Development of a Wireless Real-Time Productivity Measurement System for Rapid Construction Operations

BY

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Development of a Wireless Real-Time Productivity Measurement System for Rapid Construction Operations

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ABSTRACT

Existing on-site construction productivity measurement methods have some common limitations, such as the inability to provide data to engineers and project managers for real-time analyses and the difficulties of sharing data among participants involved in construction operations. To address these shortfalls, a **w**ireless **r**eal-t**i**me produc**t**ivity m**e**asurement (WRITE) system was developed. To validate the system, field experiments were conducted at highway and bridge construction sites. Statistical methods, such as the hypothesis test, the normality test, the paired t-test, and the Wilcoxon Signed Rank Test, were conducted to systematically analyze the experimental data. Results of the statistical analyses proved that the developed system generated identical productivity measurements compared to the stopwatch method, which is considered the classic productivity measurement method. In addition, a procedure to improve the on-site construction using the WRITE System and benchmarking technique was developed. The WRITE System has a potential to strengthen communication and coordination among participants involved in the infrastructure construction process by providing more accurate productivity information in real time.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1: INTRODUCTION

1.1 Background

Since the terrorist attacks on September 11, 2001, the United States transportation network, including highways, bridges, tunnels, intermodal facilities, seaports, and airports, has been considered as vulnerable targets. In February 2003, the White House released "The National Strategy for the Physical Protection of Critical Infrastructures and Key Assets" in order to emphasize the importance of protecting the nation's transportation systems. This document provides the fundamental strategies for developing a critical asset protection plan that can be implemented to protect and secure the national transportation system (Dorman and Maier 2005).

In addition to the protection plan, federal and state government agencies have developed vulnerability assessment methods and emergency response plans. The American Association of State Highway and Transportation Officials (AASHTO) sponsored several projects in cooperation with the Federal Highway Administration (FHWA). Some of these projects were managed by the National Cooperative Highway Research Program (NCHRP). Examples of these research projects are:

1. A Guide to Highway Vulnerability Assessment for Critical Asset Identification and Protection;
2. A Guide to Updating Highway Emergency Response Plans for Terrorist Incidents; and
3. Surface Transportation Security.

The US Congress has allocated resources to expedite highway and public transportation security projects as a part of the Federal-Aid Highway Funding Program (FAHFP) to address an imminent threat or to repair damage caused by a terrorist attack against the U.S. These projects include structural hardening, relocation of roads from underneath critical structures, property acquisition to create secure zones, and repairing or replacing a bridge or tunnel that has been damaged or destroyed by extreme events (Dorman and Maier 2005).

Besides the effort at the national level, the State Departments of Transportation (DOTs) have also developed emergency management plans for their transportation networks after extreme events, including terrorist attacks, explosions, fires, floods, and earthquakes. To respond to an extreme event, an emergency management plan must include four related components (Parsons Brinckerhoff 2002):

1. Mitigation: Steps taken in advance to reduce the potential loss from an extreme event.
2. Preparedness: Steps taken in advance to facilitate the response and recovery after an extreme event.
3. Response: Steps taken during or immediately after an extreme event to save lives and property.
4. Recovery: Steps taken to restore the affected areas to their normal status.

Results of previous research indicate that there is an urgent need to address the recovery component in emergency management plans (Burkett et al. 2004). The major element of the recovery component is how to improve the rapid replacement capability, such as when a bridge or a highway in a major transportation network is damaged by an extreme event.

1.2 Problem Statement

Rapid replacement of damaged infrastructure, such as highways and bridges, is a complicated operation because it (1) involves many parties such as state DOTs, design firms, contractors, and material suppliers, (2) varies from project to project and requires sound judgment during all stages of the project, and (3) calls for expediting because the replacement process significantly impacts the surrounding communities and the driving public. Therefore, the replacement operation requires a high degree of knowledge and skill in work zone traffic control, various construction techniques, and project lifecycle cost analysis.

Each party involved in the rapid replacement process is required to make sophisticated technical and managerial decisions at different stages in a very short period of time. Previous research results indicate that there are challenges for construction managers and engineers to estimate an accurate replacement cost and to produce a reliable schedule. For example, the replacement cost for the I-40 Webbers Falls Bridge in Oklahoma was initially estimated at $15 million, but was finished at a cost of $30 million. The estimated time for the replacement started at 12 months, then went down to six months, and ended with the actual completion time at a little over two months (Bai and Burkett 2006). Although the replacement was finished ahead of the original schedule, the process clearly indicated that it was not possible to produce a reliable schedule and provide it to government agencies, design firms, contractors, suppliers, and the general public.

Currently, most of the construction schedules are developed using the Critical Path Method (CPM). A scheduler builds a CPM network based on duration of construction activities and relationships between activities, with the consideration of resource constraints. Duration of activities is determined based on historical data (similar work done in the past) or an estimation done by someone in the company (e.g., project manager, project engineer, or superintendent). Construction duration is estimated using the following formula:

$$\text{Duration} = \frac{\text{Quantity of Work}}{\text{Construction Productivity}} \tag{1.1}$$

Because the quantity of work is relatively easy to estimate accurately using printed drawings or CAD system and specifications, the accuracy of the duration largely depends on the accuracy of construction productivity. There are many factors that will impact the construction productivity, such as weather, site condition, quality of supervision, complexity of task, and labor skill level and age. To quantify these factors and to determine exactly how these factors impact the construction productivity are beyond the capabilities of current technologies. Without accurate productivity data, it is not difficult to understand why a scheduler is unable to produce a reliable CPM schedule.

Productivity has been widely used as a performance indicator to evaluate construction operations through the entire construction phase. There are many methods that can be used to determine on-site construction productivity, such as questionnaires, activity sampling, still photographs, time study, time-lapse filming, and full-time videotape recording (Oglesby et al. 1989). Among these methods, time study, also called stopwatch study, is the classic productivity measurement method developed by Frederick W. Taylor in about 1880 (Meyers 1992). Since 1980, more and more construction companies have utilized time-lapse filming and full-time videotape recording methods because of the advancement in technologies and cost reduction of required equipment. However, these methods are conducted by employing additional people to manually collect data from the construction sites. As a result, using these methods for measuring productivity may increase the cost, delay the analyses, and interfere with construction crew activities, which may lead to inaccurate data. This indicates a need to develop an advanced productivity measurement system that will overcome these shortfalls.

In summary, poor productivity data impact the accuracy of activity duration; inaccurate activity duration makes it impossible to produce a reliable construction schedule. To improve the quality of construction schedules, there is a need to develop an innovative way to collect on-site construction productivity data.

CHAPTER 2:RESEARCH OBJECTIVES, SCOPE, AND METHODOLOGY

2.1 Research Objectives

The primary goal of this research is to develop a **w**ireless **r**eal-t**i**me produc**t**ivity m**e**asurement (WRITE) System that is capable of measuring on-site construction productivity without interfering with construction operations. The collected productivity data can be sent via a wireless network to a project manager or an engineer, who is miles away from the job site, for analysis. This goal has been realized through achieving the specified research objectives that are described as follows.

1. To build the WRITE System by identifying the key components and their connections.
2. To design field experimental procedures to test the accuracy of the WRITE System.
3. To conduct field experiments including data collection and analysis.
4. To utilize the WRITE System to improve the on-site construction productivity.
5. To identify the limitations of the WRITE System and make recommendations for future research.

Because the project was successful, this project made several major contributions to the advancement of knowledge in the construction industry. First, it advanced the applications of wireless technologies in construction operations. Second, it improved the accuracy of on-site construction productivity data. Finally, it developed new technology that is capable of continuously measuring productivity data in real-time. With these advancements, it became possible to develop an accurate and reliable construction schedule for rapid construction operations. Thus, results of this research project enhanced the capability of rapid replacement of damaged infrastructure after extreme events.

2.2 Research Scope

The developed WRITE System was tested on highway and bridge construction projects, which represented an equipment-intensive project and a labor-intensive project, respectively. Currently, the data collected by the WRITE System can be sent wirelessly via internet from job site to office with no distance limitation.

2.3 Research Methodology

The research objectives will be accomplished in the manner explained below.

2.3.1 Literature Review

The first phase of this research is an extensive literature review. The literature survey includes state-of-the-practice in rapid infrastructure replacement, construction productivity measurement, and theory of statistical tests. The reviewed literature includes journal papers, research reports, conference proceedings, theses, dissertations, and online publications.

2.3.2 Building the WRITE System

During this stage, the author first identifies the necessary hardware and software that are required to build the WRITE System. Then, a framework that shows the component connections is developed. Finally, the author purchases the required hardware and software and builds the system.

2.3.3 Experimental Design

The developed WRITE System is tested to determine its accuracy in the construction sites. Productivity measurements produced by the WRITE System will be compared with measurement results provided by a time study, a classic productivity measurement method developed by Frederick W. Taylor. The author determines whether the measurement results produced by these two methods are statistically the same or not. In order to make the comparison, the author must design field experiments that include experimental site selection, experimental layout, experimental procedure, data collection procedure, and data analysis methods.

2.3.4 Field Experiments

Based on the procedure developed at the experimental design stage, field experiments were conducted at highway and bridge construction sites. The author defined construction activities performed by either equipment or human beings.

Productivity data were collected using the WRITE System and the time study method, simultaneously.

2.3.5 Data Analysis

The author employed the Statistical Analysis System (SAS®) to analyze data collected using the WRITE System and the time study method. Statistical analysis methods, such as hypothesis test, analysis of variance, and test of independence, were conducted to systematically analyze experimental data.

2.3.6 Writing of Dissertation

The end product of this research is a dissertation describing the work performed and presenting the results and conclusions. Recommendations for the direction of future research are also included.

2.4 Dissertation Organization

The chapters of this Ph.D. dissertation are organized in the following manner. Chapter 1 introduces the research background and problem statement. Chapter 2 presents the research objectives, scope, and methodology. Chapter 3, Literature Review, provides an overview of state-of-the-practice in rapid infrastructure replacement, construction productivity measurement, and theory of statistical tests. Chapter 4, Development of the WRITE System, presents the major components of the developed system and how these components are connected to each other. Chapter 5, Phase One – Productivity Measurements for Highway Construction Operations, presents the field experiments conducted in the highway construction projects during the summer of 2007, including field experimental site selection, layout, and the method of construction operations. Chapter 6, Phase Two – Productivity Measurements for Bridge Construction Operations, presents the field experiments conducted on the bridge construction projects during the spring of 2008, including the same sections as in Chapter 5. Chapter 7, Productivity Improvements, describe how the WRITE System was utilized to improvement the on-site construction productivity. Chapter 8, Conclusions and Recommendations, concludes this research project and provides recommendations for future research.

CHAPTER 3:LITERATURE REVIEW

The following subchapters outline findings from the literature review that includes the state-of-the-practice in rapid infrastructure replacement, construction productivity measurement, and theory of statistical tests.

3.1 Rapid Infrastructure Replacement

The scope of the literature review regarding rapid infrastructure replacement is limited to highways and bridges because of the nature of this research project. In the following subchapters, findings on rapid bridge replacement are introduced first, followed by rapid highway replacement.

3.1.1 Rapid Bridge Replacement

3.1.1.1 Introduction

Twenty four papers presented in Table 1 were reviewed to identify bridge construction techniques for expediting the completion of projects, which have evolved and have been practiced in the construction industry for many years. Papers in this subchapter cover the following technology issues: rapid bridge replacement procedures including traffic detour, demolition, design, contract, and reconstruction, and innovative bridge constructions as well as prefabricated technologies. The references cited include a technical book, journal papers, FHWA reports, conference proceedings, and magazine articles.

Table 1. List of Previous Research on Rapid Bridge Replacement

No	Study Subject	Researchers	Study Scope	Funding Agency	Year
1	Design of Highway Bridges	Barker and Puckett	National	Technical book	1997
2	Security of Road and Bridge Infrastructure	Stidger	National	N/A	2003
3	Rapid Bridge Replacement: Processes and Techniques	Bai and Burkett	National	GDOT, IDOT, MnDOT, MDOT, NJDOT, NMDOT, ODOT, SCDOT, and TxDOT	2006
4		Bai et al.	National		2006
5		Burkett et al.	National		2004
6	Innovative Contract Delivery Method: A+B Method	Kent	National	FWHA	2006
7		Beard	National	N/A	2001
8		Swanson and Windau	Ohio	N/A	2004
9	Bridge Replacement	Mammino and Tonon	Italy	N/A	2004
10	Prefabricated Technique	Mistry and Mangus	National	FWHA	2006
11		Tadros et al.	Nebraska	Nebraska	1997
12		Short	Europe	FWHA	2004
13		FHWA	National	FWHA	2006
14		Anon.	National	N/A	1987
15		Khaleghi	WS state	Washington State	2005
16		Wenzlick	Missouri	MODOT	2005
17		Shahawy	National	NCHRP	2003
18		Umphrey et al.	Georgia	GDOT	2007
19		Culmo	Connecticut	Connecticut DOT	2000
20		Scanlon et al.	Pennsylvania	Penn DOT	2002
21		Ralls and Tang	National	AASHTO	2004
22		Capers. Jr.	New Jersey	NJDOT	2005
23		Issa et al.	Illinois	IDOT	1995
24		Chan and Lu	Hong Kong	Hong Kong Government	2005

According to Barker and Puckett (1997a), highway bridges are the critical component of the nation's transportation network because:

1. A bridge controls the capacity of a transportation system.
2. A bridge has the highest cost per mile of the system.
3. If a bridge fails, the system fails.

"A Guide to Assess State DOT Vulnerability," developed under the sponsorship of AASHTO, identified bridges and overpasses as one of 12 critical transportation assets. This guide provided the following procedures to assess the importance of bridges including: 1) establishing vulnerability for critical transportation assets; 2) determining the level of exposure depending on the visibility and usage, access to the asset, and site specific hazards; and 3) assessing possible consequences and potential risks once extreme events occur (Stidger 2003).

U.S. highway bridges have been strategically rehabilitated or replaced since deficient structures became a critical issue in the 1980s. Subsequently, the Intermodal Surface Transportation Efficiency Act of 1991 came into effect and state agencies implemented a bridge management system (BMS) that considers the life-cycle costs of alternative improvement options: maintenance, rehabilitation, reconstruction, and replacement. According to the 2002 biennial report, 28% of the 590,000 bridges in the U.S. were structurally deficient, indicating that they needed to be replaced or rehabilitated (Shahawy 2003). Among the above improvement options, the expense of bridge replacement is the highest and the most sensitive to total agency and user costs, which causes the most funding needs for some agencies. Bridge replacement costs vary by bridge size, site characteristics, and the degree of damage (Abed-Al-Rahim and Johnston 1995).

The consideration of geological and geomechanical aspects is noteworthy in establishing the overall replacement plan. For example, in the replacement of the Pontesei bridge in Italy, the abutments and deck were constructed under an existing temporary bridge while maintaining traffic because of the steep canyons and the instability of existing earth on which the abutments were placed (Mammino and Tonon 2004).

Case studies on bridge replacement have been conducted to identify strategies and technologies to quickly restore damaged bridges (Bai and Burkett 2006). As a result of these case studies, a general model for bridge replacement was developed, shown as Figure 1. Three key elements of this model are major players, major tasks, and major decisions. Major players, such as state DOTs, design firms, contractors, material suppliers, and vendors, have the responsibility to conduct the bridge replacement tasks and make major decisions during the bridge replacement process. The major tasks of a bridge replacement are traffic detour, bridge demolition, design, contract, and reconstruction. At each stage, major decisions need to be made, which have significant impacts on the outcome of a bridge replacement. For example, during the design stage, the most important decision is to establish whether the bridge shall be rebuilt using an identical structure or a new design. If the decision is to use the identical structure, then the design work is simple if the original drawings and specifications are archived.

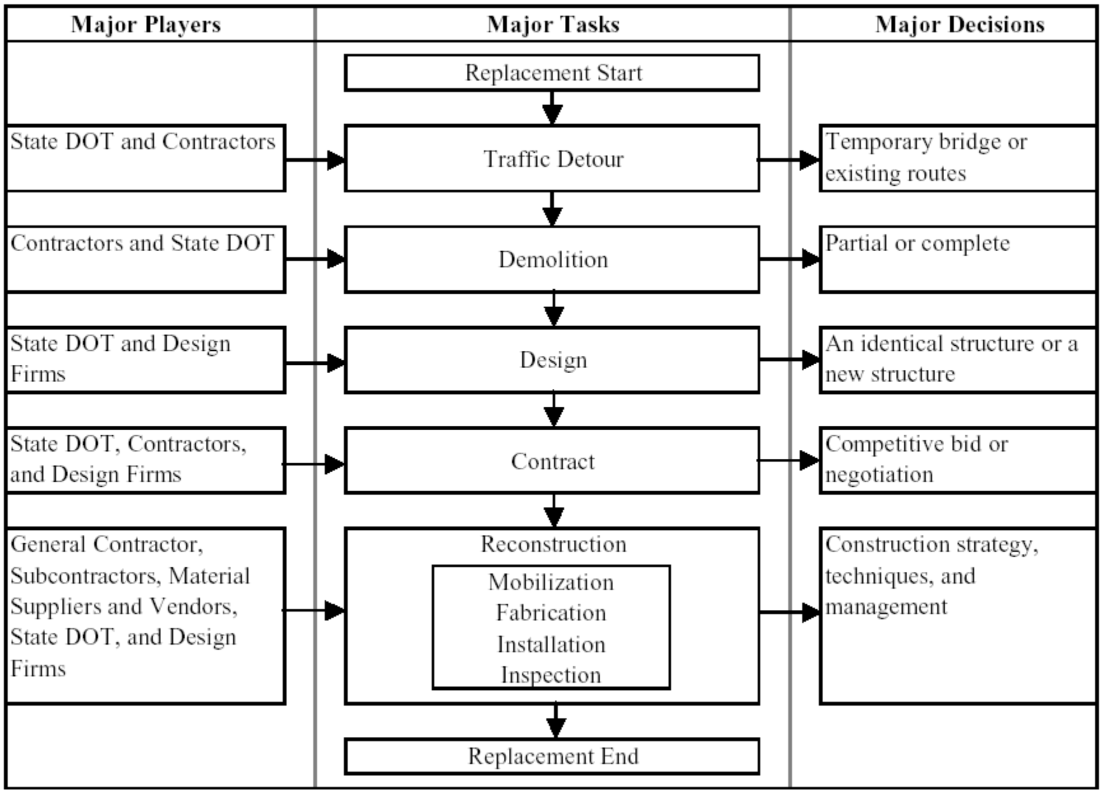


Figure 1. A general model for rapid bridge replacement (Bai and Burkett 2006)

3.1.1.2 Procedures of Rapid Bridge Replacement

3.1.1.2.1 Traffic Detour

Traffic detour is one of the most urgent tasks that state DOTs must perform immediately following an incident, and the DOTs must maintain these routes during the entire period of the bridge replacement. Three common methods used to establish detour routes are as follows (Bai and Burkett 2006):

1. Using the undamaged portion of the bridge,
2. Switching the traffic's direction on to the adjacent existing routes,
3. Installing prefabricated temporary bridges.

A major concern is the condition of the incident site when selecting the most effective temporary detour. No single method is applicable to all situations. For example, using the first method may cause traffic congestion. The second method may cause increased traffic volume on other existing highways, higher user costs and travel time because of the increased travel distance, and deterioration of the detour road. The third method may be the best option for maintaining the traffic speed and reducing inconvenience to the traveling public. However, this method entails higher costs and longer time to set up the temporary bridges. Because of these reasons, it is a challenge for decision makers to consider a variety of factors and select the best alternative within a short period of time.

3.1.1.2.2 Demolition

During demolition, the first challenge is that a partially damaged bridge always has potential risk of further damage during demolition of the damaged section. The second challenge is to demolish the bridge under water. The contractor who demolished the I-40 Webbers Falls Bridge faced these two challenges. Part of the bridge was damaged because of vessel impact, shown in Figure 2. The Oklahoma Department of Transportation (ODOT) awarded a demolition contract ($850,000 with a 16-day duration) to remove the damaged section immediately after the incident. Incentive and disincentive clauses were used to expedite the demolition process. The contractor would receive a $50,000 per day bonus for each day it finished ahead of schedule and would be penalized $50,000 per day for each day over schedule.

Various demolition devices were used to meet the different needs at the site. Underwater demolition was one of the most hazardous operations. This operation needs to be improved in both productivity and safety (Bai et al. 2006).

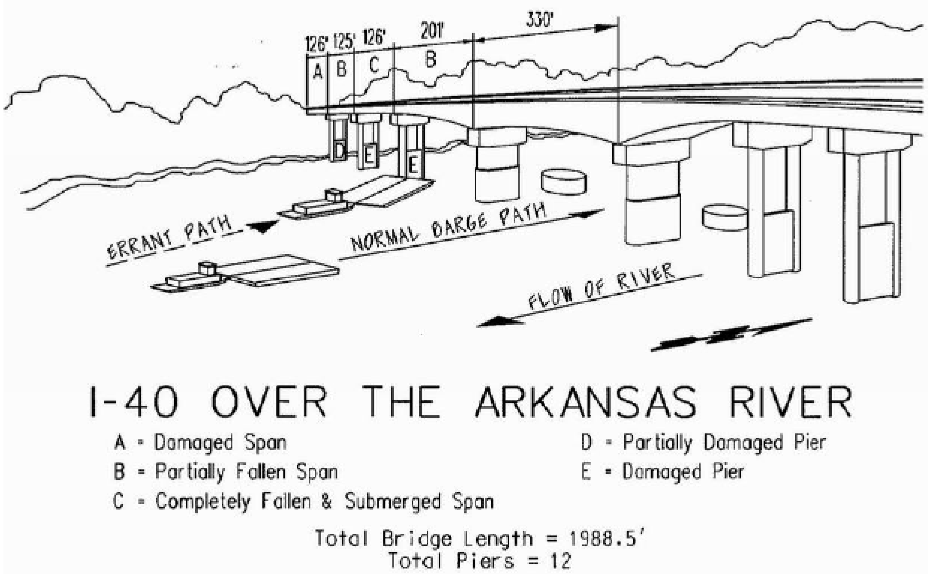


Figure 2. I-40 Bridge incident sketch (Bai et al. 2006)

3.1.1.2.3 Design

There are two major objectives during the design stage for rapid bridge replacement. One objective is to make sure that reconstruction of the bridge can be conducted quickly based on the design drawings and specifications. Another is to expedite the design process itself. Bridge design could be expedited by adopting the following methods during the design phase (Bai et al. 2006):

1. Using incentive/disincentive clauses;
2. Providing the original design information quickly to the design firms;

3. Providing whatever required information/data design firms need whenever they need it; and
4. Changing the state DOTs' operational procedure, such as allowing quick review and approval of design submittals, including design drawings and specifications.

3.1.1.2.4 Contract

Several contracting methods were used in the rapid bridge replacement projects and all were found to be effective. These methods include Incentive/Disincentive (I/D), A plus B, and design-build. The I/D contracting method includes a bonus/penalty scheme that rewards contractors for early completion and penalizes them for late completion of a contract. This method is usually used on a project that has a significant impact on the public as well as high user costs. The I/D amount should not be determined through the negotiation between the owner and the contractor, but should be decided based on user costs and government agency costs (Bai and Burkett 2006).

The A plus B method, an innovative project delivery method, was developed to encourage contractors to more actively manage their work schedule and, when necessary, to adopt innovative and aggressive scheduling and construction management processes that will shorten the construction duration and reduce the inconvenience to the driving public. In the contract, A represents the cost of the project and B refers to the schedule of the project (Kent 2006). This method was used for the I-40 bridge reconstruction. ODOT awarded an A plus B contract to the Gilbert Central Corporation for $10.9 million with a 57 day schedule. The final project was completed in 46 days and 16 hours, which was the fastest completion of its type in U.S. history. Under normal conditions, it would have taken at least six months to complete the reconstruction project.

Design-build is usually an ideal contract method for fast track construction, resulting in much time-saving. Using this method, design and construction can be overlapped and bidding time can be shortened. Construction can even begin in advance of the design completion (Beard et al. 2001). To minimize the time that the bridge would be closed, the Ohio Department of Transportation decided to use the design-build method for implementing rehabilitation of the Pickaway County State Route 22 Bridge over the Scioto River. The project scope was to widen a 45-year-old, deteriorated six-span steel-girder bridge. The project was completed in only 47 days, which was the fastest project involving similar type of bridges in the U.S. (Swanson and Windau 2004).

3.1.1.2.5 Reconstruction

This final stage during the bridge replacement requires applying construction strategies, techniques, and management to replace the damaged bridges in the shortest time period with the purpose of minimizing the inconvenience to the public and surrounding communities. This subsection introduces the following techniques that have been used for rapid bridge replacement:

1. Use of various construction schedules
2. Changing normal operational procedures
3. Staged construction
4. Community and interagency cooperation

A variety of construction work schedules can significantly impact bridge replacement. When a specific work schedule is determined, the contractor must consider the following issues:

1. The increased amount of costs typically associated with accelerated construction schedules
2. Decreases in user costs and public inconvenience
3. Availability of state DOT personnel for inspection and problem solving during off-duty hours
4. Availability of materials and material delivery
5. Loss of worker productivity, loss of quality control, and increased worker safety issues typically associated with accelerated or nighttime construction or extended work shifts

Besides the standard work schedule (8 hours per day and five days per week), other schedules are possible, such as a 24-hour work schedule, a 12-hour work schedule, and a nighttime-only work schedule. Selecting a work schedule depends on construction cost and duration, severity of circumstances, and job site location. Utilization of a 24-hour construction schedule is warranted when circumstances are severe enough to justify the increase in cost associated with its use. Utilization of a

12-hour construction schedule is warranted when circumstances are not severe enough to justify a 24-hour schedule, along with its significant cost increase, but critical enough that a standard 8-hour day will not provide an acceptable estimated project completion schedule. Nighttime-only construction is used when a job site is located in urban areas with high traffic volume, as daytime construction would clearly cause undesirable traffic disruptions to these areas.

Changing normal operational procedures may be required by all parties involved in the rapid bridge replacement to meet the specific deadline. For the I-40 Webbers Falls bridge incident, the assistant bridge engineer from ODOT was available to answer any questions from the design firm, around the clock. During the I-95 Chester Creek bridge replacement process, the Pennsylvania Department of Transportation (Penn DOT) had to change its normal inspection procedure by performing inspection at the steel fabrication plant because the fabrication and delivery of the steel beams were the critical activities (Bai and Burkett 2006).

Staged construction is where bridge reconstruction is done in planned sequential stages, maintaining portions of the bridge in an operating condition for traffic while other portions are closed for replacement. The New York State Thruway Authority (NYSTA) used a staged construction approach to replace its I-87 New York Thruway fire damaged bridge. Once the initial damaged bridge was removed, two temporary prefabricated bridges were installed near the original site to carry the traffic flow while a portion of the bridge was reconstructed. Once the initial portion of the reconstructed bridge was ready for traffic, traffic was rerouted onto it, and one of the two temporary bridges was removed. Once the second portion of reconstructed bridge was ready for traffic, traffic was rerouted onto it, and the last temporary bridge was removed, thus allowing reconstruction of the last portion of the bridge.

Support from communities and interagency cooperation are critical to make a bridge replacement project successful. During the I-40 Webbers Falls Bridge replacement, coordination among federal, state, and tribal governments was essential to replace the damaged bridge on a fast track. The Cherokee Nation, the sole owner of the Arkansas Riverbed and Banks at Webbers Falls provided immediate access to the land and manpower to contractors. Three million dollars of federal emergency relief funds were released by the FHWA, thus, the repair work could start immediately. FHWA also provided technical expertise and assistance to ODOT for bidding and contract administration. In addition, the US Army Corps of Engineers, the US Coast Guard, and other state DOTs also provided technical help and support to ODOT (Bai and Burkett 2006).

3.1.1.3 Bridge Construction Technology

For the last several decades, the construction industry has been developing innovative construction techniques in attempting to expedite bridge construction projects. For the construction of foundations, large-diameter piles or drilled shafts are used to reduce a number of required elements, and therefore accelerate construction. Sheet piles are prefabricated for the construction of retaining walls, wing walls, and abutments. Mechanically stabilized earth (MSE) abutments, often used for retaining walls in the U.S since the 1980s, have been successfully utilized. Decks and parapets, using high-performance concrete (HPC), and integral abutment bridges, contribute to saving construction time (Capers Jr 2005). The longest and largest precast segment bridge project was carried out in Bangkok, Thailand in 1995. The 20,400,000 sq-ft design-build-contracted project was completed within three and a half years (Brockmann and Rogenhofer 2000). Two bridges were replaced by cast-in-place (CIP) segmental cantilever bridges in L.A., in an urban environment with busy intersections (Mondorf et al. 1997).

Prefabricated bridge technology is currently the most common technique in innovative bridge construction. Prefabricated technology provides an effective and economical design concept for implementing bridge replacement and rehabilitation. Using prefabricated bridges offers significant advantages over CIP construction because the construction practice can be implemented with offsite manufacturing and standardized components, which enable winter season operations and the ability to avoid falsework and formwork. As a result, it reduces time and life-cycle costs, traffic disruptions, and environmental impacts. This technology also improves labor productivity, construction workzone safety and quality, and life expectancy of bridges.

A research project sponsored by AASHTO in cooperation with FHWA was conducted by Shahaway (2003) to identify the current state of the prefabricated techniques used for bridge replacement. According to the survey of 36 agencies covering 229,000 bridges, 15% of the bridges included prefabricated elements and 0.5% contained completely prefabricated superstructures. Only 0.1%, eight bridges, included full-depth prefabricated concrete deck panels. Only 2% of bridges are innovative prefabricated bridges, such as full-depth deck panels, completely prefabricated superstructures or substructures, and fiber reinforced polymer (FRP) deck bridges, mostly in Texas, Virginia, and Tennessee (Shahawy 2003).

Among nearly all parts of a bridge that could be fabricated, the most widely used are bridge deck panels. Building bridge decks was the slowest work in the conventional CIP bridge construction because of the complexity of rebar forming (Mistry and Mangus 2006). State of the art technologies include proprietary systems, such as exodermic bridge decks, aluminum bridge decks, prefabricated channel concrete sections, and prefabricated steel systems. These bridge construction techniques commonly provide 25% to 50% less deck weight than the conventional CIP, which increases the replacement speed and the live-load capacity (Shahawy 2003). The prefabricated design technology with monolithic connections meets the load and resistance factors design (LRFD) of AASHTO for seismic-resistant bridges (Khaleghi 2005).

Full-depth prefabricated panels have been developed to increase safety and reduce costs and construction times. Full-depth prefabricated decks are placed transversely on the supporting girders and are post-tensioned longitudinally. The existing deck is usually replaced during night operations and the new panels are installed to open for traffic before the morning. In 1998 two bridge replacement projects, Dead Run (305 ft with three spans) and Turkey Run (402 ft with four spans), which are bridges on George Washington Memorial Parkway, Virginia, used an 8-in full-depth concrete deck on steel beams with noncomposite action, allowing a production rate of one bridge span per weekend (Shahawy 2003). The Missouri Department of Transportation (MoDOT) used the full-depth prefabricated deck replacement method for replacing the Nemo Bridge. As a result, MoDOT only needed to close the bridge Sunday through Thursday from 7:00 pm to 7:00 am (Wenzlick 2005).

