD-90 Steel Roller<br>1 Ford Tack Truck<br>1 Ford Water Truck |
| <b>Contract # : 4017</b> | <b>County : Davidson</b>                                                                                               | <b>Date : 7/24/97</b>                                                                                                                                                                |
| <b>Materials</b>         | <b>Labor</b>                                                                                                           | <b>Equipment</b>                                                                                                                                                                     |
| Asphalt Grade B-M        | 2 Foreman<br>1 Class C Operator<br>2 Class D Operator<br>3 Skilled Laborers                                            | 1 Roadtec RP180-10 Paver<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Ingersoll-Rand ST-105 Steel Roller<br>1 International Tack Truck<br>1 Internaitional Water Truck               |
| <b>Contract # :3701</b>  | <b>County : Madison</b>                                                                                                | <b>Date : 11/21/96</b>                                                                                                                                                               |
| <b>Materials</b>         | <b>Labor</b>                                                                                                           | <b>Equipment</b>                                                                                                                                                                     |
| Asphalt Grade B-M        | 1 Foreman<br>1 Class C Operator<br>2 Class C Operator<br>2 Truck Drivers<br>2 Unskilled Laborers<br>3 Skilled Laborers | 1 CedarRapids CR551 ( Paver)<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Tack Truck<br>1 Water Truck                                        |
| <b>Contract # :3366</b>  | <b>County : Weakley</b>                                                                                                | <b>Date : 7/23/97</b>                                                                                                                                                                |
| <b>Materials</b>         | <b>Labor</b>                                                                                                           | <b>Equipment</b>                                                                                                                                                                     |
| Asphalt Grade B-M        | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>4 Skilled Laborers                                            | 1 Blaw-Knox PF180H<br>1 Cat 534C Steel Roller<br>1 Bomag BW160AD Steel Roller<br>1 Ferguson Pneumatic Tired Roller<br>1 Huber M-850A Grader<br>1 Water Truck<br>1 Tack Truck         |

**Table E-6 Project Resources (Con,t)**

|                         |                                                                                                     |                                                                                                                                      |
|-------------------------|-----------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------|
| <b>TASK SIX</b>         | <b>ITEM # : 307-03.15</b>                                                                           |                                                                                                                                      |
|                         | <b>Description: Bituminous Plant Mix Base Grade B-M</b>                                             |                                                                                                                                      |
| <b>Contract # :4738</b> | <b>County :Weakley</b>                                                                              | <b>Date : 6/12/97</b>                                                                                                                |
| <b>Materials</b>        | <b>Labor</b>                                                                                        | <b>Equipment</b>                                                                                                                     |
| Asphalt Grade B-M       | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>4 Skilled Laborers<br>2 Unskilled Laborers | 1 Blaw-Knox PF180H<br>1 Cat 534C Steel Roller<br>1 Bomag BW160AD Steel Roller<br>1 Ferguson Pneumatic Tire Roller<br>1 Service Truck |

**Table E-7 Project Resources**

| <b>TASK SEVEN</b>        | <b>ITEM # : 411-01</b>                                                                                                   |                                                                                                                                                                                                                                         |
|--------------------------|--------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                          | <b>Description: Asphalt Cement &amp; Mineral Aggregate Grading D</b>                                                     |                                                                                                                                                                                                                                         |
| <b>Contract # : 4180</b> | <b>County : Grainger</b>                                                                                                 | <b>Date : 8/18/96</b>                                                                                                                                                                                                                   |
| <b>Materials</b>         | <b>Labor</b>                                                                                                             | <b>Equipment</b>                                                                                                                                                                                                                        |
| Asphalt Grade D          | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>1 Skilled Laborer<br>2 Unskilled Laborers<br>2 Truck Drivers    | 1 Blaw-Knox PF180H<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Ingersoll-Rand DD-90 Steel Roller<br>1 Ingersoll-Rand ST-105 Steel Roller<br>1 Cat 14G Grader<br>1 Ford Service Truck<br>1 Chevrolet                                    |
| <b>Contract # : 4400</b> | <b>County : Knox</b>                                                                                                     | <b>Date : 11/6/96</b>                                                                                                                                                                                                                   |
| <b>Materials</b>         | <b>Labor</b>                                                                                                             | <b>Equipment</b>                                                                                                                                                                                                                        |
| Asphalt Grade D          | 2 Foreman<br>1 Class C Operator<br>4 Class D Operator<br>1 Skilled Laborer<br>4 Unskilled Laborers<br><br>1 Truck Driver | 1 CedarRapids CR451<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Ingersoll-Rand DD-90 Steel Roller<br>1 Rosco Pnuematic Roller<br>1 Cat 120G Grader<br>1 Chevrolet Pilot Vehicle<br>1 Chevrolet Service Truck<br>1 Chevrolet Tack Truck |
| <b>Contract # : 4687</b> | <b>County : McMinn</b>                                                                                                   | <b>Date : 7/16/97</b>                                                                                                                                                                                                                   |
| <b>Materials</b>         | <b>Labor</b>                                                                                                             | <b>Equipment</b>                                                                                                                                                                                                                        |
| Asphalt Grade D          | 1 Foreman<br>2 Class C Operator<br>3 Class D Operator<br>3 Unskilled Laborers                                            | 1 Blaw-Knox PF-3200<br>1 Roadtec SB2500(MTV) Shuttle Buggy<br>1 Dynapac CA251 Steel Roller<br>1 Ferguson B12B Steel Roller<br>1 Ingram Pnuematic Roller<br>1 Chevrolet Water Truck<br>1 Chevrolet Tack Truck                            |
| <b>Contract # : 3707</b> | <b>County : Rhea</b>                                                                                                     | <b>Date : 7/18/97</b>                                                                                                                                                                                                                   |
| <b>Materials</b>         | <b>Labor</b>                                                                                                             | <b>Equipment</b>                                                                                                                                                                                                                        |
| Asphalt Grade D          | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>3 Skilled Laborers<br>1 Truck Driver                            | 1 CedarRapids CR551 Paver<br>1 Hypac C778A Steel Roller<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Ingram Pnuematic Roller<br>1 Chevrolet Water Truck<br>1 Chevrolet Tack Truck                                                       |

