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COLLEGE OF ENGINEERING

Research Report, Part 1

ANALYSIS OF TRAFFIC IMPACTS FOR RAPID BRIDGE DECK REPLACEMENT PROJECTS

Submitted to

The Alabama Department of Transportation

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16. Abstract
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Research Supervisors

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ANALYSIS OF TRAFFIC IMPACTS FOR RAPID BRIDGE DECK REPLACEMENT PROJECTS

Part 1: Modeling the Effects of Bridge Deck Replacement Methods on Construction Performance Factors

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ANALYSIS OF TRAFFIC IMPACTS FOR RAPID BRIDGE DECK REPLACEMENT PROJECTS

Part 1: Modeling the Effects of Bridge Deck Replacement Methods on Construction Performance Factors

Abstract

The objective of this research was to develop and evaluate a methodology for measuring the effect of various bridge deck replacement methods on the total cost, schedule, and road user costs of a bridge project. Steps are outlined for data collection, normalizing, and nested ANOVA statistical analysis of created construction performance factors: unit cost, production rate, and road user cost. A hypothetical example problem was created which demonstrated how the methodology and analysis outlined can be used to aid engineers in justifiably selecting the most viable bridge deck replacement method(s) to use on future projects, based upon regional constraints and agency priorities.

Chapter 1: Introduction

1.1 Bridge Deck Replacement Methods

Increasing traffic volumes and aging infrastructure has led to more frequent major bridge rehabilitation and replacement projects. As much of the Interstate highway system in Alabama is 40 to 50 years old and many bridges of this age are in need of major rehabilitation or replacement, accelerated bridge construction methods are receiving more attention in order to minimize the impact of these necessary activities on the traveling public. To this end, the Alabama Department of Transportation has expressed interest and supported a series of research projects on this topic. The research presented in this report in focuses on the traffic impacts and road user costs (RUCs) of several accelerated bridge replacement designs that were considered for replacing a pair of bridges on Interstate 59 near Collinsville. Candidate alternatives developed from various combinations of bridge deck designs, casting techniques, and construction sequencing, are described herein. A methodology was then developed to estimate the effect of each alternative bridge replacement strategy on total cost, schedule, and road user costs. An extensive series of microscopic traffic simulations was designed and executed to quantify traffic impacts and support that key component of road user costs. This research was carried out during the 2009-2012 period; inputs for estimating costs are from this time period.

A growing concern in the transportation industry is the confounding effect and impact construction schedules have on the traveling public. Longer construction schedules typically result in extended lane closures which lead to traffic congestion and ultimately result in high road user costs (RUCs) absorbed by the motoring public. In addition, if accelerated construction techniques are implemented on projects to reduce RUCs by minimizing traffic related impacts, higher construction costs could be experienced straining a state highway agency's budget. Cost-benefit analyses must be performed for upcoming projects under consideration to make sound justifiable engineering decisions on whether or not to employ an accelerated construction method(s). For a project being considered for accelerated bridge construction (ABC) techniques, a decision maker needs to have a fundamental understanding of the interaction between the cost, schedule, and traffic impact in order to perform an effective cost-benefit analysis. From this information engineers can determine, based on the needs and resources of a project under consideration, which accelerated method(s) is the most financially viable option. In this research, a set of candidate ABC techniques, along with associated construction sequencing and resulting project costs, are evaluated.

"The Alabama Department of Transportation (ALDOT) has over three total miles of major interstate bridges (i.e., 3 to 5 lanes wide with approximately 600,000 ft^2 of deck near downtown Birmingham) with significant levels of deck cracking and deterioration" (Ramey and Oliver, 1998). To address the current state of these deteriorating interstate bridges, a combination of accelerated bridge deck replacement methods were being proposed for use in Birmingham at the time of this research. The bridges on I-59 near Collinsville were viewed as a test case for ABC approaches; the cost and impacts of four different ABC approaches were estimated in this study. This location was identified for testing and evaluation since the bridges are located in a rural area where construction related impacts would be relatively minimal since the location has an annual average daily traffic (AADT) of 13,420 vehicles (ALDOT, 2011).

The I-59 bridge replacement project that was proposed for the Collinsville site, and evaluated in this research project, is unique in that it would employ three different bridge deck systems, two construction sequences, and two different casting techniques for bridge deck reconstruction. Each of the three elements: (1) deck system, (2) construction sequence, and (3) casting technique, will be used to evaluate these accelerated bridge deck replacement methods from a constructability perspective and are defined separately in the following sections.

1.1.1 Deck System

The term deck system refers to the design and materials used to construct a modular bridge deck achieving a particular desired structural integrity. An earlier phase of this line of research was to determine the number of deck systems that could be tested on the I-59 bridges, and which systems were most beneficial for future use. From that effort, the three deck systems to be evaluated in this research include: (1) Exodermic™, (2) Steel Grid (Partial Depth), and (3) NCHRP (Full Depth). Each deck system is described separately in the following sections.

1.1.1.1 *Exodermic Deck System*

An Exodermic™ (or "composite, unfilled steel grid") deck is comprised of a reinforced concrete slab on top of, and composite with, an unfilled steel grid. This system can be constructed with a cast-in-place (CIP) or precast (PC) casting techniques. The Exodermic system maximizes the use of the compressive strength of concrete and the tensile strength of steel (Exodermic Bridge Deck, 2011). Figure 1-1 shows the typical design of an Exodermic deck system.

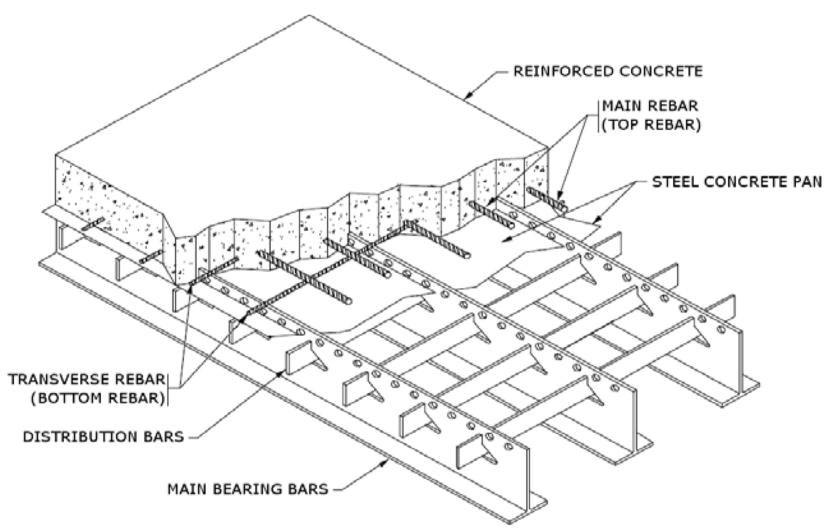


Figure 1-1 Exodermic Deck System (Harvey, 2011).

1.1.1.2 *Steel Grid Deck System*

Three steel grid deck system combinations exist: open, full, and partial depth. An open steel grid deck system is the lightest system and the easiest to install, however, it also offers the poorest ride quality. A full depth steel grid deck system is the heaviest modular deck system of the three with the relative best ride quality, but it is also the most expensive and difficult to install. A partial depth steel grid deck system is in-between the open and full depth systems in terms of weight, cost, and constructability (Harvey, 2011). A partial depth steel grid deck system was selected to be further investigated for its feasibility on the I-59 project. Figure 1-2 shows the design of a typical cast-in-place (CIP) steel grid partial depth deck system.

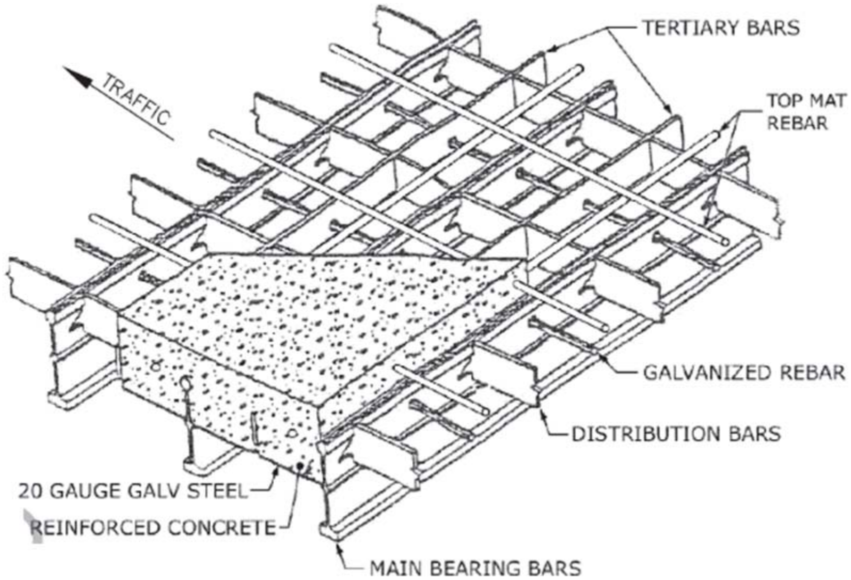
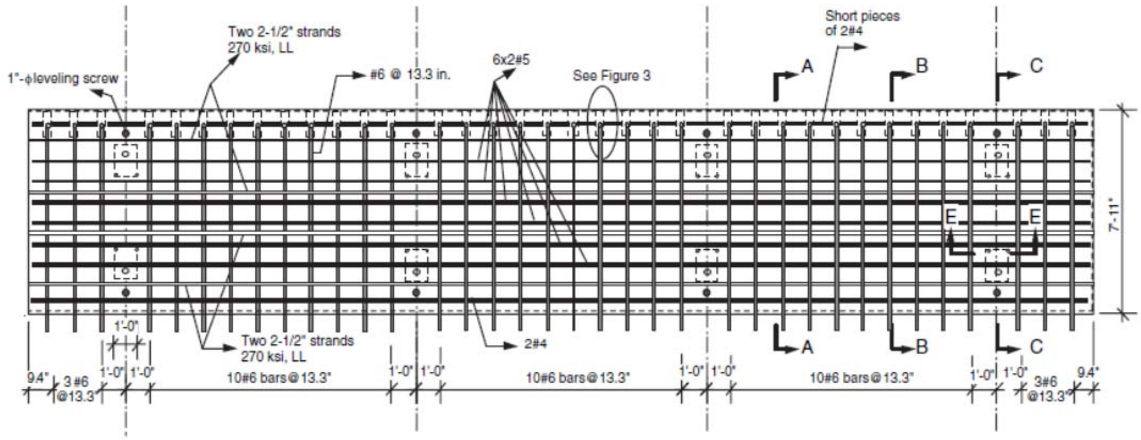


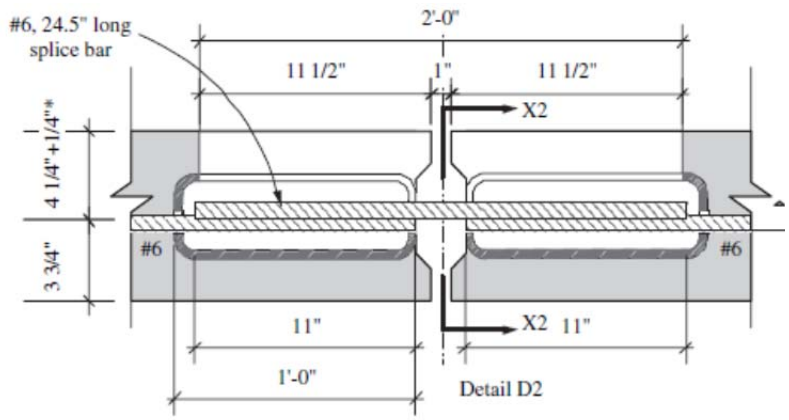
Figure 1-2 Steel Grid Deck System (Harvey, 2011).

1.1.1.3 *NCHRP Deck System*

The purpose of the National Cooperative Highway Research Program (NCHRP) Report 584 was to establish guidelines and recommendations for creating nonproprietary, full-depth, precast (PC) concrete bridge deck panel systems. The report developed: (1) recommended guidelines for the design, fabrication, and construction of full-depth PC concrete bridge deck panel systems and (2) connection details for new deck panel systems (Badie and Tadros, 2008). The NCHRP deck system that will be tested in Collinsville is CD-1(b), as identified in NCHRP report 584. The PC concrete deck panels use pre-tensioned transverse and conventional longitudinal reinforcement. Transverse panel to panel connections will be accomplished through the use of a splice slot located along the transverse reinforcement of each deck panel system. Once the panels are in place, an additional splice bar will be inserted into the slot and the slot will be filled with grout. Figure 1-3 shows the unfilled NCHRP deck system and transverse panel to panel connections.



(a) Plan View of Deck System Showing Reinforcement Location



(b) CD-1(b) Splice Panel to Panel Connection

Figure 1-3 NCHRP Deck System (Badie and Tadros, 2008).

1.1.2 Casting Technique

Casting technique refers to whether the bridge deck systems were precast (PC) offsite or cast-in-place (CIP) at the project location. PC is defined as a product created in a reusable mold off-site and then transported to the construction location for installation. Often PC concrete is cast in a controlled environment under ideal concrete curing conditions. CIP is defined as concrete that is cast at the project location into a specific form created for one unique project. The environmental conditions are often beyond the contractor's control during the curing process and equipment such as mats and driers are used to aid the curing of concrete if necessary.

1.1.3 Construction Sequencing

Construction sequencing refers to the scheduling and staging of bridge deck replacement activities that are employed by the contractor throughout the project duration. The two types of construction sequencing evaluated in this research include traditional construction sequencing and accelerated construction sequencing. Each type of construction sequencing evaluated as part of the I-59 project is defined below.

1.1.3.1 *Traditional Construction Sequencing*

Traditional construction sequencing is defined as a construction sequence that uses a permanent lane closure to replace the entire length of bridge lane. During this sequencing, temporary concrete barriers (TCB) will be used to establish a lane closure while the adjacent lane is maintained open for vehicle travel. Once demolition and construction is completed for the full length of a lane (i.e., all four lane-spans), the TCB is removed and the closed lane is reopened for use by the motoring public.

1.1.3.2 *Accelerated Construction Sequencing*

Accelerated construction sequencing employs intermittent lane closures, as defined by a contractual time-based provision, to perform construction during periods of low traffic volume. This construction sequence employs TCBs to establish a closed lane while maintaining an open lane of travel adjacent to the work space. The purpose of using intermittent lane closures during non-peak travel time periods is to minimize traffic disruption on the motoring public. An intermittent lane closure could be considered a weeknight closure (e.g., 6 p.m. to 6 a.m.) or weekend closure (e.g., Friday at 6 p.m. to Monday at 6 a.m.). During these intermittent lane closure periods, demolition and construction are to occur on a single lane-span or on the amount of bridge decking the contractor can demolish and replace within a given work period. Once construction on the lane-span under consideration is complete, the closed lane is reopened for traffic and both lanes remain operational for traffic movements until work begins on the subsequent lane-span, during the next non-peak travel time period. The lane is then closed once again so demolition and construction can occur on the subsequent lane-span under consideration. This process is repeated until all lane-spans over the entire length of the bridge are completed. After total lane reconstruction work is complete, the TCBs are removed permanently and both lanes on the bridge are reopened to the traveling public.

1.2 Research Objectives

The purpose of this research is to develop a framework that will be used to evaluate the impact of different bridge deck replacement methods from a construction perspective based on the total project cost, schedule, and traffic impact. The specific objectives of this research are:

1. Develop a methodology for statistically evaluating the effects that a particular bridge deck's replacement methods: deck system, construction sequence, and casting technique have on the three specified construction performance factors: (1) unit cost, (2) production rate, and (3) road user cost.
2. Perform a hypothetical case study using the methodology developed to demonstrate the applicability of the method and how the results can be used to select the most viable

bridge deck replacement method to use on a future project based upon regional constraints and agency priorities.