Another deck replacement project involved replacement of an entire superstructure using fiber reinforced plastic (FRP). FRP has been developed and used in the bridge industry for the last several decades, since its first use in China in 1982 (Shahawy 2003). During the 1990s, Japan, Europe, and the U.S. used this method and then, a glass fiber-reinforced plastic (GFRP) was used in the world's first long-span composite structure built in Scotland over the River Tay at Aberfeldy in 1992. The lighter structure allowed use of lightweight equipment and a shorter erection time, about 10 to 20% of that necessary for a conventional concrete deck (Shahawy 2003).

In a scenario similar to other bridge replacement projects, the need for traffic accommodation was significant when the West Virginia Department of Transportation (WVDOT) overhauled the Howell's Mill Bridge in Cabell County in 2003. The West Virginia project also had constructability challenges, such as difficult elevations, long stretches over water, and crowding by adjacent buildings. The 245-foot-long and 32.5-foot-wide bridge required a replacement deck of 7,833 square feet. The prefabricated FRP deck arrived onsite in 8- by 32.5-foot panels with a factory-applied skid-resistant surface. All panels were attached in just 3 working days (Mistry and Mangus 2006).

The NCHRP Report 407 “Rapid Replacement of Bridge Decks” evaluated existing rapid bridge-deck replacement methods and developed new superstructure designs for future rapid deck replacement. The reports provided detailed design information for a prefabricated bridge deck and the likelihood of reducing replacement time. In this study, construction time of deck replacement using CIP, stay-in-place (SIP), and the full-depth prefabricated technique were compared. The results indicated that the construction time for precast was 76% of that for CIP and 78% of that for SIP (Tadros and Baishya 1998).

For a bridge built over Lake Ray Hubbard in Dallas, engineers from the Texas Department of Transportation (TxDOT) designed the bridge pier caps, and the contractor prefabricated them to construct a 4,300-foot long bridge. Construction with the prefabricated caps took a year less than the original schedule. While it usually takes eight to nine days to form, tie, pour, and cure each cap using the CIP method, utilizing the prefabricated method only took one day to set each prefabricated bridge cap at the construction site (Mistry and Mangus 2006).

A guideline was developed by FHWA to help government agencies make a decision as to whether prefabricated elements should be used for bridge replacement. Based on the guide, the decision maker can determine whether to use prefabricated bridge elements or not by answering the following questions (Ralls 2006):

1. Is the construction over an existing high-traffic-volume highway?

2. Is this project an emergency bridge replacement?
3. Is the bridge an evacuation route, or over a railroad or navigable waterway?
4. Will the bridge construction impact traffic in terms of requiring lane closures or detours?
5. Will the bridge impact the critical path for the total project?
6. Can the bridge be closed during off-peak traffic periods such as nights and weekends?
7. Is rapid recovery from extreme events needed for this bridge?

Table 2 shows the projects using prefabricated technologies including full- and partial-depth concrete deck panels, total substructure and superstructure systems, exodermic deck panel, prefabricated piers and caps, and total prefabricated system (Shahawy 2003).

FHWA and AASHTO sponsored a study on the accelerated bridge construction techniques currently used in Japan and Europe. The study focused on the bridge span lengths ranging from 20 to 140 ft, which represents the majority of bridge structures in the U.S. In Japan and France, a technique, using computer controlled self-propelled modular transporters (SPMTs), was implemented where completely fabricated bridges were slid on roller skates horizontally to place the entire unit from the construction location to its final position. The weight of bridge structures ranged from 3,600 to 13,200 tons. The Sumitomo precast form for resisting earthquakes and for rapid construction (SPER) system, first developed in

Table 2. Projects that used Prefabricated Technology (Shahawy 2003)

Date of Construction	Bridge	Location	Prefabricated Elements (full and partial depth)
1961	Lavaca Bay Causeway	Over the Lavaca Bay, Texas	Girder/slab/diaphragm/parapet walls, prefabricated and prestressed; prefabricated monolithic beams
1983	Linn Cove Viaduct	Grandfather Mountain, North Carolina	Total prefabricated system
1988	Spur Overpass over AT&SF Railroad	Downtown Lubbock, Texas	Prefabricated full-depth concrete deck panels
1991	Edison Bridge	Fort Myers, Florida	Columns and bent caps
1992	Baldorioty de Castro Avenue Overpasses	San Juan, Puerto Rico	Total prefabricated system
1993	US-27 over Pitman Creek	Somerset, Kentucky	Full-depth concrete deck panels
1994	SH-249/Louetta Road Overpass	Houston, Texas	Total substructure systems; pretensioned partial-depth concrete deck panels
1995	Troy-Menands Bridge	Rensselaer and Albany Counties, New York	Exodermic deck panels
1995	George P. Coleman Bridge	Yorktown, Virginia	Total superstructure systems: Truss span
1997	I-45/Pierce Elevated Downtown	Houston, Texas	Bent caps; prestressed partial-depth deck panels; prestressed I-beams
1998	Dead Run and Turkey Run bridges	George Washington Memorial Parkway, Virginia	Prefabricated concrete; post-tensioned full-depth deck panels
1999	Route 7 over Route 50	Fairfax County	Virginia Prefabricated full-depth deck panels
2000	Keaiwa Stream Bridge	Route 11 near Pahala, Hawaii	Prestressed partial-depth concrete deck
2001	I-5/South 38th Street Interchange	Tacoma, Washington	Partial-depth concrete deck panels; post-tensioned tub girders
2001	Illinois Route 29 over Sugar Creek	Sangamon County, Illinois	Full-depth post-tensioned deck panels, parapets
2002	SH-66/Lake Ray Hubbard	Near Dallas, Texas	Bent caps; prestressed I-beams; prestressed partial-depth deck panels
2002	Wesley Street Bridge	Ragsdale Creek in Jacksonville, Texas	Prefabricated/prestressed slab beams
2002	I-95 James River Bridge	Richmond, Virginia	Total superstructure systems: Truss span
2003	Howell's Mill Bridge	Cabell County, West Virginia	FRP deck
2004	SH-36 over Lake Belton	Near Waco, Texas	Bent caps; prestressed U-beams; prestressed partial-depth deck panels

Japan, was adopted in the U.S. because it was not only designed for earthquake resistance, but also expedited the operation by 60% to 70% over CIP construction (Federal Highway Administration 2004b; Russell et al. 2005).

Besides the advantages provided by the prefabricated technologies, there are concerns including high initial cost, design and standardization issues, lack of specialized contractors, and sound connection between elements. For partial- and full-depth prefabricated deck panels, problems were reported with cracking and spalling. In addition, appropriate design and construction joints are required to ensure adequate performance (Shahawy 2003). To address these concerns, an analytical model is needed to predict the deterioration and to assess the life cycle cost of the prefabricated bridge decks (Hong and Hastak 2006).

Long distance (more than 50 miles) transporting is another issue when using prefabricated elements (Shahawy 2003). A research project on a viaduct construction project in Hong Kong was conducted that simulated the hauling of the precast segments from storage locations to the gantry to identify cycle time and influencing factors. This research project was based on the fact that limited site space did not allow on-site storage of the bulky precast viaduct segments. The results of the simulation indicated that the distance between the gantry and the storage spots should be kept within 24 minutes to reach the target cycle time that is one of significant productivity factors of installing the segments (Chan and Lu 2005). A longer shipping distance (require more than 24 minutes of transporting) would impact the construction productivity for this project.

3.1.2 Rapid Highway Replacement

Fifteen papers were reviewed to identify how highway construction techniques have been developed to expedite the completion of projects so as to minimize traffic disruptions to the public. This subsection covers the following technology issues: highway paving strategies, techniques for minimizing traffic disruptions, accelerated construction technologies, and precast paving technologies. The references listed in Table 3 comprise 12 journal papers, one FHWA report, one conference proceeding, and one magazine article.

Table 3. List of Previous Research on Rapid Highway Replacement

No	Study Subject	Researcher(s)	Study Scope	Funding Agency	Year
1	Construction Techniques	Meyer et al.	National	AASHTO	1976
2	Rehabilitation Strategies	De Solminihac and Harrison	US	N/A	1993
3		Arditi et al	Illinois	ITRC	1997
4		Wade et al.	National	IPRF	2007
5		Anderson et al.	National	NCHRP	2003
6		Lee and Ibbs	California	Caltrans	2005
7		Lee et al.	California	Caltrans	2005
8	Minimizing Traffic Disruptions	Dunston et al.	Washington	WSDOT	2000
9		FHWA	Michigan	FHWA	2004
10	Accelerated Construction	Lee and Thomas	California	Caltrans	2007
11	Precast Pavement Technologies	Carol Carder	Colorado	N/A	2005
12		Merritt et al.	Texas	FHWA	2001
13		Merritt et al.	Texas	FHWA	2003
14		Tyson and Merritt	Texas	CTRUTA	2005
15		Switzer et al.	Washington	N/A	2002

Note for Abbreviations: ITRC (the Illinois Transportation Research Center), IPRF (Innovative Pavement Research Foundation), CTRUTA (the Center for Transportation Research at the University of Texas at Austin)

Meyer and his colleagues (1978) identified technologies by which pavement structures in U.S. urban areas can be rapidly replaced to extend the designed service life. Following a review of 500 projects, the researchers discussed problems at each site and possible solutions with experts during site visits. A rehabilitation strategy was developed to cover diverse situations that might be encountered including: A) all layers are structurally unsound; B) the surface layer is structurally unsound while the sub-layers are structurally sound; and C) the surface layer and all sub-layers are structurally sound.

Findings from this research project were: 1) an adjacent lane closure was required for the effective rehabilitation of a freeway lane; 2) no improvement of the existing subgrade or natural soil could be accomplished because of the time constraint (a construction period of 48 hours); 3) construction management techniques using precedence diagramming and analysis bar charting indicated the critical aspects of each rehabilitation strategy and provided information to complete the rehabilitation within the time constraint; and 4) for the worst case (denoted by Scenario A), the concurrent paving method for replacing new pavement at a quarter mile long interval enabled a reduction in duration from 43 hours to 35 hours. If no single solution to a problem could be developed, then several solutions were proposed: deep lift asphaltic concrete, rapid hardening, high early strength concrete, sulphur systems for pavements, precast Portland cement concrete (PCC) panels, and combination systems (Meyer et al. 1978).

Highway reconstruction projects with high volumes of traffic are usually faced with situations, such as congestion, safety problems, and limited site access. Hence, these construction processes should be expedited to mitigate complications using innovative construction and traffic management technologies (de Solminihac and Harrison 1993). Moreover, management techniques such as contingency management, incentives/disincentives (I/D), and A+B bidding can be incorporated with accelerated construction technology (Arditi et al. 1997). Therefore, establishing appropriate strategies in a timely manner is a key element during accelerated pavement operations (Wade et al. 2007).

Anderson and his colleagues (2003) developed the process model of strategies for rehabilitation of PCC pavements. The research objective was to help state highway agencies select appropriate strategies for maintenance, rehabilitation, and reconstruction (MRR) of PCC pavements under high traffic volumes. An integrated process for the selection of the MRR strategies was developed based on the following critical factors: current pavement performance (structural and functional condition), traffic management needs (traffic control costs, road user costs, traffic congestion mitigation strategies, and public perceptions), construction needs (constructability, contracting, environmental impact, technology, schedule), and life-cycle costs (construction costs, user costs, future MRR costs, and salvage value). To select an MRR strategy, an individual treatment or a combination of treatments and their critical factors are applied, as illustrated in Figure 3.

The researchers initially reviewed four existing MRR strategy selection processes, developed by the American Concrete Paving Association (ACPA), AASHTO, the Wisconsin Department of Transportation (Wisconsin DOT), and NCHRP. In addition, interviews were conducted with five other state agencies to identify their practices. The developed selection process model was validated using case studies to confirm that the model was comprehensive, logical, and practical. The development of the model comprises four major steps: 1) identifying candidate sections, 2) identifying pavement conditions, 3) screening potential strategies, and 4) evaluating feasible strategies. In the first step, planners identify the candidate sections. Pavement conditions are determined and possible treatments are employed in the second step. Following these two steps, special traffic and construction issues are identified, and preliminary costs and feasible strategies are evaluated in step three. In step four, planners determine the level of traffic and construction effort, and conduct various analyses to determine the most appropriate MRR strategy. This MRR strategy selection process provides a preferred strategy with a greater focus on traffic and construction management, as well as life cycle costs. Researchers indicated that this selecting method could be used with the existing methods and might be also useful for lower traffic volume conditions and other types of pavements (Anderson et al. 2003).

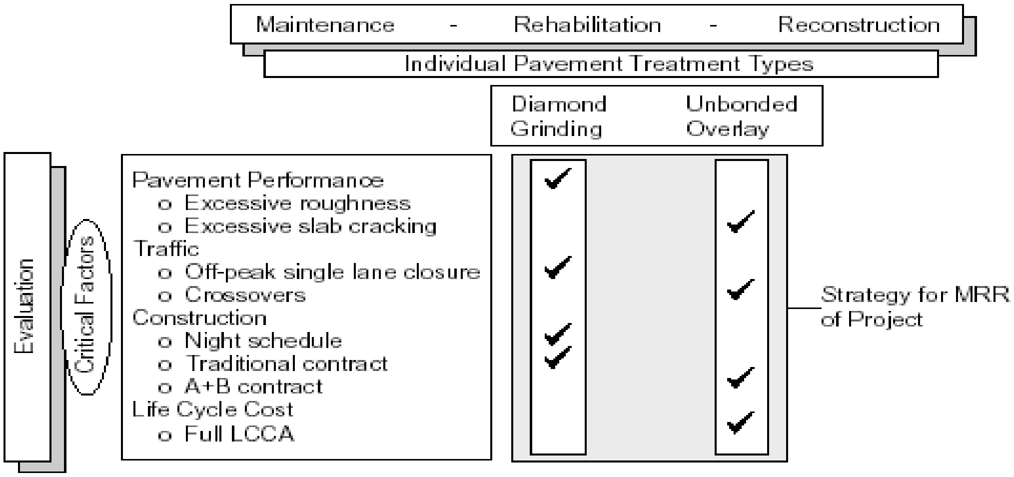


Figure 3. Framework for selecting strategies for MRR (Anderson et al. 2003)

Lee and Ibbs (2005) developed a simulation model software, Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS). The research purpose was to provide a construction engineering and management tool to the California Department of Transportation (Caltrans) for the rehabilitation and reconstruction of highways during the planning and design phases. The software can be used to estimate the maximum probable length of highway pavement that can be rehabilitated or reconstructed given various parameters, such as pavement materials and design, lane closure schemes, schedule interfaces, and contractors' logistics and resources. By integrating with traffic simulation models, the newly developed model quantified road user costs during construction so that all parties involved in reconstruction could determine which pavement strategies maximize production and minimize traffic delays. The software was verified with Caltrans' first two projects of the Long-Life Pavement Rehabilitation Strategies (LLPRS) program: the I-10 Pomona project for

PCC pavement under a 55-hour weekend closure (10:00 pm on Friday to 5:00 am on Monday) and the I-710 Long Beach project for asphalt pavement under eight 55-hour weekend closures. Use of repeated weekend closure for rehabilitation operations improves contractors' productivity in the succeeding weekend closures (Lee and Ibbs 2005).

In the third LLPRS project to rebuild a 4.2 km section of I-15 in Devore, California, the most economical reconstruction closure scenario was determined by comparing four construction closure scenarios: a traditional 10-hour nighttime closure, a 72-hour weekday (Tuesday to Thursday), a 55-hour weekend (Friday to Sunday), and a one-roadbed continuous closure. The analysis demonstrated that the one-roadbed continuous closure scenario was the best scenario because it had 81% less total closure time, 29% less road user costs, and 28% less agency costs than the traditional nighttime closure (Lee et al. 2005).

Full road closure has been increasingly used with successful results because the approach often reduces project duration and costs, and improves the quality and safety for both travelers and workers. Dunston and his colleagues (2000) evaluated construction of asphalt overlays for an urban highway project on I-405 in the Seattle area to identify the full weekend closure as a possible alternative to the nighttime closure. The construction quality between nighttime and daytime paving was compared to identify the difference with respect to smoothness, density, gradation, and cyclic segregation. Results revealed that productivity under the full weekend closure scheme was improved with consistent quality. Although the partial nighttime closure scheme was the most popular with the public, the full weekend closure scheme might be used more by state government agencies, because of better efficiency (Dunston et al. 2000).

Another full road closure in a construction work zone (CWZ) was studied by FHWA on an M-10 rehabilitation project in Detroit, Michigan. The project was completed in only 53 days, although the baseline schedule was longer than six months. While no quantitative information on cost savings was available from this project, significant cost savings appear to have been accomplished based on the information provided by engineers from the Michigan Department of Transportation (MDOT). In this project, initial alternative routes were kept operational until the end of the project. This resulted in traffic maintenance costs at only 1.3% of the bid price for project costs; traffic maintenance cost normally ranges from about five to ten percent of the bid price. Consequently, the contractor's production was also expedited, and there were no severe safety incidents (Federal Highway Administration 2004a).

Utilizing experiences from I-10 Pomona and I-710 Long Beach LLPRS demonstration projects, a case study was conducted to develop strategies for the reconstruction of I-15 in Devore, California. In the preconstruction stage, four lane closure scenarios were compared to determine the best scenario regarding the construction schedule, traffic inconvenience, and agency costs. These scenarios were 72-hour weekday, 55-hour weekend, 24-hour/7-day continuous and 10-hour nighttime. Caltrans initially employed the second most economic scenario, the 72-hour weekday closure. However, the scenario was discouraged by the local public. Instead, the most economical option, one-roadbed continuous closure scheme with 24-hour per day/7-day week operations, was used to complete the reconstruction in 210 hours (about 9 days) for each direction, where it was initially estimated to take 10 months when using traditional nighttime closures (Lee and Thomas 2007).

A case study of fast-track PCC pavement construction was conducted to provide information on sixteen airfield PCC paving operations. The scope of this research was to study a variety of facilities, rehabilitation methods, and closure times. Data were collected from literature reviews, site visits, telephone interviews, and emails. Several findings are described as follows (Wade et al. 2007):

1. Good communication between all parties (owners, designers, contractors, and material suppliers) enabled quick response to any issues that might affect the construction progress and quality.
2. Design modifications often proposed by an owner or a contractor during the construction phase can minimize initially planned duration and costs. For example, the specification to use a stabilized base layer under PCC pavements was altered to PCC and aggregate base course to simplify the operation. This resulted in saving two to three days on each critical runway phase for several projects.
3. Lessons learned from previous precast panel projects were adapted to the larger project by using smaller slabs to facilitate the mobility of cranes.
4. Grade preparation for concrete placement became more important given the short period of construction time because the production of pavement

removal was influenced by the equipment size and adjacent pavement or underlying pavement layers. Instead of using the saw-and-liftout method, pavement rubblization with a guillotine breaker and backhoe expedited the process after isolation cuts were made to protect adjacent pavement. Otherwise, early sawcutting during nighttime closure was carried out before the weekend operation began.

5. Successful PCC placements were accomplished by having sufficient resources, controlling the material production, adjusting the material according to pavement construction needs, providing multiple crews, maintaining the equipment more frequently, and utilizing lessons learned from previous practices.

Precast concrete paving techniques have been used for highway projects with short work periods and high traffic volumes that often require weekend closures. The cost of materials and labor was five times more than cast-in-place in the early stages of this technology (Carder 2005). To date, only a few research projects have been conducted on the subject, though there are potential advantages with this technique as shown from the success of precast concrete construction in the building and bridge industries (Merritt et al. 2001; Tyson and Merritt 2005). After an initial test and pilot project had been conducted by the Colorado DOT on US 287 near Fort Collins, Colorado, in December 2000, three types of replacement projects were completed by state highway agencies, such as the New York State DOT, the Colorado DOT, the California DOT (Caltrans), and the Texas DOT. The New York based Fort Miller Co.

Inc., installed 378 precast slabs on a heavy traffic six-lane highway project that required 47 nighttime closures in summer 2004. This duration was about half the time estimated for rapid-set concrete, because the initial design option required a 4-hour cure time out of the 8-hour work period. Further, the existing pavement panels were removed the night before and new panels were grouted the night after. The contractor installed 15 slabs of 10-foot length each night.

Other significant projects using this system included replacement of highway slabs at the New Jersey portal of the Lincoln Tunnel in July 2003, and a taxiway repair at Dulles International Airport in November 2002. Undersealed precast slabs were installed by Uretek USA on Highway 287 north of Fort Collins in Colorado in 2000. Colorado Precast Concrete of Loveland was the manufacturer. TLM Constructors Inc. of Greeley and its subcontractors installed 400 panels in Colorado in August 2004, and were scheduled to install 60 linear feet in 2005 with the production of about 10 panels each night. In March 2002 a pilot project for post-tensioned precast slabs was completed by Granite Construction on I-35 near Georgetown, Texas. The modified design was applied to the next pilot study on I-10 in Los Angeles, California. Yeager Skanska placed 31 panels with 124-foot longitudinal sections in two nights. The Pomeroy Corp. of Peris, California, manufactured the panels with a span of 37 feet or the full width of two lanes and the shoulder, which was designed to last 50 years (Carder 2005).

A feasibility study conducted by Merritt and his colleagues (2001) attempted to determine whether the precast concrete pavement technique can expedite the PCC pavement operation using overnight or weekend closure. The proposed concept used full-depth precast panels to obtain a smooth surface with proper vertical alignment and occasional diamond grinding of the finished pavement. The panels were designed to be pretensioned in the transverse direction during fabrication and to be post-tensioned in the longitudinal direction after placement. The post-tensioning also tied the individual panels together. In addition to the prestressed techniques, different design concepts for base and surface preparation were proposed. Comparison with conventional pavement shows that the precast technique allows grouting of the posttensioning strands to be done at a later time, and the stressing pockets do not have to be filled before traffic opens. The only thing that must be completed before traffic opens is the posttensioning. The method could also decrease the thickness of slab, and increase the length of slab for fewer joints and higher durability (Merritt et al. 2001).

Follow-up research was conducted to test and to further develop a precast pavement based on a pilot project for installing nearly 340 precast panels near I-35 in Georgetown, TX, in 2002. Since the previous project proved the feasibility and usability of precast panels for PCC pavement, several state agencies funded by the FHWA continued to test complexities and boundaries of the precast pavement. Findings from these two projects are as follows (Merritt et al. 2003; Tyson and Merritt 2005):

1. Twenty-five post-tension prestressed panels for the Texas project, equaling 250 feet of pavement, were installed in a 6-hour period, and

thirty-one panels for the California project were installed in a 9-hour period over two nighttime operations;

2. The expected life of 8-inch thick prestressed panel was 40 years, which is the same as that of 14-inch thick reinforced concrete pavement;
3. The panels should not be as tightly placed as the precast segments in bridge construction.
4. Future research projects should examine how a variety of base conditions might influence the type of precast panels and if the work speed could be improved.

Overnight pavement replacement using precast panels and conventional subgrade materials was carried out on active taxi lanes and taxiways at the Dulles International Airport, Washington, D.C. (IAD) in 2002. A short term overnight closure was allowed to complete two panels for each of three time periods: 15.5, 9.5, and 8.5 hours respectively. In the planning phase of this reconstruction project, it was determined that using cast-in-place would require closing the taxiways from 30 to 90 days. Using precast panel replacement techniques resulted in a 9-hour nighttime closure (Switzer et al. 2003).

3.2 Construction Productivity Measurement

3.2.1 Introduction to Construction Productivity

Productivity has been widely used as a performance indicator to evaluate construction operations through the entire construction phase. Construction companies have to track productivity continuously in order to gauge their performance capacity to maintain profitability and to prepare future bids (Ghanem and Abdelrazig 2006). Since the duration of a construction activity is calculated by dividing the quantity of work by the productivity, productivity analysis is a major task for predicting a project schedule (Pan 2005).

To understand productivity, it is important to differentiate the concepts of productivity and production rate. *Productivity* is production rate per unit input where *production rate* is defined as amount of production per unit time. Productivity is the amount of output related to the amount of time and money input into the production. That is, productivity is related to the concept of efficiency, because efficiency is the value of outputs compared to the cost of inputs.

Productivity has been defined in different ways depending on the scope of the research, such as the multifactor productivity model, the project-specific model (total productivity), and the activity-oriented model (labor productivity) (Liu and Song 2005). Multifactor productivity includes labor, materials, equipment, energy, and capital as total outputs and total inputs. A project-specific model is expressed using a physical unit as output and the dollars as the input. For labor productivity, the most commonly used in the construction industry, output is stated as a specific unit and input is stated as man-hours (Liu and Song 2005). Thomas and his colleagues defined productivity as a common measurement of construction productivity called factor productivity that is defined as physical output over the sum of labor, circulating capital, and fixed capital (Thomas et al. 1990).

The Business Roundtable (BRT) defined the productivity from the owner's perspective as output divided by input. The BRT focused on how many products can be produced in the designated time period (Chang 1991). Similarly, it is also defined as the dollars of output over person-hours of labor input (Adrian 2004e).

$$\text{Productivity} = \frac{\text{Output}}{\text{Input}} = \frac{\text{Dollars of Output}}{\text{Person Hours of Input}} \qquad (3.1)$$

From the standpoint of contractors, the Construction Industry Institute (CII) defined productivity as output divided by input for a restricted time interval (Thomas and Kramer 1988). The *RS Means Book,* used for the estimation of heavy construction cost data, defined productivity as labor-hours over the corresponding unit of completed work (Spencer 2006b).

$$\text{Productivity} = \frac{\text{Labor Hours}}{\text{Corresponding Unit of Completed Work}} \qquad (3.2)$$

To calculate earthmoving productivity using the most convenient method, the unit of work and the unit of cycle time are utilized to provide accurate and meaningful results (Christian and Xie 1996). In this case, productivity can be alternatively expressed as unit output over labor work-hours (Thomas et al. 1990; Noor 1998).

$$\text{Productivity} = \frac{\text{Unit Output}}{\text{Labor Work Hours}} \tag{3.3}$$

3.2.2 Motion and Time Study Theory

Motion and time studies or method improvements, originating from industrial engineering in the early 20th century, are used to determine the best method for developing optimal procedures and working conditions for an activity (Adrian 2004d). They are also used to reduce the number of motions and time in performing a task in order to increase productivity, as well as to monitor efficiency of labor and equipment, or the combination of the two.

The book titled *Motion and Time Study*, written by Fred E. Meyers, differentiates motion study and time study. A motion study is conducted for design purposes to reduce cost, while a time study measures productivity to control cost. Specifically, these studies seek to accomplish the following (Meyers 1992):

1. Increase the efficiency of activities;
2. Eliminate as many unnecessary motions as possible;
3. Reduce physical fatigue;
4. Make activities safer;
5. Improve the layout of work sites;
6. Improve material handling processes; and
7. Standardize optimum procedures and working conditions.

During the early age of motion and time studies, there were legal grievances between management and labor unions. Previous cases showed that a greater workload was imposed on employees and the time standard developed by management became the productivity standard to evaluate workers' efficiency without consent from these workers (Thomas and Holland 1980). Time-lapse video, one of the motion and time study techniques, initially faced resistance from organized labor on the legal issues regarding the nature of this method. This is because the laborer's productivity can be recorded and opened to the public, causing a possible dispute between the management and the labor union. Also, there was general resistance to productivity improvement programs. However, decisions for implementing the motion and time study results were made by owners and/or contractors who need to control productivity and make improvements (Thomas 1980).

To implement motion and time study theory, the initial task is to break the operation process down into several specific tasks so that ways to reduce or eliminate the unnecessary time required for each task can be developed. Time required to accomplish each task is summed to determine the cycle time of an operation. A cycle time can be expressed as select time, normal time, or standard time. The following is an example that shows how to calculate select time, normal time, standard time, and standard productivity for placing wood. Suppose time study data for placing wood are:

1. total cycle time is 1410 seconds with 9 cycles;
2. rating factor is 1.1;

3. allowance factor 15%;
4. wood panel size is 32 square feet per panel; and
5. crew size is 4 carpenters.

Thus, a calculation can be performed as follows (Adrian 2004d).

$$\text{Select Time} = \frac{\text{total time}}{\text{cycles}} = \frac{\text{1410 seconds}}{\text{9 cycles}} = \text{156.67 seconds}$$

$$\text{Normal Time} = \text{Select Time} \times \text{Rating Factor} = 156.67 \times 1.1 = 172.34 \text{ seconds}$$

$$\begin{aligned}\text{Standard Time} &= \text{Normal Time} + \text{Normal Time} \times \text{Allowance Factor} \\ &= 172.34 \text{ seconds} + 172.34 \times 0.15 \\ &= 198.19 \text{ seconds, or } 3.30 \text{ minutes}\end{aligned}$$

$$\begin{aligned}\text{Standard Productivity} &= \frac{3,600 \text{ seconds/hour}}{198.19 \text{ seconds}} \times \frac{32 \text{ square feet}}{4 \text{ carpenter- hour/hour}} \\ &= 145.32 \text{ square feet/carpenter-Hour} \\ &= 0.688 \text{ carpenter hour/100 square feet}\end{aligned}$$

Contractors can use this productivity information to plan construction activities, to monitor operation progress, to develop methods for improving productivity, and for estimating costs and the schedule for future projects.

3.2.3 Productivity Measurement Methods

Measuring productivity is an important task in the construction industry, because a construction company with outputs can plan and control construction costs and schedules, evaluate the performance inside the organization, and provide a basis for the improvement of their work force (Chang 1991). The purposes for measuring productivity are to identify cost effective methods in construction operations and to obtain accurate and consistent labor productivity data (Noor 1998). Productivity data are essential to estimators, labor contract negotiators, and those responsible for training the labor force and determining cost indices (Burton 1991).

Because of the sharp rise in construction labor costs since the 1970s due to a decline in labor productivity and a shortage of qualified workers, attention to productivity measurement has increased and the methods for improving construction productivity have evolved with the use of different techniques developed based on the motion and time study theory (Sprinkle 1972; Thomas and Daily 1983). As of today, construction labor productivity still remains the most difficult to understand in the U.S. economy because there are so many factors that could affect it. Productivity in the construction industry has decreased at a rate of –0.48% per year from 1964 to 1998. On the other hand, for the same period, productivity in the manufacturing industry has increased at 3.5% per year (Teicholz 2001). Construction productivity increased substantially during the 1980s and early 1990s because of depressed real wages and technological advances (Allmon et al. 2000). Recently, the evolution of Global Positioning System (GPS) technology has influenced considerable productivity increases in highway earthmoving operations (Han et al. 2005).

Productivity data collection methods can be inconsistent because various methods exist to gather data. This results in difficulties of interpreting and sharing the data. There are numerous types of productivity measurement techniques, most of which were developed using the motion and time study theory. Examples of these techniques include stopwatch study, photographic, taping video, time lapse video, activity sampling (work sampling), five minute rating, craftsman's questionnaire survey, and a foreman delay survey (Noor 1998). An ideal method for measuring construction labor productivity should satisfy the following basic criteria: 1) the method can monitor multiple trades at one job site; 2) the method is inexpensive; 3) the range of output and input should be consistent and identical; and 4) the method must not be very time consuming (Noor 1998). In the following subsection, several productivity measurement methods will be described in detail, including stopwatch study, activity sampling, survey, photographic techniques, and time-lapse video techniques.