**Table E-7 Project Resources (Con,t)**

| <b>TASK SEVEN</b>        | <b>ITEM # : 411-01</b>                                                                                                |                                                                                                                                                                                                       |
|--------------------------|-----------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
|                          | <b>Description:Asphalt Cement &amp; Mineral Aggregate Grading D</b>                                                   |                                                                                                                                                                                                       |
| <b>Contract # : 4722</b> | <b>County : Robertson</b>                                                                                             | <b>Date : 6/27/98</b>                                                                                                                                                                                 |
| <b>Materials</b>         | <b>Labor</b>                                                                                                          | <b>Equipment</b>                                                                                                                                                                                      |
| Asphalt Grade D          | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>3 Skilled Laborers<br>3 Unskilled Laborers<br>1 Truck Driver | 1 Cat AP800C Paver<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Ingersoll-Rand DD-90 Steel Roller<br>1 Ingersoll-Rand PT-125 Steel Roller<br>1 Chevrolet Service Truck<br>1 Chevrolet Tack Truck      |
| <b>Contract # :4740</b>  | <b>County : Williamson</b>                                                                                            | <b>Date : 8/5/97</b>                                                                                                                                                                                  |
| <b>Materials</b>         | <b>Labor</b>                                                                                                          | <b>Equipment</b>                                                                                                                                                                                      |
| Asphalt Grade D          | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>3 Skilled Laborers<br>3 Unskilled Laborers                   | 1 Blaw-Knox PF-180H<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Ingersoll-Rand DA-50 Steel Roller<br>1 Chevrolet Service Truck<br>1 Chevrolet Tack Truck<br>1 Sweepster Broom                        |
| <b>Contract # :4815</b>  | <b>County : Davidson/Cheatham</b>                                                                                     | <b>Date : 8/25/97</b>                                                                                                                                                                                 |
| <b>Materials</b>         | <b>Labor</b>                                                                                                          | <b>Equipment</b>                                                                                                                                                                                      |
| Asphalt Grade D          | 1 Foreman<br>2 Class C Operator<br>5 Class D Operator<br>2 Skilled Laborers                                           | 1 Roadtec RP180-10 Paver<br>1 Roadtec SB2500(MTV) Shuttle Buggy<br>1 Ingersoll-Rand DD-90 Steel Roller<br>1 Ferguson B12B Steel Roller<br>1 International Service Truck<br>1 International Tack Truck |
| <b>Contract # :4355</b>  | <b>County : Gibson</b>                                                                                                | <b>Date : 11/22/96</b>                                                                                                                                                                                |
| <b>Materials</b>         | <b>Labor</b>                                                                                                          | <b>Equipment</b>                                                                                                                                                                                      |
| Asphalt Grade D          | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>3 Skilled Laborers<br>2 Unskilled Laborers                   | 1 Blaw-Knox PF200B Paver<br>1 Ingersoll-Rand DD-110 Steel Roller<br>1 Ingersoll-Rand DD-90 Steel Roller<br>1 Ingersoll-Rand ST-105 Steel Roller<br>1 Water Truck<br>1 Service Truck<br>1 Tack Truck   |