To satisfy the research objectives and determine the bridge deck replacement methods effects on the construction performance factors outlined, the following tasks will be performed on the I-59 project:

1. Identify, describe, evaluate, and critically assess pertinent literature on the current deck systems, methods, technologies, and analysis techniques available for assessing bridge deck replacement methods.
2. Outline how the data (i.e., bridge dimensions, cost, schedule, traffic data, and contractor reports) from the Collinsville I-59 project will be collected for each bridge deck replacement method constructed.
3. Describe how construction camera technology can be used to monitor and document the construction effort for each separate lane span.
4. Use Remote Traffic Microwave Sensor (RTMS) G4 devices prior to the construction effort to capture traffic data (i.e., volumes and speeds) to aid in calculating accurate road user costs.
5. Create guidelines to perform an analysis of variance (ANOVA) to determine the effect that each bridge deck replacement method has on the construction performance factors (i.e., unit cost, production rate, and road user costs).
6. Develop an example problem to demonstrate the use of the methodology based on a hypothetical scenario of the I-59 project.

1.3 Organization of Part 1 of This Report

Part 1 of this report is divided into six chapters that organize, illustrate, and describe the steps taken to satisfy the research objectives outlined above. Chapter 2: *Literature Review* examines the current state of bridge deck replacement methods in practice. Furthermore, the literature review documents performance factors, scheduling, construction and traffic monitoring techniques, and analysis methods that pertain to performing a comparative analysis. Chapter 3: *Methodology and Data Collection* will outline the step-by-step procedures, learned and formulated out of the literature review, which will be used in the monitoring and collecting data on the I-59 project. Chapter 4: *Data Analysis Techniques* will discuss how to develop Gantt charts and normalize the raw data collected to create the selected construction performance factors: unit cost, production rate, and road user cost. After normalization of the data, analysis of variance (ANOVA) tests will be outlined. Chapter 5: *Application of Methodology* will give a detailed example from start to finish exhibiting in a step-by-step fashion, the data collection process and the application of the statistical analyses. Hypothetical scenarios will be created with fictitious data for analysis as a result of the construction effort being delayed on multiple occasions. This section should be used as a reference during actual construction of the I-59 project. Chapter 6: *Conclusion and Recommendations* will summarize the work performed in Chapters 1 through 5 with lessons learned through the course of this project and make recommendations for future bridge deck replacement research.

Chapter 2: Literature Review

2.1 Introduction

To satisfy the research objectives outlined in the previous chapter, a thorough literature review was conducted on several pertinent subjects relating to the I-59 project in Collinsville, AL. The topics that have been examined include:

1. Accelerated Bridge Construction (ABC) methods that exist or have been used and implemented on bridge rehabilitation and reconstruction projects,
2. Construction performance factors that have been measured for quantifying effectiveness of both building and roadway construction projects,
3. Scheduling effects on the overall performance of projects,
4. Traffic monitoring technologies that exist for capturing accurate and reliable vehicular data,
5. Road User Cost (RUC) estimating for bridge projects,
6. Collection locations for monitoring traffic flow,
7. Construction camera monitoring technology, and
8. Analysis methods for measuring construction performance

The following sections will discuss the results of the literature review for the abovementioned topics.

2.2 Accelerated Bridge Construction (ABC) Methods

ABC methods refer to any construction bridge effort that is intended to greatly reduce the typical overall construction schedule. This is a wide all-encompassing term. The I-59 project will be testing a variety of ABC deck systems, construction sequences, and casting techniques. A variety of cast-in-place (CIP) and precast (PC) systems have been experimented with on ABC projects in the past. Each offers its own advantages and disadvantages; a portion of this research will focus on comparing the strengths and weaknesses of each system. One such deck system that will be used on the I-59 project is an Exodermic™ system. Exodermic deck panels are comprised of an unfilled steel grid 3 to5 in. (7.63 to 12.7 cm) deep, with a 3 to 5 in. (7.63 to 12.7 cm) reinforced concrete slab on top of a composite with the steel grid. The Exodermic panels can be either PC offsite or CIP at the project location. In 2005, the Georgia Department of Transportation (GDOT) experimented with PC Exodermic deck panels on two bridges. One bridge was the Bells Mill Bridge in Gainesville, GA and the other bridge was the Atlanta I-285 bridge, over US-41. The Bells Mill Bridge was 388 ft (118.26 m) long with a two way, two lane configuration. The bridge was narrow with a total transverse width of 26 ft (7.92 m). The deck spans were replaced on a nightly schedule (Monday – Friday) 9:00 p.m. to 5:00 a.m. with two PC Exodermic panels with an area of roughly 500 ft^2 (46 m^2). The Atlanta I-285 bridge over US-41 is an eight lane bridge system (four lanes in each direction) with a total length of 240 ft (73.15 m). Due to the skew of the bridges, Exodermic trapezoidal panels were used. The project schedule for the reconstruction effort consisted of a weekend closure schedule (using partial lane closures starting at Friday 9:00 p.m. and reopening on Monday at 5:00 a.m.) to avoid high periods of traffic. During the construction phase, two lanes of traffic were maintained while the remaining two lanes were repaired at a rate of 2,527 ft^2 (235 m^2) per weekend. The project was completed in 5 weekend closures, 7 weekends ahead of the allotted 12 weekends provisioned in the GDOT bid for a total of 12,635 ft^2 (1174 m^2) of bridge decking upon completion. The construction effort of both the Bells Mill bridge and the Atlanta I-285 bridge were a success because "the bridge decks were replaced using rapid deck replacement techniques during periods of low traffic volume to reduce accident risk and improve public acceptance" (Umphrey et al., 2007).

Another ABC bridge project was conducted by the Ohio Department of Transportation (ODOT) in Quaker City, Ohio in 2003. The project used a precast deck system to rapidly replace the bridge deck. Originally the 60 ft (18.29 m) bridge, built in 1952, had been a two span, continuous, reinforced concrete slab bridge with reinforced concrete substructure. Due to time constraints, it was not possible to replace the previous slab with a new continuous concrete slab. Closure of the bridge would result in a 20 mile (32.19 km) detour for automobiles and a 40 mile (64.37 km) detour for trucks and buses (Salem et al., 2006). Another alternative explored for the Quaker City bridge was using a partial lane closure construction sequence. This process was eliminated because the bridge was a major route for school buses and a partial closure posed safety concerns to the large school buses passing through the work zone. The ODOT decided to use a post-tensioned precast system for decking replacement coupled with a compressed work schedule that took advantage of the time between spring and summer semesters of the local Ohio schools. The project was accomplished in 19 days, 3 days behind schedule. Although the project was complete 3 days behind schedule, the project was considered a success because it was completed in a reasonable enough time that school activity was not affected and the structural objectives of the reconstruction were met to satisfactory conditions (Salem et al., 2006).

The above mentioned methods of ABC are a more conservative approach to maximizing construction productivity while minimizing traffic delay impacts during rehabilitation. Other less conventional methods exist that have proven quite successful on a number of projects. One project in particular that used innovative techniques to solve a complex problem is the Church Street South Extension project over the New Haven Interlocking and Rail Yard that used one of the world's largest cranes to complete a bridge section replacement. The Connecticut Department of Transportation (ConnDOT) required that a 320 ft (97.54 m), 850 ton (743 metric ton) span of a 1,280 ft (390.14 m) bridge be replaced in a single weekend. Traditional bridge construction techniques were not possible because of the train yard that existed under the footprint of the project. A compressed construction schedule was used to minimize disruption to train service and shorten worker exposure time to active rail lines. To meet the rigorous demands outlined by the ConnDOT, the Lampson International LLC's Transilift® LTL-2600 was used to lift the 320 ft (97.54 m), 850 ton (743 metric ton) prebuilt span of bridge section into place in a 3 hour period. On an early morning, May 3rd, 2003 the crane lifted the section 65 ft (19.81 m) into the air and maneuvered it 100 ft (30.48 m) over to its final resting location. The total duration for the move was 3 hours. When the final project was completed in December 2003 it was 5 months ahead of schedule and $500,000 under its $32 million dollar budget (Mistry and Mangus, 2006).

2.3 Construction Performance Factors

An objective of the I-59 project would be to assess the effect that the bridge deck replacement methods selected has on the construction performance factors: unit cost, production rate, and road user cost. For analysis, data collection will be recorded through the duration of the project and then used to compute construction performance factors. The data collection effort regarding construction performance factors will begin prior to the construction effort, continue through all stages of the actual work, and be continued for a period after the completion of the project. From the literature review, three common measurement factors (i.e., cost, schedule, and quality) appeared many times indicating these factors as important data to be collected to perform a construction performance analysis. "Project managers like to talk about the three legged stool on which their project sits: project quality, schedule, and cost. Applying rapid bridge construction techniques such as those described here strengthens those legs tremendously" (Capers Jr, 2005). Umphrey et al. (2007) identified similar performance factors in their research of four accelerated bridge projects in Georgia. "Documentation of the GDOT work included a time sequence, deck replacement square footage per work period, total construction time, typical work period construction tasks, and photographic display/discussion of the deck replacement work" (Umphrey et al., 2007).

A method for comparing methods of construction using performance factors is to create index values or ratios of the performance factors in an effort to normalize the data to have the ability to analyze data across different sized projects. Chan and Kumaraswamy (1995) collected index values during their research of Hong Kong building construction projects. Major building construction in Hong Kong has a reputation for being both satisfactory and incredibly quick with accurate completion time forecast (Chan and Kumaraswamy, 1995). In 1995 Chan et al. formulated and tested empirical models to determine if project completion estimates could be predicted based on a set of parameters. For their research they closely examined the relationships between time-cost models, time-floor area models, and time-number of stories models. In all 3 models a linear relationship was determined with a coefficient of determination above 0.60. The results of the research showed that the index values created could be used to make future project predictions based on a known parameter. Although this example is referring to building construction, the applicability of creating performance factors for future project estimating can be used in bridge construction.

2.4 Project Schedule

Project scheduling is an important aspect to the success of any construction project. During accelerated construction, scheduling plays a significant role in ensuring the project is completed on time or ahead of schedule. In accelerated construction, scheduling becomes an essential component to ensure that projects are completed successfully on-time or ahead of schedule. Planning and coordinating sequential events keeps productivity rates high by minimizing lost work hours due to lack of material or personnel on the project site. Prior to construction an important task to consider during the scheduling process is to organize a pre-construction meeting amongst the parties involved on the project. The objective of this meeting is to discuss potential problems that could occur during the construction effort. Groups are encouraged to voice their opinions on potential issues or circumstances that could delay the project, while also indicating that they understand their individual responsibilities. This process ensures everyone is working together to successfully complete the accelerated task and finish the project on time.

In the Quaker City Bridge project discussed earlier, such a pre-construction meeting was held. Representatives from ODOT, the general contractor, the post tensioning subcontractor, the precast fabricator, and the design engineering firm met six months ahead of construction to discuss any potential delay issues that could be encountered during work. An issue that had been overlooked earlier in the planning phase was a noise ordinance permit required for heavy construction in urban areas. If proper paperwork had not been filed before construction, the noise ordinance could have caused serious delays. Due to the short duration of the construction project and the importance of the bridge being replaced, local officials gladly offered a waiver on the noise ordinance (Salem et al., 2006). By bringing a diverse group of individuals together to examine the work of their peers they were able to identify potential problems that had been overlooked in the earlier development phase of planning. Once the sequence of work and possible delay issues had been identified in the pre-construction portion of the project, the next step was to begin the construction phase of the Quaker City Bridge. During construction it is important to keep clear lines of communication open between all parties involved in the project. In the event that work cannot be carried out according to the schedule or setbacks occur that cause delay, rapid communication among key personnel to resolve issues is required to keep work moving forward. ABC requires fast decisions to keep pace with that of accelerated construction. On the Quaker City Bridge project it was noted that a key to success was the project manager's authority and ability to make tough decisions when the engineers could not be reached immediately (Salem et al. 2006). "The contractor and contracting agency formed a cordial relationship of partnering that ensured an atmosphere conducive to quality performance" (Salem et al., 2006). Giving confident and qualified individuals authority to make hard decisions rapidly is critical for accelerated projects to be accomplished on a compressed schedule successfully.

Periodic monitoring of the project should be performed during construction by comparing work accomplished to work expected at a given time. This process ensures that the project remains on schedule. Following construction, a post construction meeting should be held to analyze the work that was performed. The objectives should be to assess the work performed against the work expected and identify any successes or failures that occurred during the project. Feedback from the contractors is encouraged and should be used to revise plans for future projects. Naoum (1994) used a questionnaire following project completions to evaluate client satisfaction concerning time, cost, and quality. All aspects of the post construction analysis should be integrated into future work based upon the lessons learned to ensure projects operate more smoothly in future construction efforts.

2.5 Road User Cost

Road user cost (RUC) is a function of the volume and lane conditions at a work zone. To determine how to accurately assess a RUC for the I-59 project the following literature was reviewed. Traditionally, the Highway Capacity Manual (HCM) has been used for predicting freeway capacities. One problem that is encountered from relying on the HCM model for predicting capacities is "the Highway Capacity Manual (HCM) procedures provide generic estimates for two types of lane closures only, with no guidance as to how these estimates are affected by traffic, geometric, and environmental conditions" (Al-Kaisy and Hall, 2003). The HCM procedure for calculating a freeway capacity is to first determine an ideal base capacity and then modify it by a series of factors. As previously stated, those factors do not account for critical lane closure conditions or environmental issues. In an attempt to create a more accurate model for predicting the capacity of freeways during construction, Al-Kaisy and Hall (2003) experimented with two variations to the HCM model. Both models were built on the principles established in the HCM of determining a base capacity and then modifying it by several factors. The factors chosen by his team as most effecting to the capacity were: percent heavy vehicles, driver population, light conditions, inclement weather, work activity on-site, lane closure configuration, and rain. In the first experiment a nonlinear multiplicative capacity model was derived. The resulting model had a coefficient of determination of 0.63. In the second experiment a linear additive capacity model was created using multivariate linear regression with a coefficient of determination of 0.68. Overall, the authors determined that a model that accounted for critical lane closure conditions or environmental issue was more accurate in terms of predicting the freeway capacity than simply relying on the HCM model.

Other factors to consider when estimating a RUC include regional cost values per vehicle. The American Association of State Highway and Transportation Officials (AASHTO) reports three key factors for performing a user benefit analysis to determine a RUC from highway construction projects. The three key factors outlined are the value of time, operating cost, and accident cost per vehicle (AASHTO, 2010). The three factors depend on the lane closure conditions and the average wage and operating cost of the location in question.

2.6 Analysis Methods

The I-59 project will evaluate three elements of various bridge deck replacement methods: (1) deck system, (2) construction sequence, and (3) casting technique that exist for each bridge, but are not shared by each bridge. Due to the uniqueness of this project regarding the combinations of bridge deck replacement methods being constructed over all bridge spans, simple linear regression analysis was not considered as the most viable test. Alternatives to simple t-test and linear regression were researched. A nested analysis of variance (ANOVA) test, by definition satisfies the requirements for analysis in regards to the combination of bridge deck replacement methods being proposed for the I-59 project. "In certain multifactor experiments, the levels of one factor (e.g., factor B) are similar but not identical for different levels of another factor (e.g., factor A). Such an arrangement is called a nested, or hierarchical, design" (Montgomery, 2005). This multifactor design is applied during the organization of the I-59 project, with each of the bridge deck replacement methods be dependent on the results of one another. The nested ANOVA compares the mean value of each level to determine statistical influence of a parameter being tested. The nested ANOVA will be used to determine the effect of each bridge deck replacement method on the outlined construction performance factors.