3.2.3.1 Stopwatch Study

Stopwatch study has been widely used as the fundamental approach to measure productivity since it was invented in 1880 by Frederick W. Taylor, who was known as the father of scientific management (Meyers 1992). This is the oldest and simplest type of productivity measurement method for recording the duration of various activities comprising construction operations (Oglesby et al. 1989).

There are two major conventional ways to use a stopwatch to measure productivity: direct observation and work study. The difference between these two is that the observers continuously measure time used to complete tasks by workers using the direct observation method, while in the work study the observers select a specific time period. Work study, originated from manufacturing industry, can be used to determine both the standard time of activities and alternative working methods (Noor 1998).

The use of stopwatch study has shortfalls: First, it requires a recorder for every person or a piece of equipment being observed, which is very costly. Second, the observer must decide quickly at what time one cycle begins and another cycle ends. When activities are not clearly defined and cycles are irregularly categorized, each person will have a different interpretation about cycles. Third, because a substantial period of observation is involved, crews working on the activities may vary during the different cycles. Thus, it is inherently difficult for the observer to accurately determine the cycle time for activities. Fourth, time measurement varies depending on the characteristics of each activity, and the characteristics often interrelate among activities. Thus, detailed notes must be precisely recorded to describe reasons for delays (Oglesby et al. 1989). For example, in a study of a scraper operation, the loading time is longer than usual. There are several possible reasons, such as the scraper is waiting for the pusher; the pusher needs mechanical attention; the scraper is overfilled; or there are different ground conditions, including the gradient, soil properties, moisture content and so on. The observer must record the reason why it takes longer to load the scraper. Fifth, physical limitations or biases of the observers can affect their objectivity and produce inaccurate data. Because of these reasons, stopwatch study is seldom employed on construction sites in the U.S., except for the cases where only one or a few activities are to be observed (Oglesby et al. 1989).

3.2.3.2 Activity Sampling

In practice, it is impossible to observe and record every minute of construction operations. Thus, researchers have used the activity sampling method for measuring and analyzing crew productivity in the construction industry for the last 30 years. Activity sampling methods can be classified as work sampling, the group timing technique, and the five minute rating (Thomas and Daily 1983).

In designing a work sampling study, the most important step is to categorize activities according to the study needs. Activities can be divided into three categories: direct work, supportive work (essential contributory work), and delay or ineffective work (Adrian 2004d). Supportive work may include such tasks as material management, instructions to crew members regarding specification and drawings, setting up a timeline for equipment orders, measuring and marking bars, and moving scaffolding or other supportive work. Delay or ineffective work may include idle time, waiting for tools, materials, instructions and equipment deliveries, and no contact. No contact denotes the failure to observe workers in an assigned work location (Thomas and Daily 1983).

Three statistical parameters are used to measure the degree of certainty of sampling, which are confidence limit, limit of error, and category proportion. Confidence limit is a measure of the reliability of the inferences. Suppose that a confidence limit is 95%; this means that the inference is reliable 95% of the time. If the limit of error is 5% and nonproductive measurement is 30% of the time, then the operation is nonproductive somewhere between 25% and 35% of the time. The category proportion is the percentage of either productive or nonproductive time, which are the characteristics measured in productivity analysis (Adrian 2004d).

The required sampling size can be determined using the confidence limit, the limit of error, and the category proportion. Their relationships are shown in Table 4. For example, if the confidence limit is 90%, limit of error is 3%, and category proportion is 20 vs. 80 (20% of nonproductive and 80% productive), then the required sample size is 481. The required sampling size can also be calculated using Equation 3.4 (Thomas and Daily 1983; Oglesby et al. 1989; Adrian 2004a):

$$\mathrm{N}=\frac{\mathrm{K}^2[\mathrm{P}(1\text{-}\mathrm{P})]}{S^2}=\frac{1.645^2\times 0.2\times(1-0.2)}{0.03^2}=481 \qquad (3.4)$$

where N is the sampling size; P is the nonproductive percentage or productive percentage; S is the limit of error; and K is number of standard deviations defining the confidence interval. K is equal to the upper critical value of the normal distribution, also called z value, as shown in Figure 4. The z value can be obtained from the Table of Standard Confidence Limits.

Table 4. Sample Sizes for Selected Confidence Limits and Category Proportions (Adrian 2004d)

Sample sizes required for 95% confidence limits						Sample sizes required for 90% confidence limits					
Category Proportion (%)	Limits of error					Category Proportion (%)	Limits of error				
	1	3	5	7	10		1	3	5	7	10
50, 50	9600	1067	384	196	96	50, 50	6763	751	270	138	68
40, 60	9216	1024	369	188	92	40, 60	6492	721	260	132	65
30, 70	8064	896	323	165	81	30, 70	5681	631	227	116	57
20, 80	6144	683	246	125	61	20, 80	4328	481	173	88	43
10, 90	3456	384	138	71	35	10, 90	2435	271	97	50	24
1, 99	380	42	15	8	4	1, 99	268	30	11	5	3

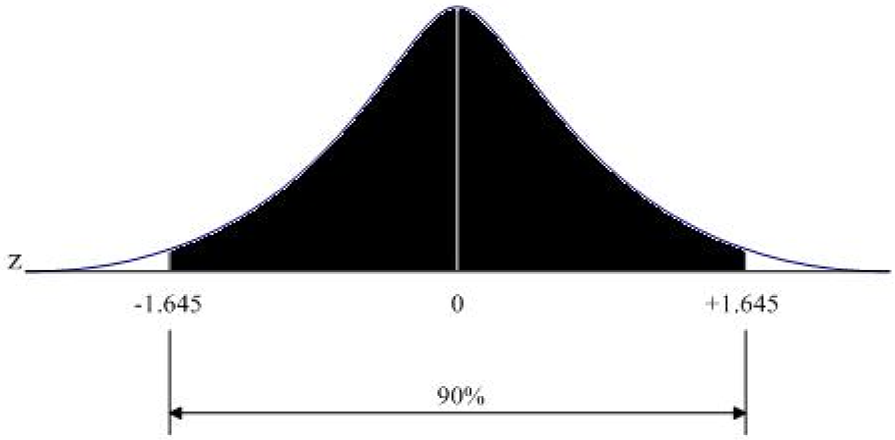


Figure 4. Standard normal cumulative distribution

Modified work sampling methods, known as the group timing technique (GTT) and five-minute rating, were developed to reduce the time spent gathering data (Noor 1998). The GTT is conducted based on the fixed time interval from 30 seconds to three minutes. Time required for this method is much less than those for the work sampling method, because instead of continuous measuring time, observers only measure the crew or equipment performance at certain fixed interval time periods. Thus, the GTT permits a single observer to evaluate the effectiveness of crew size and the work sequence. The five-minute rating technique is another approach that allows a single observer to quickly make general work evaluations. It is based on the summation of the observations made in a short study period, with the number of observations usually too small to offer the statistical reliability of work sampling (Oglesby et al. 1989). The advantage of the five minute rating is its simplicity and easy application (Thomas and Daily 1983).

3.2.3.3 Surveys

Two survey methods have been used for productivity measurement. These include the Craftsmen's Questionnaire Survey (CQS) and the Foreman Delay Survey (FDS). The CQS is more time consuming than the FDS, because CQS is required to have a larger crew size, thus, it takes more time to conduct the survey and analyze the data. The data collection process for the FDS is less disruptive to the construction operations because of the relatively less time required. Implementing the FDS usually only requires a daily visit of 15 minutes before the end of the work day. The major drawback of survey methods is that the survey data are rather qualitative and hard to quantify. This shortcoming of the survey methods can be improved by measuring the daily output that is completed by the contractor. However, the survey results were from 10% to 21% less accurate than the results of the continuous measurement method depending on the degree of delay time that the researchers ignored (Noor 1998).

3.2.3.4 Photographic Techniques

Photographic techniques, using a movie camera or a video camera, provide the following advantages: 1) data are easily and visually understandable, which is useful to illustrate activities in trouble; 2) more detailed and dependable information is available; 3) these techniques make it possible for engineers, project managers, or other people away from the job site to analyze the construction operations; 4) improved communication enables better training of workers; 5) identification of causes of construction accidents becomes easier; 6) maintenance and inspection of construction facilities can be done more efficiently; and 7) these techniques can be used as a marketing tool for construction companies (Oglesby et al. 1989; Abudayyeh 1997). In addition, only one observer is needed to obtain data at the site and bring them into the office for analysis, which is very economical as compared to other methods. Analysis of film can also be made at any later date (Fondahl 1960).

Film recording techniques have been developed and used for the recording of construction field operations for many years. In the last several decades, video recording techniques have become more popular than film recording. With the development of the technology, video recording techniques have been updated frequently from VHS video, 8 mm video, to digital video (Everett and Halkali 1998).

Since the first use, photographic techniques have shown the following technical limitations: 1) What is recorded must be within range; 2) It isn't cost effective in most cases when the cycle time of an operation is long; 3) More time is required for the observer to stay on the job site in order to collect data and measure the productivity of some activities. (Sometimes it is difficult to find an appropriate time to visit the site to observe certain activities because the schedules of the projects vary depending on the work progress, weather, and other discrete factors.); 4) The video camcorder or the digital camera both have limited memory size to store the images of construction activities that are performed continuously and repetitively; 5) Pictures or video files have to be transferred to a personal computer and re-saved in the computer every time the observer visits the job site; 6) Reliability of the data might be a problem because different persons interpret the still pictures, words, and numbers related to a problem in different ways; and 7) Recording resources can be difficult because contractors tend to alter the location of equipment and crews and place them at multiple job sites.

3.2.3.5 Time-Lapse Video Technique

The time-lapse video technique, also called the motion picture technique, has been used to view lengthy construction operations in a short period of time since the 1960s. Pictures taken using a special camera with 1- to 5-second intervals are recreated to look like a film so that observers can review an entire construction operation within a short period of time. Time-lapse video can not only reduce the time spent to view the operation, but also provide an accurate interpretation of a construction operation, even if the appearance can be rather fast and jerky. The number of frames per second controls the quality of the motion picture (Everett and Halkali 1998). This technique enables management to record videos for training, job progress reports, cost verification, and evidence used for resolving contract disputes and liability suits (Sprinkle 1972). In addition, this technique can be used to recognize problems at the job site, such as flow of workers and materials, equipment utilization and balance, and safety and working conditions (Christian and Hachey 1995).

The time-lapse film recording technique was first used at the University of Michigan in the 1970s. The construction management office at the university used the technique again in 1989 for a sports service building project to resolve a potential claim issue between the contractors and the university. Thereafter, over a six year period, the office implemented the technique to resolve several claims regarding earthmoving and earth retention. The method has been used as a powerful tool in education, special events, fundraising, media, and other public relation events. The method has not only been used for the owners but also for the contractors to improve productivity (Everett and Halkali 1998).

The time-lapse technique is a powerful tool used in the construction industry. However, there are difficulties for the observers who use this technique. First, to capture the entire project and to make the time lapse movie appropriately, sometimes the camera has to be set up at zoom out, which make it impossible to recognize the performance of individual worker or a piece of equipment. The observer has to balance the time length between zooming in and zooming out to maximize the usefulness of the video. Second, the interval between images may be too long to use the data for more detailed analysis. Third, only a high speed Internet system can transmit the immense file from the job site to the office; some construction sites may not have such facility in place (Everett and Halkali 1998). Fourth, weak illumination on the construction site is an obstacle (Noor 1998).

In addition, the amount of memory needed to store thousands of pictures with a megabyte for each picture is another challenge. There are two conventional methods used to address this issue. The first method is to increase the time interval. The National Television Standards Committee (NTSC) specifies 36 frames per second (fps) to make the pictures look real. Reducing fps to 4.6 is still valuable for productivity analysis. The second method is to reduce the size of a picture by using the JPEG format (Abeid et al. 2003). As a result, the size of a picture can be reduced to 7 or 8 kilobytes. This means researchers can store the pictures from a two year construction project with a frame rate of 4.6 fps in a ten gigabyte hard disk.

3.2.3.6 Advanced Methods using Current Technology

Several technology advances have been studied to improve the data collection methods and analyses. Global Positioning System (GPS) and Radio Frequency Identification (RFID) technology have been used to track the current status of resources or activities. Using these data also enabled researchers to avoid manual steps to convert the collected data to productivity data. These positioning data have been used to conduct data analyses in the case study of concrete drainable pipe installation (Su, Y. Y. and Liu, L. Y. 2007).

Recently, GPS technology has been used to increase productivity and the quality of earthmoving operations. Navon and Shpatnitsky (2005) used GPS technology to automatically measure earthmoving performance by identifying the locations of equipment at regular time intervals and converting the information into a project performance index (PPI). Field experiments were carried out in a road construction project to measure four activities for three weeks including: 1) spread and grade fill, 2) compact fill, 3) spread and grade subbase, and 4) spread asphalt. A GPS unit was mounted on the top of the construction equipment and the data were downloaded on a daily basis. The results of field experiments indicated that the GPS technology was feasible for automated data collection for road construction with expected accuracy. Nevertheless, the technology had limitations when measuring areas adjacent to structures and for hauling equipment that travels out of the designated work envelope.

3.2.4 Methods of Productivity Data Analyses

Engineers and project managers have conventionally estimated productivity by using historical data and references such as the Means book and equipment handbooks. This approach is called the "deterministic" method. Several deterministic models have been developed for earthmoving operations based on quantified equipment characteristics, equivalent grades, and haul distances. In deterministic model development, the duration of operations is assumed to be insignificantly variable (Halpin and Riggs 1992b). To date, probabilistic analysis methods have become common in areas of the construction industry, which regards inputs parameters as random variables with defined probability distributions (Lee et al. 2002). For the last two decades, a simulation technique has been used to estimate the productivity of repetitive construction operations (Halpin and Riggs 1992b). In the following subsections, examples of deterministic and probabilistic analysis methods are briefly discussed.

3.2.4.1 Deterministic Analysis

The Labor Rating Factor (LRF), also called the labor utilization factor, is an important parameter for determining the labor work status in construction sites. Contractors use the LRF to decide whether work is productive or nonproductive. LRF is calculated using Equations 3.5 and 3.6 (Oglesby et al. 1989; Adrian 2004b).

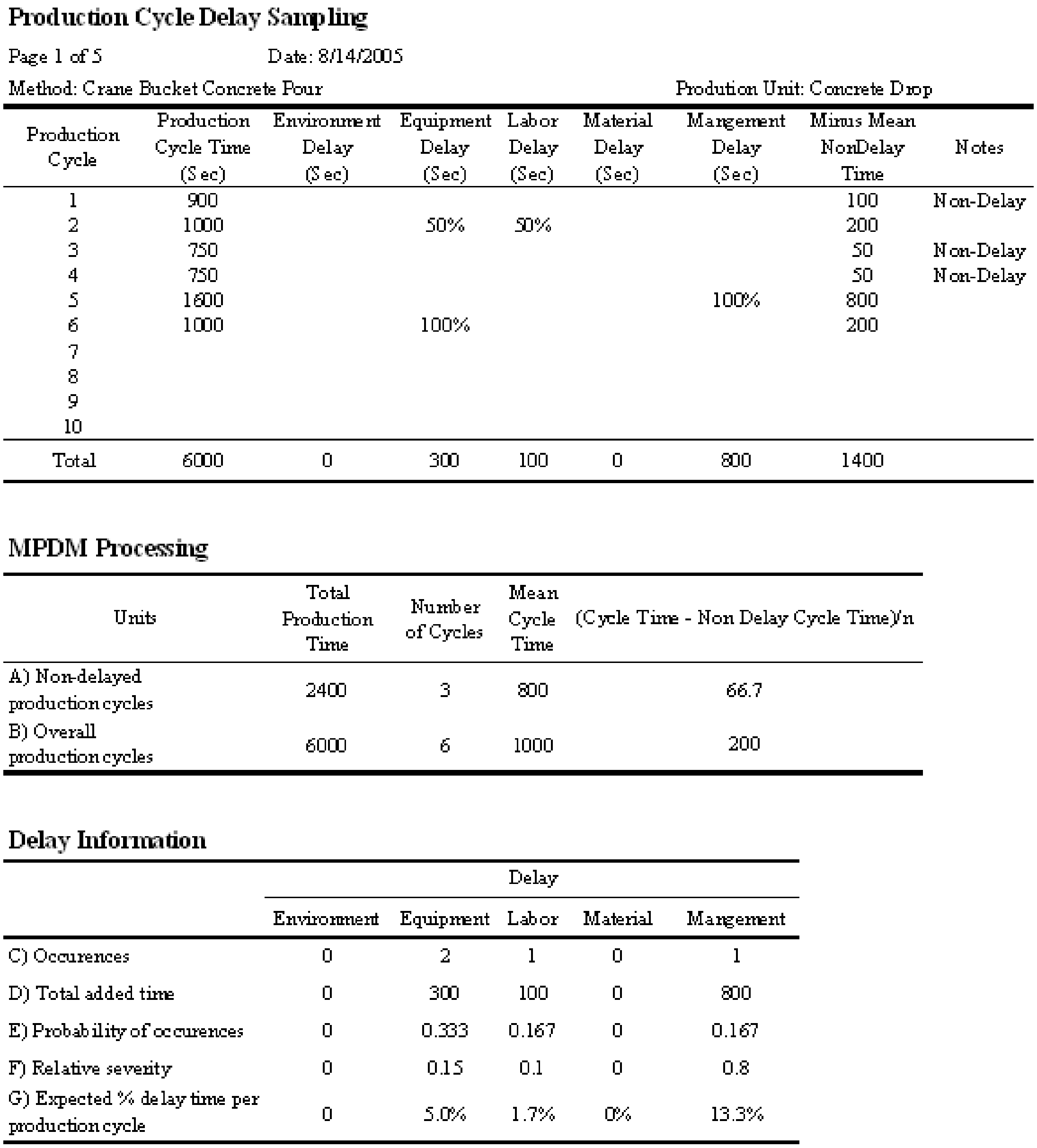
$$\text{Labor Rating Factor} = \frac{\text{Number of Observations of Productive State}}{\text{Total Number of Observations}} \tag{3.5}$$

$$\text{Labor Rating Factor} = \frac{\text{Effective work} + 0.25 \times \text{Essential Contributory Work}}{\text{Total Number of Observations}} \tag{3.6}$$

James Adrian developed the Method Productivity Delay Model (MDPM) by modifying traditional motion and time study concepts. The MDPM is used to measure, predict, and improve construction productivity. It incorporates other techniques such as work sampling, production function analysis, statistical analysis, time study, and balancing models. By collecting continuous data on cycle time and types of delays, researchers can create a new model that determines the efficiency of construction productivity, the impact of delays, and methods for improvement (Halpin and Riggs 1992a).

The MDPM model development process can be categorized into four stages: (1) data collection, (2) model processing, (3) model structuring, and (4) implementation. When developing this model, engineers or project managers must include three important items: the production unit, production cycle, and lost productivity because of delay. To ensure accuracy, the definition of the production cycle must not be too broad. Typical examples of production units are 1) arrival of a scraper in a borrow-pit, 2) a bucket load of concrete, and 3) placement of a section of formwork. Figure 5 shows an example of in-situ information records for MDPM, which includes types of delay and the method of filling the form. The MPDM method can predict the causes of delay as well as the quantity or proportion of the delays. As a result, the observer can determine the method of productivity improvements. Detailed calculations of the MPDM can be found in the Adrian's book (Adrian 2004c).

Randolph H. Thomas studied how to quantify productivity changes because of various types of disruptions, such as lack of materials, lack of tools or equipment, congestion, a task out of sequence, change of order, change of work scope, and an accident. To meet research objectives, baseline productivity was determined and a performance ratio (PR) was calculated. The PR was compared by using an ANOVA test with other factors such as, changes, rework, disruptions, weather, and pipe supports. Research results indicated that lower labor performance is strongly related to change work, rework, and disruptions. Within disruptions, "lack of materials and information" was the most significant factor resulting in the loss of efficiency in the range of 25-50% (Thomas and Napolitan 1995).



Production Cycle Delay Sampling

Page 1 of 5 Date: 8/14/2005

Method: Crane Bucket Concrete Pour Prodution Unit: Concrete Drop

Production Cycle	Production Cycle Time (Sec)	Environment Delay (Sec)	Equipment Delay (Sec)	Labor Delay (Sec)	Material Delay (Sec)	Mangement Delay (Sec)	Minus Mean NonDelay Time	Notes
1	900						100	Non-Delay
2	1000		50%	50%			200	
3	750						50	Non-Delay
4	750						50	Non-Delay
5	1600					100%	800	
6	1000		100%				200	
7								
8								
9								
10								
Total	6000	0	300	100	0	800	1400	

MPDM Processing

Units	Total Production Time	Number of Cycles	Mean Cycle Time	(Cycle Time - Non Delay Cycle Time)/n
A) Non-delayed production cycles	2400	3	800	66.7
B) Overall production cycles	6000	6	1000	200

Delay Information

	Delay				
	Environment	Equipment	Labor	Material	Mangement
C) Occurences	0	2	1	0	1
D) Total added time	0	300	100	0	800
E) Probability of occurences	0	0.333	0.167	0	0.167
F) Relative severity	0	0.15	0.1	0	0.8
G) Expected % delay time per production cycle	0	5.0%	1.7%	0%	13.3%

Figure 5. Sample MPDM data and MPDM processing sheet (Adrian 2004c)

A case study based on an electrical construction project was conducted to identify when labor inefficiency occurs in association with quantity of work. The work flow method was used to estimate inefficiencies during accelerated construction.

Labor inefficiency occurs when a contractor tries to accelerate the schedule and when the crew size is larger than the work needed (Thomas 2000).

The design complexity, also called work content (WC), was scaled to model baseline productivity based on 42 construction projects. In addition, the disruption index (DI) was calculated and compared with the project management index (PMI) to identify the best and worst performing projects. Research results concluded that if higher variability in activities exists, productivity will be low (Thomas and Zavrski 1999).

3.2.4.2 Probabilistic Analysis

Probability distributions are used to describe observed variation in work task times in the field, and the functions are useful in inferring a population with a random time duration. The commonly used distributions are Normal, Lognormal, Exponential, Gamma, and Poisson. The histogram is a method for presenting frequencies of observations from the field. The data plotted in a histogram can be also presented as a relative frequency that is equal to the number of observations in a class interval divided by total operations (Halpin and Riggs 1992b).

To date, computer simulation techniques have been widely used in operation research and management science to model real-world operations and to understand result, where repetitive work tasks are required. In the construction industry, these techniques were first proposed by Halpin and evolved to the most popular computer simulation program called CYCLONE (CYCLic Operations Network) (Wang and Halpin 2004).

The Monte Carlo technique is another frequently used simulation method. The method is usually used to sample random distributions to generate random time duration or delays. Although numeric techniques for random number generation have improved over the past 50 years, there are still disparities between observed data and model assumptions (Halpin and Riggs 1992b).

3.2.5 Bridge Construction Productivity

Many studies on bridge construction have been conducted; however, only a few articles have dealt with productivity measurements in bridge construction. A total of ten papers were reviewed, covering four different subjects: piling productivity, falsework productivity, workforce management in bridge superstructure, and crew production rates in bridge construction. Table 5 shows a summary of these studies, which comprise ten journal papers.

Major factors that impact piling operations' productivity were identified by Peurifoy and his colleagues (1996) based on site interviews, telephone calls, a questionnaire, and literature. These factors are as follows: soil type, drill type, method of spoil removal, the size of hauling units, space consideration at the construction site, pile axis adjustment, equipment driver efficiency, weather conditions, concrete pouring method and efficiency, waiting time for other operations, job and management conditions, and cycle time.

Table 5. List of Previous Research on Bridge Construction Productivity

No	Study Subject	Researcher(s)	Year
1	Piling Operation Productivity	Peurifoy et al.	1996
2		Zayed and Halpin	2004
3		Zayed and Halpin	2005
4		Zayed, T. M.	2005
5		Chong et al.	2005
6	Bridge Falsework Productivity	Thomas E. Tischer	2003
7	Workforce Management in Bridge Construction	Thomas et al.	2003
8		Thomas et al.	2003
9	Crew Production Rate of Bridge Construction	O'Connor and Huh	2005
10		O'Connor and Huh	2006

Zayed and Halpin (2004) developed two simulation models for assessing piling operation productivity and cost. Major variables, such as pile size, soil type, pile depth, pouring system, and auger height, were examined using the following steps. First, the piling process was defined and the simulation model was designed accordingly. Second, the developed model was compared with data obtained from designated questionnaires, site interviews, and telephone calls. Third, sensitivity analysis of the simulation model was conducted, and a validation factor (VF) was designed to assess the fitness degree of the simulation model. Results indicated that the simulation model was a useful tool for planning, scheduling, and controlling of piling operations.

Zayed and Halpin (2005) also studied productivity of bored piles (drilled shaft) which are widely used in the foundations of highway bridges. Research objectives were to identify the factors that impact productivity and cost of the piling process and to apply the Artificial Neural Network (ANN) to assess pile construction productivity, cycle time, and cost. The designated questionnaires were used to collect the piling cycle time and productivity under certain soil characteristics. The collected data were compared with the trained ANN data set. To check the fitness degree of the designed ANNs, Average Validity percentage (AVP) was used. As a result, 90 percent of the output variables were considered reliable and acceptable.

Zayed (2005) studied continuous flight auger operation to achieve the following objectives: 1) outlining the CFA pile installation features and procedures; 2) determining the factors that impact CFA piles productivity; 3) designating a tool for the CFA pile productivity estimate; and 4) evaluating the CFA pile's cycle time, productivity, and cost. The research project was conducted using the following steps: 1) defining the CFA piling process from the axis adjustment to pouring concrete and leaving the rebar cage; 2) assessing cycle time for activities in the piling operation based on an existing algorithm, 3) developing models for cycle time, productivity, and cost; and 4) collecting data from questionnaires, site interviews, site visits, direct data collection, and telephone calls. This research project enabled the researcher to determine the qualitative evaluations of productivity factors in the CFA pile construction operation. The qualitative evaluations were described as the qualitative factors worth (QFW) of 0.22 and the productivity index (PI) of 0.78. To validate whether the model can be used for an actual construction job site, a validation factor (VF), defined as the productivity model result (PMR) over collected productivity, needs to be calculated. If a VF is equal to 1.0, then it is a perfect fit model.

Chong and his colleagues (2005b) developed models to predict production rates of drilled shafts and prestressed concrete piles. The objective of their project was to improve the accuracy of designers' time estimation for the construction of a foundation using the regression analysis. Thus, designers can improve the construction contract time estimation and take into consideration influencing factors. During the data collection process, daily production activities and all possible factors that could impact productivity were identified by reviewing literature and current contract time estimation systems. Two sets of data, production rates and factors affecting productivity, were collected from twenty five projects over two years, based on weekly field visits. The data sets were compared with previous data collected by Hancher and his colleagues (1992) using the t-test. Although more than one significant factor was considered in the regression model, only the quantity of each project was considered the most significant factor because other significant factors were unavailable information at the design phase. The research results indicate that accuracy in estimating production rates highly depends on the piling methods, regional factors, and mobilization time.

A primary activity for cast-in-place prestressed box girder bridge construction is the erection of falsework that supports the load from the deck. Tischer and Kuprenas (2003) studied bridge falsework productivity to identify and quantify the factors that impact falsework installation productivity. Typically, there are four steps in the installation of falsework, including; 1) setting of pads; 2) constructing bents; 3) setting stringers; and 4) rolling out soffit. Productivity data were collected from six separate projects, including twenty bridges. The falsework productivity varied up to 50%, depending on factors such as steep slopes, traffic openings, height of structures, and use of crane or lift. A network diagram was developed to estimate falsework duration and to illustrate these factors, as well as their correlations with productivity. As a result of this research, the best productivity for falsework erection occurs when constructing a low structure on relatively flat ground.

Bridge superstructure construction is more labor-intensive than other heavy construction activities such as earthmoving, pipe laying, and paving. Two recent studies conducted by Thomas and his colleagues emphasized workforce management strategies and labor flow to improve labor productivity. These two studies were conducted based on the same bridge projects (four in total) in central Pennsylvania.

The first study was to quantify the impact of workforce management on construction labor efficiency and to identify the negative factors that might decrease efficiency. The study was to analyze activities such as concrete formwork, and the placement of bridge footings, abutment walls, piers, and pier caps. Baseline productivity, the productivity when no disruption exists, was calculated and compared with cumulative productivity and daily productivity to determine the labor performance. In addition, the project management index (PMI), also called project waste index (PWI), was developed as the performance indicator to determine the loss of labor efficiency. Results of the study indicate that insufficient workforce management accounts for 65% of the total inefficient work-hours. The identified problems included no alternative work assigned, insufficient production work available, and overstaffing (Thomas et al. 2003b).

The second study examined whether enhancing labor flow would improve construction productivity by applying lean construction principles. The method for data collection and analysis was the same as the previous study. The analysis results indicated that inefficient labor flow management led to labor inefficiency by 51% (Thomas et al. 2003a). Therefore, it was concluded that effective labor flow management using lean construction principles could improve construction labor performance.

O'Connor and Huh (2005) studied crew production rates of bridge construction in Texas DOT bridge projects. Research objectives were 1) to develop a standard data collection procedure; 2) to collect field data on crew production rates, and 3) to identify major factors in the reconstruction of footings, columns, and caps. The data collection process included site observations and site visits. The analysis of variance (ANOVA) and a simple regression were employed to test the statistical significance of independent variables with the production rates. The significant variables are as follows.

1. Footing: footing size (m^3/ea), excavation depth (m), and the number of footings per bent;

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

Follow-up research on the production rates of the different bridge parts, such as beam erection, bridge deck, and bridge rail, was also conducted by O'Connor and Huh (2006). Data on production rates were collected from twenty five highway bridges in the state of Texas. Results of linear regression analyses revealed the following: 1) no significant factor was found for the bridge beam erection when analyzing such variables as the average number of beams per span, total number of beams erected; and height from ground; 2) for bridge decks, shape of deck poured was the statistically significant factor for productivity; and 3) no significant factor was found for the bridge rail construction.

3.2.6 Highway Construction Productivity

3.2.6.1 Introduction

For the last decade, considerable progress has been made on measurements and analyses in highway construction productivity. Sixteen recent papers, as shown in Table 6, were reviewed to identify estimation methods used in highway construction productivity studies.

Table 6. List of Previous Research on Highway Construction Productivity

No	Study Subject	Researcher(s)	Year
1	Asphalt Pavement Productivity	Dunston et al.	2000
2		Jiang	2003
3		Lee et al.	2002
4		Lee et al.	2006
5	PCC Pavement Productivity	Lee et al.	2000
6	Earthmoving	Christian and Xie	1994
7		Hicks	1993
8		Farid and Koning	1994
9		Smith	1999
10	Impacts of Rainfall on Productivity	El-Rayes and Moselhi	2001
11		Pan et al.	2005
12	Productivity Factors Analysis	Cottrell	2006
13		Chong and O'Connor	2005
14	Contract Time Estimation	Werkmeister et al.	2000
15	Project Level Productivity Measurements	Ellis and Lee	2006
16	Productivity Measurement using GPS	Navon and Shpatnitsky	2005

In addition, state-of-the-art technologies for improving productivity were also evaluated. The following topics are covered in this subsection: asphalt paving productivity, PCC paving productivity, earthmoving productivity, impacts of rainfall on productivity, productivity factor analysis, contract time estimation, and productivity measurements. The cited references comprise fourteen journal papers and two conference proceedings.