**Table E-7 Project Resources (Con,t)**

|                          |                                                                                                    |                                                                                                                                              |
|--------------------------|----------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------|
| <b>TASK SEVEN</b>        | <b>ITEM # : 411-01</b>                                                                             |                                                                                                                                              |
|                          | <b>Discription:Asphalt Cement &amp; Mineral Aggregate Grading D</b>                                |                                                                                                                                              |
| <b>Contract # : 4660</b> | <b>County : Obion</b>                                                                              | <b>Date : 6/5/97</b>                                                                                                                         |
| <b>Materials</b>         | <b>Labor</b>                                                                                       | <b>Equipment</b>                                                                                                                             |
| Asphalt Grade D          | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>4 Skilled Laborers<br>2 Unsilled Laborers | 1 CedarRapids CR451<br>1 Cat 534C Steel Roller<br>1 Rex SP700 Steel Roller<br>1 Ferguson Pnuematic Roller<br>1 Service Truck<br>1 Tack Truck |
| <b>Contract # :4286</b>  | <b>County : Dyer</b>                                                                               | <b>Date : 6/4/97</b>                                                                                                                         |
| <b>Materials</b>         | <b>Labor</b>                                                                                       | <b>Equipment</b>                                                                                                                             |
| Asphalt Grade D          | 1 Foreman<br>1 Class C Operator<br>3 Class D Operator<br>4 Skilled Laborers<br>2 Unsilled Laborers | 1 Cat AP1000 Paver<br>1 Cat 534C Steel Roller<br>2 Ferguson B12B Steel Roller<br>1 Tack Truck                                                |

**Table E-8 Project Resources**

| <b>TASK EIGHT</b>        | <b>ITEM # : 501-01</b>                                     |                        |
|--------------------------|------------------------------------------------------------|------------------------|
|                          | <b>Description:Portland Cement Concrete Pavement(RAMP)</b> |                        |
| <b>Contract # :3701</b>  | <b>County : Madison</b>                                    | <b>Date : 11/20/96</b> |
| <b>Materials</b>         | <b>Labor</b>                                               | <b>Equipment</b>       |
| Concrete Portland Cement | 2 Foreman                                                  | 1 Fork Lift            |
| Steel Form               | 4 Skilled Laborers                                         | 1 Concrete Screed      |
| Steel Reinforcement      | 4 Unskilled Laborers                                       | 1 Vibrator             |
| Curing Material          | 1 Superintendent                                           | 1 Compressor           |
|                          |                                                            | 1 Small Tool           |
| <b>Contract # : 4044</b> | <b>County : Roane</b>                                      | <b>Date : 5/13/97</b>  |
| <b>Materials</b>         | <b>Labor</b>                                               | <b>Equipment</b>       |
| Concrete Portland Cement | 2 Foreman                                                  | 1 Concrete Screed      |
| Steel form               | 5 Skilled Laborers                                         | 1 Vibrator             |
| Basket Steel             | 2 Unskilled Laborers                                       | 1 Compressor           |
|                          | 1 Superintendent                                           | 1 Small Tool           |
| <b>Contract # : 4017</b> | <b>County : Davidson I</b>                                 | <b>Date : 6/30/97</b>  |
| <b>Materials</b>         | <b>Labor</b>                                               | <b>Equipment</b>       |
| Concrete 3000 psi        | 1 Foreman                                                  | 1 Concrete Screed      |
| Curing coupond           | 4 Finishers                                                | 1 Curing sprenger      |
| Metal form               | 2 Skilled Laborers                                         | 1 Loader               |
| Steel Reinforcement      | 2 Unskilled Laborers                                       | 1 Small Tools          |
|                          |                                                            | 1 Vibrator             |
|                          |                                                            | 1 Compressor           |
| <b>Contract # :3145</b>  | <b>County : Carroll</b>                                    | <b>Date : 6/3/97</b>   |
| <b>Materials</b>         | <b>Labor</b>                                               | <b>Equipment</b>       |
| Concrete Portland Cement | 1 Foreman                                                  | 1 Fork Lift            |
| Carin                    | 1 Operator                                                 | 1 Screed Roller        |
| Coupond                  | 8 Skilled Laborers                                         | 1 Vibrator             |
| Matal form               |                                                            | 1 Air Compressor       |
| Steel Reinforcement      |                                                            | 1 Small Tools          |