2.7 Summary of Literature Review

A thorough literature review was performed to gain knowledge of construction and bridge projects from previously conducted research. The literature review was divided into six areas that were intended to cover all aspects of the I-59 project. The eight areas covered by this literature review are listed as follows:

1. Accelerated bridge construction (ABC) methods that exist or have been used and implemented on bridge rehabilitation and reconstruction projects,
2. Construction performance factors that have been measured for quantifying effectiveness of both building and roadway construction projects,
3. Scheduling effects on the overall performance of projects,
4. Road User Cost estimating for bridge projects,
5. Analysis methods for measuring construction performance

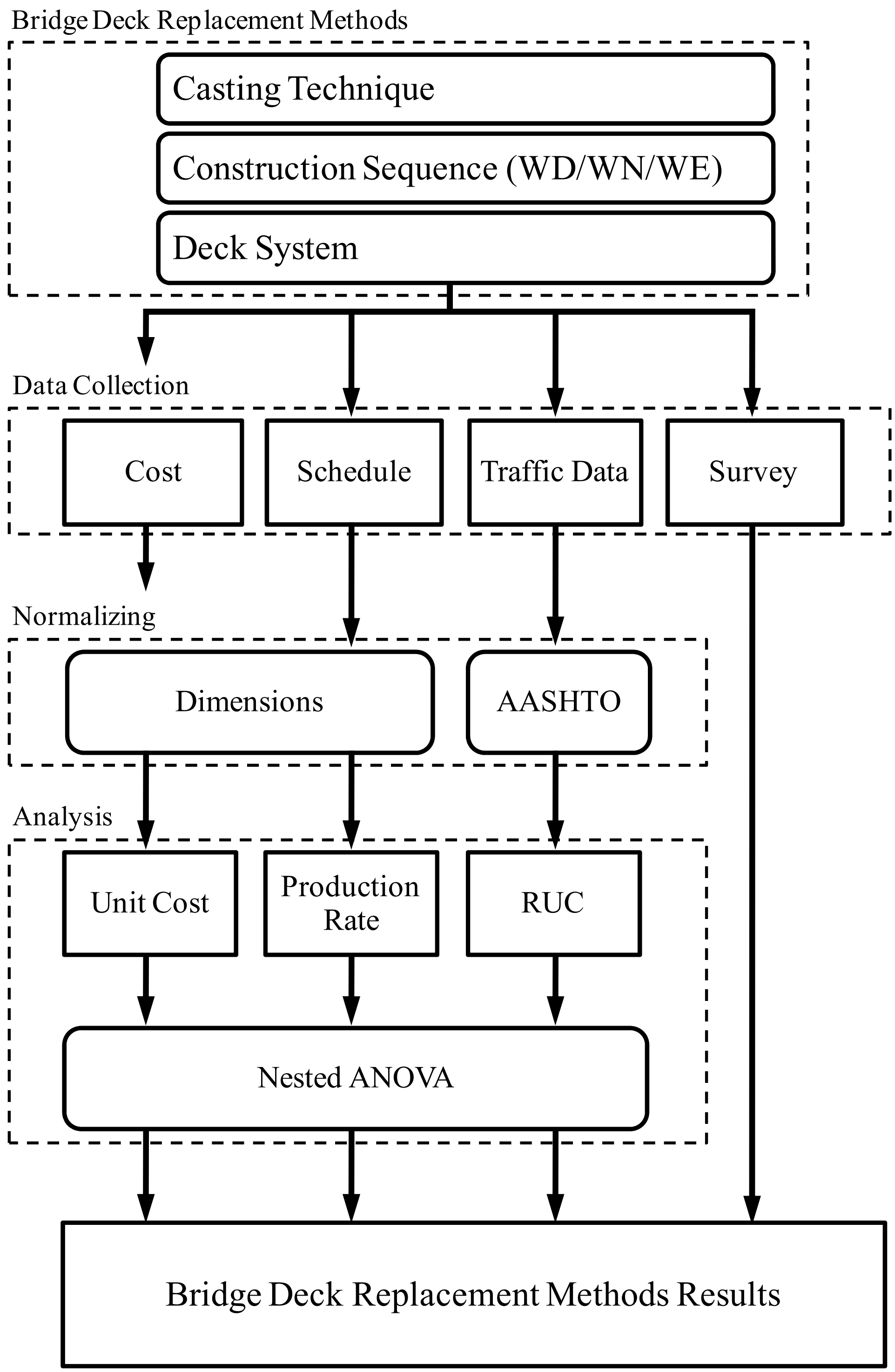
The lessons learned from the literature review were then applied to create a methodology for collecting data and analyzing it systematically, which satisfy the I-59 research objectives outlined in Chapter 1 of this report.

Chapter 3: Methodology and Data Collection

3.1 Introduction

The purpose of this chapter is to describe and establish a methodology and procedure for data collection on the I-59 bridges in Collinsville during construction. The I-59 bridges consist of four total lanes, two northbound (NB) lanes and two southbound (SB) lanes. For construction purposes, each bridge has been subdivided into four unique spans. Each span is divided by the two existing lanes: (1) the inside (passing) lane and (2) the outside (travel) lane. In this report, a span in a particular lane will be referred to as a lane-span. There are a total of eight lane-spans per bridge and sixteen lane-spans for the entire I-59 project.

Figure 3-1 illustrates a flow chart developed to show the sequencing of this research effort for the evaluation of the bridge deck replacement methods. The flow chart begins with the three major components used to evaluate each bridge deck replacement method and continues through the data collection effort, normalizing of collected data, statistical analyses, and results.



Note:
*WD - Weekday Lane Closure Scenario
*WN - Weeknight Lane Closure Scenario
*WE - Weekend Lane Closure Scenario

Figure 3-1 Project Flow Chart for Evaluating Bridge Deck Replacement Methods.

Data collection for the I-59 project will be performed on each individual lane-span for each bridge deck replacement method. Four unique bridge deck replacement methods are to be constructed and evaluated during the reconstruction of the I-59 NB and SB bridges. The inside lane on both the NB and SB bridges will be constructed using a traditional construction sequence while the outside lanes on both bridges will be constructed using an accelerated construction sequence. The NB bridge will be constructed using cast-in-place (CIP) casting techniques while the SB bridge will be constructed using precast (PC) casting techniques. Figure 3-2 shows the NB and SB bridges' lane orientations and directions of travel. The four spans for each bridge are labeled and identified for each individual lane-span. Lane-spans that are shaded white will be constructed with traditional construction sequencing, while lane-spans that are cross hatched will be constructed with accelerated construction sequencing. Above each bridge, the deck system that corresponds to the lane-span has been identified. For referencing purposes each lane-span has been given an identification number. A particular lane-span's identification number will be composed of the direction of travel, whether it is the inside or outside lane, and the individual bridge-lane-span number. For example the lane-span on the NB bridge, on the inside lane of span 1 will have an identification number of NBI1.

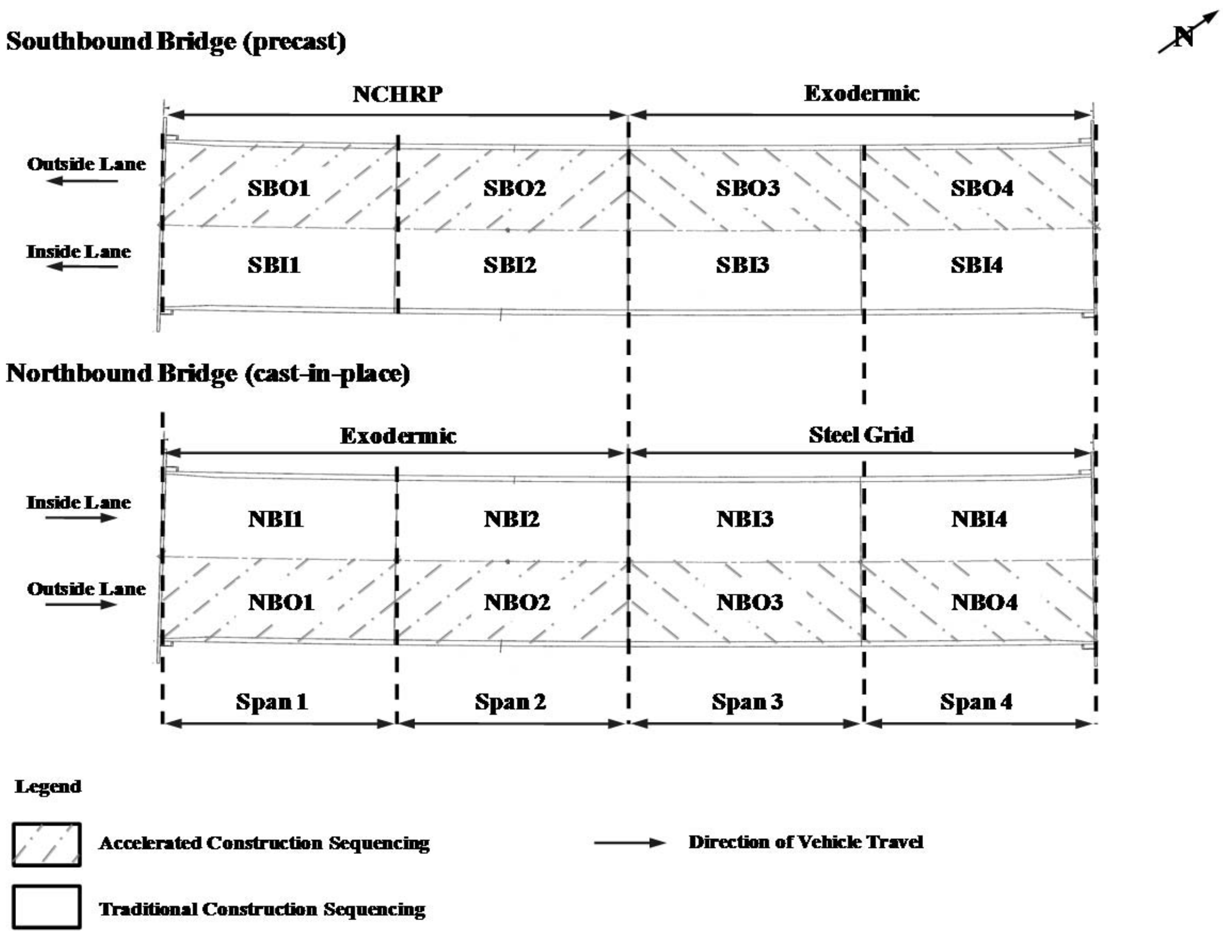


Figure 3-2 Plan View of I-59 Bridge Project Divided into Lanes and Lane-Spans.

Data to be collected for each bridge deck replacement method will include (1) lane-span dimensions (i.e., existing and post-construction length of lane-span and area of lane-span), (2) cost, (3) schedule, and (4) traffic data (i.e., lane volumes and speeds). All data collected is considered to be raw data. The raw data will be used to calculate the following three construction performance factors: (1) unit cost, (2) production rate, and (3) road user cost (RUC). A nested analysis of variance (ANOVA) technique will be used to determine the effect that each individual bridge deck replacement method has on the construction performance factors.

References for data collection include reported values from the contractor, inspector project diaries, visual inspection of the project via EarthCam construction camera technology, the ALDOT plans set, and traffic data collected by the RTMS G4.

3.2 I-59 Bridge Dimensions

Dimensions for all lane-spans have been calculated from the ALDOT plan set for Project No. BR-1059 (I-59 Collinsville). Two additional girders will be added to the previous existing four girders for a total of six girders at completion, to accommodate the widening of the bridge. The addition of substructure and superstructure elements associated with the bridge widening is not being considered in this research effort and corresponding data will not be collected. This research is solely focused on data associated with the demolition or construction of the bridge deck.

The length of each span was calculated using ALDOT surveying station information from the plan set. The stations were marked along the centerline of each bridge. The deck width was measured from the longitudinal construction joint to the outside edge of the shoulders. Because the construction joint is located off-center, individual outside lane-span deck widths to be demolished and constructed are greater than the deck width of individual inside lane-spans. A typical existing and post-construction inside lane-span deck width is 12.58 ft (3.8 m) and 19.38 ft (5.87 m) respectively. While, a typical existing and post-construction outside lane-span deck width are 20.58 ft (6.24 m) and 27.38 ft (8.3 m) respectively. The total existing lane-span deck width is 33.2 ft (10.1 m) and the total post-construction lane-span deck width is 46.76 ft (14.2 m).

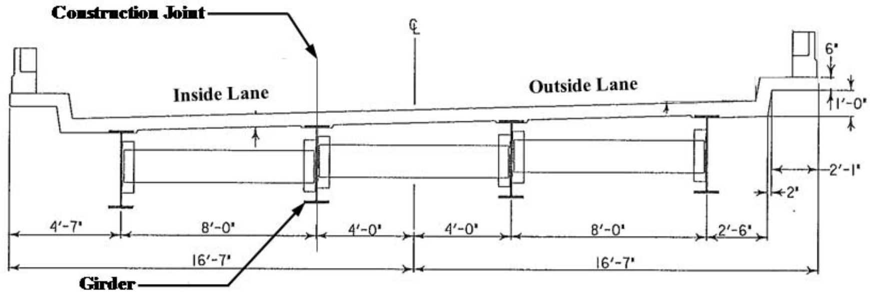
The area of the existing lane-span is determined by lane-span width multiplied by the length of the lane-span, calculated from dimensions included in the ALDOT plan set. Similarly, the area of the post-construction lane-span deck has been calculated as the constructed lane-span width multiplied by the length of the lane-span under consideration. Table 3-1 provides a complete summary of all lane-span deck dimensions (i.e., length, width, and area). These values are calculated based on the dimensions shown on ALDOT plan sheets and should be confirmed by the contractor during the course of the construction effort. Lanes identified with an asterisks could have varying areas due to the skew of the bridge.

Table 3-1 Lane-Span Dimensions for Northbound/Southbound Bridges

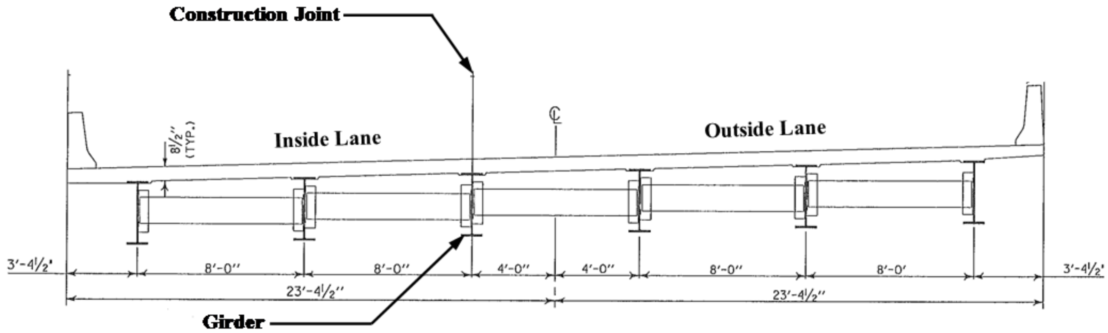
		Existing		Post Construction	
Lane Span ID	Length (ft)	Width (ft)	Area(ft^2)	Width(ft)	Area(ft^2)
NBI1	56.83	12.58	714.9	19.38	1101.4
NBI2*	56.00	12.58	704.5	19.38	1085.3
NBI3*	56.00	12.58	704.5	19.38	1085.3
NBI4	56.83	12.58	714.9	19.38	1101.4
NBO1	56.83	20.58	1169.6	27.38	1556.0
NBO2*	56.00	20.58	1152.5	27.38	1533.4
NBO3*	56.00	20.58	1152.5	27.38	1533.4
NBO4	56.83	20.58	1169.6	27.38	1556.0
SBI1	56.83	12.58	714.9	19.38	1101.4
SBI2	56.00	12.58	704.5	19.38	1085.3
SBI3	56.00	12.58	704.5	19.38	1085.3
SBI4	56.83	12.58	714.9	19.38	1101.4
SBO1	56.83	20.58	1169.6	27.38	1556.0
SBO2	56.00	20.58	1152.5	27.38	1533.4
SBO3	56.00	20.58	1152.5	27.38	1533.4
SBO4	56.83	20.58	1169.6	27.38	1556.0

Note:
NBI(#) - Northbound inside (lane-span number)
NBO(#) – Northbound outside (lane-span number)
SBI(#) - Southbound inside (lane-span number)
SBO(#) - Southbound outside (lane-span number)

Demolition and construction will occur off-center from the centerline of the bridge, creating inside lane-span dimensions that are smaller than outside lane-span dimensions. By performing construction off-center, the new construction joint of the lane-spans will occur over the center of a girder providing the joint more stability during construction. The longitudinal construction joint is identified as the location where individual lane-spans will join, progressing in the longitudinal direction of travel. Figure 3-3 below shows a typical existing and post-construction cross-section of the longitudinal construction joint over the existing girder.