3.2.6.2 Highway Paving Productivity

Dunston and his colleagues studied the effects of weekend closure on the construction of urban highway asphalt overlays. Production rates for weekend closure on I-405 in Seattle, Washington, were compared with those for a nighttime paving project on I-5 in Seattle, Washington. As shown in Table 7, the average production rate of 317 Mg/h ((314+320)/2) was achieved with the full weekend closure strategy under such working conditions as use of a single paver, short distance from the asphalt plant to the construction site, and traffic-free access. It was concluded that the continuous and unobstructed paving operation resulted in an approximate 24% increase in production rates (Dunston et al. 2000). A survey of six state highway agencies by the researchers showed that the partial nighttime closure strategy was still the most popular strategy for minimizing highway reconstruction impact on the public. Since the nighttime closure strategy had problems related to the quality and productivity, the state highway agencies suggested that A+B bidding and lane rental options be used with the nighttime closure strategy which may motivate contractors to develop innovative construction methods (Dunston et al. 2000).

Table 7. Asphalt Production Rates Comparison for Weekend Closure and Nighttime Paving

Project (1)	Construction Duration (2)	Maximum [Mg/h (tons/h)] (3)	Minimum [Mg/h (tons/h)] (4)	Project Average [Mg/h(tons/h)] (5)	Average (Mg/h) (6)
I-5 NB, 1993	Nighttime	254 (280)	122 (135)	200 (220)	242
I-5 NB, 1994	Nighttime	300 (331)	261 (288)	284 (313)	
I-5 SB, 1994	Nighttime	293 (323)	135 (149)	242 (267)	
I-405 SB, 1997	Weekend	375 (413)	251 (277)	314 (346)	317
I-405 NB, 1997	Weekend	361 (398)	288 (318)	320 (354)	

Jiang (2003) conducted a research project to determine how traffic impacted asphalt pavement productivity in highway work zones. Two common types of work zones in Indiana, partial closure work zone (or single lane closure) and crossover work zone (or two-lane closure), were studied. Research results indicated that 1) vehicle queues reduced delivery rates and resulted in an unbalanced construction operation; 2) the starting time of operation affected productivity because the traffic conditions varied during different starting times. For example, when construction operation started at 8:00 a.m. or 9:00 a.m., productivity was the lowest; and 3) traffic flow and changing patterns at work zones were essential information for traffic control and highway construction activities.

Lee and his colleagues (2002) used data from a rehabilitation project on I-710, Long Beach, California in 2002 to analyze urban asphalt paving productivity. The Caltrans-sponsored research project was to determine the maximum AC paving production capability within a 55-hour weekend closure window and compare different rehabilitation windows such as continuous construction and daytime construction. Two different AC rehabilitation methods, crack seat and overlays (CSOL) and full-depth AC replacement (FDR), were compared in detail with regard to different rehabilitation strategies, resource constraints, design profiles, and lane closures. To accomplish the research objectives, researchers initially identified information on the project, such as construction windows, paving materials, and design profiles. Following this step, a number of field trips were made to collect data on resource constraints, construction schedule, and cooling times. The researchers concluded that: 1) within a 55-hour weekend closure, the production rates of FDR and CSOL reached only 30% and 40%, respectively, as compared to baseline productivity; 2) Numbers of dump trucks for demolition and asphalt concrete delivery trucks were major constraints that impact productivity; 3) the total layer thickness of AC pavement was the major factor in determining productivity. For example, the overall production of FDR was about 60% of CSOL production for a weekend closure; 4) the most efficient scheme for CSOL was half road closure with nighttime or daytime construction. For FDR, single-lane rehabilitation was more efficient than double-lane rehabilitation; and 5) the AC cooling time depended on the lane closure schemes and pavement profiles. Efficient lane closure schemes with pavement profile adjustments would minimize non-working time and improve the productivity of urban highway AC paving projects.

Lee and his colleagues (2006) also analyzed the asphalt paving productivity data collected from the rehabilitation project on I-710, Long Beach, California, in 2003. The Caltrans sponsored research project was to determine the factors that impacted productivity for an eight 55-hour weekend closure project. During the eight weeks of construction, 8 to12 staff members were stationed around the work zone to record actual activity duration, material quantities, truck cycle time, and hourly production rates of the major construction activities. Results indicated that using the repeated weekend closures continuously improved the production rates for the period of research in the rehabilitation project.

A research project was conducted by Lee and his colleagues (2000) on construction productivity and constraints for PCC pavement rehabilitation in California. The first objective was to determine whether a 55-hour weekend closure was a realistic method for 6 km PCC pavement rehabilitation on a California urban freeway. The second objective was to determine the maximum production capability within the weekend closure scheme. To accomplish these objectives, the researchers had a series of meetings with contractors and personnel of the American Concrete Pavement Association (ACPA). Construction analysis software, using a linear scheduling technique, was used to identify resource constraints and the maximum production capability. Production rates were compared in detail with regard to curing time, design profiles, construction method, and lane closures.

Results of the analyses revealed that only a few options met the production objective of 6 km either for single-lane paving or double-lane paving within the 55-hour weekend closure. Table 8 shows the productivity reduction for different types of options. The selection of the design profile had the greatest impact on the production rate. The construction of 254- or 305-mm slabs had an approximately 40–50% lower production rate than those of 203 mm slabs. Production was decreased by 20% because of variations in curing time from 4 to 12 hours. In the comparison of two construction methods, the concurrent method had 25% more production, on average than that of the sequential method.

Table 8. Percent Reduction in Production (Lee et al. 2000)

Option (1)		Comparison (2)	Reduction (3)
Design Profile		203 mm to 254 mm	40%
		203 mm to 305 mm	47%
		254 mm to 305 mm	12%
Curing Time		4 hours to 8 hours	10%
		8 hours to 12 hours	11%
		4 hours to 12 hours	19%
Construction Method	203 mm slab	Concurrent to Sequential	29%
	254 or 305 mm slab	Concurrent to Sequential	21%
Paving Lane	203 mm slab	Double to Single	17%
	254 or 205 mm slab	Double to Single	7%
End Dump Truck Capacity		22 to 15 tons	15%
Load/Discharge Time		3 to 4 minutes	24%

Table 9 shows how many lanes and weekend closures were required to rebuild a 20-km freeway, subject to the construction method and the design profile. The greatest impact on the productivity of the rehabilitation was the selection of the design profile because constructing 254- or 305-mm slabs was up to 50% less productive than construction of 203-mm slabs. The most productive strategy was the concurrent method with double-lane paving. However, the sequential method with single-lane paving was the most advantageous to traffic control and road users (Lee et al. 2000).

Table 9. Numbers of Lane-Weekends Closed for Different Construction Methods for 55-hour of Weekend Closure (8 hours of curing) (Lee et al. 2000)

Slab Thickness (1)	Lanes Closed (2)	Method (3)	Production (4)	Number of Weekends Closed (5)	Lane-Weekends Blocked (6)
203 mm	2 Lanes	Sequential/Single	4.7	4.3	8.6
	3 Lanes	Sequential/Double	5.4	3.7	11.0
	3 Lanes	Concurrent/Single	6.4	3.1	9.4
	4 Lanes	Concurrent/Double	7.9	2.5	10.1
254 mm	2 Lanes	Sequential/Single	3.2	6.3	12.7
	3 Lanes	Sequential/Double	3.4	5.9	17.7
	3 Lanes	Concurrent/Single	4.0	5.0	15.1
	4 Lanes	Concurrent/Double	4.3	4.7	18.7
305 mm	2 Lanes	Sequential/Single	2.7	7.3	14.7
	3 Lanes	Sequential/Double	2.9	6.8	20.4
	3 Lanes	Concurrent/Single	3.5	5.7	5.3
	4 Lanes	Concurrent/Double	3.8	5.3	21.1

Note: (1) Column Six “Lane Weekends Blocked” was the result of Column Two (“Lanes closed”) times number of weekends closed. (2) The concurrent method is the simultaneous procedure of demolition of the existing pavement and the new paving, while two procedures are executed one after another in the sequential method.

3.2.6.3 Earthmoving Productivity

Earthmoving productivity has long been a major research subject in the area of construction engineering and management for the following reasons: (1) Earthmoving is required for most construction projects; (2) Earthmoving requires intensive equipment operations; (3) Estimating earthmoving productivity not only determines the efficiency of operation but also identifies significant factors that impact productivity. Proper planning and scheduling will minimize waiting time and other delays, make the earthmoving process more productive, and decrease the risk of cost overruns (Christian and Xie 1994).

The efficiency of earthmoving operations varies widely, subject to properties of earth such as ruggedness, moisture content, and swelling and shrinkage. A computer program was developed to determine coefficients to calculate haul unit performance in an efficient, accurate, and convenient manner (Hicks 1993). Farid and Koning (1994) proposed that overall earthmoving productivity depended on the productivity of loading facilities regardless of the size, number, and speed of the hauling units. Christian and Xie (1994) categorized the factors of earthmoving operations into machine selection, production and cost, based on a survey of industry data as well as expert opinions. Smith (1999) identified the factors that influence earthmoving operations by using linear regression techniques. These factors included bucket capacity, match factor, and the total number of trucks being used.

3.2.6.4 Other Related Research

Weather conditions such as rainfall, temperature, wind velocity, relative humidity, and solar radiation are major uncertainty factors. Among these factors, rainfall is considered the most significant factor that causes delays and cost overruns in highway construction. There are two projects that studied rainfall impact on construction productivity and duration.

A research paper written by El-Rayes and Moselhi (2001) presents the development of a decision support system, WEATHER, that quantifies the effect of rainfall on productivity and duration in highway construction operations such as earthmoving, spreading the subbase and base course, and paving. The researchers systematically interviewed six experts eight times and identified three main factors: 1) the type of construction operation; 2) the intensity of rainfall; and 3) drying conditions on site. WEATHER was built based on experts' knowledge and historical records from five weather stations in Toronto and Montreal covering a period of 30 years. Researchers estimated the probabilistic construction duration using the WEATHER system and compared it with the common practices of local highway contractors and the Ministry of Transportation of Ontario (MTO) in Canada to validate the results. In this research, the WEATHER system was proven to be an effective tool for estimating activity duration.

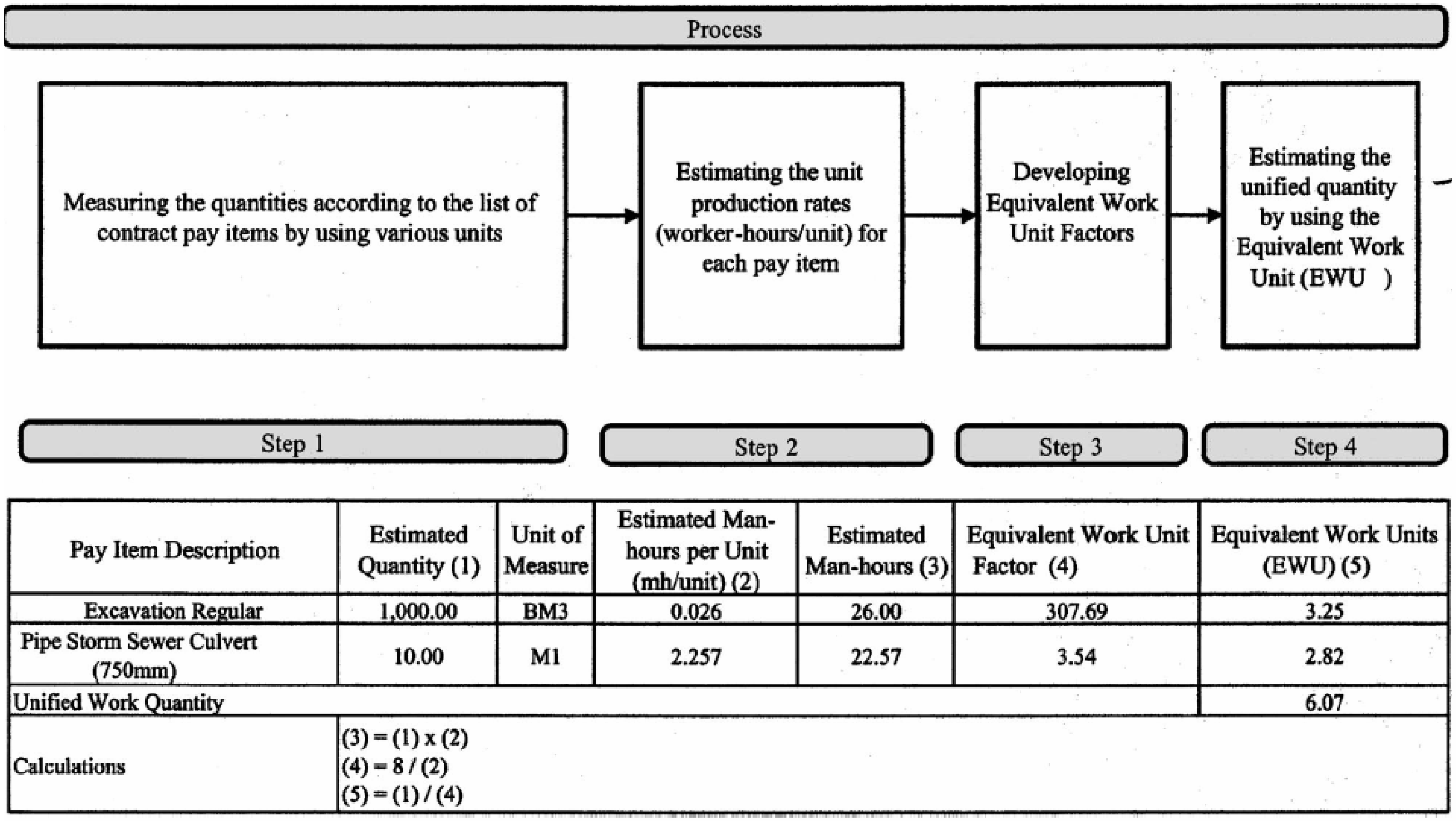
Pan (2005) also assessed the impact of rainfall on productivity and duration in highway construction. The researcher analyzed construction delays because of rainfall using the concept of fuzzy sets. Data were collected from Taiwan, a place where the rainfall impact on highway construction productivity is significant. Rainfall impact on productivity was identified using data such as experts' knowledge, historical daily rainfall, types of soils, locations of construction sites, types of construction activities, and rain sensitivity for each task. A Fuzzy Reasoning Knowledge-based Scheduling System (FRESS) was developed to estimate the impact of rainfall on productivity loss and duration of highway construction. Planned schedules estimated by experts and FRESS were compared. Results indicated that the developed system allowed users to simulate experts' experience and to produce reliable activity duration and project completion dates. Although the model was based on data from Taiwan, it could be applied in other places if databases were prepared.

Chong and his colleagues (2005) studied the productivity of reinforced concrete pipe construction to identify the most common disruptions and to quantify these disruptions on productivity using a statistical model. The data were collected from 28 highway projects in Texas and were compared with baseline productivity data from ten pre-selected projects. According to the analysis, the three most common disruptions were: weather, shortage of material, and conflicts with utilities and old structures (Chong et al. 2005a).

Follow-up research by Chong and O'Connor (2005) based on 44 Texas highway projects proposed methods for estimating the production rates of reinforced concrete pipe and precast concrete box culverts. Two field data sets were collected from weekly site visits for two and half years. Regression and t-test methods were used to determine significant factors and the relationships between production rates and factors that impact productivity. This research concluded the following: 1) construction production rate factors vary according to project types and locations; 2) congestion-related factors impacted productivity more than soil condition related factors; 3) accurate estimations of production rates were still difficult to achieve; and 4) factors such as rain could become predictable if there were more data available.

Ellis and Lee (2006) developed a method for measuring and analyzing project level productivity (PLP). Their research objective was to develop methods for quantifying and evaluating total productivity of highway construction projects. A procedure for measuring PLP was developed and validated using three case studies. PLP in this research was defined as the total output or work produced on all activities per the total input or work effort on all activities. Hence, the output value for calculating PLP was obtained by unifying all work quantities. To develop the unified quantity value, the researchers went through four steps, as shown in Figure 6. The first step was to establish a database of all project activities and related information based on unit price pay items. The second step was to determine a unit production rate (UPR) for each pay item. The third step was to develop equivalent work unit factors (Adewuyi and Oyenekan). The final step was to estimate a total project level work quantity value by using the EWU factor. Project level productivity was estimated based on the unified quantity measured by EWU and total man hours:

$$\text{PLP} = \frac{\text{Total Man Hours}}{\text{Total EWU}} \tag{3.7}$$



Pay Item Description	Estimated Quantity (1)	Unit of Measure	Estimated Man-hours per Unit (mh/unit) (2)	Estimated Man-hours (3)	Equivalent Work Unit Factor (4)	Equivalent Work Units (EWU) (5)
Excavation Regular	1,000.00	BM3	0.026	26.00	307.69	3.25
Pipe Storm Sewer Culvert (750mm)	10.00	M1	2.257	22.57	3.54	2.82
Unified Work Quantity						6.07
Calculations	(3) = (1) x (2) (4) = 8 / (2) (5) = (1) / (4)					

Figure 6. Procedures for developing unified quantity value (Ellis and Lee 2006)

3.3 Statistical Theories

In the following subsections, the researcher presents a literature review of statistical theories that are utilized in the proposed research project. These theories include sampling distribution, confidence interval, hypothesis test, sample size and power, population inferences, ANOVA test, and experimental design and analysis.

3.3.1 Sampling Distribution

A sampling distribution is formed by values drawn from a population or a process. If response variables are statistically independent and follow a normal probability distribution, then the distribution of all possible sample means $\bar{y}_1,\ \bar{y}_2, \ldots$ of size *n* from this population is also normal with the population mean μ and a standard error (standard deviation) of $\sigma / n^{1/2}$. The standard error of a statistic, or the standard deviation of its sampling distribution, is the most frequently used measure of the precision of a parameter estimator (Mason et al. 2003).

For a reasonable size of samples (at least 30), the sampling distribution, or the distribution of sample means, can be approximated by a normal distribution, as shown in Figure 7. The sampling distribution of independent observations from a normal distribution can be standardized to find z and compare it with z_c which is determined by the α value. If the p-value is less than α (i.e., $z > z_c$), then the hypothesis can be rejected (Frigon and Mathews 1997a; Mason et al. 2003).

$$z = \frac{(\bar{y} - \mu)}{\sigma_{\bar{y}}} = \frac{(\bar{y} - \mu)}{\sigma / \sqrt{n}} \approx \frac{(\bar{y} - \bar{\bar{y}})}{s_{\bar{y}}} \tag{3.8}$$

where z = test statistic

$\bar{y}$ = the sample mean

μ = the known population mean

$\sigma_{\bar{y}}$ = standard deviation of the sampling distribution,

σ = the known population standard deviation

n = number of sample means (sample sizes, but the sample consists of means),

$s_{\bar{y}}$ = estimated standard deviation of the sampling distribution.

$\bar{\bar{y}}$ = the grand mean of the k sample means

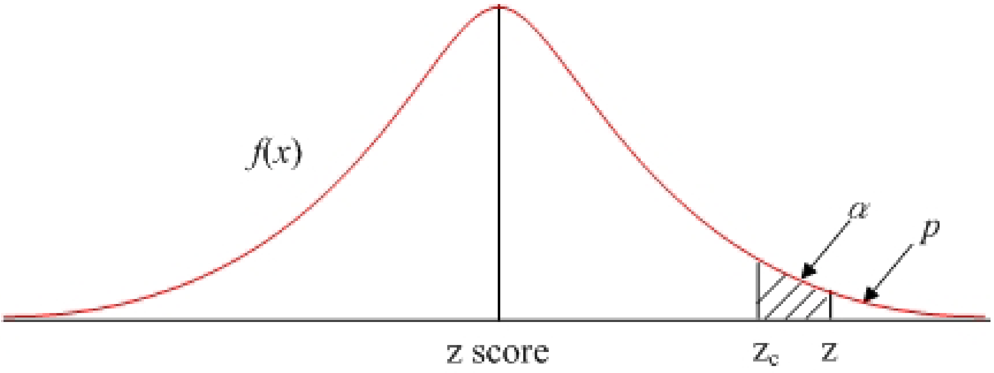


Figure 7. P value, Z, and Zc

In many experiments, the number of samples n is too small to apply the normal distribution for estimating population. In a small sample size with unknown variance (usually less than 30), the t distribution, also called Student's t-distribution, is used with the best estimate of μ, $\bar{\bar{y}}$, and the sample variance, instead of using the normal distribution. The t distribution is primarily used for determining the statistically significant difference between two sample means and confidence intervals of the difference between two population means.

The t value, as shown in Equation 3.9, is calculated in the same way as z with σ replaced by $s/\sqrt{n}$, the standard deviation for a sampling distribution of a set of means $\bar{y}$.

$$t = \frac{(\bar{y} - \mu)}{s/\sqrt{n}} = \frac{\sqrt{n} \cdot (\bar{y} - \mu)}{s} \tag{3.9}$$

Student's t distribution looks like a normal distribution with fatter tails, as shown in Figure 8. Probabilities for Student's t-distribution depend on the sample size n. The distribution becomes a normal distribution as the degree of freedom approaches infinity.

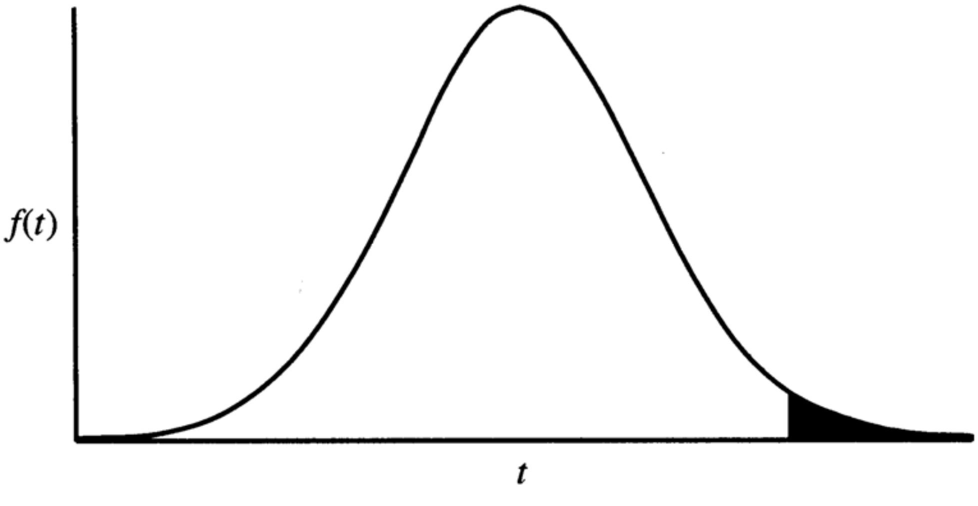


Figure 8. PDF of the t distribution (Frigon and Mathews 1997a)

Chi-square χ^2 distribution is used for determining whether the measured difference between a random variable $\bar{y}$ and a constant value μ, $(\bar{y} - \mu)$, is significantly larger than an expected value σ. When researchers compare the variation in single population or process, the ratio of sample variance (s^2), divided by its population variances (σ^2), is called chi-square statistic, as shown in Equation 3.10. This distribution can be used for inferring variances on single population.

$$\chi^2 = \frac{(n-1)(\bar{y}-\mu)^2}{\sigma^2} = \frac{(n-1)s^2}{\sigma^2} \tag{3.10}$$

where n is the size of the sample used to calculate $\bar{y}$, constant μ is population parameter, and s is the sample standard deviation.

A chi-square test evaluates whether the relative variance of the means is greater than a critical value from a chi-square table. A chi-square test also examines the independency of variables to determine the appropriateness of hypothesis. Figure 9 shows sampling distributions for each degree of freedom and indicates that the chi-square distribution becomes symmetric and closer to the normal distribution as degrees of freedom increase.

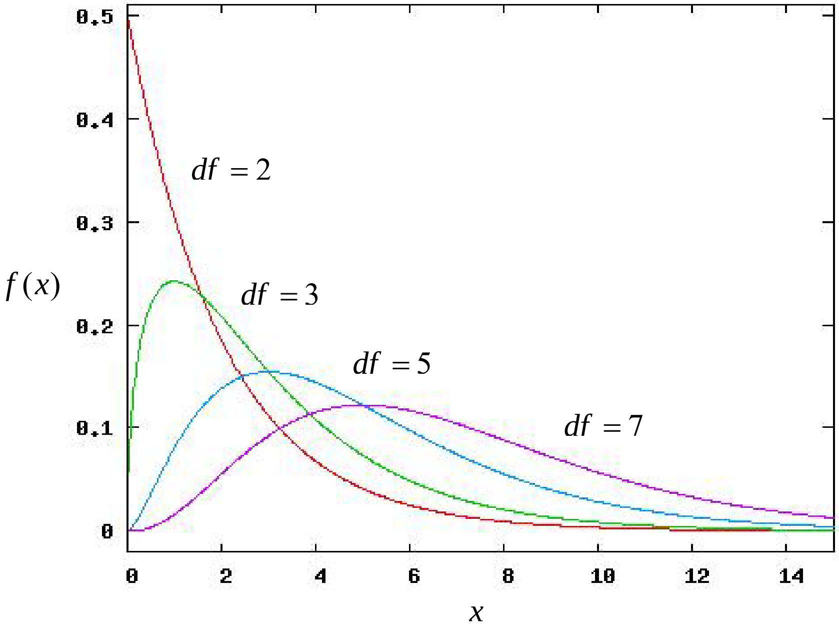


Figure 9. Chi-Square probability density function (CPNTOOLS-HELP 2004)

When researchers compare the variation in two populations or processes, the ratio of two sample variances (s^2), each divided by its population variances (σ^2), is called an F-statistic, as shown in Equation 3.11. F-statistic is also the ratio of two independent chi-square statistics, $(n_i - 1)s_i^2 / \sigma_i^2$. The value of an F-statistic depends on the numbers of degrees of freedom, n_1-1 numerator degrees of freedom, and n_2-1 denominator degrees of freedom. Examples of F distributions, also known as Snedecor's F distribution or the Fisher-Snedecor distribution, are presented in Figure 10.

$$F = \frac{s_1^2 / \sigma_1^2}{s_2^2 / \sigma_2^2} = \frac{s_1^2 \sigma_2^2}{s_2^2 \sigma_1^2} \tag{3.11}$$

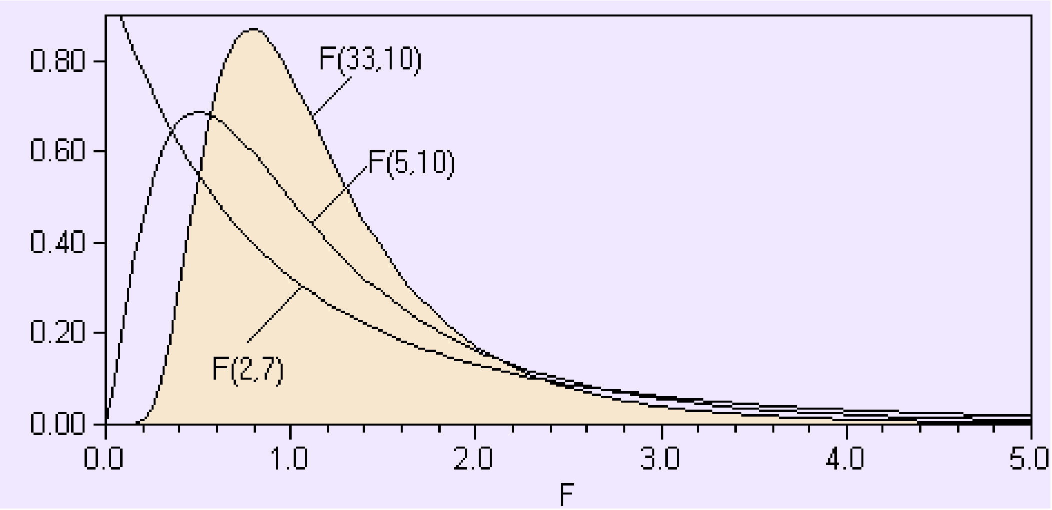


Figure 10. F distribution (H. Lohninger 1999)

Sampling distributions require that individual response variables be independent and be drawn from a single normal probability distribution. However, in many instances, this requirement is not reasonable. The central limit theory allows these statistics to be used when individual response variables are not normally distributed. If a sample of *n* observations $y_1, y_2, \ldots, y_n$ is independent from a single probability distribution with mean μ and standard deviation σ and the sample size is large enough, the sampling distribution of the sample mean will be well approximated by a normal distribution with mean μ and standard deviation $\sigma / n^{1/2}$ (Mason et al. 2003).

3.3.2 Confidence Interval

Confidence interval (CI) outlines the range of parameter estimates, and its length provides a direct measure of the precision of the estimator. If the confidence interval is shorter, the estimator is more precise. The lower and upper limits, $L(\hat{\theta})$ and $U(\hat{\theta})$, are functions of the estimator $\hat{\theta}$ of the parameter θ. The $100(1-\alpha)\%$ CI for the population mean of a normal distribution is expressed as Equations 3.12 and 3.13 (Mason et al. 2003).

$$\text{CI with known } \sigma = \left\{ \bar{y} - z_{\alpha/2}\sigma_{\bar{y}} < \mu < \bar{y} + z_{\alpha/2}\sigma_{\bar{y}} \right\} \tag{3.12}$$

$$\text{CI with unknown } \sigma = \left\{ \bar{y} - t_{\alpha/2}s_{\bar{y}} < \mu < \bar{y} + t_{\alpha/2}s_{\bar{y}} \right\} \tag{3.13}$$

where $\bar{y}$ is the average of the sample variables $y_1, y_2, \ldots, y_n$; $z_{\alpha/2}$ and $t_{\alpha/2}$ are the critical values corresponding to the significance level α in two-sided test; $\sigma_{\bar{y}}$ is equal to $\sigma / n^{1/2}$; and $s_{\bar{y}}$ is equal to $s / n^{1/2}$.

3.3.3 Hypothesis Test

The sample means and variances from the same distribution have their own useful properties, as sample data tend to follow a normal distribution even if the parent distribution may not be normally distributed. In a statistical test, a statement about population parameters is hypothesized before the proof, and is estimated by samples. The hypothesis test is often used when comparing two populations of sample data. Means, variances, and proportions are the three main population parameters, as well as statistical interests of hypothesis tests. There are two types of hypotheses: null hypothesis (H_o) and alternative hypothesis (H_a) (Mason et al. 2003). The null hypothesis and the alternative hypothesis are initially stated. Subject to the goal of research, the significance level is determined next, and then the upper critical limit and lower limit are determined. The test statistics, based on sampled data, are compared with the critical values corresponding to the significance level to determine if the statistics are in the acceptance or rejection region. The appropriate conclusion and interpretation of the results are drawn from the test (Mason et al. 2003).

Statistical hypothesis test is to determine if a mean μ differs from a hypothesized value, μ_0, as symbolized by Equation 3.14.

$$\begin{aligned} H_o &: \mu = \mu_0 \\ H_a &: \mu \neq \mu_0 \end{aligned} \tag{3.14}$$

The t statistic is compared with $t_{critical}$ value corresponding to the significance level α. For example, the $\alpha = 5\%$ indicates that researchers could indicate 95% confidence in the decision to reject the null hypothesis.