**Table E-8 Project Resources (Con,t)**

| <b>TASK EIGHT</b>        | <b>ITEM # : 501-01</b>                                     |                       |
|--------------------------|------------------------------------------------------------|-----------------------|
|                          | <b>Description:Portland Cement Concrete Pavement(RAMP)</b> |                       |
| <b>Contract # : 4017</b> | <b>County : Davidson II</b>                                | <b>Date : 7/25/97</b> |
| <b>Materials</b>         | <b>Labor</b>                                               | <b>Equipment</b>      |
| Concrete Portland Cement | 1 Foreman                                                  | 1 Concrete Screenshot |
| Compound                 | 1 Operator                                                 | 1 Vibrator            |
| Metal Form               | 3 Finisher                                                 | 1 Compressor          |
| Steel Reinforcement      | 2 Skilled Laborers                                         | 1 Small Tools         |
|                          | 1 Unskilled Laborer                                        |                       |

**Table E-9 Project Resources**

|                                           |                                                                                                                         |                                                                                             |
|-------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| <b>TASK NINE</b>                          | <b>ITEM # : 606-02.03</b>                                                                                               |                                                                                             |
|                                           | <b>Description: Steel Piles 10"</b>                                                                                     |                                                                                             |
| <b>Contract # :3571</b>                   | <b>County :Knox</b>                                                                                                     | <b>Date : 3/13/97</b>                                                                       |
| <b>Materials</b>                          | <b>Labor</b>                                                                                                            | <b>Equipment</b>                                                                            |
| Steel Piled<br>Fuel<br>Welding            | 1 Foreman<br>3 Skilled Laborers<br>2 Operators<br>3 Unskilled Laborers                                                  | 1 Crane<br>1 Backhoe<br>1 Hammer driver                                                     |
| <b>Contract # : 4334</b>                  | <b>County : Wayne</b>                                                                                                   | <b>Date : 6/10/97</b>                                                                       |
| <b>Materials</b>                          | <b>Labor</b>                                                                                                            | <b>Equipment</b>                                                                            |
| 24 piece 12" Steel Pile<br>Fuel           | 1 Foreman<br>2 Crane Operators<br>2 Welders<br>2 Skilled Laborers<br>1 Unskilled Laborer                                | 1 Crane 120ft<br>1 Diesel Driver 80ft<br>1 Crane 60ft                                       |
| <b>Contract # :3564</b>                   | <b>County : Grainger</b>                                                                                                | <b>Date : 8/9/96</b>                                                                        |
| <b>Materials</b>                          | <b>Labor</b>                                                                                                            | <b>Equipment</b>                                                                            |
| 20 Steel Piles 250 mm<br>Diesel Fuel      | 1 Foreman<br>1 Crane Operator<br>1 Excavator Operator<br>4 Skilled Laborers<br>2 Unskilled Laborers<br>1 Superintendent | 1 Excavator Cat 225<br>1 Crane 75ft linkBelt<br>1 68ft Diesel Driver<br>1 Welding equipment |
| <b>Contract # :4124</b>                   | <b>County : Knox</b>                                                                                                    | <b>Date : 10/15/96</b>                                                                      |
| <b>Materials</b>                          | <b>Labor</b>                                                                                                            | <b>Equipment</b>                                                                            |
| 11 Steel Piles 10"<br>Weld<br>Diesel Fuel | 4 Skilled Laborers<br>2 Unskilled Laborers<br>1 Superintendent<br>1 Operator                                            | 1 75 LinkBelt<br>1 68ft Diesel Driver<br>1 Welding equipment                                |

**APPENDIX F**

**SUMMARY OF DATA COLLECTION  
AND MAP OF TENNESSEE REGIONS**

Table F-1. Summary of Data Collection

Table F-1.A Date of Data Collection

| Item # | Description                                      | Region I | Region II | Region III | Region IV |
|--------|--------------------------------------------------|----------|-----------|------------|-----------|
| 1      | 203-01 Road and Drainage Excavation              | 7/26/96  | 5/23/97   | 5/29/97    | 6/19/97   |
| 2      | 203-03.01 Borrow Excavation                      | 8/6/96   | 7/7/97    | 6/18/97    | 7/16/97   |
| 3      | 303-01 Mineral Aggregate Mix                     | 5/21/97  | 6/19/97   | 7/28/97    | 8/21/97   |
| 4      | 307-01.03 Aggregate Grade A.S. Mix               | 10/25/96 | 6/16/97   | 8/20/97    | 11/23/96  |
| 5      | 307-03.09 Bituminous Plant Mix (hot mix) Grade A | 7/31/97  | 5/30/97   | 8/21/97    | 11/20/96  |
| 6      | 307-03.15 Bituminous Plant Mix Base Grade B-M    | 8/19/96  | 7/22/97   | 5/28/97    | 11/21/96  |
| 7      | 411-01.01 Mineral Aggregate (ACS) Grading D      | 8/18/96  | 7/16/97   | 8/5/97     | 11/22/96  |
| 8      | 411-01.02 Asphalt Cement (ACS) Grading D         | X        | X         | X          | X         |
| 9      | 501-01 Portland Cement Concrete Pavement (RAMP)  | 5/13/97  |           | 7/25/97    | 6/3/97    |
| 10     | 606-02.03 Steel Piles 10"                        | 8/9/96   | 3/13/97   | 6/10/97    |           |