(a) Existing Deck Conditions



(b) Post Construction Deck Conditions

Figure 3-3 Elevation Views of Longitudinal Construction Joint.

During work activity, the longitudinal construction joint will be protected from vehicular traffic by temporary concrete barriers (TCBs). During traditional construction sequencing, one row of TCBs will be used to divide the lanes into a work space and traffic space to protect the construction joint from vehicular traffic. Figure 3-4 shows the placement of TCBs for an inside lane under traditional construction sequencing.

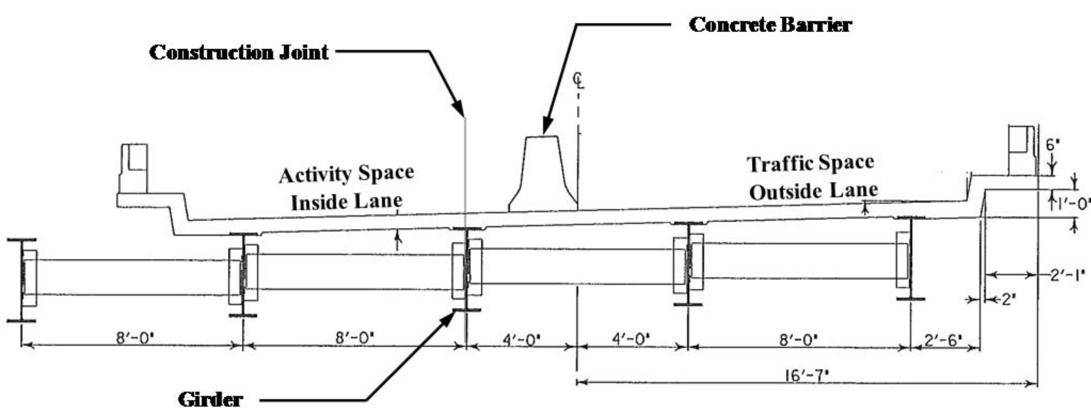


Figure 3-4 Traditional Construction Sequence TTC Concrete Barrier Placement.

During accelerated construction sequencing there will be a period during construction that both the inside and outside lanes will be open for travel. To accomplish periods with two travel lanes while continuing to protect the construction joint, three rows of TCB will be used. Figure 3-5 shows the location of TCB being used during accelerated construction sequencing scenarios.

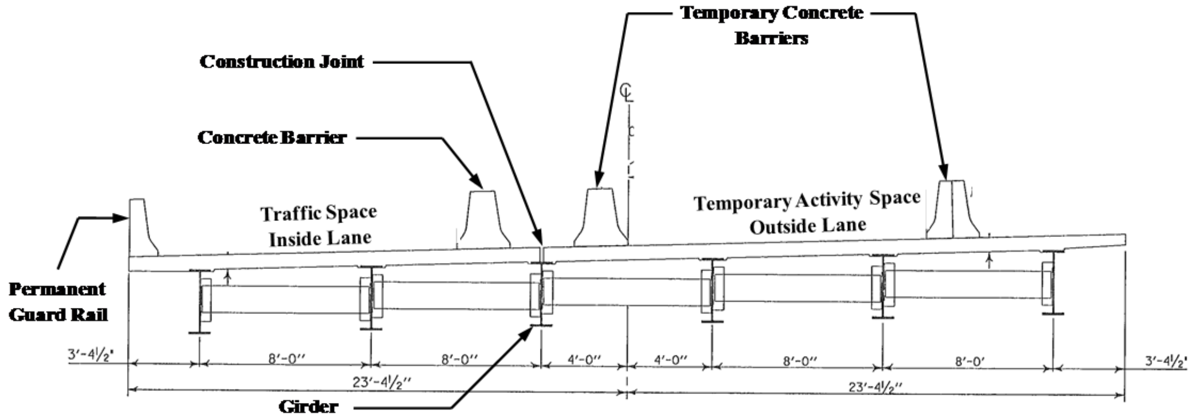


Figure 3-5 Accelerated Construction Sequencing TTC Concrete Barrier Placement.

At decking completion a permanent guard rail (concrete barrier) will be installed at the edge of the new decking, reducing the actual lane width by 1.38 ft (0.42 m) as seen in Figure 3-5.

3.2.1 Northbound (NB) Bridge Deck Details

All lane-span construction on the NB bridge will be accomplished with CIP techniques. For NB lane-spans 1 and 2, both the inside and outside lanes will be built with Exodermic deck systems. For NB lane-spans 3 and 4, both the inside and outside lanes will be reconstructed with Steel Grid deck systems. All work performed on the inside lane of the NB bridge will be done with a traditional construction sequence; while all work accomplished on the outside lane will be performed with an accelerated construction sequence. Work accomplished in a traditional construction sequence, will be performed in the direction of travel. Work completed with an accelerated construction sequence on the NB bridge, outside lane, will be performed in the opposing direction of travel. The reason for having work activity progress in the opposing direction of vehicle travel, during accelerated construction sequencing, is so the oncoming end of the permanent existing barrier rail system can stay in place as long as possible. By using the existing barrier rail, the contractor does not have to protect the blunt end of a temporary barrier from oncoming traffic. Figure 3-6 shows the lane-span details for the NB bridge with arrows identify the direction of travel and reconstruction work activity.

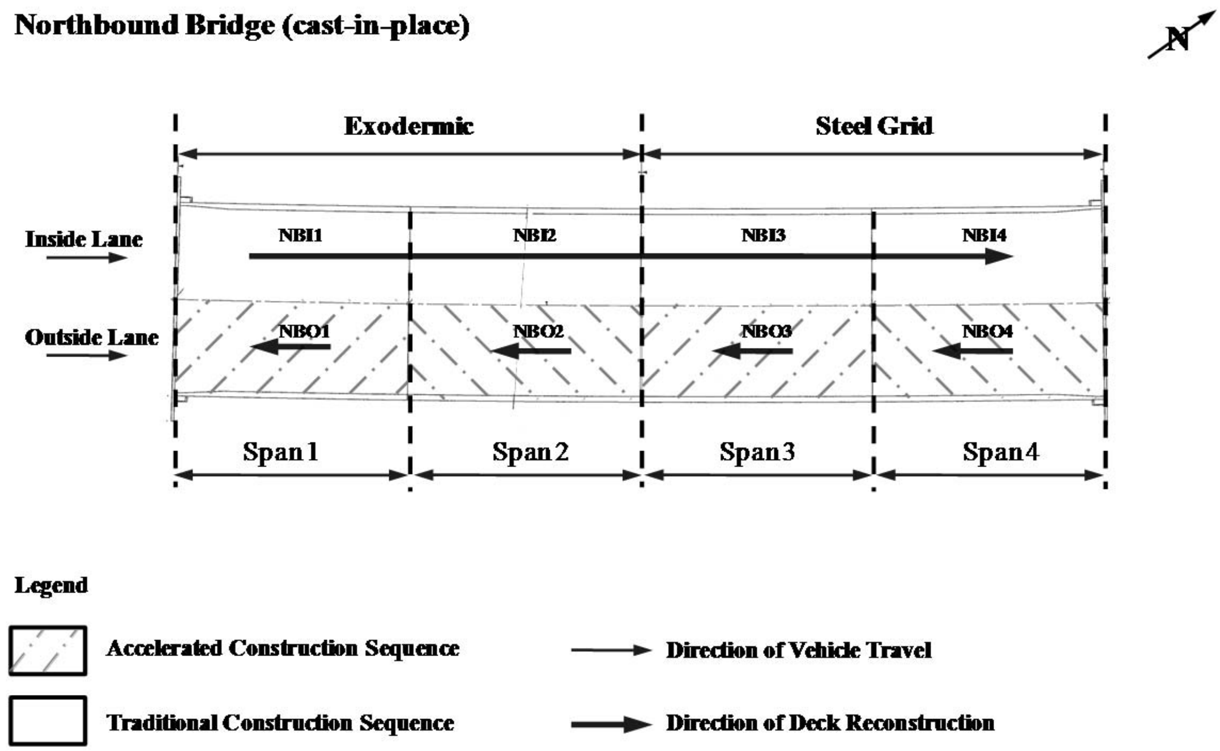
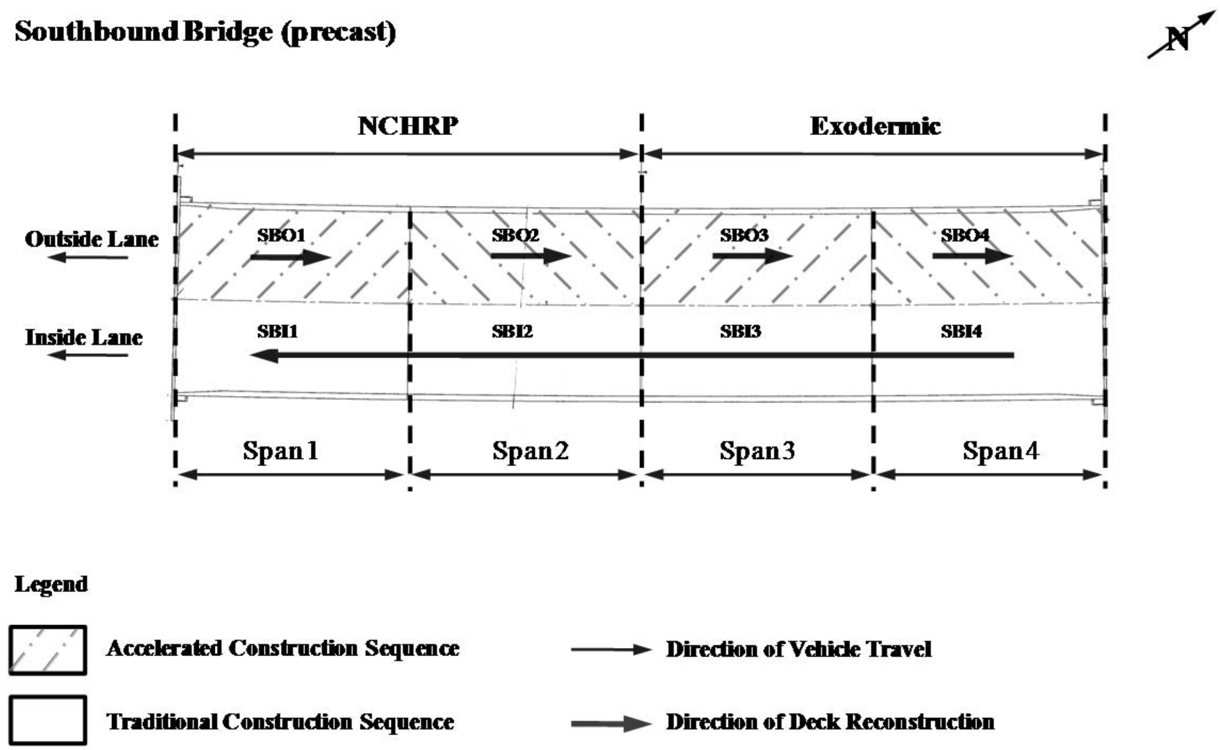


Figure 3-6 Northbound Bridge Span Construction Details.

3.2.2 Southbound (SB) Bridge Deck Details

All bridge deck replacement methods on the SB bridge will use PC techniques. Both SB inside and outside lane-spans 1 and 2 will be built with NCHRP deck systems. Likewise, both SB inside and outside lane-spans 3 and 4 will be constructed with Exodermic deck systems.

All inside lane construction sequencing for the SB bridge will employ traditional construction sequencing, while the outside lane will employ accelerated construction sequencing. All work accomplished in a traditional construction sequence, inside lane on the SB bridge, will be performed in the direction of vehicle travel. All work completed in an accelerated construction sequence, outside lane on the SB bridge, will be performed in the opposing direction of vehicle travel. As previously stated, the purpose for working in the direction opposing travel, during the accelerated construction sequence, is to consider motorist safety by maintaining the permanent features of the oncoming end of the existing guard rail as long as possible. Figure 3-7 shows the lane-span details for the SB bridge with arrows indicating the direction of travel and reconstruction work activity.



Note: Arrows on bridge lane-spans represent the direction work will progress.

Figure 3-7 Southbound Bridge Span Construction Details.

3.3 Data Collection Location

For data collection purposes, only items that are used during construction, located in the activity area, (e.g., bridge deck materials, equipment, labor, and temporary concrete barrier) will be considered for cost, schedule, and traffic data. For this report the activity area is defined to begin at the beginning bridge deck station and end at the end bridge deck station.

3.4 Data Collection

The data that will be collected for each bridge deck replacement method will include the cost, schedule, and traffic data. Cost and schedule have been further subdivided into three work activities: (1) TCB management, (2) demolition, and (3) construction. These activities have the greatest potential for creating a cost or schedule variance between the bridge deck replacement methods and therefore are being recorded independently. Information on each category and procedures for data collection are given in the following sections.

3.4.1 Cost

Cost data will be collected for each bridge deck replacement method constructed. Cost will be collected for each TCB used within the activity area, demolition of existing lane-spans, and construction of each lane-span. This value will represent the total cost of labor, materials, and equipment required to demolish and replace a particular lane-span under consideration.

3.4.1.1 *Temporary Concrete Barrier: Cost*

Cost of temporary concrete barrier (TCB) will include all equipment, material, and labor required to install, rearrange, and remove all TCBs under consideration within the defined activity area. All TCB cost data will be reported in dollars. Because there are four lane-spans per lane, TCB cost assigned to traditional construction sequence lane-spans will be one fourth the total lane cost of initial and final TCB installation and removal. Figure 3-8 shows an example of the installation of TCB along the longitudinal length of the bridge, dividing it into a work space and traffic space.