In a hypothesis test, determining type I error (α) and II error (β) are important. The type I error occurs when the null hypothesis is rejected when it is in fact true, and the type II error occurs when the null hypothesis, is not rejected when it is in fact false (Easton and McColl 2006).

3.3.4 Sample Size and Power

Determining the sample size is an important task in the design of experiments, which ensures precision by controlling the power of a statistical test, $1-\beta$. In practice, the largest number of observations is the best sample size for precision. However, doing so will spend unnecessary resources in obtaining and analyzing the data. Determining the optimal sample size in the design of the experiment enables researchers to achieve accurate results with reasonable resources. However, sample size and power of experiments have been historically difficult to determine because of complex mathematical considerations and many different formulas (Lewis 2000).

There is a method to determine the required sample size in a hypothesis test when the standard deviation σ is known. The length of the confidence interval, $2z_{\alpha/2}\,\sigma/n^{1/2}$, is often used to determine the sample size. If the standard deviation σ is not precise enough, researchers can use an upper limit of σ, for example,

$\pm\sigma$, $\pm 2\sigma$, or $\pm 3\sigma$ and half-length of the confidence interval, L, as shown in 3.15. In addition to using the confidence interval, power curves (plots of $(1-\beta)$) are used to determine the sample size (Mason et al. 2003; Giesbrecht and Gumpertz 2004b).

$$n = \left(\frac{2 z_{\alpha/2} \sigma}{L} \right)^2 \tag{3.15}$$

where $z_{\alpha/2}$ is the standard normal statistic and L is the half width of a $100(1-\alpha)\%$ confidence interval. Based on this method, Beal (1989) developed a table for sample size determination based on the confidence interval, power, L, and standard deviation (Giesbrecht and Gumpertz 2004b).

In a hypothesis test when σ is unknown, four factors are usually estimated to determine the minimum required sample size: 1) effect size, 2) the population standard deviation, 3) the desired power $(1-\beta)$ of the experiment, and 4) the significance level α (Dell et al. 2002). For example, statistical analyses such as a two-sample t-test and a comparison of two proportions by the chi-squared test require the effect size and the population standard deviation for continuous data. The effect size, *d*, is defined as the difference between the two groups' means divided by standard deviation, σ, of either group.

Several methods have been proposed for determining the sample size using statistical theories, such as Cohen's d (δ/σ), Hedges's g, and operating characteristic (OC) curve (Drain 1997). A sample standard deviation can be obtained from a pilot study or similar experiments conducted in the past (Dell et al. 2002). In addition, the sample size can be varied by scientific goals, a pilot study, ethics, and study design (Lenth 2001).

3.3.5 Inferences on a Population Mean

The response model can be presented with independent observations obtained from one population.

$$y_i = \mu + e_i, \qquad i = 1,\ 2, \ldots, n \tag{3.16}$$

where y_i is a measurement of a continuous variate, μ is the unknown mean of the population, and e_i are random errors associated with the variation in the observations. These errors are assumed to be independent and have normal distribution with mean of zero and constant variance of σ^2.

3.3.6 Inferences on Two Populations or Processes using Independent Pairs of Correlated Data Values

The responses can be modeled by using independent pairs of correlated data values sampled from two populations or processes:

$$y_{ij} = \mu_i + e_{ij}, \qquad i = 1,\ 2, \quad j = 1,\ 2, \ldots, n \tag{3.17}$$

where y_{ij} is the *j*th measurement taken from the i_{th} population, μ_i is the unknown mean of the i_{th} population, and e_{ij} is a random error associated with the variation in the measurements. The model can be also expressed as d_j which is equal to $y_{1j} - y_{2j}$, or $\mu_d + e_j$.

When the two sample sizes are equal and samples in each group are paired, the differences d_j of the paired sample are statistically independent because measurements on the different pairs are assumed independent. If the responses are normally distributed, d_j are independent and have normal distribution with mean $\mu_d = \mu_1 - \mu_2$ and a standard deviation σ_d. If each sample is not normally distributed, but sample size is large enough (usually more than 30), the distribution of the difference $\overline{y}_1 - \overline{y}_2$ would be expected to have a nearly normal distribution because of the central limit theorem.

The t-statistic and the $100(1-\alpha)\%$ confidence interval for μ_d can be calculated with the degree of freedom $\upsilon = n-1$, as shown in Equation 3.18 and 3.19 (Mason et al. 2003).

$$\mathrm{t} = \frac{\overline{d} \text{ - } \mu_d}{s_d / \sqrt{n}} \tag{3.18}$$

$$\overline{d} - t_{(\alpha/2,\, n-1)} \frac{s_d}{\sqrt{n}} < \mu_d < \overline{d} + t_{(\alpha/2,\, n-1)} \frac{s_d}{\sqrt{n}} \tag{3.19}$$

3.3.7 Analysis of Variance (ANOVA) Test

3.3.7.1 Introduction to ANOVA

Analysis of Variance (ANOVA) is the most common type of test in experimental result analysis (Frigon and Mathews 1997a). In this test, the observed variance represents the sum of squares that are partitioned into components because of different explanatory variables. Thus, the test determines which factors affect the experiment by comparing them with errors.

It is an effective analysis tool allowing the simultaneous comparison of populations to determine if they are identical or significantly different. ANOVA provides information if the variance is significant and if the significance can be measured. This is accomplished by measuring the variance of different treatments and treatment levels, such as time, temperature, cost, manufacturer, or process. These treatments are also called independent variables or input variables. The variables whose values are affected by these treatments are called response variables, outcome variables, or dependent variables.

ANOVA determines whether means for several treatments are equal by examining population variances using Fisher's F Statistic. ANOVA compares two estimated variances: the variance within treatments (S^2 Within), also called error, and the variance between treatment means (S^2 Treatments). The variance within treatments (S^2 Within) is estimated from the variance within all the data from several distinct treatments or different levels of one treatment. The variance between the individual treatment means estimates the variance between treatment means (SS

Treatments). Assumptions for the ANOVA test, which are relatively simple, are presented as follows:

1. The populations corresponding to each treatment have equal variance.
2. The populations corresponding to each treatment have a normal distribution.
3. Observations for each significance level are randomly collected and independent.

In the following subsections, two types of ANOVA, One-Way ANOVA and Two-Way ANOVA, are discussed.

3.3.7.2 One-Way ANOVA

One-Way ANOVA entails with the analysis of a population with a single treatment. For example, an ANOVA can be conducted to determine if there is difference in the quality of materials coming from two suppliers or the same product produced by two processes (Frigon and Mathews 1997a).

The statistical model for One-Way ANOVA is:

$$y_{ij} = \mu_i + e_{ij} \tag{3.20}$$

The alternative model is expressed by using the equation $\alpha_i = \mu_i - \mu$

$$y_{ij} = \mu + \alpha_i + e_{ij} \tag{3.21}$$

where y_{ij} is the response variable for the j_{th} measurement in the i_{th} level of the treatment.

μ_i is the overall mean of the i_{th} level of the treatment or the i_{th} population.

μ is the overall mean of response variable.

α_i is the effect of the i_{th} level of the treatment and is equal to $\mu_i - \mu$. Their sum is zero, that is, $\sum_{i=1}^{n} \alpha_i = 0$.

e_{ij} is a random error for the j_{th} measurement in the i_{th} level of the treatment. These errors are assumed to be independent and normally distributed with mean of zero and constant variance of σ^2.

i=1, 2 … *l*, where *l* is the number of levels of the treatment.

j=1, 2 … *n*, where *n* is the number of replicates at each level of each treatment.

Frigon and Mattews (1997) summarize five steps for developing a generic computation and decision table in ANOVA test. These steps can be applied to both One-Way ANOVA and Two-WAY ANOVA.

1. Calculate the sum of the squares.
2. Determine the degrees of freedom.
3. Calculate the mean squares.
4. Calculate the F ratio, look up the critical value of F, and compare the two.
5. Calculate the percentage contribution.

The percentage contribution is the quotient of the sum of the squares for the treatment and within, and the sum of the square for total, as shown in equation 3.22. The variables and calculations are shown in Table 10.

$$Percent\ Contribution\ Treatment = \frac{SS_{Treatment}}{SS_{Total}} \tag{3.22}$$

Table 10. One-Way ANOVA Computation and Decision Table

Source of Variation	Sum of the Squares	Degree of Freedom	Mean Squares	F ratio	F' Critical	Percent Contribution
Treatment	$SS_{Treatment}$	$df_{Treatment}$	$MS_{Treatment}$	$F_{Treatment}$	$F'_{Treatment}$	$\%_{Treatment}$
Within	SS_{Within}	df_{Within}	MS_{Within}			$\%_{Within}$
Total	SS_{Total}	df_{Total}				

3.3.7.3 Two-Way ANOVA

Two-way ANOVA determines if two different treatments have effects on a process or product and if they are significant, while one-way ANOVA deals with one treatment and one hypothesis that all means are equal. Calculation steps and formulas for the two-way ANOVA are almost the same as one-way ANOVA. As shown in Table 11, there are two treatments, Treatment A (Supplier) and Treatment B (Test set). By using the ANOVA table, researchers can determine the following:

1. Whether the variance caused by the respective treatment A and B is significant or not.
2. Percent contributions to the overall product variability by the test set treatment.
3. Percent not accounted for the variability.

The statistical model for Two-Way ANOVA without replication is:

$$y_{ij} = \mu + \alpha_i + \beta_j + \varepsilon_{ij} \tag{3.23}$$

where y_{ij} is the response variable for the j_{th} measurement and the i_{th} measurement.

μ is the overall mean of response variable.

α_i and β_j are effects of treatment A and treatment B. $\sum_{i=1}^{n} \alpha_i = \sum_{i=1}^{n} \beta_j = 0$

ε_{ij} is a random error. These errors are assumed to be independent and normally distributed with mean of zero and constant variance of σ^2.

i=1, 2 … *l*, where *l* is the number of levels of the treatment A.

j=1, 2 … *n*, where *n* is the number of levels of the treatment B.

Table 11. Two-Way ANOVA Table without Replication

Source of Variation	Sum of the Squares	Degree of Freedom	Mean Squares	F ratio	F' Critical	% Contribution
Treatment A	SS_A	df_A	MS_A	F_A	F'_A	$\% A$
Treatment B	SS_B	df_B	MS_A	F_B	F'_B	$\% B$
Within	SS_{Within}	df_{Within}	MS_{Within}			$\%_{Within}$
Total	SS_{Total}	df_{Total}				

y_{ijk} is the k_{th} response variable for the i_{th} level of the treatment A and the j_{th} treatment B. If the model has *h* numbers of replicated response variables at each level for each treatment, it is necessary to determine if there is interaction between treatments. As shown in Table 12, interaction for two treatments is added. The statistical model for Two-Way ANOVA with the replication is:

$$y_{ijk} = \mu + \alpha_i + \beta_j + \alpha\beta_{ij} + \varepsilon_{ijk} \tag{3.24}$$

where μ is the overall mean of response variable.

α_i and β_j are main effects of the i_{th} level of the treatment A and the j_{th} level of the treatment B. $\alpha\beta_{ij}$ is the interaction effect of the treatment A and the treatment B.

ε_{ijk} is a random error. These errors are assumed to be independent and normally distributed with a mean of zero and constant variance of σ^2.

i=1, 2 … *l*, where *l* is the number of levels of the treatment A.

j=1, 2 … *n*, where *n* is the number of levels of the treatment B.

k=1, 2 … *h*, where *h* is the number of replications at each level of each treatment. $\sum_{i=1}^{l} \alpha_i = \sum_{j=1}^{n} \beta_j = \sum_{i=1}^{l} \alpha\beta_{ij} = \sum_{j=1}^{n} \alpha\beta_{ij} = 0$

Table 12. Two-Way ANOVA Table with Replication

Source of Variation	Sum of the Squares	Degree of Freedom	Mean Squares	F ratio	F' Critical	% Contribution
Treatment A	SS_A	df_A	MS_A	F_A	F'_A	% *A*
Treatment B	SS_B	df_B	MS_B	F_B	F'_B	% *B*
Interaction AB	SS_{AB}	df_{AB}	MS_{AB}	F_{AB}	F'_{AB}	% *AB*
Within	SS_{Within}	df_{Within}	MS_{Within}			$\%_{\ Within}$
Total	SS_{Total}	df_{Total}				

3.3.7.4 Design of ANOVA

Steps for the design of an ANOVA test are described as follows (Drain 1997):

1. Define the purpose and scope of the experiment (Comparative experiments are to determine if a factor has an effect on a response);
2. Examine scientific literature and documentation from previous experiments. (Mistakes or errors should be avoided to improve future experiments.)
3. Choose experiment responses;

4. Choose experiment factors and levels;
5. Account for other experiment variables such as time and weather conditions;
6. Choose the experiment structure; and
7. Determine experiment risks and resource requirements (Alpha risk is often fixed at 5% and beta risk is at 10%).

3.3.8 Experimental Design and Analysis

3.3.8.1 Introduction to Experimental Design

Experiments involving statistical data analysis must be strategically designed to eliminate bias, avoid wasting resources, and reduce variations based on sound statistical knowledge and previous experience (Frigon and Mathews 1997b). Statistical experimental design, or design of experiment (DOE), is often used to minimize the effect of errors, reduce the number of experiment runs, and improve systems (Mason et al. 2003). Using DOE helps researchers to conduct better experiments, efficiently analyze data, and lead from the results of analyses to clear conclusions. Therefore, optimum input settings under the DOE can be the basis of simple, fast, economical, and reliable experimentation (Drain 1997; Wu and Hamada 2000).

Experimental design has been widely used in a variety of fields such as agriculture, medicine, biology, marketing research, engineering and manufacturing. Table 13 represents the evolution of modern experimental design techniques, which can be divided into three eras since their first use by R. A. Fisher in the 1930s (Wu and Hamada 2000).

There are five objectives in experimental design: treatment comparisons, variable screening, response surface exploration, system optimization, and determining system robustness. The key objective of treatment comparisons is to compare several treatments and their differences and then determine the best one. Randomized complete block and split-plot designs, initially developed for agricultural research, are widely used in every field (Wu and Hamada 2000). Latin squares were also developed in agricultural experiments. Currently, they are employed mostly in medical and pharmaceutical clinical trials, animal science, marketing studies, and elections (Giesbrecht and Gumpertz 2004b). The full factorial experiment is more appropriate in which factors are simultaneously varied rather than one-factor-at-a-time (Chen et al. 1999). Fractional factorial designs are also common types of design in industry. Fractional factorials, Plackett-Burman plans, and orthogonal arrays are employed for screening possible variables to improve efficiency of statistical experiments. If an experiment needs large screening variables, the response surface method can be used and is often followed by linear and quadratic regression modeling. The response surface design is one that optimizes systems to find the best combination for maximizing production and performance of a system and to minimize the number of defects and costs in industrial experimentation. The robust parameter design, often called Taguchi method, is used to improve a system, a product, or a process, in which quality and productivity are the major focuses (Wu and Hamada 2000; Giesbrecht and Gumpertz 2004a).

Table 13. Historical Background of Experimental Design Techniques

Pioneers	Focuses	Industry	Time
R. A. Fisher	Development of modern experimental design	Agriculture	First era: 1930s to World War II
F. Yates and D. J. Finney	Development of blocking, randomization, replication, orthogonality, and the use of analysis of variance and fractional factorial designs	Agriculture and Biology	
R. C. Bose	Theory of combinatorial designs	Social Science, textile, and woolen	
G. E. P. Box	Process modeling and optimization: central composite designs and optimal designs relying on regression modeling and graphical analysis	Chemical industries	Second era: Post World War II to 1970s
J. Kiefer	Optimal designs with computational algorithms		
G. Taguchi	System Robustness: variance reduction in quality characteristics and productivity improvement	Manufacturing	Third era: 1970s to Present

3.3.8.2 Experimental Design Principles and Criteria

Four key principles must apply to experimental design: 1) *representativeness*, 2) *randomization*, 3) *replication*, and 4) *error control or blocking*. A measure of representativeness can be defined as reliability of the statistical inference on how accurately the sample or the experiment represents the entire population (Fortune

1999). Thus, adequate number of data collected from true representatives of the target population is of utmost importance (Giesbrecht and Gumpertz 2004a). Randomization avoids unwanted biases by unanticipated factors reflected on the experimental results. Replication and error control ensure the reliability of the results and the circumstances of a precise experiment. The precision of estimates and the power of the hypothesis rely on the amount of replications and the magnitude of unexplained variation. Blocking refers to the arrangement of data into the homogeneous units so that the within-block variation is smaller than the between-block variation. For example, if treatments can be applied the same day, the daily variation is eliminated. The block-to-block variation can be eliminated under an effective block design (Wu and Hamada 2000; Giesbrecht and Gumpertz 2004a).

Understanding statistical design criteria is of importance in selecting appropriate experiment design methods. Mason et al. (2003) described five criteria including:

1. Consideration of Objectives: nature of anticipated conclusions, definition of concepts, and determination of observable variables
2. Factor Effects: elimination of systematic error, measurement of covariates, identification of relationships, and exploration of entire experimental region
3. Precision: estimation of variability (uncertainty), blocking, repeat tests, replication, and adjustment for covariates

4. Efficiency: multiple factors, screening experiments, and fractional factorials
5. Randomization

3.3.8.3 Experimental Design Techniques

Papers described in this section demonstrate the experimental design concepts that have been applied in engineering and construction-related research projects. Nineteen recent papers that used experimental design techniques were reviewed to identify data collection and analysis methods, as summarized in Table 14. The subjects covered by these papers are as follows: comparative studies, factor analysis (such as regression analysis), factorial design, response surface analysis, and the Taguchi design method. The cited references comprise fourteen journal papers and two conference proceedings.

3.3.8.3.1 Comparative Study

A comparative statistical study tests two or more treatments and levels to statistically determine if they produce equivalent results and to quantify the effects of different factors and equipment. For example, in the manufacturing industry, comparative tests are used to qualify process changes to ensure that a new process is equivalent to or better than the standard process. This test begins with the null hypothesis that there is no difference between two populations (H_0: μ_1-μ_2 = μ_d=0).

Table 14. Recent Studies Related to Experimental Design

No	Researchers	Statistical Data Analysis		Journal	Year
		Main Test	Supplemental Techniques		
1	Ho and Chang	ANOVA test	Randomized block model, Factorial Analysis	JSE	1997
2	McCabe et al.		Independent t tests , Minimum sample size	JIS	1999
3	McCabe et al.		Independent t tests	JCEM	2002
4	Shen and Du		The GRA method	JMCE	2005
5	Singh and Shoura		Questionnaire and data design	JME	1999
6	Al-Balbissi			JTE	2001
7	Irizarry et al.		Log transformation, Tukey-Kramer multiple comparison	JCEM	2005
8	Debella and Ries		Independent t tests, Anderson Darling Method Log Transformation	JCEM	2006
9	Law and Kelton	Full factorial design	Simulation	Book	2003
10	Kelton and Barton			WSC	2003
11	Wang and Halpin			WSC	2004
12	Vepa and George	Fractional factorial design	Regression Modeling	JTE	1997
13	Polettini et al.			JEE	2003
14	Faniran et al.	Regression Modeling	Questionnaire and data design, Shapiro-Wilks' test	JCEM	1999
15	Bai & Bernold		Factorial design	JCEM	2001
16	Smith and Forde	Response surface method	Full factorial design, Simulation	JCEM	1995
17	Yao and Wen		Monte Carlo simulation	JSTE	1996
18	Drabkin		factional experimental design	JPIEEP	1996
19	Chawla and Frost		Monte Carlo simulation	CCEP	2005

Note: JSE (Journal of Surveying Engineering), JIS (Journal of Infrastructure Systems, JCEM (Journal of Construction and Engineering Management), JME (Journal of Mechanical Engineering), JTE (Journal of Transportation Engineering), JMCE (Journal of Materials in Civil Engineering), WSC (Winter Simulation Conference), JEE (Journal of Environmental Engineering), JSTE (Journal of Structural Engineering), JPIEEP (Journal of Professional Issues in Engineering Education and Practice), CCEP (Computing in Civil Engineering Proceedings).

Randomized block model variance analysis was used to assess factors that affect the quality of two digitized methods: digitizing tablet and desktop scanner (Ho and Chang 1997). McCabe and his colleagues (1999) determined whether the minimum number of tests affects the mean values, the degree of confidence, and quality-related price adjustment to the contractor. The ANOVA test and independent *t*-test were used to compare the means and variances of three asphalt quality measures (McCabe et al. 2002). These asphalt concrete quality measures, namely asphalt content, degree of compaction, and aggregate gradation, were compared to investigate the timing of sampling and its effect on the quality assurance program. Samples designed for three asphalt pavements were drawn from during-construction quality assurances (DQA), post-construction quality assurances (PQA), and contractor's quality control (CQC). This research project identified differences among each sample source. Shen and Du (2005) compared three reclaimed building materials (RBM) used for hot mix asphalt (HMA): waste concrete, brick, and tile. ANOVA tests evaluated the significant effects on permanent deformation, resilient modulus, and stripping for the RBM.

Al-Balbissi (2001) determined significant causes of crashes from the evaluation of accident trends for rental cars using the ANOVA test. Irizarry and his colleagues (2002) conducted research on the effects of unsafe working conditions on workers' performance by observing steel erection activities and analyzing task duration data. 186 steel erection task durations were analyzed using ANOVA to determine if there were significant differences between the average duration of steel erection tasks under different safety conditions and environmental conditions presented at job sites.

Debella and Ries (2006) compared the performance of construction delivery systems for school district projects. The research steps included defining quantitative and qualitative data metrics, conducting a pilot study, surveying for data collection, and analyzing data. Elements of data metrics were construction speed, unit cost, cost increase, construction schedule increase, and others. The data was initially tested for data normality using the Anderson-Darling test. If the data were not normally distributed, a log transformation was used. Next, three experiments were conducted: a one-way ANOVA test for comparing mean values from three different delivery systems, two-sample *t* tests for comparing two delivery systems, and a chi-square test for verifying the possible relationship between two sets of qualitative data.

3.3.8.3.2 Regression Analysis

Faniran and his colleagues (1999) developed regression models using the following variables: planning input, cost variance, and time variance. Data collected from a structured questionnaire were normalized and then modeled by using logistic regressions and linear/curvilinear regressions techniques. In this research, the Shapiro-Wilks's test was carried out for data normality. To convert the continuous project performance measures into discrete categorical variables, the data was classified into three ranges: the first quartile, interquartile, and the third quartile. Logistic regression analysis was performed to estimate the probability that each event would occur. Linear and curvilinear regression analyses were performed to examine the correlation between project performance and planning input of construction projects.

3.3.8.3.3 Factorial Design

Factor studies and sensitivity analyses can be used to identify combinations of resources for maximum productivity. However, the factorial design method, one of the experimental design methods, has been proved to have more advantages because of 1) fewer runs required for the same precision, 2) better capacity to estimate interactions, and 3) more specific conclusions. The factorial experiment is an experimental design method where responses are observed for every combination of factor levels (Freund and Wilson 2003). Law and Kelton (2000) presented a simulation method based on factorial design as an alternative to classical methods such as the inspection approach, confidence interval, and time-series approaches. To determine the appropriateness of the models developed using the simulation method, two-sample chi-square tests and two-sample t-tests were used to validate these simulation models.

Kelton and Barton (2003) used experimental design concepts in their construction simulation study, including randomized design, variance reduction techniques, full factorial design, factor-screening designs, and response surface methods. In their paper, several limitations of the full factorial design were described since interaction factors cause their own complexity and obscure interpretation of main effects. Fractional factorial design can often be an alternative method in which some of the potential interactions are eliminated. Replications, or independently repeating, can also reduce considerable variances of the main effect, and interactions.

A research project conducted by Wang and Halpin (2004) used methods including simulation, design of experiment, regression analysis, and mathematical programming. The purpose of their research was to develop a model by using experimental design techniques and to compare the outcomes between the developed model and the simulation model. By using the factorial design method, a fitted regression model was developed, which excluded interactive factors. The comparison demonstrated that the regression model (the developed model) could be very sensitive to the outcomes of the mathematical programming. Results of their research indicated that the use of the factorial design method and mathematical programming could eliminate the interaction effects in the simulation modeling.

Vepa and George (1997) developed dynamic deflection prediction models using a finite-element program, "ABACUS." Initial causal factors for deflected pavements were determined based on engineering judgment and experience, and combinational design procedures were used to assemble the factorial, which resulted in possible runs of 1,296 ($2^4 3^4$). To reduce the number of runs, a one-eighth fractional factorial design was adopted without any changes in effects to all factors and their interaction on response, which resulted in 162 combinations. Linear regression equations developed from the experimental design method were validated by the field data from two in-service pavements.

A fractional factorial design method was used by Polettini and his colleagues (2003) to simulate the behavior of cement-based systems containing MSWI ESP ash. Pure compounds such as $MgCl_2$, K_2SO_4, $Zn(NO_3)_2$, and $NaNO_2$ were added to Portland cement to study the evolution of physical and mechanical properties and neutralization capacity with curing time.

Bai and Bernold (2001) conducted lab experiments using a factorial design to determine the values of painting process planning parameters for coating thickness distribution functions on steel bridge features. Factors were defined as spray gun angle, air pressure, fluid pressure, distance, and moving speed. A regression model for the coating thickness was developed based on the results of experiments with the multiple coefficient of determination (R^2) at 0.89.

3.3.8.3.4 Response Surface Analysis

Response surface methodology (RSM) uses several statistical analysis methods to examine the relationship between the response and variations in the values of input variables. Smith and his colleagues (1995) utilized RSM to study the relationship between the truck travel time and truck spot time. Full-factorial designs were used to decrease the number of experimental runs and identify the most significant factors including number of trucks, the haul and return time (travel time), the number of passes per load, and the loading rate. Factorial design was followed by the response-surface design to identify the fundamental information including which factors are the most significant, and their ranges. The iterative experimental design method provided information on the overall system and eliminated the less significant factors. The results indicated that load pass time was the most significant factor in earthmoving productivity. The simulation technique for travel time was also employed to determine the sensitivity of the operational output.

Yao and Wen (1996) used RSM to approximate the failure probability of structures subjected to time-variant loads during earthquakes. The proposed empirical measure for validating the response surfaces provides a reasonable compromise between Faravelli's λ_F (1989) measure and two alternative measures proposed by Böhm and Brückner-Foit (1992). In addition, Monte Carlo simulations and Karamchandani's (1990) sampling techniques were employed to evaluate the proposed time-invariant limit-state formulation.

Chawla and Frost (2005) used RSM to develop a methodology to compute the multi-hazard response of a levee system. Seven main model parameters were computed and used to develop the response surface regression equation. The equation approximated the factor of safety as a polynomial function of the predictor variables. The use of the DOE technique reduced the number of simulation runs required to model the levee for various cases. The fitted regression equation was validated with Monte Carlo Simulation and tested with an ArcGIS framework.

3.4 Summary of Literature Review

The literature review for this research project covers three subjects including rapid highways and bridges replacement, productivity measurement methods, and statistical theories. A total of 144 references were reviewed and results were summarized in this chapter.

To date, research projects on rapid bridge and highway replacement have been conducted focusing on the following major topics: 1) rapid bridge replacement techniques after extreme events; 2) the development of prefabricated techniques; 3) accelerated construction techniques; 4) urban rehabilitation techniques; and 5) traffic control using different closure schemes. Most of these research projects indicated that there were limitations to fully utilizing information in improving construction productivity. In addition, there were no previous research projects on productivity measurements and analyses for rapid bridge and highway replacement for emergency response. Such research is needed to provide more reliable construction duration and cost to government agencies and industries.

Productivity measurement methods have been developed with the advancement of modern technologies. The literature survey on construction productivity measurement indicates that the conventional method requires additional labor and space to conduct measurements, takes more time to transmit and analyze data, and poses difficulties for gathering and obtaining accurate data. Advanced methods such as GPS and RFID have been developed to address the shortfalls of conventional methods. However, some of the advanced methods have not been scientifically proven in either accuracy or practicability.

Research papers on statistical theories have been reviewed to obtain knowledge on how to minimize the effect of errors, reduce the number of experiment runs, and improve the designed system. Thus, the author can better design experiments, efficiently analyze data, and draw sound conclusions from the results of analyses. In the next Chapter, the author will present the development of the WRITE System.

CHAPTER 4:DEVELOPMENT OF THE WRITE SYSTEM

4.1 Introduction

The **w**ireless **r**eal-t**i**me produc**t**ivity m**e**asurement (WRITE) System can provide pictorial data via wireless network so that anyone in the construction field office or home office will be able to monitor construction activities and analyze productivity in real time. The WRITE System has several unique advantages. First, there is no disruption to construction operations because the system can cover up to approximately one mile in diameter. Thus, the system can take pictures from any place in the construction field. Second, the system can be operated by one person for data collection and analysis. Thus, it reduces labor costs for data collection and analysis. The savings may be able to offset the cost of installing the system. Third, the collected data can be shared by all parties in the construction operations via wireless network at any time.

The author utilized the Erdman Video System (EVS) to build the prototype WRITE System. The EVS system is composed of three modules: a transformer box, a data processor, and a camera housing unit. There is one video camera and one digital camera in the camera housing unit. The video camera can take up to 30 pictures every second, and the digital camera can take high-resolution pictures of seven mega pixels. The EVS system can be installed on the construction site with a Local Area Network (LAN) or without a LAN.

4.2 WRITE System Components

The WRITE System can provide pictorial data via a wireless network so that anyone in the construction field office or home office can monitor construction activities and analyze productivity in real-time as long as there is Internet service available at the location. The WRITE System has several unique advantages. First, there is no disruption to construction operations. Second, the on-site construction productivity can be determined in real-time so that the project manager will be able to take action immediately if necessary. Third, the collected data can be shared by all parties in the construction project via the Internet at any time and at any location.