F-1.B Location of Data Collection

| Item # | Description                                      | Region I | Region II | Region III | Region IV |
|--------|--------------------------------------------------|----------|-----------|------------|-----------|
| 1      | 203-01 Road and Drainage Excavation              | Grainger | White     | Davidson   | Weakley   |
| 2      | 203-03.01 Borrow Excavation                      | Grainger | Rhea      | Davidson   | McNairy   |
| 3      | 303-01 Mineral Aggregate Mix                     | Roane    | Marion    | Davidson   | Henderson |
| 4      | 307-01.03 Aggregate Grade A.S. Mix               | Knox     | Rhea      | Wilson     | Fayette   |
| 5      | 307-03.09 Bituminous Plant Mix (hot mix) Grade A | Knox     | White     | Wilson     | Shelby    |
| 6      | 307-03.15 Bituminous Plant Mix Base Grade B-M    | Hancock  | Rhea      | Davidson   | Weakley   |
| 7      | 411-01.01 Mineral Aggregate (ACS) Grading D      | Grainger | Bradley   | Williamson | Weakley   |
| 8      | 411-01.02 Asphalt Cement (ACS) Grading D         | X        | Rhea      | Williamson | Obion     |
| 9      | 501-01 Portland Cement Concrete Pmt. (RAMP)      | X        | X         | X          | X         |
| 10     | 606-02.03 Steel Piles 10"                        | Roane    | Wayne     | Davidson   | Carroll   |

F-1.C Contracts Number

| Item # | Description                                      | Region I | Region II | Region III | Region IV |
|--------|--------------------------------------------------|----------|-----------|------------|-----------|
| 1      | 203-01 Road and Drainage Excavation              | 3564     | 4384      | 4251       | 4572      |
| 2      | 203-03.01 Borrow Excavation                      | 3564     | 3866      | 4017       | 4696      |
| 3      | 303-01 Mineral Aggregate Mix                     | 2440     | 4160      | 4251       | 3502      |
| 4      | 307-01.03 Aggregate Grade A.S. Mix               | 4123     | 3707      | 3935       | 3145      |
| 5      | 307-03.09 Bituminous Plant Mix (hot mix) Grade A | 4123     | 3707      | 3935       | 4729      |
| 6      | 307-03.15 Bituminous Plant Mix Base Grade B-M    | 4298     | 3707      | 4017       | 3366      |
| 7      | 411-01.01 Mineral Aggregate (ACS) Grading D      | 4180     | 4687      | 4740       | 4286      |
| 8      | 411-01.02 Asphalt Cement (ACS) Grading D         | X        | X         | X          | X         |
| 9      | 501-01 Portland Cement Concrete Pavement (RAMP)  | 4044     | 4017      | 4017       | 3145      |
| 10     | 606-02.03 Steel Piles 10"                        | 4124     | 3571      | 4334       |           |



## VITA

Abdulrazak B. Abdulghafour was born in El Hasakah, Syria on April 21, 1963.

After graduating from Abo-Ther El-Ghefary High School in 1979, he attended the Mosul Institute of Technology in Iraq where he graduated as Valedictorian with a Technical Degree in Civil Engineering in September 1984. In July 1988, he received his Bachelor of Science in Architectural Engineering from the Technical University of Budapest (Hungary).

In Spring 1989, he entered the University of Tennessee, Knoxville to pursue the Master of Science in Civil Engineering, which he received in Fall 1991. While studying for his Master's degree, he served as a graduate research assistant in the Civil Engineering Department.

After receiving the Master's degree, he remained at UT to pursue the Doctor of Philosophy in Civil Engineering. During this period, he worked as an instructor in the UT School of Architecture where he taught the design of steel, concrete, and wood structures. In addition, he designed and taught numerous seminars in the field of Construction Engineering. In 1992, he was employed as a project engineer for Shelby State Community College in Memphis, Tennessee. Then, in 1993, he was hired by the Tennessee Department of Transportation in Nashville, Tennessee as a project engineer. In June 1996, he began serving as a research associate in the UTK Transportation Center. The Ph.D. was received in May 1998.