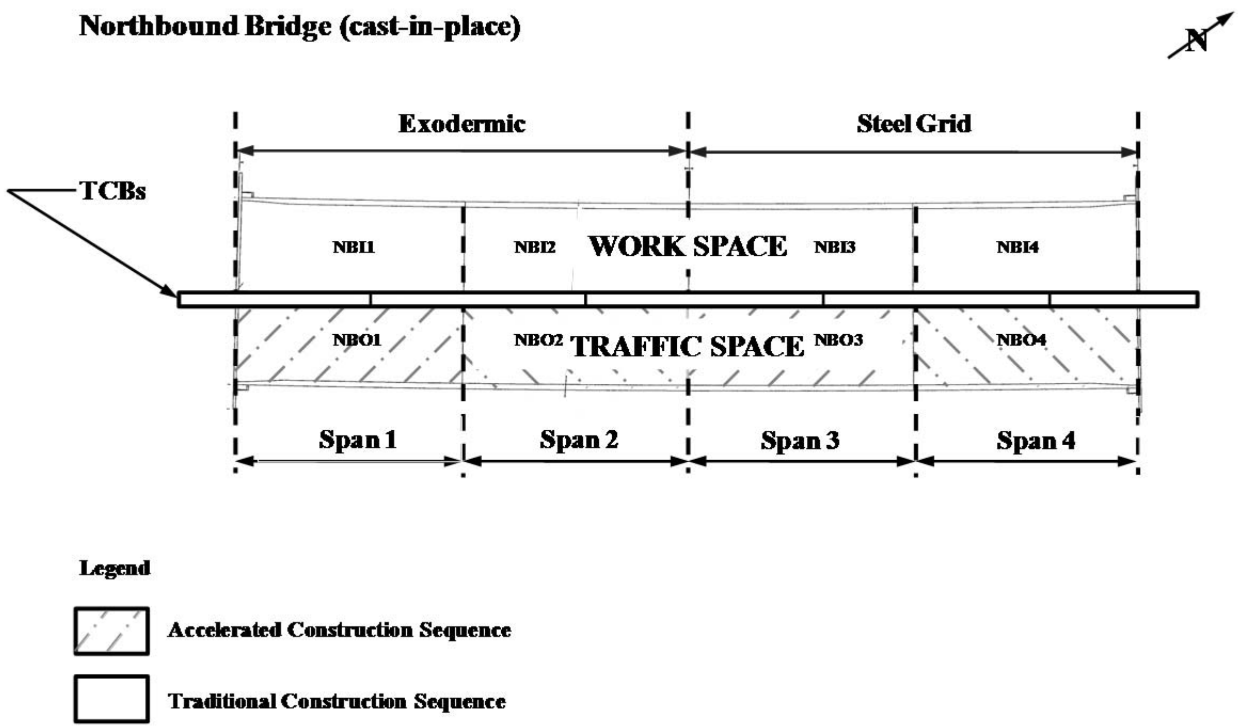
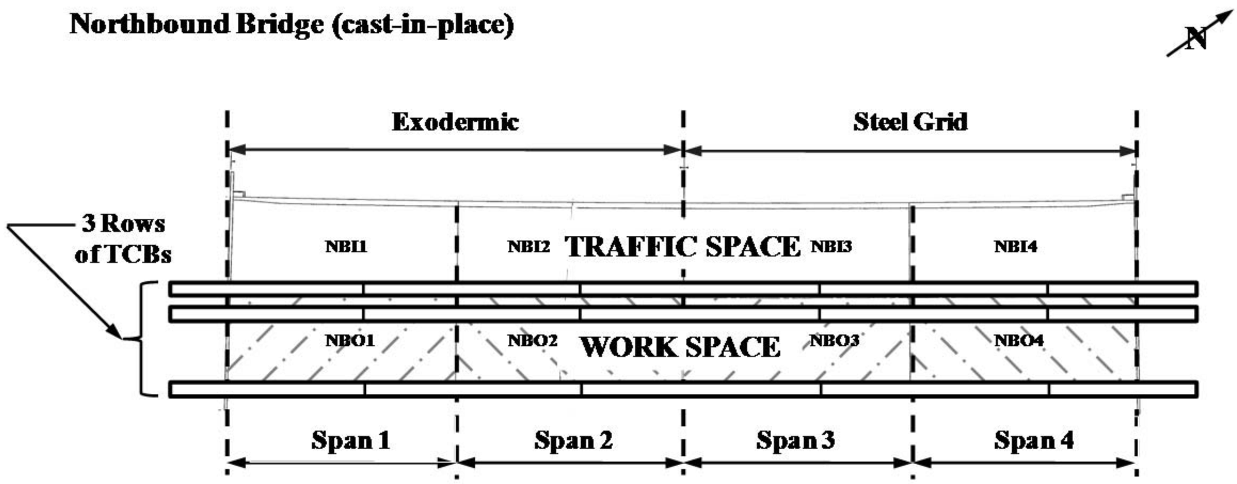
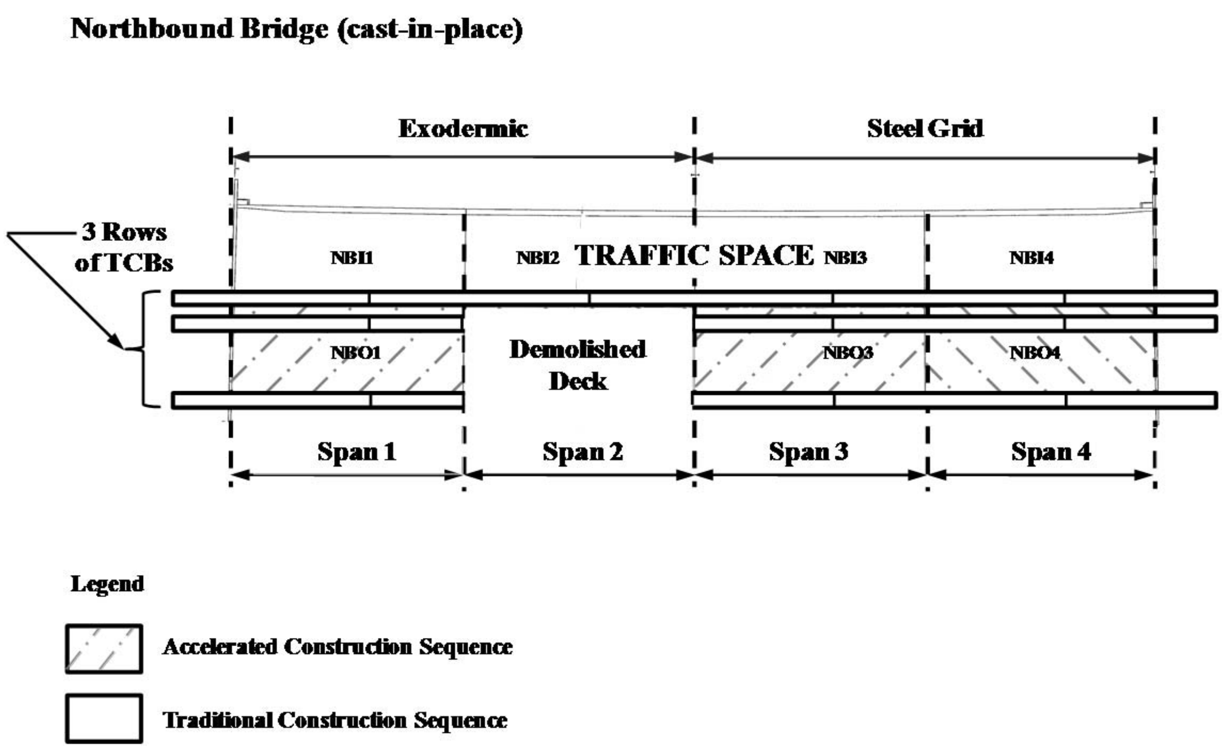


Figure 3-8 Lane Configuration of TCBs for Traditional Construction Sequence.

During the accelerated construction sequencing there will be an initial and final TCB installation and deployment with additional TCB rearrangement for each lane-span. To optimize lane closure and open times, TCB will be rearranged continuously as construction advances from one lane-span to the next. The total TCB cost for a lane-span using an accelerated construction sequence will be one fourth the total lane cost, of initial and final TCB installation and removal, plus the TCB rearrangement cost occurring for individual lane-span demolition and construction activities. Figure 3-9(a) shows an image of an accelerated construction sequence lane with initial TCB installed, while Figure 3-9(b) shows the rearrangement of TCBs on lane-span 2 so demolition and construction can be performed. In example Figure 3-9, after construction is complete the TCBs will be rearranged back onto lane-span 2 and work activity will advance onto lane-span 3.



(a) Lane Configuration of TCBs for the Accelerated Construction Sequencing



(b) Rearrangement of TCBs for the Accelerated Construction Sequence for Demolition

Figure 3-9 Lane Configuration of TCBs for Accelerated Construction Sequencing before and After Lane-Span Demolition.

To keep track of all costs and fees for TCBs, Table 3-2 has been developed. The table is ordered by deck system type, construction sequence, and casting technique with the appropriate lane-span identification. The researcher will record the total cost for initial and final TCB installation and removal for an entire lane in the column title 'Lane TCB'. The 'Lane TCB' cost; will be divided by four and recorded in the column labeled '¼ Lane TCB'. This fee represents the shared cost for the initial deployment and removal of TCBs that are common amongst the different bridge deck replacement methods. For traditional construction sequencing the 'Total TCB' cost will be the same as the '¼ Lane TCB' cost. For accelerated construction sequencing the cost for TCB rearrangement must be recorded and included in the total TCB cost. The total TCB cost will be the addition of the '¼ Lane TCB' and the 'TCB Rearrangement' and will be written in the column titled 'Total TCB'.

Table 3-2 Northbound/Southbound Bridge TCB Cost Data Collection Summary

NORTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane Span ID	COST ($) Lane TCB	COST ($) ¼ Lane TCB	COST ($) TCB Rearrangement	COST ($) Total TCB
Exodermic	Traditional	CIP	NBI1			No Rearrangement Required	
			NBI2				
	Accelerated	CIP	NBO1				
			NBO2				
Steel Grid	Traditional	CIP	NBI3			No Rearrangement Required	
			NBI4				
	Accelerated	CIP	NBO3				
			NBO4				

SOUTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane Span ID	COST ($) Lane TCB	COST ($) ¼ Lane TCB	COST ($) TCB Rearrangement	COST ($) Total TCB
NCHRP	Traditional	PC	SBI1			No Rearrangement Required	
			SBI2				
	Accelerated	PC	SBO1				
			SBO2				
Exodermic	Traditional	PC	SBI3			No Rearrangement Required	
			SBI4				
	Accelerated	PC	SBO3				
			SBO4				

3.4.1.2 *Demolition: Cost*

The demolition cost for each lane-span will be reported by the contractor in dollars. The cost of demolition will include all material, labor, and equipment used in the demolition of each existing lane-span. Only cost associated with actual demolition of the bridge deck should be considered. Any demolition or preparation work performed on the bridge below the deck area is beyond the scope of this research. Table 3-3 has been created to aid researchers in the collection of demolition cost data.

Table 3-3 Northbound/Southbound Bridge Demolition Cost Data Collection Summary

NORTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane-Span ID	COST ($) Demolition
Exodermic	Traditional	CIP	NBI1	
			NBI2	
	Accelerated	CIP	NBO1	
			NBO2	
Steel Grid	Traditional	CIP	NBI3	
			NBI4	
	Accelerated	CIP	NBO3	
			NBO4	

SOUTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane-Span ID	COST ($) Demolition
NCHRP	Traditional	PC	SBI1	
			SBI2	
	Accelerated	PC	SBO1	
			SBO2	
Exodermic	Traditional	PC	SBI3	
			SBI4	
	Accelerated	PC	SBO3	
			SBO4	

3.4.1.3 *Construction: Cost*

The cost to construct each deck system for each lane -span will be reported by the contractor in dollars. This cost will include all labor, materials, and equipment required to construct the deck system in question. The following Table 3-4 has been provided to collect construction related data for each lane-span.

Table 3-4 Northbound/Southbound Bridge Demolition Cost Data Table

NORTHBOUND				
Deck System	**Construction Sequence**	**Casting Technique**	**Lane-Span ID**	**COST ($)** **Construction**
Exodermic	Traditional	CIP	NBI1	
			NBI2	
	Accelerated	CIP	NBO1	
			NBO2	
Steel Grid	Traditional	CIP	NBI3	
			NBI4	
	Accelerated	CIP	NBO3	
			NBO4	

SOUTHBOUND				
Deck System	**Construction Sequence**	**Casting Technique**	**Lane-Span ID**	**COST ($)** **Construction**
NCHRP	Traditional	PC	SBI1	
			SBI2	
	Accelerated	PC	SBO1	
			SBO2	
Exodermic	Traditional	PC	SBI3	
			SBI4	
	Accelerated	PC	SBO3	
			SBO4	

3.4.2 Schedule

Scheduling for all lane-span activities will be recorded in hours. This time will represent the total time required to reproduce the activity under consideration. Scheduling will be recorded independently for TCB, demolition, and construction. Scheduling tables have been provided in each scheduling subsection to aid in the collection of durations.

3.4.2.1 *Temporary Concrete Barriers: Schedule*

The duration or total time of project spent installing and removing TCBs will be recorded in hours. Total lane duration of initial deployment and final removal of TCBs will be shared by all four lane-spans in the activity lane. The duration for installation and removal of TCBs for traditional construction sequence lane-spans will be one fourth the total duration for deployment and removal of TCBs. The previous Figure 3-8 shows the typical lane configuration of TCB deployment for a traditional construction sequence within the activity area.

For accelerated construction sequence bride deck replacement methods, the total duration for deployment, rearrangement, and removal of TCBs will be one fourth the total duration of initial deployment and final removal of TCBs, plus the duration required to rearrange TCBs during individual lane-span construction. See Figure 3-9 in the previous section for a typical accelerated construction sequence setup.

The start and finish time for all activities will be documented in the ALDOT inspector project diaries. EarthCam construction cameras may be used to verify times reported by the contractor to ensure accuracy. Table 3-5 is provided below for documenting all start and finish times and to calculate total durations for all TCB deployment, rearrangement, and removal activities. Durations will be reported as the period that elapsed between the start and finish time. For traditional construction sequence the lane-span TCB duration is one quarter the total lane TCB duration. There are no TCB rearrangement times in traditional construction sequencing.

Table 3-5 Northbound/Southbound Bridge TCB Schedule Data Collection Summary

NORTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane Span ID	Lane TCB				Rearrangement TCB			Total (hrs)
				Start Time	Finish Time	Duration (hr)	¼ Duration (hr)	Start Time	Finish Time	Durations (hrs)	
Exodermic	Traditional	CIP	NBI1					No Rearrangement Required			
			NBI2								
	Accelerated	CIP	NBO1								
			NBO2								
Steel Grid	Traditional	CIP	NBI3					No Rearrangement Required			
			NBI4								
	Accelerated	CIP	NBO3								
			NBO4								

SOUTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane Span ID	Lane TCB				Rearrangement TCB			Total (hrs)
				Start Time	Finish Time	Duration	¼ Duration	Start Time	Finish Time	Durations (hrs)	
NCHRP	Traditional	PC	SBI1					No Rearrangement Required			
			SBI2								
	Accelerated	PC	SBO1								
			SBO2								
Exodermic	Traditional	PC	SBI3					No Rearrangement Required			
			SBI4								
	Accelerated	PC	SBO3								
			SBO4								

3.4.2.2 *Demolition: Schedule*

The duration of time spent demolishing existing decking will be collected by the project inspectors in hours and will be recorded in their diaries for each individual lane-span. This data will be collected by recording the start and finish time of demolition activity for each lane-span. The duration will be reported as the time elapsed between start and finish times. The EarthCam video surveillance equipment may be used to verify all time values recorded. Table 3-6 should be used to collect and document start and finish times and calculate lane-span demolition durations.

Table 3-6 Northbound/Southbound Bridge Demolition Schedule Data Collection Summary

NORTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane-Span ID	Demolition		
				Start Time	Finish Time	Durations (hrs)
Exodermic	Traditional	CIP	NBI1			
			NBI2			
	Accelerated	CIP	NBO1			
			NBO2			
Steel Grid	Traditional	CIP	NBI3			
			NBI4			
	Accelerated	CIP	NBO3			
			NBO4			

SOUTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane-Span ID	Demolition		
				Start Time	Start Time	Durations (hrs)
NCHRP	Traditional	PC	SBI1			
			SBI2			
	Accelerated	PC	SBO1			
			SBO2			
Exodermic	Traditional	PC	SBI3			
			SBI4			
	Accelerated	PC	SBO3			
			SBO4			

3.4.2.3 *Construction: Schedule*

Construction duration will follow demolition duration and include all the time required to form, pour, place, and cure each bridge deck replacement method. The construction start time for each lane-span will be recorded by the inspector and reported in their daily inspection reports.

Construction will be considered finished once the bridge deck replacement method is identified as structurally capable of sustaining motor vehicle travel. This period may be prior or post permanent guard rail installation. The time that the lane-span is designated as structurally sound will be identified and reported by the inspector as the finish time of construction. The duration of construction for each bridge deck replacement method will be reported as the elapsed time from start to finish of construction activity. Table 3-7 should be used to track the start and finish time of construction activity and to calculate the bridge deck replacement method construction durations.