The WRITE system is composed of four major components that are shown in Figure 11. Their functions are briefly described as follows:

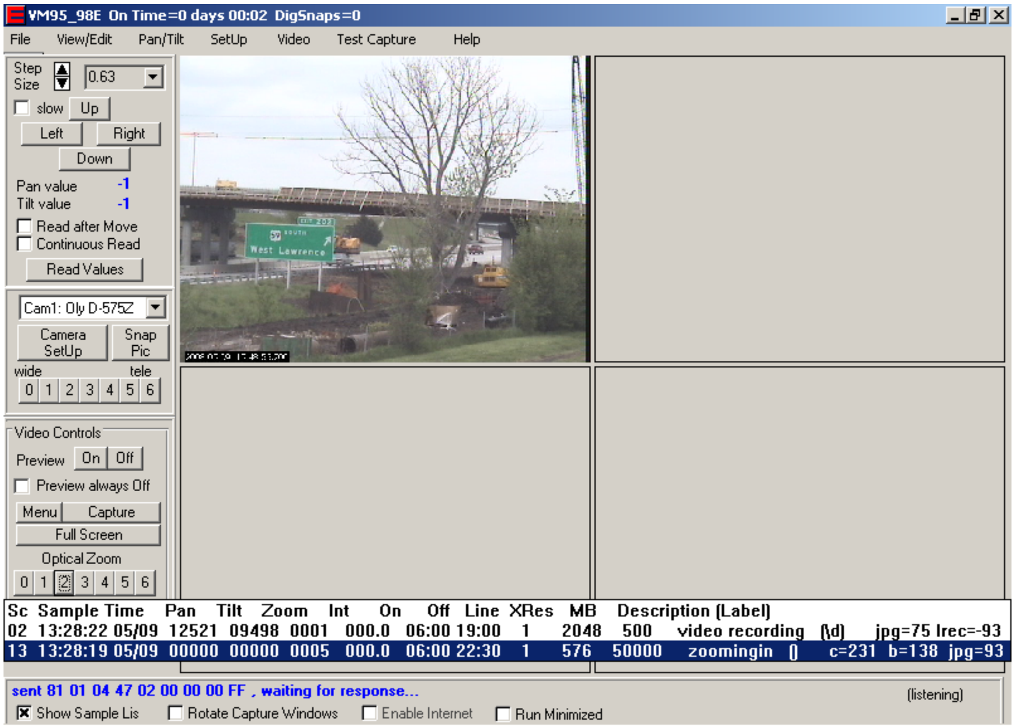
1. Pan/Tilt Camera Housing (upper right in Figure 11): This steel box contains a digital camera and a video camera that are connected to the data processor. The video camera can take up to 30 pictures every second, and the digital camera can take high-resolution pictures of seven mega pixels. The camera housing is weatherproof and vandalism-resistant. It is mounted on a rugged 360° outdoor pan/tilt unit that can be attached to a pole, wall, or pedestal mount.
2. Data Processor (the second item from the left in the first row of Figure 11): The data processor, also known as a biscuit computer or mini computer, contains a program called VM95 that can control the camera housing

movement, the number and duration of shots, and zooming. A snapshot of the VM95 program is presented in Figure 12.

3. AC Transformer (the first item from the left in the first row of Figure 11): This device transfers electric energy to the other circuits. The transformer unit should be mounted close to the AC power source. One end of a phone line plugs into a jack inside the transformer box, and the other end of the phone line, plus the low voltage AC line, passes through the transformer to the data processor box. The maximum length of cable is 100 meters. The transformer box can be mounted indoors or outdoors and can be mounted to a wall or pole.
4. Computer: This is a necessary item for anyone who wants to view the pictorial data at a different location via a wireless modem or a local area network (LAN). If the computer is equipped with VW View software, it can control the cameras with adjustments such as, zoom in and zoom out. A snapshot of the VM View is shown in Figure 13.

Besides these major components, additional items are also required to operate the system. They include wireless modems, a generator to provide electricity at the job site, a steel pole to mount the camera box, and cables to connect the components.

Figure 11. Major components of the WRITE System



VM95_98E On Time=0 days 00:02 DigSnaps=0

Step Size 0.63

☐ slow

Pan value -1

Tilt value -1

☐ Read after Move

☐ Continuous Read

Cam1: Oly D-575Z

☐ Preview always Off

```
Sc Sample Time     Pan   Tilt  Zoom  Int   On    Off   Line XRes  MB   Description (Label)
02 13:28:22 05/09 12521 09498 0001  000.0 06:00 19:00  1    2048  500   video recording  (\d)    jpg=75 lrec=-93
13 13:28:19 05/09 00000 00000 0005  000.0 06:00 22:30  1    576   50000  zoomingin  ()    c=231  b=138  jpg=93
```

sent 81 01 04 47 02 00 00 00 FF , waiting for response...

(listening)

☒ Show Sample Lis ☐ Rotate Capture Windows ☐ Enable Internet ☐ Run Minimized

Figure 12. A snapshot of VM95 program

○ 192 ○ 576
○ 384 ● 768
☑ HQ

Step Size 5

108.06 KBytes .4 fps 42.32

Successfully connected...requesting

#Pics=176/176

Figure 13. A snapshot of VM View program

4.3 WRITE System Framework

Figure 14 presents the framework of the WRITE System that was developed during the process of this research project. Once the video camera takes pictures from the construction site, the data processor immediately saves the pictorial data into files. Then, these files are transmitted in real-time via a wireless modem. An engineer or a project manager can access the data files via a wireless modem or a LAN with an IP address at another location to conduct productivity analysis using a computer with VM View software. After finishing the data analysis, productivity data and live pictures are presented in a website so that other users such as the owner, engineers, contractors, and material suppliers can share the information.

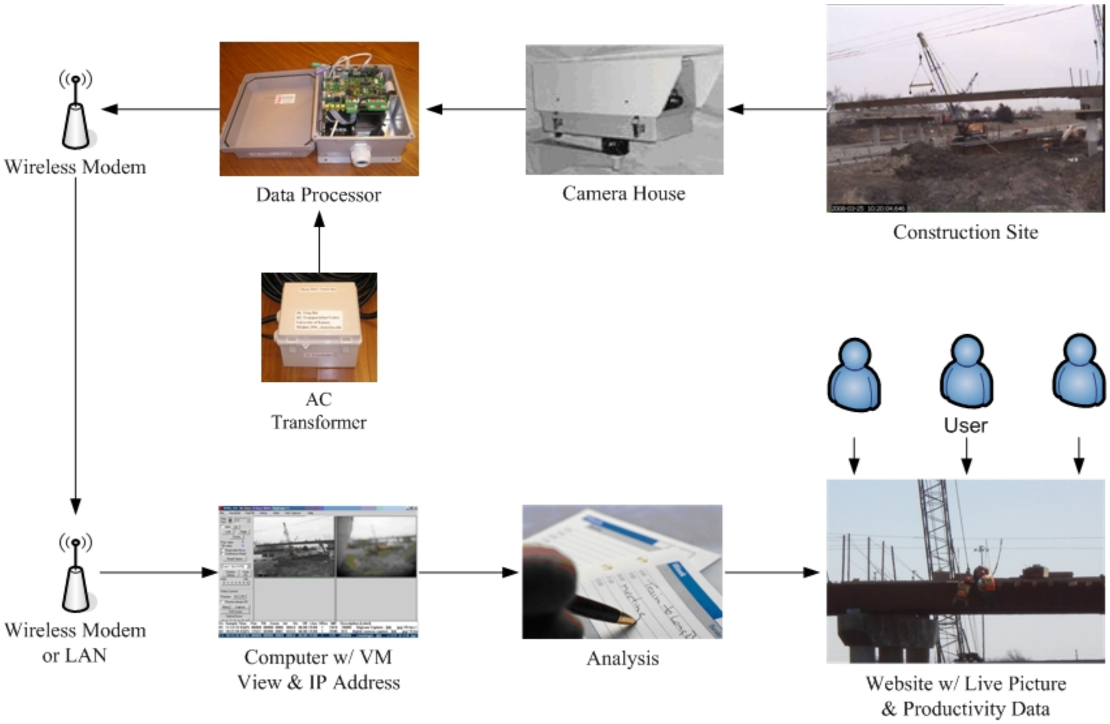


Figure 14. Framework of the WRITE System

4.4 System Installation Procedure

Using the correct method for installing the WRITE System at the construction site is critical when conducting field experiments. A rapid and proper installation will increase efficiency in data collection and analysis. In addition, safe practices must be enforced at each stage of the installation. Major steps for the installation of the WRITE System are illustrated in Figures 15 to 21):

Figure 15. Mounting camera on the pole

Figure 16. Erecting the pole perpendicular to the ground

Figure 17. Supporting the pole with three steel legs

Figure 18. Hammering big nails into the ground

Figure 19. Adding gas to the portable generator

Figure 20. Connecting the data processor with camera and AC transformer

Figure 21. Operating the system

CHAPTER 5:TESTING THE WRITE SYSTEM FOR HIGHWAY CONSTRUCTION OPERATIONS

5.1 Introduction

The author conducted preliminary field experiments to collect productivity data using the WRITE System from three highway maintenance projects. The objective of these experiments was to determine whether the WRITE System is a feasible tool for measuring highway productivity data. To accomplish the objective, productivity data was collected simultaneously using the stopwatch method and the WRITE System. Both results were compared using statistical methods to determine if there was significant difference.

Three highway projects were selected with help from KDOT engineers. One project was a hot-mixed-asphalt (HMA) overlay project and the other two were hot-in-place recycling (HIR) projects. During the preliminary field experiments, the author focused on rehabilitation for asphalt pavements, including the HMA overlay and the HIR projects, except for asphalt mixture production at the mix plant and the material delivery from the mix plant to the construction site. Prior to the field experiments, *Heavy Construction Cost Data* and other publications regarding asphalt paving process were reviewed to obtain information with regard to crew size and historical daily outputs (Spencer 2006a). In addition, the author visited the job sites to obtain geographical information to develop the field experiment plan. During the development stage, the author obtained the pavement specifications from the KDOT Web site.

The HMA overlay project was carried out by paving a net length of 9.176 miles with a thickness of 1.5 inches and a width of 31 feet on US 36 near Washington, KS. Hall Brothers Inc., the contractor, was awarded the project at $983,798 including milling, bituminous overlay, and shoulder rock. The estimated duration was 12 working days from June 11 to June 25, 2007. Productivity data were collected on the overlay operation for four days from June 18 to June 21, 2007. A section of pavement is shown in Figure 22.

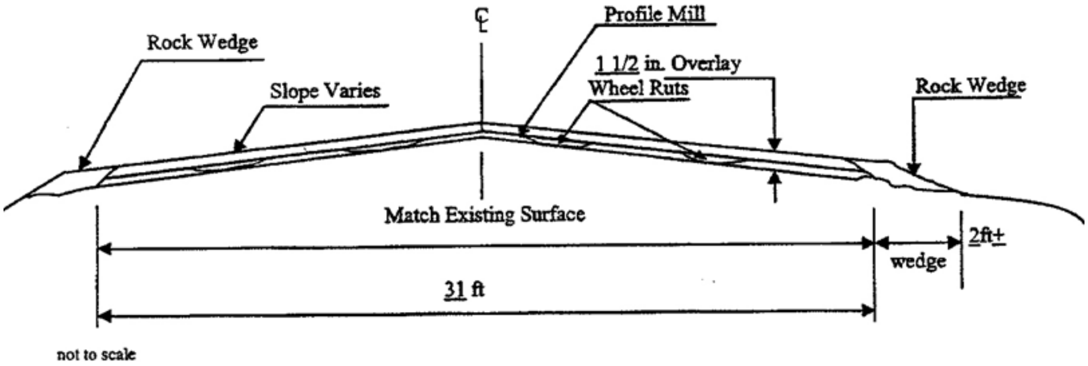


Figure 22. Cross-section of the HMA overlay projects

Two HIR asphalt rehabilitation projects were carried out on K-192 near Winchester, KS and K-16 near Tonganoxie, KS. The total length of highway was 23.8 miles. The contractor, Dustrol Inc., was awarded these projects at the cost of $1,768,101 and completed them in 12 working days from July 5 to July 20, 2007. Productivity data were collected for ten days from July 9 to July 20, 2007. A section of the pavement is presented in Figure 23.

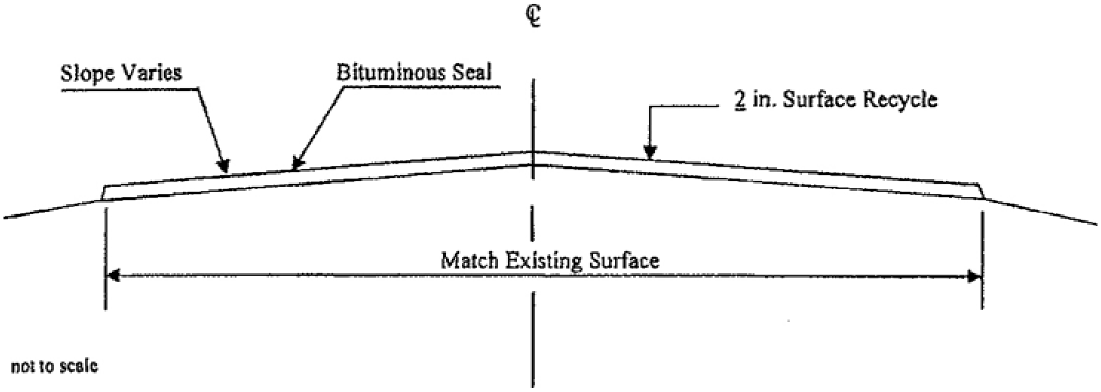


Figure 23. Cross-section of the Hot-in-Place recycling projects

Traffic control was one of the important concerns in these projects. The contractor maintained a single lane open by using a pilot car, as shown in Figure 24. Single lane closures are the most frequently used method by state government agencies (Dunston et al. 2000).

Figure 24. Traffic control (single lane closure)

5.2 Rehabilitation Methods for Asphalt Pavements

5.2.1 HMA Overlay

The most typical rehabilitation treatment for low volume HMA pavement is a thin HMA overlay.

5.2.1.1 Preparation

Two major operations in the preparation phase for HMA overlay are plant operation and road preparation. Plant operation includes preparation of the asphalt binder, mineral aggregate, and HMA. In a surface overlay, the existing surface must be prepared before any mix is placed. The degree of preparation depends on the condition of the existing surface. In general, the existing pavement should be structurally sound, level, clean, and capable of bonding to the overlay. Common preparation practices are pavement replacement and patching, crack filling, leveling courses, and milling or cold planing, as shown in Figure 25.

Figure 25. Milling (Washington Asphalt Pavement Association 2002)

5.2.1.2 Tack Coat

Prior to the HMA overlay, the existing surface should be applied with a tack coat. A tack coat ensures that the new asphalt overlay bonds to the existing pavement surface (See Figure 26). Before applying the tack coat, the surface must be cleaned to remove dust and dirt by using mechanical brooming or flushing with air or water. Otherwise, new pavement may be shoved in a longitudinal direction in the future by heavy accelerating and decelerating traffic. The amount of water in an asphalt emulsion and the amount of diluted material in asphalt must be taken into consideration to maintain workability (Transportation Research Board 2000a).

Figure 26. Tack coat material applied by a pressure distributor

5.2.1.3 Paving Operations

Asphalt paving is an operation that spreads a bituminous asphalt mixture prepared at a batch plant and brought to the construction site. The primary purpose of an asphalt paving machine is to place the HMA at the desired width and thickness. Bituminous material is delivered in dump trucks and funneled toward the paving machine through the hopper. Although the operation is relatively simple, large equipment and large labor crew size are required (Williams 1999). Required pieces of equipment are as follows (Peurifoy and Schexnayder 2003):

1. Sweeper/brooms for removing dust from the surface to be paved
2. Trucks for hauling the asphalt from the plant to the construction site
3. Asphalt distributor truck for applying the prime tack, or seal coats
4. Material transfer vehicle (optional)
5. Windrow elevator (optional)
6. Paver or spreader
7. Rollers
8. Pilot car (optional)

The asphalt paving operation can be categorized into two primary tasks: unloading the asphalt mix into the paver and spreading the asphalt mix as the paving machine moves forward (see Figure 27). After the asphalt mix was spread, the contractor takes a sample to test it in the lab for quality control purposes, as shown in Figure 28.

Figure 27. HMA paving

Figure 28. Sampling the asphalt mix for lab test

5.2.1.4 Asphalt Compaction

Compaction is a task in the paving operation in which the asphalt mix is compressed to remove air voids. As a result, the asphalt-coated aggregates in the mix are compressed, increasing aggregate interlock and interparticle friction. This task determines the quality of the asphalt mix, such as the fatigue life, permanent deformation (rutting), aging, moisture, strength and stability, and low temperature cracking. Six major factors impact the capacity of a compaction operation: the properties of the materials, layer thickness, air, base temperature, jobsite condition, and the type of compaction equipment (Transportation Research Board 2000b). In the experimental project, three vibratory and steel wheel rollers were employed, as shown in Figure 29.

Figure 29. Compaction

5.2.2 HIR Operation

HIR is an asphalt recycling method that removes pavement surface materials using heat, then combines them with new pavement materials and a recycling agent. Having been used in the U.S. since the 1980s, this asphalt recycling method allows crews to remove the deteriorated asphalt pavements by eliminating surface irregularities and cracks up to two-inches in depth without any loss of the original pavement. A schematic concept of the HIR, showing each process, is presented in Figure 30. The major HIR operations identified by the Asphalt Recycling and Reclaiming Association (ARRA) include heating, scarifying, rejuvenating, leveling, reprofiling, laying new hot mix, and compacting (Kandhal and Mallick 1997; Button et al. 1999).

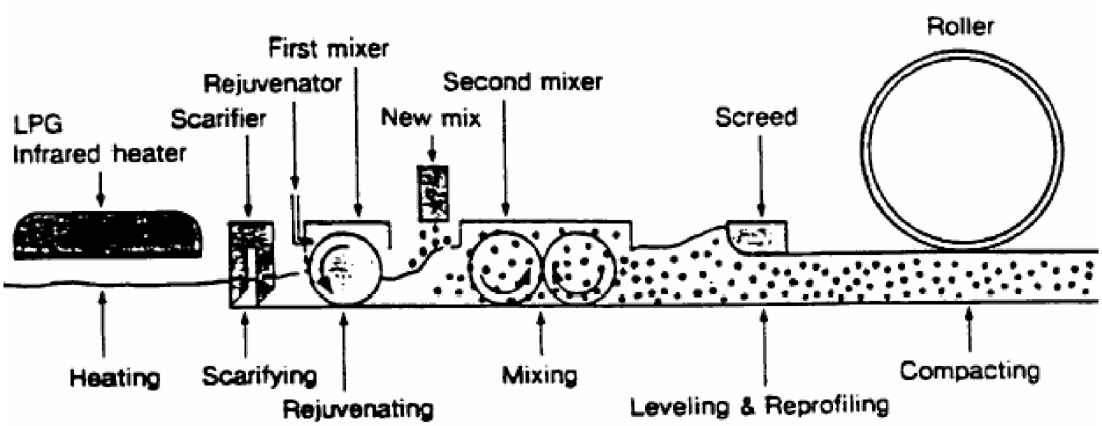


Figure 30. Schematic concept of the remixing method (Kandhal and Mallick 1997)

Figure 31 shows the HIR equipment fleet used in the experimental projects, which includes four heating trucks, four milling trucks, an asphalt mix paver, and a tandem roller. There are four major tasks in a HIR operation. First, the customized propane-fueled preheater heats the surface and scarifies the surface, shown in Figure 32. Second, the heated asphalt pavements are milled (see Figure 33). Third, the rejuvenator adds rejuvenation oil prior to the mixing process whereby new asphalt material blends with existing material from the surface, as shown Figure 34. Finally, the asphalt recycle paver and roller at the end of the equipment fleet pave and compact the new pavement surface, as shown in Figures 35 and 36 (Dustrol Inc. 2000).

Figure 31. HIR equipment

Figure 32. Heating equipment

Figure 33. Milling heater

Figure 34. Rejuvenating and mixing equipment

Figure 35. Surface paving equipment

Figure 36. Compaction

5.3 Data Collection

Information regarding crew size was provided by contractors and compared with RS means to understand the magnitude of operations before the data collection process. The comparison showed that the crew size for the HMA overlay project was similar to the RS means' numbers, as shown in Table 15. However, the crew size for the HIR project was greater than the RS means, as shown in Table 16. In addition to the crew size, KDOT inspectors provided contractors' daily production rates, which were used by the author to determine the reliability of the collected data.

Table 15. Crew Size for the HMA Overlay and RS Means (Spencer 2006a)

Source (1)	Foreman (2)	Laborers (3)	Equipment Operator (4)	Asphalt Paver (5)	Roller (6)	Water Truck (7)
RS Means	1	7	4	1	3	3
Job Site	1	6	6	1	3	3

Table 16. Crew Size for the HIR and RS Means (Spencer 2006a)

Crew (1)	RS Means (2)	Job Site (3)
Foreman	1	1
Laborers	3	3
Equipment Operator	4	12
Mechanic	-	1
Flagger	-	3
Superintendent	-	1
Total No. of Labor	8	21
Asphalt Paver	1	1
Roller	1	2
Heater	-	4
Profileometer	1	1
Water Truck	-	1
Milling Heater	1	4
Total No. of Equipment	4	13

Two different data collection methods were employed: the stopwatch method (See Figure 37) and the WRITE System method (See Figure 38). The stopwatch method, also called the classic method, was used to measure cycle time for the paving machine and results were immediately recorded onto the data collection form at the job sites (See Figure 39). Then, data were converted to productivity data at the office. On the other hand, the WRITE System collected raw data in video pictures at one frame per one or two seconds, and then the author converted picture data to the productivity data at the office. All data sets on cycle time and productivity collected from asphalt maintenance projects are presented in Appendix A. Figure 40 shows the operation cycle time of the HMA overlay based on pictures taken from the WRITE System. The pictures taken by the author, at four seconds per frame, demonstrate the construction progress at the beginning and end of the cycle time.

Figure 37. Time study using stopwatch

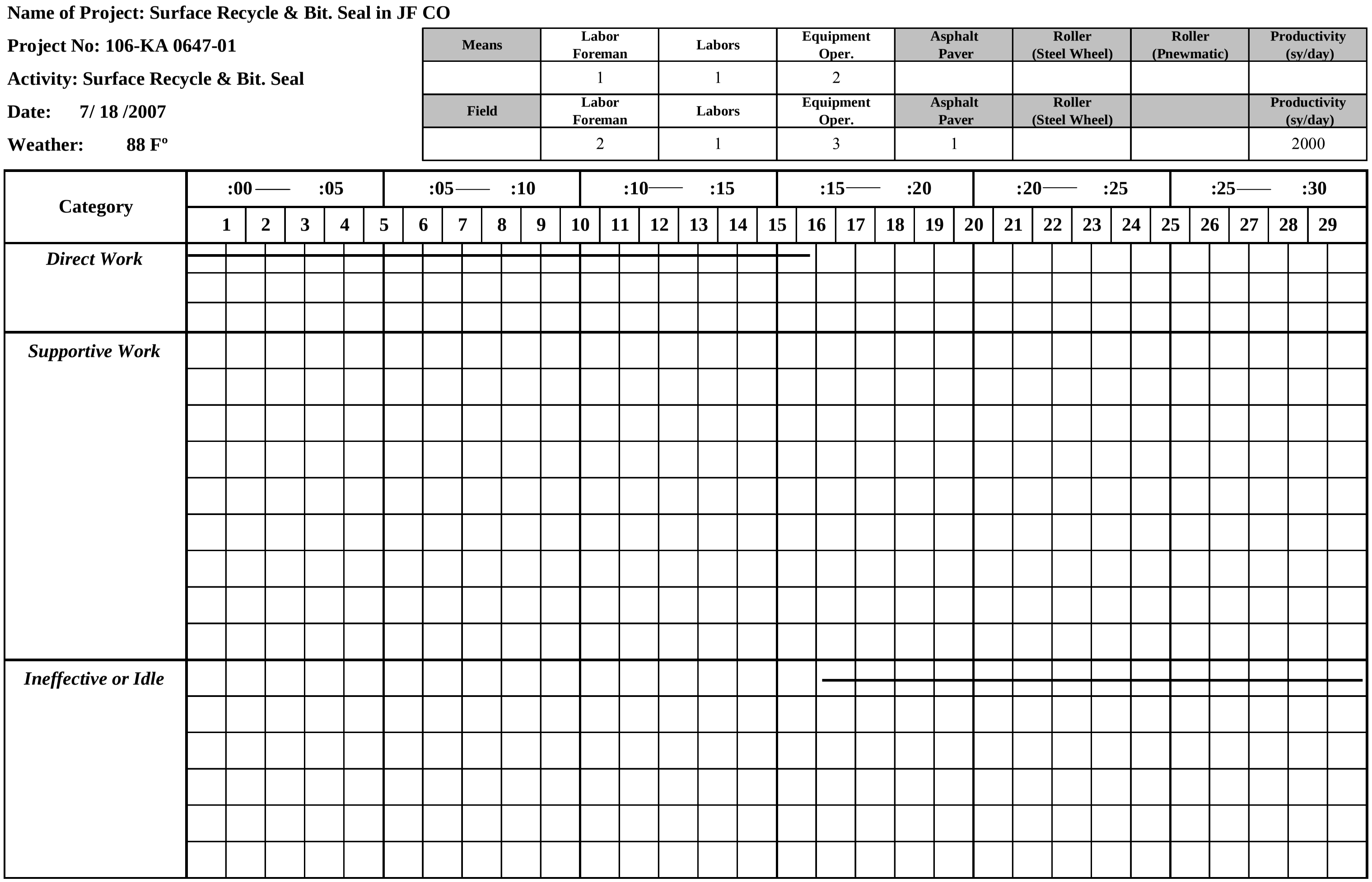
Figure 38. Time study using WRITE System

The author measured the cycle time of the HMA overlay for 21 hours during three days from June 19 to 21, 2007. The cycle time of the HMA overlay was used to calculate productivity. Working time and nonworking time of the asphalt paver (in seconds) were also measured. Working time in the HMA overlay operation was defined as the period during which the paver moved forward, while nonworking time was considered the period during which the paver stopped and waited for asphalt mix material.

A total of nine cycles were collected from the HMA operation and recorded as data in working and nonworking time for 4,800 seconds or 1.33 hours. Total data collection time for the two HIR projects was 167,952 seconds or 47 hours. The HIR productivity data were also recorded as working and nonworking time, expressed at one hour intervals, thereby extrapolating the 47 hours to the 60 hours.

Data collected from these two asphalt maintenance operations showed different characteristics. In the HMA operation, each cycle time should include nonworking time because the paving machine had to wait for the trucks to unload the asphalt. However, data collected from the HIR operations included little nonworking time except in the case of equipment problems, mobilization, safety, and weather issues.

Daily production rates for the HMA and HIR projects, provided by KDOT inspectors, are presented in Tables 17, 18, and 19. Table 20 shows hourly production rates for each project.



Name of Project: Surface Recycle & Bit. Seal in JF CO

Project No: 106-KA 0647-01

Activity: Surface Recycle & Bit. Seal

Date: 7/ 18 /2007

Weather: 88 F°

Means	**Labor Foreman**	**Labors**	**Equipment Oper.**	**Asphalt Paver**	**Roller (Steel Wheel)**	**Roller (Pnewmatic)**	**Productivity (sy/day)**
	1	1	2				
Field	**Labor Foreman**	**Labors**	**Equipment Oper.**	**Asphalt Paver**	**Roller (Steel Wheel)**		**Productivity (sy/day)**
	2	1	3	1			2000

Category	**:00—— :05**					**:05—— :10**					**:10—— :15**					**:15—— :20**					**:20—— :25**					**:25—— :30**			
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
Direct Work																													
Supportive Work																													
Ineffective or Idle																													

Figure 39. Data collection form used in the stopwatch method

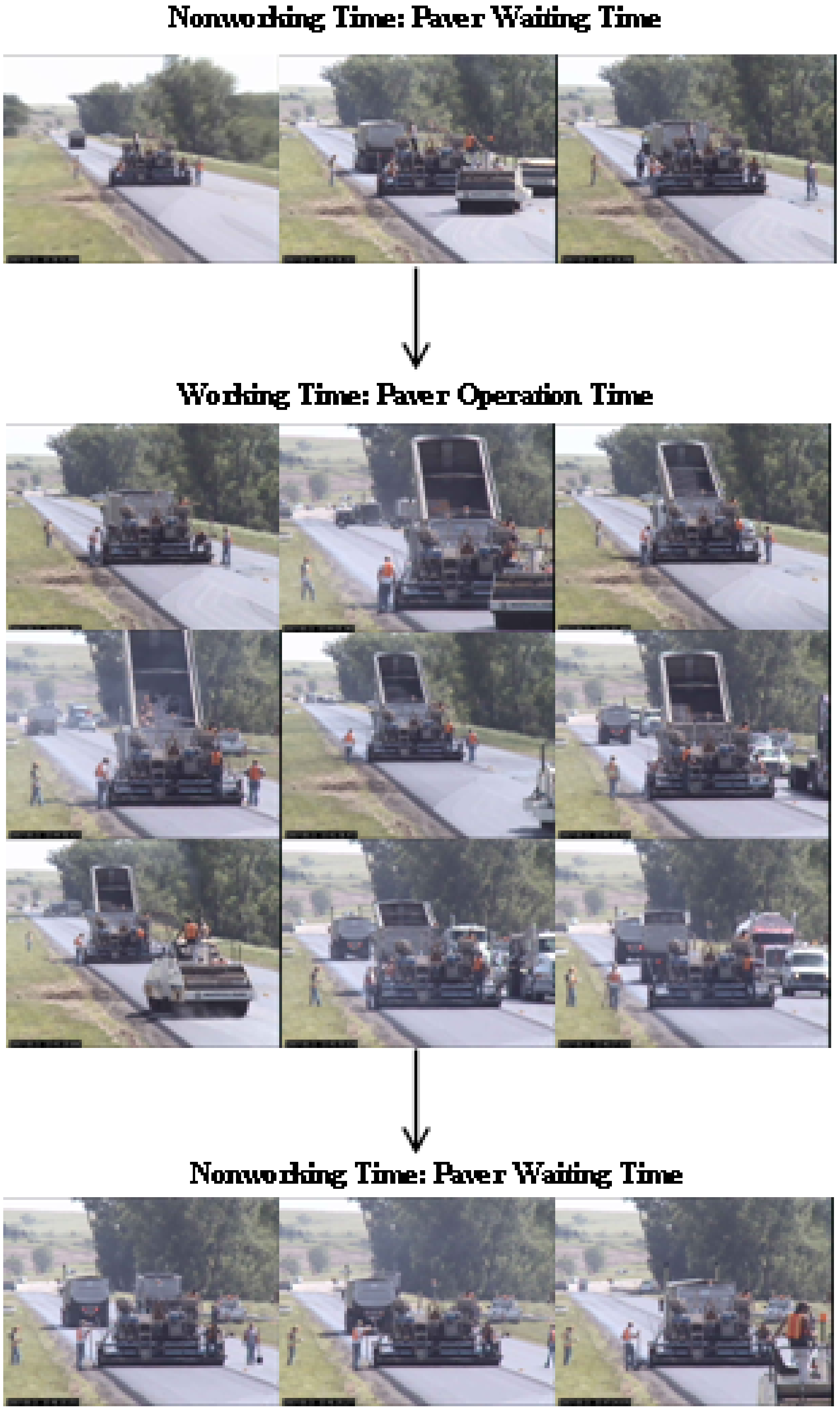


Figure 40. Nonworking time and working time in HMA overlay

Table 17. Daily Production Rates for the HMA Overlay Provided by KDOT

Date	Tons	Miles
6/7/2007	1,166	1.52
6/8/2007	2,096	2.74
6/11/2007	2,282	2.98
6/13/2007	800	1.04
6/14/2007	1,753	2.29
6/15/2007	1,873	2.45
6/18/2007	380	0.50
6/19/2007	1,038	1.36
6/20/2007	1,516	1.98
6/21/2007	726	0.95
Total	**13,630**	**17.80**

Table 18. Daily Production Rates for the HIR (Chip Seal)

Date	Tons	Miles
7/5/2007	1,722	2.31
7/6/2007	1,770	2.38
7/9/2007	1,304	1.75
7/10/2007	1,170	1.57
7/11/2007	1,340	1.80
7/12/2007	1,974	2.65
7/13/2007	2,033	2.73
Total	**11,313**	**15.20**

Table 19. Daily Production Rates for the HIR (w/o Chip Seal)

Date	Tons	Miles
7/16/2007	1,861	2.50
7/17/2007	2,482	3.33
7/18/2007	2,609	3.50
7/19/2007	2,538	3.41
7/20/2007	2,538	3.41
Total	**12,028**	**16.16**

Table 20. Hourly Production Rates Measured (Tons/Hr)

Type of the HMA Operation	Date	Hours (8:00 to 18:00)									
		8-9	**9-10**	**10-11**	**11-12**	**12-13**	**13-14**	**14-15**	**15-16**	**16-17**	**17-18**
Overlay	6/19/2007	-	93.0	93.0	93.0	113.0	53.0	196.0	151.0	91.0	151.0
	6/20/2007	222.0	222.0	189.0	189.0	189.0	189.0	106.0	106.0	106.0	-
	6/21/2007	106.0	211.0	286.0	121.0	-	-	-	-	-	-
HIR with Chip Seal	7/9/2007	-	-	-	-	-	-	-	245.7	156.3	67.0
	7/10/2007	-	52.1	148.9	171.2	141.5	171.2	171.2	74.5	74.5	163.8
	7/11/2007	-	178.7	186.1	134.0	134.0	186.1	193.6	148.9	178.7	-
	7/12/2007	-	253.1	96.8	148.9	201.0	245.7	275.5	268.0	335.0	148.9
	7/13/2007	134.0	193.6	171.2	148.9	171.2	148.9	305.2	305.2	245.7	134.0
HIR without Chip Seal	7/16/2007	-	-	-	186.1	193.6	320.1	409.5	-	-	-
	7/17/2007	67.0	96.8	208.5	171.2	96.8	89.3	171.2	-	-	-
	7/18/2007	-	-	312.7	364.8	245.7	507.0	-	-	-	-
	7/19/2007	-	-	193.6	245.7	238.2	260.6	201.0	178.7	282.9	104.2
	7/20/2007	-	327.6	148.9	387.1	-	-	-	-	-	-

5.4 Data Analysis

Four statistical methods were employed for the data analyses. First, data normality tests were performed to determine whether data had a normal distribution since data normality was a required assumption for the hypothesis test. For data without normality, data were transformed to the normal distribution, and then the outliers were removed where the transformed data were not normal. Second, a paired t-test was conducted as a parametric test to compare two dependant variables that were two productivity measurement methods, and nonparametric tests (such as the Wilcoxon Signed Rank test) were carried out where data did not have a normal distribution. Finally, the variability for the two productivity measurement methods was compared by using the t-statistic (only for HMA overlay data analyses).

5.4.1 Data Analysis on HMA Operation

5.4.1.1 Box Plots and Summary Statistics

A box plot is a two-dimensional graphical data display that highlights the location and a set of data to approximately compare means and standard deviation of quantitative data (Mason et al. 2003). As shown in Figure 41, the box plot displays cycle time data measured by two productivity measurement methods, which includes upper adjacent value, upper quartile (Q_1), median, mean, and lower quartile (Q_3), and lower adjacent value. This Figure indicates that the mean and Q_3 were nearly identical between the stopwatch and the WRITE System measurements. It also shows cycle time data using the WRITE System had a little more variability than that of the stopwatch method.

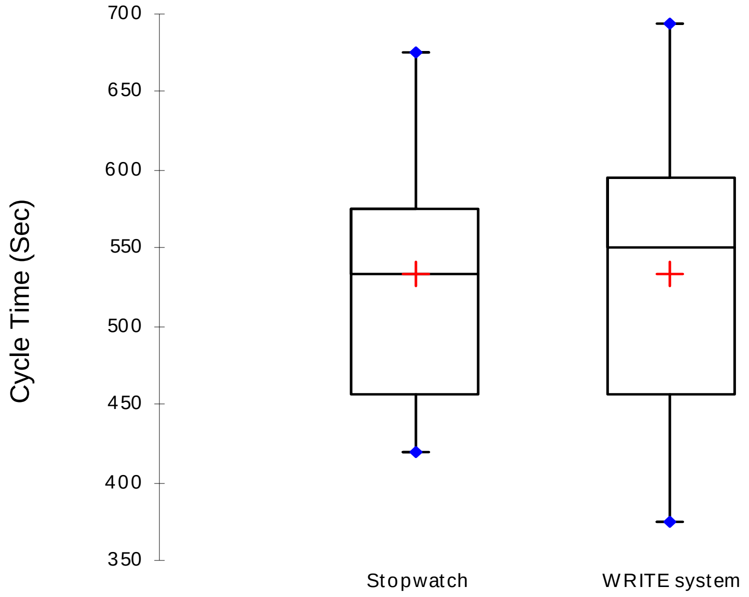


Figure 41. Box plots on cycle time

As shown in Table 21, summary statistics demonstrate overall data characteristics. Mean values for cycle time were nearly identical with respective standard deviations of 80.48 seconds for the stopwatch and 109.01 seconds for the WRITE System. The variance and the standard deviation show the magnitude of data dispersion. The skewness coefficient and kurtosis coefficient indicate the shape of the distribution of the sample. Based on the skewness and the kurtosis, cycle time data are concentrated on the right of the mean and the peak of the distribution is compressed lower than that of a normal distribution.

Table 21. Summary Statistics

Statistic	Stopwatch Method			WRITE Method		
	SN	SW	SC	WN	WW	WC
No. of observations	9.00	9.00	9.00	9.00	9.00	9.00
Minimum	80.00	120.00	420.00	145.00	126.00	374.00
Maximum	415.00	364.00	675.00	455.00	321.00	694.00
Range	335.00	244.00	255.00	310.00	195.00	320.00
1st Quartile	332.00	182.00	456.00	188.00	226.00	456.00
Median	336.00	223.00	533.00	334.00	229.00	551.00
3rd Quartile	351.00	255.00	575.00	368.00	239.00	595.00
SIQR	69.50	9.50	36.50	59.50	90.00	6.50
Sum	2736.00	2061.00	4806.00	2733.00	2067.00	4800.00
Mean	304.00	229.00	534.00	303.67	229.67	533.33
Variance (n-1)	10642.50	6625.25	6476.25	13182.75	2454.00	11882.50
Std.(n-1)	103.16	81.40	80.48	114.82	49.54	109.01
Skewness (Fisher)	-1.62	0.63	0.19	-0.38	-0.46	0.10
Kurtosis (Fisher)	2.21	-0.45	-0.37	-1.36	3.66	-1.12
Standard error	34.39	27.13	26.83	38.27	16.51	36.34

Abbreviations: SN (stopwatch nonworking time), SW (stopwatch working time), SC (stopwatch cycle time), WN (WRITE System nonworking time), WW (WRITE System working time), WC (WRITE System cycle time), Std. (standard deviation), SIQR (the semi-interquartile range)

5.4.1.2 Data Normality Test

In a paired t-test, an important assumption is that sample means, d_j, follow a normal distribution. Four normality tests (Shapiro-Wilk, Kolmogorov-Smirnov, Cramér-von Mises, and Anderson-Darling) were conducted to determine data normality. As shown in Table 22, the Shapiro-Wilk test statistic W is 0.950594, and the probability of a greater value of W, also referred to as a p-value, is 0.6966. Compared to the significance level of 5%, this probability indicates that differences of cycle time for the HMA overlay operation measured by the stopwatch and the WRITE System are normally distributed. Results of the Kolmogorov-Smirnov, Cramér-von Mises, and Anderson-Darling tests also indicated that data follow the normal distribution because respective p values of these three tests were 0.15, 0.25, and 0.25 greater than α value of 0.05. Therefore, it was concluded that the paired t-test could be conducted.

Table 22. Tests for normality on sample differences d_j

Test	Statistic		p Value
Shapiro-Wilk	W	0.950594	0.6966
Kolmogorov-Smirnov	D	0.187761	0.1500
Cramér-von Mises	W-Sq	0.049107	0.2500
Anderson-Darling	A-Sq	0.290162	0.2500

5.4.1.3 Paired t-test

Since two data values in a pair are not statistically independent, and pairs of data values are independent in the sample groups, the paired t-test was selected as the test method. This test is usually used to compare before and after treatments, or two different treatments used at the same time, where two data sets are sampled from the same population. Hence, the paired t-test does not follow the assumption of the independent sample t-test that two samples should be either independent or the same in standard deviations. In the paired t-test, differences between two samples, d_j, are statistically independent and normally distributed. This is also a case of a randomized complete block design (RCBD) (Mason et al. 2003).

5.4.1.3.1 Testing Hypotheses

Productivity data from two time study methods on the asphalt overlay project were compared to determine whether these two groups were sampled from the same population. The null hypothesis and alternative hypothesis for this analysis are as follows:

$$\begin{aligned} H_0 &: \ \mu_d = 0 \\ H_1 &: \ \mu_d \neq 0 \end{aligned} \qquad (5.1)$$

where $\mu_d = \mu_1 - \mu_2$; μ_1 and μ_2 are means of cycle time measured by the stopwatch and the WRITE System, respectively.

5.4.1.3.2 Data Analysis Results

In the hypothesis test, μ_1 and μ_2 represent means of cycle time for the HMA overlay project measured by the stopwatch and the WRITE System, respectively. Cycle time is the sum of working time (applying hot mix asphalt to the desired width and thickness) and nonworking time (idle or waiting) of asphalt paving. The standard deviation s_d is equal to 90.807 seconds, as shown in Table 23. $\bar{d} = 0.667$ and $t_{(0.025,8)} = 2.306$ were estimated by using Equation 3.18 in Section 3.3.6.

$$t\ statistic = \frac{\bar{d}\text{ - }0}{s_d / \sqrt{n}} = \frac{0.667}{90.807/\sqrt{9}} = 0.022$$

Using the two-tail t test, the null hypothesis cannot be rejected at the significance level of 5% ($|t| = 0.022$ < $t_{(0.025,\,8)} = 2.306$). This result indicates that statistically there is no difference between productivity measurements taken by the WRITE System and using a stopwatch.

Table 23. Results of Paired t-test

Difference	DF	Std. Deviation	Std. Error	t value	$t_{critical}$	Pr > |t|
Cycle Time	8	90.807	30.269	0.022	2.306	0.9830

Table 24 shows that the 95% confidence limit of $\mu_d (\mu_1 - \mu_2)$ is $-69.134 < \mu_d < 70.467$. Because this confidence limit includes zero, the author can infer that the equality of the means cannot be rejected. Confidence limits of standard deviation and variances are also included in Table 24.

Table 24. 95% Confidence Limits for μ_d

Parameter	Estimate	95% Confidence Limits	
Mean	0.667	-69.134	70.467
Std Deviation	90.807	61.337	173.966
Variance	8246	3762	30264

5.4.1.4 Comparing Variability for Two Productivity Measurement Methods

To compare variances of paired measurements, the concept of linear correlation was used because two sample standard deviations were not statistically independent nor were they linearly correlated. The sums and differences of the pairs are linearly correlated if the standard deviations are not equal (Bradley and Blackwood 1989). Figure 42 shows differences and sums between two cycle time measurements. The statistical significance of the sample correlation was assessed using a t-statistic that tested the following hypothesis: $H_0 : \rho = 0 \; vs \; H_a : \rho \neq 0$, where ρ is the correlation coefficient for a population of pairs. The t-statistic for the two measurements was t = -0.998, as shown in the calculation below.

$$t = \frac{r(n-2)^{1/2}}{(1-r^2)^{1/2}} = \frac{-0.353(9-2)^{1/2}}{(1-0.353^2)^{1/2}} = -0.998$$

where the Pearson correlation coefficient *r* was –0.353.

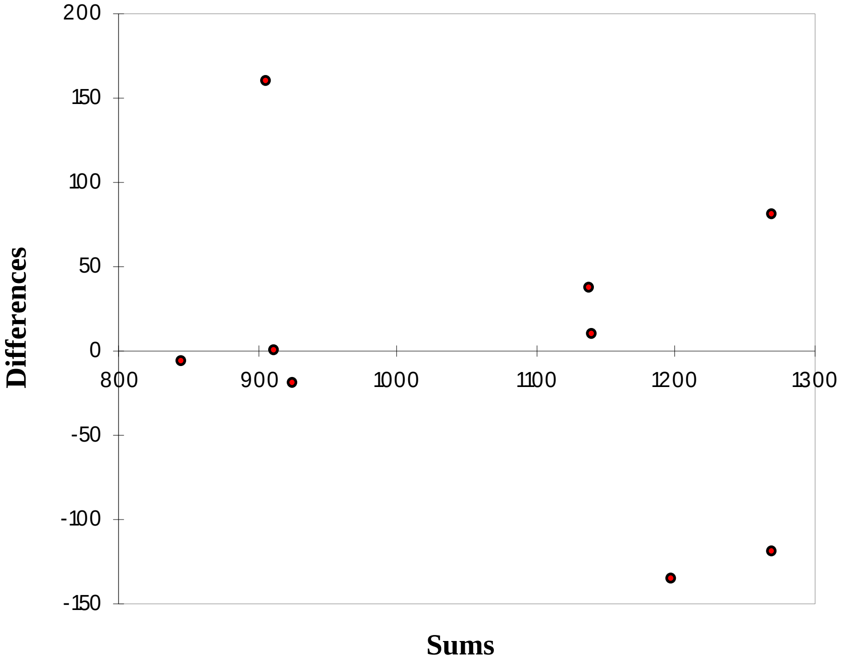


Figure 42. Differences and sums of two cycle time measurements

Using a two-tail t test, the null hypothesis cannot be rejected at the significant level of 5% ($|t| = 0.998 < t_{(0.025,\,7)} = 2.365$). This result indicated that statistically there was no difference between standard deviations of the productivity measurements taken by the WRITE System and the stopwatch.

5.4.2 Data Analysis on the HIR Operations

5.4.2.1 Box Plots and Summary Statistics

In Figure 43, a box plot presents working time, nonworking time, and time difference based on data from two HIR projects in Winchester and Tonganoxie in Kansas. The box plot displays a significant characteristic of the HIR operation, namely that working time (WS and WW) was much more than nonworking time (NS and NW). Working time measured using the stopwatch (WS) and the WRITE System (WW) were nearly identical in Q_1, mean, Q_3, and variability.

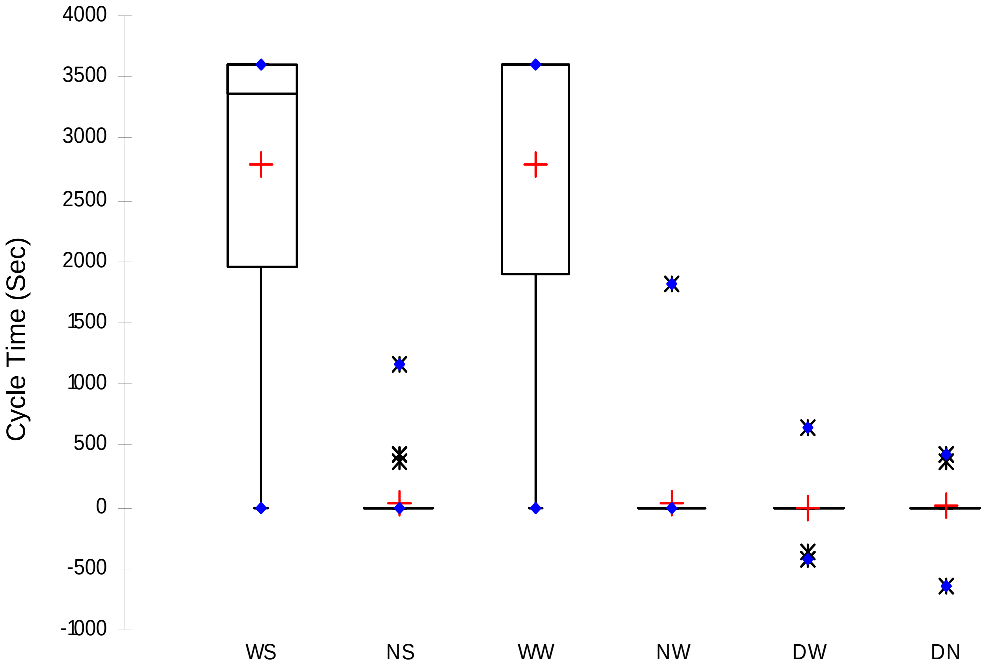


Figure 43. Box plots for HIR operation cycle time

Note: WS (working time using stopwatch), NS (nonworking time using stopwatch), WW (working time using WRITE System), NW (nonworking time using WRITE System), DW (difference in working time), DN (difference in nonworking time)

As shown in Table 25, summary statistics demonstrate overall data characteristics. For working time, the mean values were nearly identical to each other with respective standard deviations of 1,094.39 and 1,112.41. Skewness and Kurtosis tests were conducted to obtain information on the shape of distributions of samples. The distributions were concentrated on the left of the mean because the skewness values of WS and WW were negative. The distributions were more peaked than a normal distribution, because the kurtosis values for WS and WW were positive.

Table 25. Summary Statistics

Statistic	Stopwatch Method		WRITE Method		Differences	
	WS	NS	WW	NW	DW	DN
No. of observations	60.00	60.00	60.00	60.00	60.00	60.00
Minimum	0.00	0.00	0.00	0.00	-420.00	-651.00
Maximum	3600.00	1159.00	3600.00	1810.00	651.00	420.00
Range	3600.00	1159.00	3600.00	1810.00	1071.00	1071.00
1st Quartile	1965.00	0.00	1890.00	0.00	0.00	0.00
Median	3360.00	0.00	3600.00	0.00	0.00	0.00
3rd Quartile	3600.00	0.00	3600.00	0.00	0.00	0.00
Sum	166803.00	2359.00	167352.00	1810.00	-549.00	549.00
Mean	2780.05	39.32	2789.20	30.17	-9.15	9.15
Variance (n-1)	1197689.57	29371.75	1237447.21	54601.67	15274.20	15274.20
Standard deviation (n-1)	1094.39	171.38	1112.41	233.67	123.59	123.59
Skewness (Fisher)	-1.17	5.38	-1.13	7.75	0.98	-0.98
Kurtosis (Fisher)	0.15	32.17	0.01	60.00	17.92	17.92
Standard error of the mean	141.29	22.13	143.61	30.17	15.96	15.96

Note: WS (working time using stopwatch), NS (nonworking time using stopwatch), WW (working time using WRITE System), NW (nonworking time using WRITE System), DW (difference in working time), DN (difference in nonworking time),.

5.4.2.2 Normality Tests for the HIR Projects

As shown in Table 26, the Shapiro-Wilk test statistic W is 0.251294, and the probability of a greater value of W is 0.0001. Compared to the significance level of 5%, this probability indicated that differences of cycle time for the HMA overlay operation measured by the stopwatch and the WRITE System are normally distributed. Results of the Kolmogorov-Smirnov, Cramér-von Mises, and Anderson-Darling tests also indicated that data follow the normal distribution because respective p values of these three tests were 0.0001, 0.005, and 0.005 all of which are smaller than α value of 0.05. Therefore, it was concluded that the nonparametric test such as the signed rank test could be conducted.

Table 26. Tests for Normality on DW and DN

Test	Statistic		p Value
Shapiro-Wilk	W	0.251294	0.0001
Kolmogorov-Smirnov	D	0.535574	0.0100
Cramér-von Mises	W-Sq	4.375992	0.0050
Anderson-Darling	A-Sq	20.81394	0.0050

5.4.2.3 Wilcoxon Signed-Rank Test

A nonparametric test, the Wilcoxon signed rank test, was utilized as an alternative to the paired t test because the paired measurements for a random sample from the HIR operation did not follow normal distribution. The test produced a test statistic for the null hypothesis that the median of the paired sample differences was equal to a given value $\mu_d = 0$ against the alternative hypothesis that it is not equal to

$\mu_d = 0$. As shown in Table 27, the test accepted the null hypothesis at the significance level of 5% as the computed p-value of 0.25 was greater than α value of 0.05. The result indicated that there was no statistically significant difference in the medians and distributions of two samples, namely, the working time measured using the stopwatch and the WRITE System.

Table 27. Result of the Wilcoxon Signed-Rank Test

Test	**Statistic**		**p Value**
Signed-Rank	S	-4	0.250

Note: S (Signed-Rank Statistic)

CHAPTER 6:TESTING THE WRITE SYSTEM FOR BRIDGE CONSTRUCTION OPERATIONS

6.1 Introduction

Bridge construction is more labor-intensive than highway construction. After experiments on highway construction projects, the author conducted additional field experiments on a bridge construction project to determine the accuracy of the WRITE System. Data collected from the WRITE System were compared with data collected from the stopwatch method. Through comparison, the author could determine if the WRITE System is as accurate as the classical method. If the WRITE System produced accurate results, then a conclusion can be reached; that is, the developed system can be used to measure labor productivity in lieu of the stopwatch method.

During the field experiment, productivity data were collected using the WRITE System and a stopwatch simultaneously at a bridge construction site. Then the data collected using the WRITE System was compared with data collected using the stopwatch method in order to determine the accuracy of this system. Several statistical techniques were utilized to conduct analyses including normality test, Box-Cox transformation, and Wilcoxon Signed Rank Test.

6.2 Prestressed Girder Bridge Construction

A steel girder bridge reconstruction project over Interstate 70 in Lawrence, Kansas, was selected because steel girder bridges are the most common short span bridges in the U.S. They feature long lasting structures, easy construction, and economical cost (Barker and Puckett 1997b). The Kansas Turnpike Authority (KTA) awarded this 327.8 feet (100 meter) bridge reconstruction project to a contractor for the total price of $1.9 million, and the period of construction was about four months from February to June in 2008. Productivity data were collected for two months from March 24 to May 23 in 2008.

6.2.1 Work Breakdown Structure (WBS) for Prestressed Girder Bridge Construction

The work breakdown structure (WBS) has been widely used to manage the project. WBS is defined as "a deliverable-oriented grouping of project elements," which organizes and defines the hierarchical structure of the entire project (Jung and Woo 2004). It is often used in the complex construction projects to identify project information and improve the efficiency of control processes (Chua and Godinot 2006). WBS is also used for integrating the project cost and the project schedule to better manage these two functions. A WBS shows the relationship of all elements of a project in different levels and makes all elements more manageable and measurable. The number of levels depends on the size and complexity of the projects (U.S. Department of Energy 1997). Prior to this field experiment, the bridge reconstruction project was broken down into four levels including Level 1 (project), Level 2 (work zone), Level 3 (activity), and Level 4 (operation). Examples of the levels of steel girder bridge WBS are shown in Table 28. With the WBS, it was possible for the author to measure on-site construction productivity at the operational level.

Table 28. Examples of WBS for Steel Girder Bridge Reconstruction

LEVEL 1 (Project)	LEVEL 2 (Work Zone)	LEVEL 3 (Activity)	LEVEL 4 (Operation)
Steel Girder Bridge	General Abutment Pier 1 Pier 2 Pier 3 North side South side Span 1 Span 2 Span 3 Span 4	Mobilization Traffic Control Demolition Excavation Abutment 1 Abutment 2 Pier Drill Shafts Pier Columns Pier Cap Slope protection Beam Setting Deck Forming Reinforcing Deck Bridge Barrier Rail Concrete Barrier Backfill Abutments Approach road	Set up Crane Moving concrete safety barrier Driving pile Forming Structural excavation Slope protection (filter fabric and rock) Set bearing devices Unload beams Set beams Install diaphragms Bolting and tightening splice Ground splice Prepare deck material Prepare deck forming Overhangs Strip Place backwall (strip drain & backfill) Tying rebar Pouring and curing Strip and check elevation Others

6.3 Data Collection using the WRITE System and Stopwatch

Two different data collection methods were employed: the stopwatch method (shown in Figure 37) and the WRITE System method (shown in Figure 44). The stopwatch method was used to measure the cycle times of a construction operation (bolting), and the results were immediately recorded onto the data collection form at the job site. Simultaneously, the WRITE System recorded the cycle times of the same operation in video pictures. Then the author converted picture data to time study data.

Figure 44. Time study using the WRITE System

The author measured the cycle times of a randomly selected laborer in a bridge beam setting operation, called bolting, from March 24 to 26 in 2008. Working time and nonworking time of the laborer were measured and recorded using a measurement unit of seconds per five minutes. Working time in the operation was defined as the period during which the laborer was productive, such as installing and tightening bolts; while nonworking time was considered the period during which the laborer was not productive, such as waiting for materials or receiving instructions.

6.4 Data Analysis

A three-step approach was employed for the data analyses using SAS®. First, tests were performed to determine whether data had a normal distribution, since data normality was a required assumption for the hypothesis test. Second, if data didn't have normality, the author would try to transform the data into normal distribution using the Box-Cox transformation method. Third, after the transformation, if the data had a normal distribution, a paired t-test would be conducted as a parametric test to compare the two productivity measurement methods. Otherwise, the Wilcoxon Signed Rank test would be carried out. Table 29 shows the measurement data used for analysis. Three pictures, as shown in Figures 45, 46, and 47, present the bolting operations in this bridge reconstruction project.

Table 29. Description of Measurement Data

Measurement Method (1)	WBS Level (2)	Measurement Units (3)	No. of Cycle (4)
WRITE System	Bolting Operation (Labor Cycle Time)	Seconds per five minutes	231
Stopwatch Method	Bolting Operation (Labor Cycle Time)	Seconds per five minutes	231

Figure 45. Bolting Operation on the Edge Span

Figure 46. Bolting Operation on the Middle Span

Figure 47. Bolting Operation using Jumbo Lift

6.4.1 Statistical Comparison

6.4.1.1 Normality Tests

Two normality tests, the Anderson-Darling test and the Shapiro Wilk test, were conducted to determine if the experimental data follow a normal distribution. As shown in columns (4) and (5) of Table 30, all computed p values were lower than the significance level of 5%. Thus, the null hypothesis that measurements follow a normal distribution was rejected at the significance level of 5%. This means that at this significance level, working time and nonworking time measured by the stopwatch and the WRITE System were not normally distributed. Thus, the author tried the

Box-Cox transformation method to transform the data into a normal distribution. As shown in columns (6) and (7) of Table 31, p values for labor cycle time were lower than the significance level of 5%. This result meant that the experimental data didn't have normality even after the transformation. Therefore, it was concluded that a nonparametric test, the Wilcoxon Signed Rank Test, was needed to analyze the data.

Table 30. p values on Normality Test

Variable (1)	**Data before Transformation (2)**		**Data after Transformation (3)**	
	Stopwatch Method (4)	**WRITE System (5)**	**Stopwatch Method (6)**	**WRITE System (7)**
Bolting Operation (Labor Cycle Time)	<0.0001	<0.0001	<0.0001	<0.0001

6.4.1.2 Wilcoxon Signed-Rank Test

Productivity data measured by the WRITE System were compared with the data measured by the stopwatch method for the bridge reconstruction project. The null hypothesis and alternative hypothesis for this analysis are as follows:

$$\begin{aligned} H_0 &: \ \mu_d = 0 \\ H_1 &: \ \mu_d \neq 0 \end{aligned} \tag{6.1}$$

where μ_d is the mean difference of data measured by stopwatch method and the WRITE System. As shown in Table 31, test results indicated that the null hypothesis was accepted at the significance level of 5%, because the computed p-value of 0.571

was greater than the value of 0.05. Thus, statistically, there was no difference in the means of the two productivity measurements collected using the stopwatch method and the WRITE System. In other words, statistically speaking, working time and non working time for bolting, as measured by the stopwatch and the WRITE System, was identical.

Table 31. Results of the Wilcoxon Signed-Rank Test

Variable (1)	Test (2)	Degree of Freedom (3)	Statistic (4)	p-value (Two-tailed) (5)
Bolting Operation (Labor Cycle Time)	Signed-rank	230	21.5	0.571

CHAPTER 7:DATA ANALYSIS FOR PRODUCTIVITY IMPROVEMENTS USING THE WRITE SYSTEM

7.1 Introduction

In the previous chapters, the results of data analyses proved the feasibility using the WRITE System as an alternative to the classic time study method to measure on-site construction productivity. This chapter presents how the collected data using the WRITE System can be utilized so that construction project managers or engineers can identify how the work is currently being done at the job sites and take immediate action for construction productivity improvements. In the following subchapters, the working time and nonworking time for bridge operations were identified first. Then, a survey was conducted to obtain professional intuitions about rates of working time and nonworking time for bridge operations. Finally, the author compared the data from the survey with data collected from the WRITE System and proposed a method for improving on-site construction productivity.

7.2 Working and Nonworking Time

Working hours, or total time (TT) includes the actual working time (WT) and nonworking time (NWT). Working time is the sum of direct work and supportive work, while nonworking time generates zero output. Supportive or contributory work is included in the working time; however, it does generate output lower than baseline productivity because it is composed of various situations or factors that affect productivity loss. Such factors are a lack of materials, a waiting period for preceding work done by other crews, severe weather conditions, and congested areas (Choy and Ruwanpura 2006). McTague and Jergeas (2003) and Dozzi and AbouRizk (1993) presented actual working time of construction workers at 56% in nuclear plant construction projects, meaning that nonworking time was 44% (Hewage and Ruwanpura 2006). Christian and Hachey (1995) studied concrete-placement operations, and the finding was 61% working time and 39% nonworking time. According to the previous research projects, the ratio of working time and nonworking time is approximately 50:50 or 60:40. To date, approximate working time and nonworking time have been previously studied; however, there is no consensus in the construction industry, because construction projects have different natures, such as different types of projects, activities, and operations.

Identifying the nonworking time in a certain operation is challenging, because there are many factors that affect construction productivity loss, and they are interrelated (Choy and Ruwanpura 2006). A recent research project conducted by Hewage and Ruwanpura focused on critical human factors in construction productivity by observing, interviewing, and surveying 101 carpentry workers. Their research project recommended the following factors that can improve productivity, including improvements of on-site communication between construction managers, changes in learning new working methods, proper supervision of field workers, as well as proper equipment and material utilization. Previous research projects have stated that there are too many influential factors on productivity loss based on situations of nonworking time, which in turn makes it too complicated and impractical to apply to any construction projects (Hewage and Ruwanpura 2006).

7.3 Benchmarking in Construction Productivity

Benchmarking has been used as a tool to improve productivity since it was first used by Robert C. Camp and his team at Xerox in the early 1980s. This strategy aims at continuous process improvements without quality loss (Jackson et al. 1994). The Construction Industry Institute (CII) has established construction productivity metrics and a reporting format for construction productivity benchmarking and improvement (Park et al. 2005). With development and comparison of benchmark databases with the data from individual projects, resource planning and progress tracking became possible in electrical and mechanical construction projects (Hanna 2003).