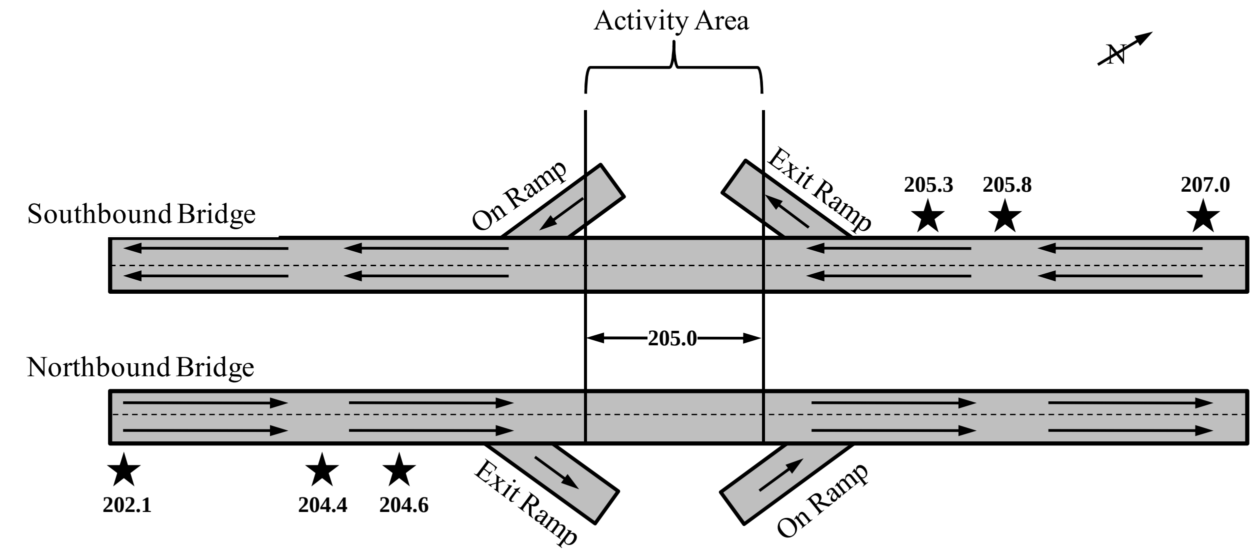
Table 3-7 Northbound/Southbound Bridge Construction Schedule Data Collection Summary

NORTHBOUND						
Deck System	**Construction Sequence**	**Casting Technique**	**Lane-Span ID**	**Construction**		
				Start Time	**Finish Time**	**Durations (hrs)**
Exodermic	Traditional	CIP	NBI1			
			NBI2			
	Accelerated	CIP	NBO1			
			NBO2			
Steel Grid	Traditional	CIP	NBI3			
			NBI4			
	Accelerated	CIP	NBO3			
			NBO4			

SOUTHBOUND						
Deck System	**Construction Sequence**	**Casting Technique**	**Lane-Span ID**	**Construction**		
				Start Time	**Start Time**	**Durations (hrs)**
NCHRP	Traditional	PC	SBI1			
			SBI2			
	Accelerated	PC	SBO1			
			SBO2			
Exodermic	Traditional	PC	SBI3			
			SBI4			
	Accelerated	PC	SBO3			
			SBO4			

3.4.3 Traffic Data

Prior to construction activity on the I-59 bridges, "before" construction traffic values were collected using RTMS G4 microwave radar traffic sensing devices. "Before" construction traffic values included traffic volumes and speeds on the I-59 bridges during normal two lane operating conditions. The RTMS G4 devices were deployed in a sidefire position along the roadway in three locations for traffic data collection. Data were collected over a seven-day week for both the NB and SB bridges. The trailers were deployed twice prior to construction, once for the NB direction and once for the SB direction in advance of the bridges. The traffic collections on the NB bridge were at mile markers 202.1, 204.4, and 204.6. The traffic collections on the SB bridge was located in the vicinity of mile marker 205.3, 205.8, and 207.0. These collection locations were used to capture traffic prior to and in the transition areas. In Figure 3-10 the trailer locations are represented by stars for the NB and SB bridges respectively. The directions of vehicle travel and the orientation of the entrance and exit ramps have been identified.



*Not to scale

Figure 3-10 RTMS G4 Traffic Collection Locations.

The data were separated into two vehicle classifications, passenger vehicles and trucks, for later RUC estimating. The RTMS units identified classification by vehicle length. Passenger vehicle is any vehicle that was less than 46.9 ft (14.2m) and truck is any vehicle greater than 46.9 ft (14.2m). This vehicle classification was determined from the AASHTO publication "Geometric Design of Highways and Streets". From the collected traffic data for the NB and SB bridges, average vehicle volumes and speeds were calculated for three possible closure scenarios. The three possible work closure scenarios are (1) a weekday closure with a full 24 hour closure, (2) a weeknight closure with a 12 hour work period (e.g., closure occurs on Tuesday at 6:00 pm and reopens on Wednesday at 6:00 am), (3) a weekend closure (i.e. closure occurs on Friday at 6:00 pm and reopens to traffic Monday at 6:00 am). The weekend and weeknight closures will be possible with TCB rearrangement. The volume and speed data calculated from the RTMS G4 traffic data collection can be seen on Table 3-8. The weekend volume is based on a 60 hour weekend period. The values in Table 3-8 represent a typical weekday, weeknight, and weekend vehicle volumes and speeds for the six individual collection points collected with the RTMS G4 devices. To calculate weekday volumes and speeds, the average vehicle volumes and speeds for Tuesday, Wednesday, and Thursday were used. Likewise, the non-peak vehicle volumes (i.e. 6:00 pm to 6:00 am) were used for Tuesday, Wednesday, and Thursday to calculate weeknight vehicle volumes and speeds. Weekend vehicle volumes and speeds were calculated as the average of the six RTMS G4 collections points for the period of Friday at 6pm to Monday at 6am.

Table 3-8 Northbound/Southbound Traffic Data by Work Closure Period

Time of Day	Vehicle Volume			Average Speed (mph)	
	Passenger Vehicle	Truck	Total	Passenger Vehicle	Truck
Weekday (24hr)	7,974	4,164	12,138	75	77
Weeknight (12hr)	2,314	1,328	3,644	66	70
Weekend (60hr)	27,120	5,984	33,104	77	79

During the I-59 project the RTMS G4 devices will be deployed again at the predetermined locations to capture traffic data (vehicle volumes and the corresponding traveling speeds). This data will be compared to the before construction values gathered prior to the start of the I-59 project to determine road user costs (RUC). Further details will be provided for calculating RUC in Chapter 4.

3.5 Summary of Methodology & Data Collection

For each bridge deck replacement method constructed on the I-59 project, four areas required data to be collected. Those four areas include: (1) lane-span dimensions (length of lane-span, areas of lane-span both existing and post-construction), (2) cost, (3) schedule, (4) traffic data (volumes and speeds). Cost and schedule data have been further subdivided into TCBs, demolition, and construction activity. Using the bridge dimensions and the American Association of State Highway and Transportation Officials (AASHTO) publication "User Benefit Analysis for Highways Manual" three construction performance factors will be created, those three factors being, (1) unit cost, (2) production rate, and (3) RUC. From the construction performance factors, statistical analyses will be performed using nested analysis of variance (ANOVA) statistical testing. All subsection raw data tables described and found in this chapter should be compiled into one summary table as seen in Table 3-9 below for use in Chapter 4.

Table 3-9 Northbound/Southbound Bridge Comprehensive Raw Data Summary

NORTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane Span ID	Span Length	Construction Area (ft^2)		Cost ($)			Schedule (hrs)			T.D.
					Exist	Post	TCB	Demo	Const	TCB	Demo	Const	Veh Vol
Exodermic	Traditional	CIP	NBI1	56.83									
			NBI2	56.00									
	Accelerated	CIP	NBO1	56.83									
			NBO2	56.00									
Steel Grid	Traditional	CIP	NBI3	56.00									
			NBI4	56.83									
	Accelerated	CIP	NBO3	56.00									
			NBO4	56.83									

SOUTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane Span ID	Span Length	Construction Area (ft^2)		Cost ($)			Schedule (hrs)			T.D.
					Exist	Post	TCB	Demo	Const	TCB	Demo	Const	Veh Vol
NCHRP	Traditional	PC	SBI1	56.83									
			SBI2	56.00									
	Accelerated	PC	SBO1	56.83									
			SBO2	56.00									
Exodermic	Traditional	PC	SBI3	56.00									
			SBI4	56.83									
	Accelerated	PC	SBO3	56.00									
			SBO4	56.83									

Note:
*Exist – Existing Construction Area
*TCB – Temporary Concrete Barrier
*Demo - Demolition
*Const – Construction
*T.D. Veh Vol – Traffic Data Vehicle Volume

Chapter 4: Data Analysis Techniques

4.1 Introduction

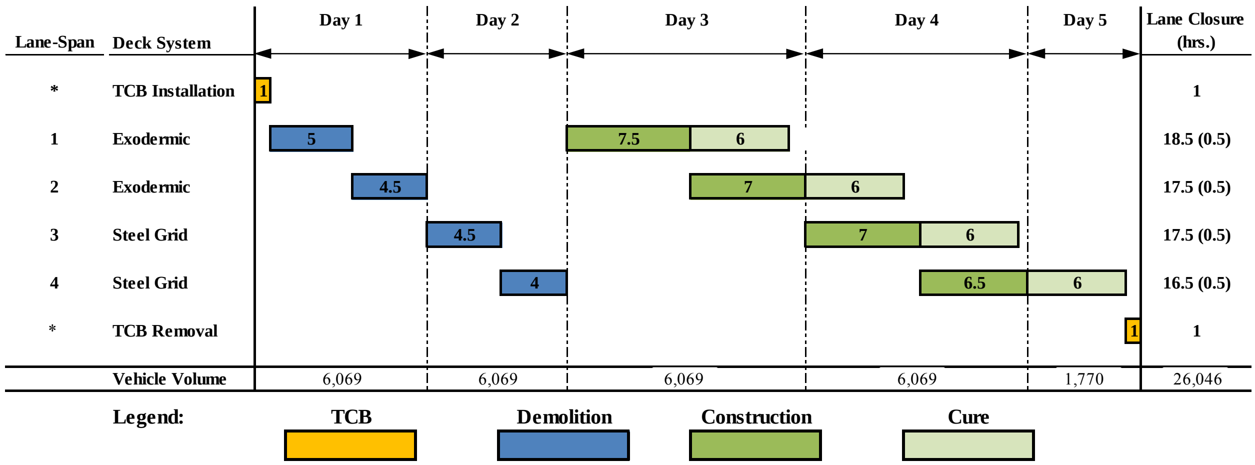
The purpose of this chapter is to develop techniques to be applied to perform data analyses on data collected during the construction of the I-59 bridges in Collinsville. The analysis of the data collected will be used to determine the interaction between bridge deck replacement methods and the construction performance factors being tested. Results will be compiled for the I-59 project that summarizes all analyses performed. From the results it will be possible to infer which bridge deck replacement methods would be most viable on future bridge projects, based on geographic, project specific and monetary constraints. The results will be demonstrated and interpreted in three main sections, (1) Gantt charts, (2) summary of construction performance factors, and (3) nested analysis of variance (ANOVA) tests with interaction tree diagrams. The following sections will outline the steps and analyses required to compile the results mentioned above.

4.2 Gantt Charts

Scheduling data will be used, from the I-59 project, to create Gantt (bar) charts for each lane (i.e., inside or outside lane) under construction. The Gantt charts will show the construciton process from beginning to end and they will be used to compare different construction sequence lane closure strategies. The Gantt charts will graphically depict the total lane closure period(s), work performed during peak and non-peak hours, vehicle volumes, and the flow of the scheduled tasks. This will highlight the advantages and disadvantages of traditional and accelerated construction sequence scenarios.

Total lane closure duration will be the period of time that the lane being reconstructed is closed from vehicular traffic until it is reopened. In traditional construction sequencing, this time period will be continuous from the deployment of temporary concrete barriers (TCBs) to final TCB removal. In contrast, accelerated construction sequencing lane closures will occur intermittently as the lane opens and closes for each reconstruction activity to be performed on individual lane-spans. The total lane closure for the accelerated construction sequence will be the sum of the closures and rearrangement of TCBs for all individual lane-spans to be reconstructed, plus the initial and final closures associated with TCB deployment and removal.

Figure 4-1 illustrates a typical Gantt chart for a cast-in-place (CIP) traditional construction sequence lane closure for the I-59 project.



Note:
* The work period for this example is a 12 hour work day
* Only work activity is shown, but each day represents a 24 hour lane closure unless noted otherwise
* Number in parenthesis in the 'Lane Closure' column are shared TCB values

Figure 4-1 Typical Traditional Construction Sequence Gantt Chart.

Figure 4-1 illustrates the activities TCB deployment/removal, demolition, construction, and concrete curing time. For CIP casting techniques the curing time will be absorbed into the construction aspect of the performance factors. The number values on the various bars indicate hours spent on that particular work activity. The work schedule developed in this example was for a typical, 12 hour work period during daytime conditions. However, it should be noted that each day interval represents a 24 hour lane closure period when employing traditional construction sequencing.

The TCB deployment and TCB removal is a shared value, divided equally among all lane spans in the reconstruction lane. The shared time is indicated in parenthesis next to the lane closure times for each bridge deck replacement method. Directly below the TCB removal activity are the reported average vehicle volumes for each work period. In the above example, the weekday traffic volume of 6,069 vehicles from Table 3-8 was used for each 24 hour period. In the example, the final day (Day 5) consisted only of 7 hours of work activity. A ratio of a 24 hour vehicle volume was applied to a 7 hour work period to obtain a vehicle volume of 1,770. Work activity is considered complete at the end of Day 5 and all TCB have been removed from the bridge no longer affecting the motoring public.

Work could occur during weekdays, weekends, or weeknights. The decision as to which work schedule will be used, will be decided by ALDOT and the contractor at the time of actual construction of the I-59 project. Each work scenario will have a different effect on the total lane closure period. An example problem will be created in Chapter 5 that assumes a traditional construction sequence lane, with a weekday closure, and an accelerated construction sequence lane, with a weekend closure, to determine the effect of the bridge deck replacement methods on the construction performance factors of: unit cost, production rate, and RUC.

4.3 Normalizing Collected Data

Before analysis, the raw data collected must be normalized into the construction performance factors: unit cost, production rate, and RUC. For this particular projects, normalizing is required and is a process which accounts for the slight differences in areas so comparisons can be made between the construction performance factors. Cost and schedule data will be normalized by the lane-span geometry to create unit costs and production rates. RUC will be estimated with the aid of the RTMS G4 data collected and guidelines from the American Association of State Highway and Transportation Officials (AASHTO)"User and Non-User Benefit Analysis For Highways" manual.

Normalizing the collected data is performed for two reasons: (1) it accounts for the difference in inside and outside lane areas, and (2) it allows the research to be applicable to similar scale bridge deck replacement projects for future comparisons. As discussed in Chapter 3, due to the location of the construction joint, the inside and outside lane areas are different. On both bridges the inside lane is roughly 8 ft (2.4 m) smaller than the outside lane. If normalizing were not performed it would not be possible to compare the cost and schedule data of each bridge deck replacement method for each individual lane-span.

4.3.1 Unit Cost

The unit cost represents the cost in (\$/ft or ft^2), normalized by the dimensions of the bridge , required to produce a bridge deck replacement method on one lane-span of the I-59 bridges. Unit cost has been independently calculated for TCB, demolition, and construction activity.

TCB unit cost is calculated as the total cost spent for concrete barriers for a lane-span divided by the linear length of the lane-span. The TCB unit cost is reported in dollars per foot (\$/ft). Equation 4-1 below shows the calculation for determining TCB unit cost.

$$\text{TCB Unit Cost}\left(\frac{\$}{\text{ft}}\right) = \frac{\text{TCB Cost (\$)}}{\text{Lane-Span Length (ft)}} \tag{4-1}$$

Demolition unit cost will be calculated as the total cost for demolition of an individual lane-span divided by the area of existing deck of the lane-span under consideration. The demolition unit cost will be reported in dollars per square foot of existing deck (\$/ft^2). Equation 4-2 will be used to calculate the demolition unit cost.

$$\text{Demolition Unit Cost}\left(\frac{\$}{\text{ft}^2}\right) = \frac{\text{Demolition Cost (\$)}}{\text{Existing Lane-Span Area (ft}^2\text{)}} \tag{4-2}$$

Construction unit cost will be calculated as the total cost required to construct the lane-span under consideration with the appropriate deck system. This cost will include all labor, materials, and equipment that was required to construct a lane-span that was structurally capable of carrying vehicles. The construction unit cost, seen in equation 4-3, will be reported in dollars per square foot of post lane-span area ($\$/ft^2$).

$$\text{Construction Unit Cost}\left(\frac{\$}{\text{ft}^2}\right)=\frac{\text{Construction Cost (\$)}}{\text{Post Lane-Span Area (ft}^2\text{)}} \tag{4-3}$$

4.3.2 Production Rate

Production rate has been independently calculated for TCB, demolition, and construction activity. The production rate will indicate the amount of the construction performance factor that could be reproduced in a period of time.

TCB production rate will be calculated as the linear length of a lane-span divided by the total duration of time spent installing or removing TCB for the lane-span in question. The production rate for TCB will be reported in feet per hour (ft/hr). Equation 4-4 is used to determine a bridge deck replacement method's TCB production rates.

$$\text{TCB Production Rate}\left(\frac{\text{ft}}{\text{hr}}\right)=\frac{\text{Lane-Span Length (ft)}}{\text{TCB Duration (hr)}} \tag{4-4}$$

Demolition production rate will be determined by dividing the existing lane-span area by the total duration spent on the demolition process of a single lane-span. Demolition production rate will be reported in square feet per hour (ft^2/hr). Equation 4-5 is used to calculate demolition production rates.

$$\text{Demolition Production Rate}\left(\frac{\text{ft}^2}{\text{hr}}\right)=\frac{\text{Existing Lane-Span Area (ft}^2\text{)}}{\text{Demolition Duration (hr)}} \tag{4-5}$$

Construction production rate will be calculated by dividing the post construction area by the total duration of the construction period for each lane-span. Construction production rate will be calculated using equation 4-6 and reported in square feet per hour (ft^2/hr).

$$\text{Construction Production Rate}\left(\frac{\text{ft}^2}{\text{hr}}\right)=\frac{\text{Post Lane-Span Area (ft}^2\text{)}}{\text{Construction Duration (hr)}} \tag{4-6}$$

4.3.3 Road User Cost

The traffic data of volumes and speeds collected with the RTMS G4 will be used to determine a RUC for each lane. RUC is a function of the delay experienced per vehicle that travels through the activity area of the I-59 project. For this methodology only the delay aspect of RUC is being considered. Alternative routes are not a part of the RUC for this research. It was assumed that the construction activity would not divert vehicles from using the I-59 bridges. The ALDOT temporary traffic control plan has the potential to create delay to the motoring public traversing the work zone. This delay typically comes in the form of one or both of the following, (1) enforced lower work zone speed limits, and (2) traffic congestion reducing vehicle flow due to the closure of travel lanes. Since the I-59 project is located on a very low-volume interstate segment, the only delay expected to be experienced will come from an enforced lower work zone speed. In a high-volume road network, delay could be expected from both lower work zone speeds and vehicle congestion from lane closures.

RUC is divided into two parts: (1) value of time of the occupants per vehicle and (2) the operating and ownership cost per vehicle. To determine the value of time aspect the researcher must gather average hourly wages by industry type for the geographic location in question. Based on the transportation mode and trip purpose the average hourly wage is adjusted by a percentage factor. Next, the researcher must determine the average vehicle occupancy. This is performed by visual inspection of the vehicles traveling the project location. Average values for the information stated above can be found in Chapter 5 of the AASHTO manual. It is recommended that the AASHTO manual be consulted when estimating all value of time information.

The value of time is determined by the product of the average hourly wage, percentage of hourly wage, and average vehicle occupancy and is reported in dollars per vehicle hour ($/veh-hr). Equation 4-7 below can be used to calculate the value of time per vehicle hour.

$$\text{Value of Time per Hour}\left(\frac{\$}{\text{veh - hr}}\right) = \text{Wage} \times \text{Percentage} \times \text{Occupancy} \tag{4-7}$$

To calculate the operating and ownership cost the following information is required: finance rate, other operating costs per mile (tires, maintenance, etc.), vehicle service life (years), vehicle cost, salvage value at end of service life, and insurance per year. Again, the AASHTO manual offers guidance for estimating all the operating and ownership cost stated. With this information the amortized vehicle cost per hour and the insurance cost per hour can be calculated. The amortized vehicle cost per vehicle hour ($/veh-hr) or the depreciation value is determined by applying equation 4-8. The value 8,760 is a conversion factor used to convert years to hours.

$$\text{Amortized Cost per Vehicle Hour}\left(\frac{\$}{\text{veh - hr}}\right) = \left[\frac{(i\ (P(1+i)^{n} - F)}{(1+i)^{n} - 1)}\right] / 8,760 \tag{4-8}$$

Where:

i = Finance rate

P =Vehicle Cost ($)

F = Salvage Value ($)

n = vehicle life in years

The insurance cost per hour is calculated by simply dividing the insurance cost per vehicle hour by the number of hours in a year. Equation 4-9 is used to determine insurance cost per vehicle hour ($/veh-hr).

$$\text{Insurance Cost per Vehicle Hour}\left(\frac{\$}{\text{veh - hr}}\right) = \frac{\text{insurance cost per year}}{8,760} \tag{4-9}$$

Equation 4-10 is used to calculate the total cost per vehicle hour ($/veh-hr) which is the addition of the value of time, amortized value, and the insurance cost per vehicle hour. This value will be multiplied by the travel time before and during lane closures to determine a final RUC.

$$\text{Total Cost per Vehicle Hour}\left(\frac{\$}{\text{veh -hr}}\right) = \text{Value of Time} + \text{Amortized} + \text{Insurance} \tag{4-10}$$

The travel time for the before lane closure is calculated by dividing the segment length, in feet, by the average travel speed before closure, in miles per hour, of the vehicle classification in question. Likewise, the travel time per vehicle during lane closures is calculated by dividing the segment length, in feet, by the average travel speed during the lane closure, in miles per hour, of the vehicle classification in question. It is expected that the before lane closure average travel speed is greater than the during lane closure travel speed. This will be a result of the regulatory reduced work zone speed limit. Therefore it is expected that the travel time before the lane closure will be less than the travel time during the lane closure. Given the low-volume of the I-59 location, possible delay from queuing will not be considered in this research. Equation 4-11 shows how to calculate the travel time associated with both before and during lane closures. The value 5,280 is a conversion factor used to convert feet to miles, while 3,600 is a conversion factor used to convert hours to seconds. The travel time is reported in seconds.

$$\text{Travel Time (sec)} = \left(\frac{\text{Segment length (ft)}}{5,280}\right) \times \left(\frac{3,600}{\text{Speed (mph)}}\right) \tag{4-11}$$

Once travel time has been determined for both before and during lane closures, the cost per vehicle can be calculated. This is accomplished by multiplying the total cost per vehicle hour, determined with equation 4-10, by the before and during travel time values calculated in Equation 4-11. Equation 4-12 is used to calculate cost per vehicle for both before and during lane closure.

$$\text{Cost per Vehicle}\left(\frac{\$}{\text{veh}}\right) = \left(\frac{\text{Total Cost per veh - hr}}{3,600}\right) \text{x Delay} \tag{4-12}$$

The realized cost per vehicle is calculated by subtracting the cost per vehicle before the lane closure from the cost per vehicle during the lane closure. The realized cost represents the monetary value, had there been no delay from regulatory reduced work zone speed limits, the motorist incurs as a result of the work zone conditions. Equation 4-13 is used to determine the realized cost per vehicle.

$$\text{Realized Cost per Vehicle}\left(\frac{\$}{\text{veh}}\right) = \text{Cost After Lane Closure} - \text{Cost Before Lane Closure} \tag{4-13}$$

To calculate RUC for each lane and vehicle classification, the volume of vehicles that traversed the lane during the construction effort is multiplied by the realized cost per vehicle and the percentage of vehicle classification.

$$\text{Lane RUC (\$)} = \text{Realized Cost} \times \text{Volume} \times \text{Class Percentage} \tag{4-14}$$

The volumes and speeds of the vehicles before construction have already been collected. During the actual I-59 project the RTMS G4 devices will be used to determine the volumes and speeds of vehicles during construction. The RUC will be reported for each lane as a dollar amount ($). Because each lane-span contributes to the total project closure, the total RUC will be shared as a percentage of the total closure for each lane-span. Lane-span closure will be calculated as lane-span duration divided by total lane-span closure multiplied by lane RUC from equation 4-14. See equation 4-15 for lane-span RUC.

$$\text{Lane-Span RUC (\$)} = \left(\frac{\text{Lane-Span Duration (hr)}}{\text{Total Lane-Span Duration (hr)}} \right) \times \text{Lane RUC (\$)} \tag{4-15}$$

A RUC template has been created to aid the researcher in organizing and calculating a RUC for each lane. The template follows the steps detailed in equations 4-7 through 4-14. A blank template is located in Appendix A. In the RUC template, vehicles have been divided into two classifications, passenger vehicles and trucks. Passenger vehicles represent any vehicle shorter than 46.9 ft (14.2m) in length, while trucks are any vehicle greater than 46.9 ft (14.2m) in length.

Once the unit cost, production rate, and RUC have been created, a summary table of the construction performance factors will be compiled. Table 4-1 demonstrates how a summary table of the construction performance factors should be organized.

Table 4-1 Northbound/Southbound Bridge Construction Performance Factors

NORTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane Span ID	Span Length	Construction Area (ft^2) Exist	Post	Unit Cost TCB ($/ft)	Demo ($/$ft^2$)	Const ($/$ft^2$)	Production Rate TCB (ft/hr)	Demo (ft^2/hr)	Const (ft^2/hr)	RUC ($)
Exodermic	Traditional	CIP	NBI1	56.83									
			NBI2	56.00									
	Accelerated	CIP	NBO1	56.83									
			NBO2	56.00									
Steel Grid	Traditional	CIP	NBI3	56.00									
			NBI4	56.83									
	Accelerated	CIP	NBO3	56.00									
			NBO4	56.83									

SOUTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane Span ID	Span Length	Construction Area (ft^2) Exist	Post	Unit Cost TCB ($/ft)	Demo ($/$ft^2$)	Const ($/$ft^2$)	Production Rate TCB (ft/hr)	Demo (ft^2/hr)	Const (ft^2/hr)	RUC ($)
NCHRP	Traditional	PC	SBI1	56.83									
			SBI2	56.00									
	Accelerated	PC	SBO1	56.83									
			SBO2	56.00									
Exodermic	Traditional	PC	SBI3	56.00									
			SBI4	56.83									
	Accelerated	PC	SBO3	56.00									
			SBO4	56.83									

Note:
*Exist – Existing Construction Area
*TCB – Temporary Concrete Barrier
*Demo - Demolition
*Const – Construction
*RUC – Road User Cost

4.4 Nested ANOVA Statistical Procedure

The construction performance factors will be processed with a nested ANOVA statistical test. The ANOVA test will report validity of the model and statistical significance of the bridge deck replacement method on the construction performance factor being tested. From the ANOVA test, interaction tree diagrams will be created. The interaction tree diagrams will graphically explain the model being tested and show the nested location of the construction performance factors in relation to the bridge deck replacement methods.

The I-59 project is a multifactor project with the bridge deck replacement methods being mixed with both shared and independent structure depending on the method under consideration. Three bridge deck replacement methods will be tested and therefore a three stage nested ANOVA design will be developed and modeled accordingly. The nesting was based on the uniqueness or shared attribute of the method under consideration. Methods that were cleary independent were nested closer to a top level while methods that were hard to independantly define were nested deeper in the model. Casting technique was chosen as the first nested level because it is clearly unique to the northbound and southbound bridges. Construction sequence was nested at the second level of the model. Unlike the casting technique the construction sequences, traditional and accelerated construction sequence, are proposed for both the northbound and southbound bridges. However, there did exist a shared aspect in the fact that each bridge's inside lane would be constructed with a traditional construction sequence while the outside lane would be constructed with an accelerated construction sequence. Finally, deck system was nested at the third level because it had the least shared amongst each individual method for each bridge. The Exodermic deck system was shared for both the northbound and southbound bridge while each bridge also received an additional deck system that was independent of the other bridge. Those deck systems being the steel grid on the northbound bridge and the NCHRP on the southbound bridge. The model for the three-stage nested design is as follows in equation 4-15.

$$y(ijkl) = \mu + \alpha_i + \beta_{j(i)} + \gamma_{k(ij)} + \epsilon_{(ijk)l} \quad \begin{cases} i = 1, 2, \ldots, n \\ j = 1, 2, \ldots, n \\ k = 1, 2, \ldots, n \\ l = 1, 2, \ldots, n \end{cases} \tag{4-15}$$

The term y(ijkl)) is the dependent factor of: unit cost, production rate, or RUC. The μ is the mean of the 16 values of the performance factor in question and the $\epsilon_{(ijk)l}$ is the usual nested identically distributed (NID) $(0, \sigma^2)$ error term. For this model, α_i is the effect of the i^{th} casting technique, $\beta_{j(i)}$ is the effect of the j^{th} construction sequence within the i^{th} casting technique, $\gamma_{k(ij)}$ is the effect of the k^{th} deck system within the j^{th} construction sequence and i^{th} casting technique. An assumption of the nested ANOVA test is that the random effects model of the α_i , $\beta_{j(i)}$, and $\gamma_{k(ij)}$ terms are $\alpha_i \sim$ Normal $(0, \sigma_A^2)$, $\beta_{i(j)} \sim$ Normal $\left(0, \sigma_{B|A}^2\right)$, $\gamma_{k(ij)} \sim$ Normal $\left(0, \sigma_{G|B}^2\right)$ respectively. That is to say that as the analysis moves through the nested levels each set of factors at the level is question is treated as normally distributed. The results of the factors are dependent on the stages in which it is nested. If the arrangement of the levels were changed (i.e. if construction sequence was moved to the first level) it could be expected that the ANOVA test would report different results. To understand the nested nature of the ANOVA, Figure 4-2 has been created and shows the typical nested ANOVA interaction tree diagram of the design model being used.

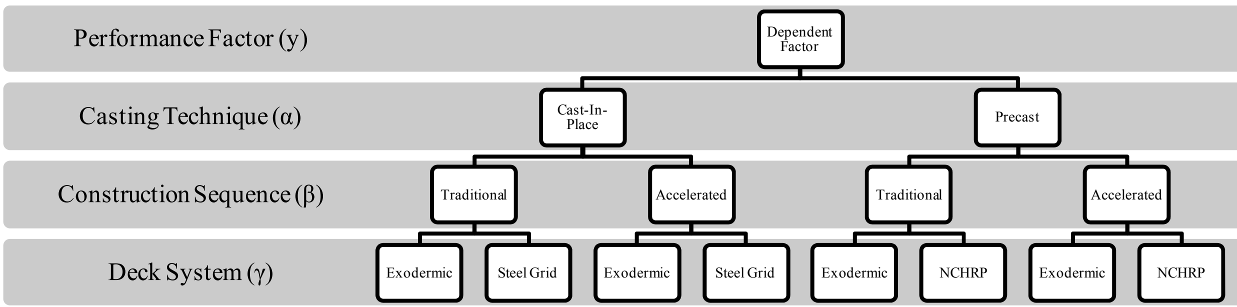


Figure 4-2 Nested ANOVA Interaction Tree Diagram.