7.4 Identifying Working and Nonworking Time for Bridge Operation

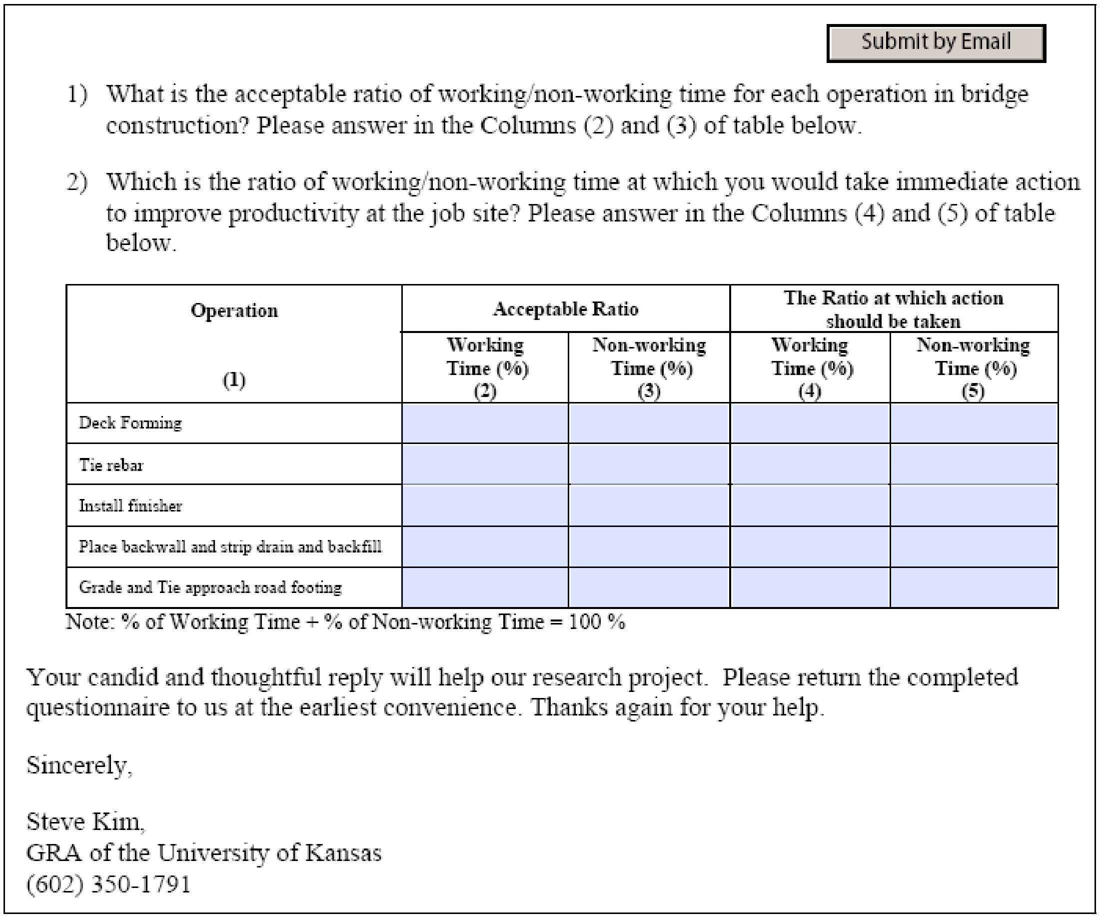
In this research, working time and nonworking time for five bridge operations were identified including deck forming, tying rebar, installing finisher, backfilling, and placing approach road footing, as shown in Table 32. A total of 66 work hours of tapes video were selected and investigated to determine the rates for the five bridge operations. These videos were all taken zoomed-in, so that the author could identify the working and nonworking time for each operation. The rate of working and nonworking time was 86% and 14% on average. The only operation which had lower working time than the average rate was the installing finisher, because the crew size on the operation was much larger than the other operations, which ended up causing more nonworking time.

Table 32. Ratio of Working and Nonworking Time determined by the WRITE System

Operation	Time (Second)		Percent	
	Working Time	Nonworking Time	Working Time	Nonworking Time
Deck forming	24,720	2,160	92%	8%
Tie rebar	40,320	5,880	87%	13%
Installing finisher	71,230	21,100	77%	23%
Place backwall and strip drain and backfill	44,850	1,950	96%	4%
Grade and tie approach road footing	21,275	2,725	89%	11%
Total	202,395	33,815	86%	14%

7.5 Construction Productivity Improvements using the WRITE System

An email survey was developed and distributed to two bridge contractors in Kansas. This benchmarking survey was conducted to identify the ratio between working and nonworking time for several operations in the real-world bridge construction. As shown in Figure 48, the form was designed to immediately collect data by using PDF (Portable Document Format) Professional 8.0. The five operations in the survey form were the same as in Table 32.



1) What is the acceptable ratio of working/non-working time for each operation in bridge construction? Please answer in the Columns (2) and (3) of table below.
2) Which is the ratio of working/non-working time at which you would take immediate action to improve productivity at the job site? Please answer in the Columns (4) and (5) of table below.

Operation (1)	Acceptable Ratio		The Ratio at which action should be taken	
	Working Time (%) (2)	Non-working Time (%) (3)	Working Time (%) (4)	Non-working Time (%) (5)
Deck Forming				
Tie rebar				
Install finisher				
Place backwall and strip drain and backfill				
Grade and Tie approach road footing				

Note: % of Working Time + % of Non-working Time = 100 %

Your candid and thoughtful reply will help our research project. Please return the completed questionnaire to us at the earliest convenience. Thanks again for your help.

Sincerely,

Steve Kim,
GRA of the University of Kansas
(602) 350-1791

Figure 48. Survey Form for the Benchmarking Study

Two questions were given to four construction professionals (as shown in Table 33) involved in the steel girder bridge reconstruction project over Interstate 70 in Lawrence, KS, where the WRITE System was employed. The participants were asked to identify an acceptable ratio and the ratio at which action should be initiated.

Table 33. Bridge Construction Contractors Surveyed

Name	Company	Construction Specialty	Position
Ken Johnson	BRB contractors, Inc.	Bridge	Project Manager
Mike Laird	BRB contractors, Inc.	Bridge and Plant	Project Manager
Ray Rinne	A.M. Cohron & Son, Inc.	Bridge	Superintendent
Christopher J. Rech	A.M. Cohron & Son, Inc.	Bridge	Project Manager

Table 34 shows acceptable ratios provided by four survey participants. The overall average ratio for WT was 81% and overall average ratio for NWT was 19%. Tying rebar had the highest nonworking ratio of 21%, while deck forming had the lowest rate of 16%. Based on the result of the survey, these participants were willing to accept the working time ratio of at least 79%.

Table 34. Acceptable Ratio

Operation	**BRB 1**		**BRB 2**		**A & M Cohron 1**		**A & M Cohron 2**		**Average**	
	WT (%)	**NWT (%)**	**WT (%)**	**NWT (%)**	**WT (%)**	**NWT (%)**	**WT (%)**	**NWT (%)**	**WT (%)**	**NWT (%)**
Deck forming	85	15	80	20	85	15	85	15	84	16
Tie rebar	80	20	75	25	80	20	80	20	**79**	21
Install finisher	85	15	75	25	85	15	85	15	82	18
Place backwall and strip drain and backfill	70	30	80	20	85	15	85	15	80	20
Grade and tie approach road footing	80	20	80	20	85	15	85	15	82	18
Average	80	20	78	22	84	16	84	16	**81**	**19**

Table 35 shows ratios at which action should be initiated by project managers or engineers to improve on-site construction productivity. The overall average ratio for WT was 75% and overall average for NWT was 25%. Tying rebar had the highest nonworking time rate of 28%, while deck forming had the lowest rate of 23%. Based on the result of the survey, participants may have to take action if the working time ratio falls under 72%.

Table 36 presents the comparison results between survey and the WRITE System. In the case of the installing finisher, the nonworking ratio of 24% was equal to the ratio at which action should be initiated by construction management, as indicated by the participants. The rest of operations had more working time ratios than the minimum required working ratios.

Table 35. Ratio at Which Action Should be Taken

Operation	BRB 1		BRB 2		A & M Cohron 1		A & M Cohron 2		Average	
	WT (%)	NWT (%)	WT (%)	NWT (%)	WT (%)	NWT (%)	WT (%)	NWT (%)	WT (%)	NWT (%)
Deck Forming	75	25	75	25	80	20	80	20	77	23
Tie rebar	70	30	70	30	75	25	75	25	**72**	28
Install finisher	75	25	70	30	80	20	80	20	76	24
Place backwall and strip drain and backfill	60	40	75	25	80	20	80	20	74	26
Grade and tie approach road footing	70	30	75	25	80	20	80	20	76	24
Average	70	30	73	27	79	21	79	21	**75**	**25**

Table 36. Comparing Figures from the WRITE and the Industry Benchmarks

Operation	Acceptable Ratio		Ratio at which action should be taken		WRITE System	
	WT (%)	NWT (%)	WT (%)	NWT (%)	WT (%)	NWT (%)
Decking Forming	84	16	77	23	92	8
Tie rebar	79	21	72	28	87	13
Install finisher	82	18	76	24	76	24
Place backwall and strip drain and backfill	80	20	74	26	96	4
Grade and tie approach road footing	82	18	76	24	89	11
Average	81	19	75	25	88	12

By using the rates from the WRITE System, project managers or engineers can take actions for improving on-site construction productivity in real-time. As shown in Table 37, if the ratio measured by the WRITE System is higher than the acceptable ratio, then, no action is required. If the ratio is between acceptable ratios and ratios at which action should be initiated, then management needs to be aware that an action may be needed in the near future. If the ratios are lower than the minimum required rate, then they need to take actions immediately, determining whether or not the crew size should be increased or decreased, or whether or not more equipment should be employed.

Table 37. Making Management Decisions Using the WRITE System

Ratios from the WRITE System	Action
Higher than acceptable ratios	No action needed
Between acceptable ratios and ratios at which action should be taken	Aware that action may be needed
Lower than ratios at which action should be taken	Action is required

With the information obtained so far, the author developed a flow chart for improving on-site construction productivity using the WRITE System, shown in Figure 49. In the flow chart, the first task is to collect pictorial data using the WRITE System. The second task is to determine real-time productivity data which is the ratio between working and nonworking time. The third task is to compare the productivity data with the benchmark data based on a survey or historical information. The comparison is divided into two stages in which management will answer two questions and make decisions accordingly. The first question is whether the real-time data is higher than the benchmark data at which action should be taken. If the answer for the first question is no, management needs to take actions immediately to improve the on-site productivity. Management should identify the reasons that result the low productivity at the project site and initiate actions for improvements. If the answer for the first question is yes, management goes to the next stage to compare the real-time data with the acceptable benchmark data. If the real-time data is higher than the acceptable benchmark data, no action is needed. Otherwise, management needs to be aware that an action may be needed in the near future and close monitoring is necessary at the project site. The developed procedure can be executed for the entire period of construction or for the segments of construction.

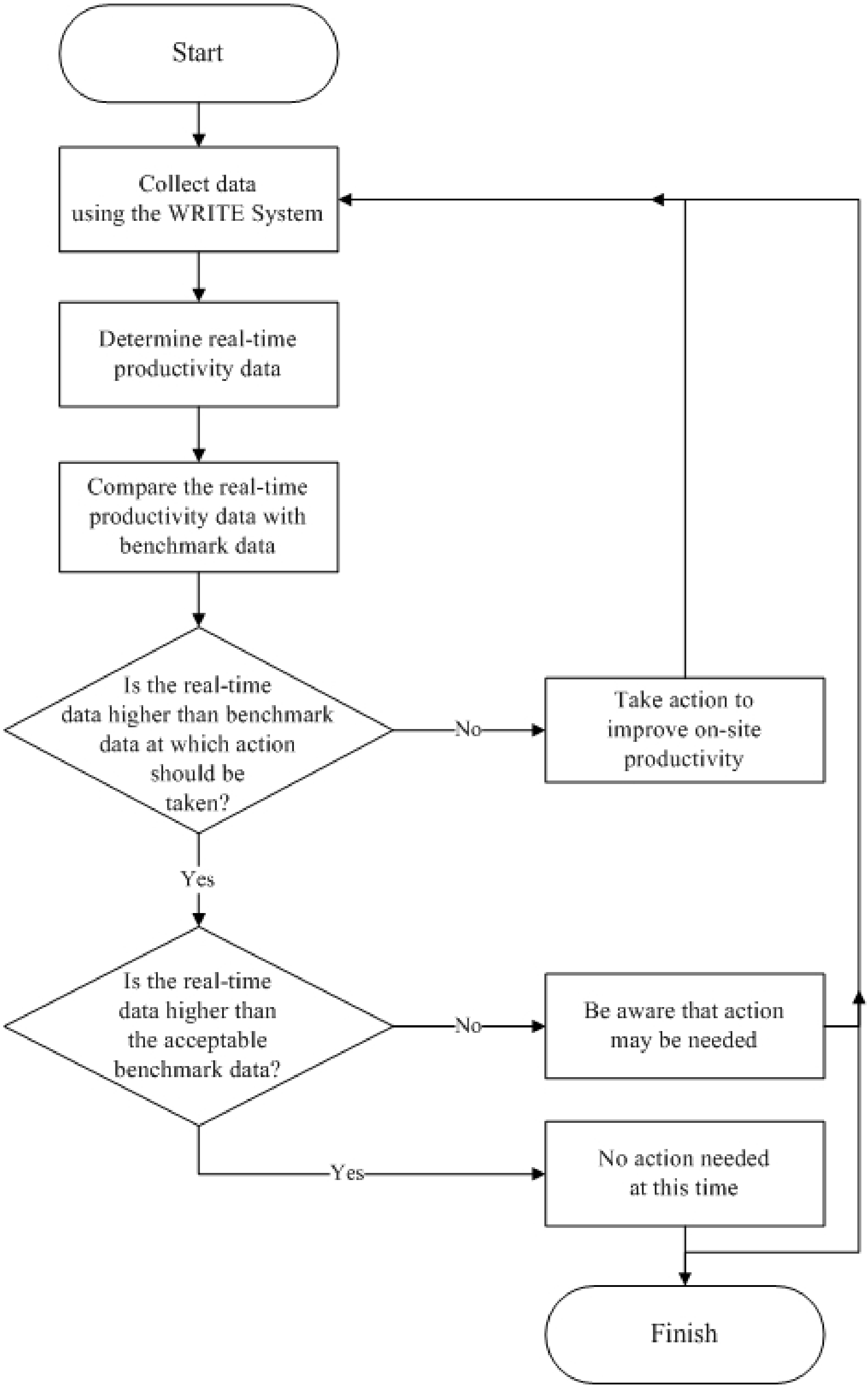


Figure 49. Procedures using the WRITE System for Productivity Improvements

CHAPTER 8: CONCLUSIONS AND RECOMMENDATIONS

8.1 Summary

Since the terrorist attacks on September 11, 2001, several research projects have been conducted on the rapid replacement of damaged infrastructure. The research results indicate that there are challenges for construction managers and engineers in producing reliable schedules for rapid replacement operations. Using existing construction productivity measurement methods takes significant time to transmit data and poses difficulties for sharing and communicating data among participants involved in construction operations. To address these shortfalls, the WRITE System has been developed using advanced technologies. The technology underneath the system is the integration of wireless technology and time-lapse filming.

The primary goal of this research was to develop the WRITE System that is assembled using advanced techniques to transfer real-time productivity data from construction sites to home offices for analysis. To achieve this goal, the author has conducted the following tasks including: 1) reviewing the literature; 2) identifying the key components of the WRITE System and their connections; 3) designing the field experiment; 4) conducting field experiments including data collection and analysis; and 5) benchmarking a study using the WRITE System for improving on-site construction productivity.

144 publications in the areas of rapid bridge and highway replacement, construction productivity measurements and analyses, and statistical theories were

reviewed. The results of the literature review indicate that no quantitative research projects have been conducted on rapid bridge and highway replacement in terms of on-site productivity measurement. In addition, there have not been any studies on statistically evaluating productivity measurement systems for rapid bridge or highway replacement.

The second task of the research project was to develop the WRITE System, which is an advanced on-site construction productivity measurement tool using wireless technologies. The specific steps for this task were to identify the system components, to establish the system framework, and to build the system in the lab.

After the author built the WRITE System in the lab, field experiments were design and conducted to determine its feasibility and accuracy as a productivity measurement tool. In the summer of 2007, preliminary field experiments and data analyses on three highway construction projects (HMA paving and HIR) were conducted to measure real-time productivity for equipment-intensive construction. The developed system was compared with the classic productivity measurement method using a stopwatch. Additional field experiments on a bridge construction project near Lawrence, KS were conducted to determine whether the WRITE System can be used to measure real-time productivity for this labor-intensive construction. Statistical methods were used to design the field experiments and to conduct data analyses. Results of the statistical analyses indicate that the WRITE System produced accurate productivity measurements on the three highway projects and one bridge project.

In the bridge construction project, the author also studied on-site construction productivity improvements using the WRITE System and a benchmarking technique. The benchmarking of five bridge construction operations was established through a survey of construction professionals in the bridge construction business. A real-time model for improving the on-site construction productivity was proposed by constantly comparing the productivity data from the WRITE System with the benchmarking. If the productivity data from the WRITE System is lower than the benchmarking, then, the project managers or engineers can take action immediately.

8.2 Conclusions

This research has produced several conclusions. They are as follows.

1. The WRITE System can be used as an alternative tool to measure the on-site construction productivity. Construction productivity measured by the WRITE System and the stopwatch method were scientifically compared and the results indicated that the paired data are statistically identical.
2. Results of the field experiments enabled the author to conclude that the WRITE System can be used in an equipment-intensive highway construction project and a labor-intensive bridge construction project.
3. Due to the fact that the developed WRITE System is capable of continuously collecting and transporting the on-site construction productivity data, construction managers and engineers now have a new technology to determine the on-site construction productivity in real-time.

4. Productivity data gathered by the WRITE System can be sent to a website so that owners, engineers, contractors, and material suppliers can share data and make necessary actions in remote locations as long as they have the Internet service at these locations.
5. Integrating the benchmarking technique and the WRITE System makes it possible for the construction managers and engineers to continuously improve the on-site construction productivity in real-time.
6. With advancements made by utilizing the WRITE System, communication and coordination will be improved at the construction project sites. Thus, the developed system will enhance the contractors' capability of managing construction projects.

The WRITE System in its current form has some limitations. First, it is difficult or impossible to cover the entire construction site using only one camera housing, particularly if the site is very large. Second, the images may not be clear enough for human eyes to distinguish types of construction operations. Third, even if the images are clear, there is still a possibility for a person to misinterpret the construction operations. Fourth, identifying the work quantity still remains laborious because it depends on human beings. Fifth, currently no database has been established for real-time productivity data improvement using the WRITE System and benchmarking data. There is no standard process for management to increase or decrease the crew size during the construction. To overcome these limitations, further research is needed.

8.3 Research Contributions

This research project made several major contributions to the advancement of knowledge in the construction industry. First, it advances the applications of wireless technologies in construction operations. Second, the developed WRITE System is capable of continuously collecting and transporting the on-site construction productivity data so that engineers and project managers can determine productivity in real-time. Third, productivity data gathered by the WRITE System can be sent to a website so that owners, engineers, contractors, and material suppliers are able to share data and make necessary actions in real-time as long as they have Internet access at their locations. With these advancements, communication and coordination are improved at the construction site. Thus, using the WRITE System will enhance the contractors' capability of managing construction projects.

8.4 Recommendations

This research project can be extended in several ways. First, the developed WRITE System was only tested in a few highway construction operations and a bridge construction operation due to resource constraints. If more resources are available in the future, the System should be tested in additional operations/projects. Second, because the process of determining working status with the live images obtained from the WRITE System is time-consuming and subject to human error and bias, there is a need to develop an algorithm to automatically classify working or non-working actions based on human poses that are associated with construction activities so that misinterpretation can be reduced. Third, it is necessary to install several cameras at different locations in order to cover the entire project site. Thus, with additional cameras, there is a need to develop a user interface and algorithms that can be used to collect, store, retrieve, manipulate, transform, and display the data that are sent by the different cameras. Fourth, using the WRITE System, it may be possible to identify resources in construction job sites and integrate the information with the project management database system. Fifth, the developed WRITE System may be able to measure the quantity of lost productivity during the construction operations, which is beyond the current capabilities of the construction industry. Sixth, information on the standard working ratio between working and nonworking time can be stored in databases for future benchmark study. Seventh, validating and modifying the procedures for improving productivity using the WRITE System need to be performed in future research. Finally, there is a need to quantify costs and benefits for the use of the WRITE System for construction projects.

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APPENDIX A: DATASETS

DATASET 1. Cycle Time Collected from the HMA Paving Project

No.	Waiting Time		Paving Time		Cycle Time	
	Write System	Stopwatch	Write System	Stopwatch	Write System	Stopwatch
1	188	188	238	232	426	420
2	334	333	217	255	551	588
3	339	352	226	223	565	575
4	368	332	227	343	595	675
5	145	351	229	182	374	533
6	422	349	244	182	666	531
7	455	415	239	160	694	575
8	152	80	321	364	473	453
9	330	336	126	120	456	456

DATASET 2. Cycle Time for HIR Projects Using Two Different Methods

No	Stopwatch		WRITE System		Difference	
	Working	Nonworking	Working	Nonworking	Working	Nonworking
1	3360	0	3360	0	0	0
2	2441	1159	2390	1210	51	-51
3	1320	0	1320	0	0	0
4	1800	0	1800	0	0	0
5	3600	0	3600	0	0	0
6	3600	0	3600	0	0	0
7	3600	0	3600	0	0	0
8	3180	420	3600	0	-420	420
9	3600	0	3600	0	0	0
10	2100	0	2100	0	0	0
11	2400	0	2400	0	0	0
12	3600	0	3600	0	0	0
13	840	0	840	0	0	0
14	1200	0	1200	0	0	0
15	1710	0	1710	0	0	0
16	3600	0	3600	0	0	0
17	3240	360	3600	0	-360	360
18	3600	0	3600	0	0	0
19	3600	0	3600	0	0	0
20	3600	0	3600	0	0	0
21	1800	0	1800	0	0	0
22	3180	420	3600	0	-420	420
23	3600	0	3600	0	0	0
24	3600	0	3600	0	0	0
25	1920	0	1920	0	0	0
26	1800	0	1800	0	0	0
27	3300	0	3300	0	0	0
28	1980	0	1980	0	0	0
29	180	0	180	0	0	0
30	3372	0	3372	0	0	0
31	3180	0	3180	0	0	0
32	3600	0	3600	0	0	0
33	3600	0	3600	0	0	0
34	3600	0	3600	0	0	0
35	1800	0	1800	0	0	0
36	3600	0	3600	0	0	0
37	3600	0	3600	0	0	0
38	3600	0	3600	0	0	0

39	3600	0	3600	0	0	0
40	150	0	150	0	0	0
41	3600	0	3600	0	0	0
42	3600	0	3600	0	0	0
43	3600	0	3600	0	0	0
44	3600	0	3600	0	0	0
45	720	0	720	0	0	0
46	2400	0	2400	0	0	0
47	3600	0	3600	0	0	0
48	3600	0	3600	0	0	0
49	3600	0	3600	0	0	0
50	2530	0	2530	0	0	0
51	3600	0	3600	0	0	0
52	1200	0	1200	0	0	0
53	300	0	300	0	0	0
54	3180	0	3180	0	0	0
55	3000	0	3000	0	0	0
56	3600	0	3600	0	0	0
57	420	0	420	0	0	0
58	2640	0	2640	0	0	0
59	3600	0	3600	0	0	0
60	3360	0	3360	0	0	0

DATASET 3. Cycle Time for the Bolting Operation Using Two Methods

No	Stopwatch		WRITE System		Difference	
	Working	Nonworking	Working	Nonworking	Working	Nonworking
1	300	0	300	0	0	0
2	300	0	300	0	0	0
3	300	0	300	0	0	0
4	300	0	300	0	0	0
5	300	0	300	0	0	0
6	300	0	300	0	0	0
7	300	0	300	0	0	0
8	300	0	250	50	50	-50
9	300	0	300	0	0	0
10	300	0	300	0	0	0
11	300	0	300	0	0	0
12	300	0	300	0	0	0
13	300	0	300	0	0	0
14	300	0	300	0	0	0
15	300	0	300	0	0	0
16	300	0	300	0	0	0
17	300	0	300	0	0	0
18	300	0	300	0	0	0
19	300	0	300	0	0	0
20	300	0	300	0	0	0
21	300	0	300	0	0	0
22	300	0	300	0	0	0
23	300	0	300	0	0	0
24	300	0	300	0	0	0
25	300	0	300	0	0	0
26	300	0	300	0	0	0
27	300	0	300	0	0	0
28	300	0	300	0	0	0
29	300	0	300	0	0	0
30	300	0	300	0	0	0
31	180	120	300	0	-120	120
32	240	60	0	300	240	-240
33	300	0	300	0	0	0
34	300	0	300	0	0	0
35	300	0	300	0	0	0
36	300	0	300	0	0	0
37	300	0	300	0	0	0
38	300	0	300	0	0	0

39	300	0	300	0	0	0
40	300	0	300	0	0	0
41	300	0	300	0	0	0
42	300	0	300	0	0	0
43	300	0	300	0	0	0
44	180	120	180	120	0	0
45	300	0	300	0	0	0
46	300	0	300	0	0	0
47	180	120	180	120	0	0
48	180	120	180	120	0	0
49	300	0	300	0	0	0
50	300	0	300	0	0	0
51	300	0	300	0	0	0
52	300	0	300	0	0	0
53	300	0	300	0	0	0
54	300	0	300	0	0	0
55	300	0	300	0	0	0
56	300	0	300	0	0	0
57	300	0	300	0	0	0
58	300	0	300	0	0	0
59	300	0	300	0	0	0
60	300	0	300	0	0	0
61	240	60	280	20	-40	40
62	300	0	300		0	0
63	300	0	240	60	60	-60
64	300	0	240	60	60	-60
65	300	0	300		0	0
66	60	240	240	60	-180	180
67	300	0	300	0	0	0
68	300	0	300	0	0	0
69	300	0	300	0	0	0
70	300	0	300	0	0	0
71	60	240	60	240	0	0
72	0	300	0	300	0	0
73	0	300	0	300	0	0
74	240	60	240	60	0	0
75	300	0	300	0	0	0
76	300	0	300	0	0	0
77	300	0	300	0	0	0
78	300	0	300	0	0	0
79	300	0	300	0	0	0
80	300	0	240	60	60	-60

81	300	0	300	0	0	0
82	300	0	300	0	0	0
83	300	0	300	0	0	0
84	300	0	300	0	0	0
85	300	0	300	0	0	0
86	300	0	300	0	0	0
87	60	240	60	240	0	0
88	300	0	300	0	0	0
89	300	0	300	0	0	0
90	300	0	300	0	0	0
91	60	240	60	240	0	0
92	0	300	0	300	0	0
93	240	60	300	0	-60	60
94	300	0	300	0	0	0
95	300	0	300	0	0	0
96	300	0	300	0	0	0
97	300	0	300	0	0	0
98	300	0	300	0	0	0
99	300	0	300	0	0	0
100	300	0	300	0	0	0
101	300	0	240	0	60	0
102	300	0	300	0	0	0
103	240	60	180	120	60	-60
104	300	0	300	0	0	0
105	300	0	300	0	0	0
106	300	0	300	0	0	0
107	300	0	300	0	0	0
108	300	0	300	0	0	0
109	300	0	300	0	0	0
110	300	0	300	0	0	0
111	300	0	300	0	0	0
112	300	0	300	0	0	0
113	300	0	300	0	0	0
114	300	0	300	0	0	0
115	300	0	300	0	0	0
116	300	0	300	0	0	0
117	300	0	300	0	0	0
118	300	0	300	0	0	0
119	300	0	300	0	0	0
120	300	0	300	0	0	0
121	120	180	120	180	0	0
122	0	300	0	300	0	0

123	60	240	80	220	-20	20
124	180	120	180	120	0	0
125	300	0	300		0	0
126	300	0	300		0	0
127	300	0	300		0	0
128	120	180	290	10	-170	170
129	0	300	0	300	0	0
130	300	0	300		0	0
131	300	0	300		0	0
132	300	0	120	180	180	-180
133	180	120	300	0	-120	120
134	300	0	300	0	0	0
135	300	0	60	240	240	-240
136	300	0	300	0	0	0
137	300	0	300	0	0	0
138	300	0	300	0	0	0
139	300	0	300	0	0	0
140	300	0	300	0	0	0
141	300	0	300	0	0	0
142	300	0	300	0	0	0
143	300	0	300	0	0	0
144	300	0	300	0	0	0
145	300	0	300	0	0	0
146	300	0	300	0	0	0
147	300	0	300	0	0	0
148	300	0	300	0	0	0
149	300	0	300	0	0	0
150	300	0	300	0	0	0
151	300	0	300	0	0	0
152	300	0	300	0	0	0
153	300	0	300	0	0	0
154	300	0	300	0	0	0
155	300	0	300	0	0	0
156	300	0	300	0	0	0
157	300	0	300	0	0	0
158	300	0	300	0	0	0
159	300	0	300	0	0	0
160	300	0	300	0	0	0
161	300	0	240	60	60	-60
162	300	0	300	0	0	0
163	300	0	300	0	0	0
164	300	0	300	0	0	0

165	300	0	300	0	0	0
166	300	0	300	0	0	0
167	300	0	300	0	0	0
168	300	0	240	60	60	-60
169	300	0	300		0	0
170	240	60	180	120	60	-60
171	0	300	150	150	-150	150
172	300	0	300	0	0	0
173	300	0	300	0	0	0
174	300	0	300	0	0	0
175	300	0	300	0	0	0
176	300	0	300	0	0	0
177	300	0	300	0	0	0
178	120	180	300	0	-180	180
179	300	0	290	10	10	-10
180	300	0	0	300	300	-300
181	300	0	300	0	0	0
182	300	0	300	0	0	0
183	60	240	60	240	0	0
184	0	300	0	300	0	0
185	120	180	120	180	0	0
186	175	125	180	120	-5	5
187	0	300	0	300	0	0
188	0	300	0	300	0	0
189	0	300	0	300	0	0
190	0	300	0	300	0	0
191	0	300	0	300	0	0
192	0	300	0	300	0	0
193	0	300	0	300	0	0
194	60	240	120	180	-60	60
195	300	0	300	0	0	0
196	300	0	300	0	0	0
197	300	0	300	0	0	0
198	300	0	300	0	0	0
199	300	0	300	0	0	0
200	0	300	0	300	0	0
201	0	300	0	300	0	0
202	300	0	300	0	0	0
203	300	0	300	0	0	0
204	300	0	300	0	0	0
205	300	0	300	0	0	0
206	300	0	300	0	0	0

207	300	0	300	0	0	0
208	0	300	0	300	0	0
209	0	300	0	300	0	0
210	0	300	0	300	0	0
211	0	300	0	300	0	0
212	0	300	0	300	0	0
213	0	300	0	300	0	0
214	0	300	0	300	0	0
215	0	300	0	300	0	0
216	0	300	0	300	0	0
217	0	300	0	300	0	0
218	0	300	0	300	0	0
219	0	300	0	300	0	0
220	0	300	0	300	0	0
221	0	300	0	300	0	0
222	0	300	0	300	0	0
223	0	300	0	300	0	0
224	0	300	0	300	0	0
225	0	300	0	300	0	0
226	0	300	0	300	0	0
227	0	300	0	300	0	0
228	0	300	0	300	0	0
229	0	300	0	300	0	0
230	0	300	0	300	0	0
231	0	300	0	300	0	0

APPENDIX B: PICTURES FROM THE BRIDGE CONSTRUCTION

Substructure Construction

Beam Setting

Deck Forming

Placing Rebar

Pouring Concrete

Approach Road Pouring

Barrier Rail Pouring