The nested ANOVA test will be performed a total of seven times for the seven unique construction performance factors, from Table 4-1, across the different nested levels. Those seven construction performance factors being: (1) TCB unit cost, (2) demolition unit cost, (3) construction unit cost, (4) TCB production rate, (5) demolition production rate, (6) construction production rate, and (7) RUC.

The null hypothesis (H_0) will test that the mean value of the construction performance factor in question, regardless of path selected to the deck system level, are equal. This is to say that the bridge deck replacement methods have no statistical significant difference on the mean value of the factor being tested. The alternative hypothesis (H_a) will test that the path selected does result in a statistical significant difference in the mean value of the construction performance factor in question. Table 4-2 summarizes the construction performance factors and the null and alternative hypotheses that will be tested in the nested ANOVA.

Table 4-2 Nested ANOVA Null and Alternative Hypothesis Test for Construction Performance Factors

Construction Performance Factor	Null Hypothesis (H_0)	Alternative Hypothesis (H_a)
1. TCB Unit Cost	$\mu_1 = \cdots = \mu_8$	not all μ_i are equal
2. Demolition Unit Cost	$\mu_1 = \cdots = \mu_8$	not all μ_i are equal
3. Construction Unit Cost	$\mu_1 = \cdots = \mu_8$	not all μ_i are equal
4. TCB Production Rate	$\mu_1 = \cdots = \mu_8$	not all μ_i are equal
5. Demolition Production Rate	$\mu_1 = \cdots = \mu_8$	not all μ_i are equal
6. Construction Production Rate	$\mu_1 = \cdots = \mu_8$	not all μ_i are equal
7. RUC	$\mu_1 = \cdots = \mu_8$	not all μ_i are equal

For each test performed, an ANOVA statistical table and an interaction tree diagram will be produced. The ANOVA statistical table will report the p-value for each bridge replacement method and the R^2 value for the model being tested.

The p-value will identify the effect that a bridge deck replacement method has on the overall construction performance factor being tested. Because of the limited data points for this experiment, a p-value of 0.05 or smaller will be identified as having a statistically significant difference on the mean value of the performance factor. That is to say that if this project was reproduced with the same bridge deck replacement methods on a similar scale project, 95 % of the future construction performance factors would be within ± 1.96 standard deviations of the mean of the construction performance factors that were analyzed in this research. The R^2 value reports the goodness-of-fit of the model. A goodness-of-fit statistic is a quantity that measures how well a model explains a given set of data. The acceptable tolerance of the goodness-of-fit for this research is set at a value of 0.60, where any model that results in an R^2 value below 0.60 will be classified as an inaccurate model and researchers can not accurately draw any conclusions from the accompanied p-values. The R^2 value of 0.60 is generally accepted in statistics as a threshold for goodness-of-fit and was seen in the literature review as used by researchers performing comparison analysis, specifically Chan and Kumaraswamy.

Interaction tree diagrams will be created to give a reference for the magnitude of cost in the ANOVA test. Under each node on the interaction tree diagram the mean and standard deviation will be presented. On the far right of the interaction tree diagram the p-value, determined in the ANOVA test, will be reported. ANOVA statistical table and interaction tree diagram will be described in more detail in the hypothetical example problem produced in the following chapter.

4.5 Summary of Data Analysis Techniques

To determine the interaction between bridge deck replacement methods and construction performance factors on the I-59 project, steps for analysis have been outlined. From the analyses, results for the bridge deck replacement methods can be compiled. The results will be divided into three main categories (1) Gantt charts, (2) summary of construction performance factors, and (3) nested ANOVA tests with interaction tree diagrams,. From the results it will be determined if all or any of the bridge deck replacement methods have a statistical significant impact of the mean value of the construction performance factors being tested.

Gantt charts will be constructed using scheduling and vehicle volumes collected. No normalizing or transformation of the data will be required at that time. The Gantt charts give a graphical representation of the work activities and help explain the logical order of construction.

To develop construction performance factors, the raw data that are to be collected must be normalized before actual analyses can be applied. Normalizing will be accomplished on cost and schedule by using the bridge dimensions. From this we will be able to create a unit cost and a production rate for each of the three subparts: TCB, demolition, and construction. To create the RUC, volumes and speeds must be collected both before and after lane closures. This will be accomplished with the RTMS G4 devices. The previously mentioned AASHTO manual will be referenced with the volume and speed values collected, to determine a final RUC per lane. The RUC per lane-span will be calculated as a ratio of contribution of a lane-span to the total lane closure.

Nested ANOVA tests can be performed after the raw data has been normalized into the construction performance factors of unit cost, production rate, and RUC. ANOVA tests will be performed seven times, once for each individual construction performance factor. From the analyses, p-values and R^2 values will be reported in conjuction with an interaction tree diagram for each test. The p-value will be used to report whether a bridge deck replacement method has a statistical significant impact on the overall construction performance factor in question. The R^2 value will report the goodness-of-fit of the nested ANOVA model. For this research, a p-value of 0.05 or lower will be considered as statistically significant. An R^2 value of 0.60 or greater will be seen as a model that fits well enough to use the corresponding p-value to conclude statistical significance.

This research was originally intended to be conducted in conjunction with the actual I-59 project. However, due to setbacks beyond the control of this research team, actual construction was not able to be accomplished. To outline in greater detail the methodology detailed in this research an example problem will be produced in the following chapter. The example problem will guide the reader through all the methodologies, data collection, analyses, and results outlined in the previous chapters.

Chapter 5: Application of Methodology

5.1 Introduction

A hypothetical example scenario has been created to demonstrate the applicability of the methodology and statistical analysis outlined in Chapters 3 and 4 of this report. The following example will be applied to the proposed I-59 project using hypothetical construction schedules, durations, and construction costs, as a result of the actual I-59 project being delayed. The purpose of the example is to demonstrate the application of the analytical procedures developed which are used to determine the effect, using statistical testing, that the bridge deck replacement methods have on the three selected construction performance factors: (1) unit cost, (2) production rate, and (3) road user cost (RUC). The elements of each bridge deck replacement method that are being used in the analyses include: type of deck system, construction sequence, and casting technique. The bridge dimensions and lane-span identification numbers used throughout the example are identical to the actual I-59 project to be constructed in the future. Figure 5-1 shows the details of the northbound (NB) and southbound (SB) bridges used in this example. The deck system, construction sequence, casting technique, direction of vehicle travel, and lane-span identification numbers have been labeled for each bridge and are shown on Figure 5-1.

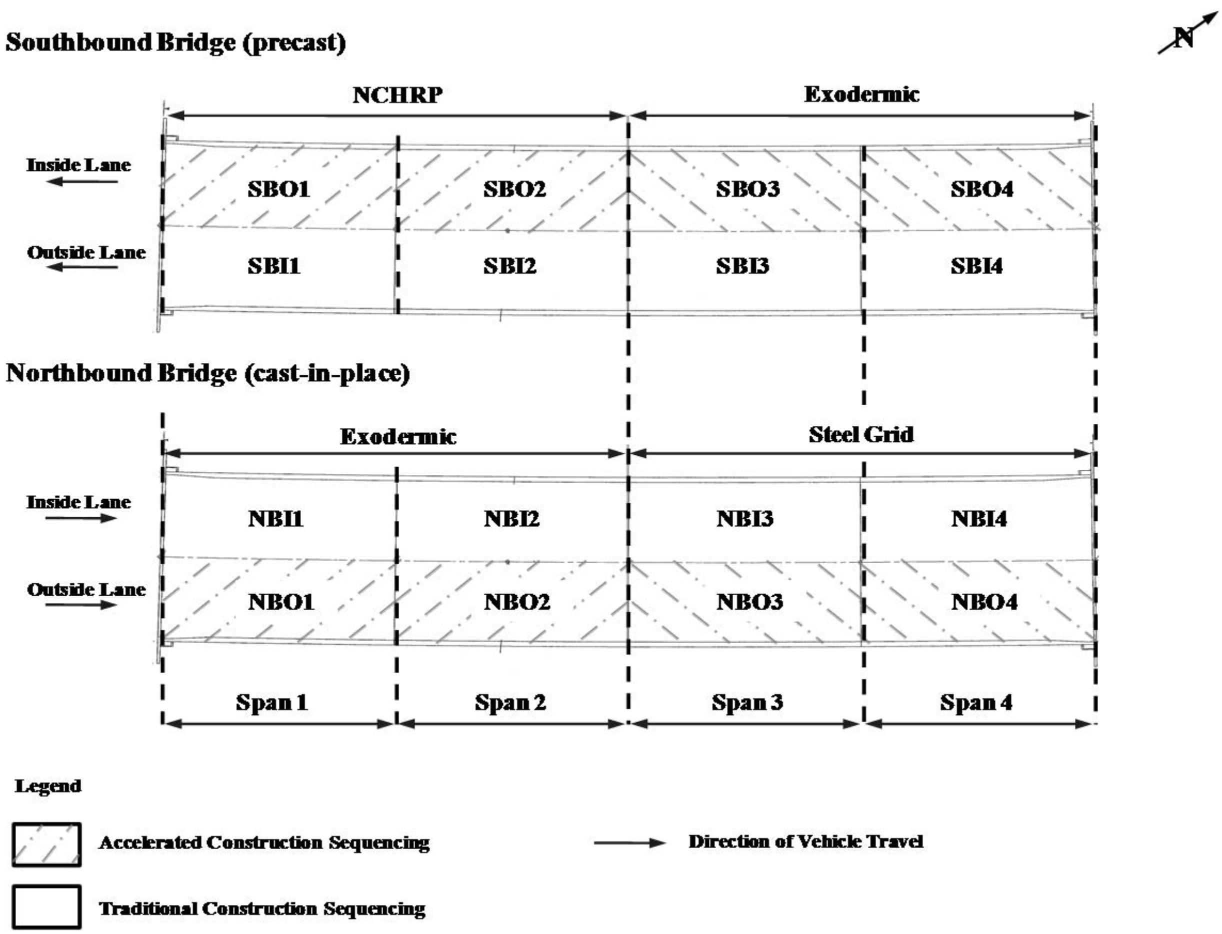


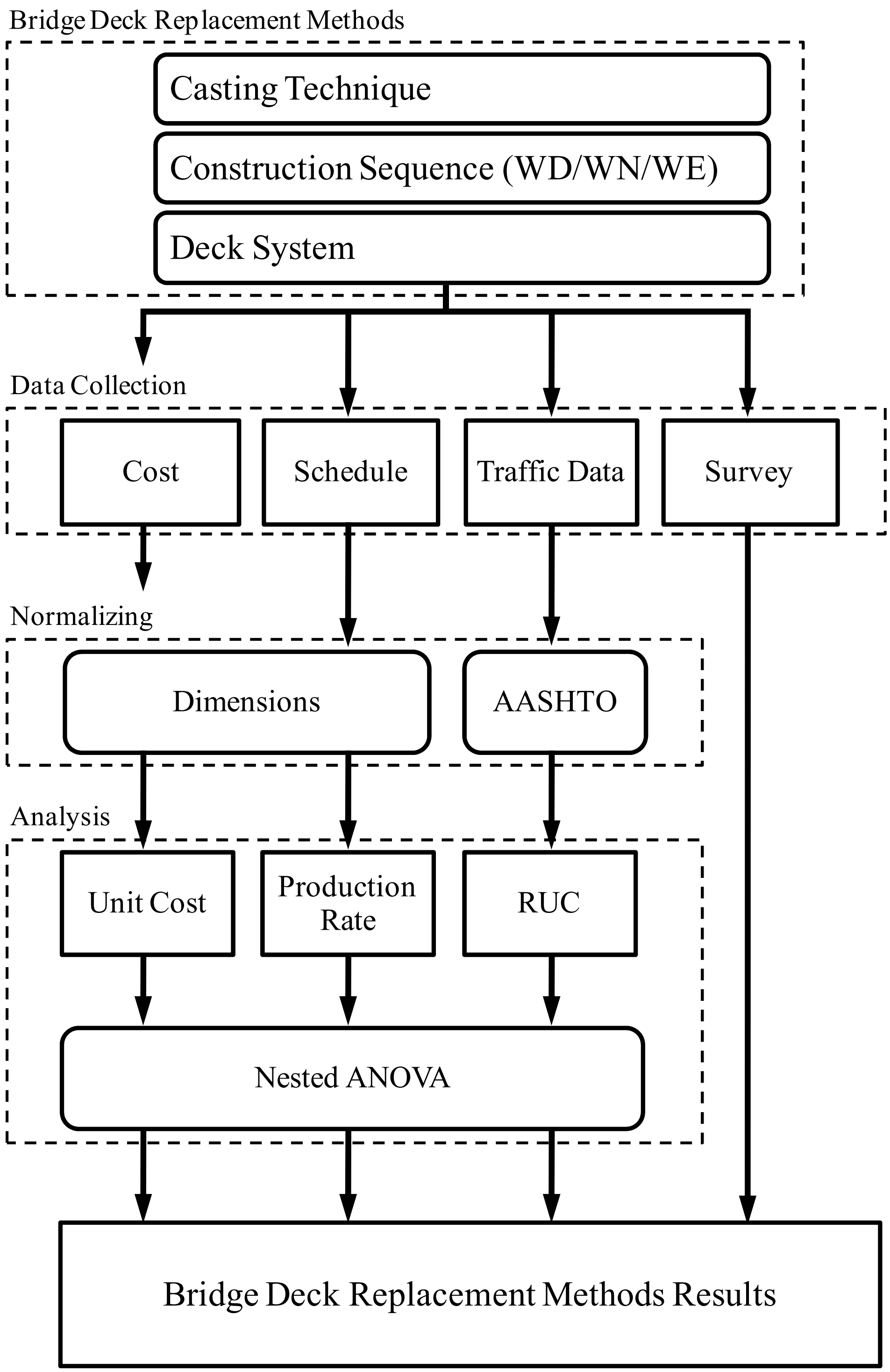
Figure 5-1 Plan View of the I-59 Project Divided into Lanes and Lane-Spans.

For traditional construction sequence lane reconstruction, all durations values are based on an assumed 12 hour, daytime work period. For accelerated construction sequence lane reconstruction, a work closure period of Friday night at 6pm to Monday morning at 6am was assumed. The weekend vehicle volumes are based off a typical 60 hour weekend work period and will be adjusted accordingly. Table 5-1 shows volumes and speeds of both passenger vehicles and trucks that were collected using the RTMS G4 devices.

Table 5-1 Northbound/Southbound Traffic Data by Work Closure Period

Time of Day	Vehicle Volume			Speed (mph)	
	Passenger Vehicle	Truck	Total	Passenger Vehicle	Truck
Weekday (24hr)	7,974	4,164	12,138	75	77
Weeknight (12hr)	2,314	1,328	3,644	66	70
Weekend (60hr)	27,120	5,984	33,104	77	79

Figure 5-2 is the project flow chart that will be followed throughout the example problem. Since this is a hypothetical example problem, the first step will be to develop raw, hypothetical cost, schedule, and traffic data. After the establishment of the hypothetical raw data, the data analysis procedures outlined in the thesis will be followed for data collection, data normalization, statistical analyses, and reporting of results. The report containing the results of the analyses will state the effect that each bridge deck replacement method has on the construction performance factors. The following is a detailed example problem showcasing the applicability of the methodology described above.



Note:
*WD - Weekday Lane Closure Scenario
*WN - Weeknight Lane Closure Scenario
*WE – Weekend Lane Closure Scenario

Figure 5-2 Project Flow Chart For Evaluating Bridge Deck Replacement Methods.

5.2 Raw Data Development

To perform an example problem, hypothetical raw data had to be developed for cost, schedule, and traffic data. Actual bridge dimensions from the I-59 project have been used in the following example. Any other similarities that exist between this example data and actual data collected in the future at the time of the I-59 project are purely coincidental. All assumptions for cost, schedule, and traffic data will be describe in the following sections. Average bid prices for TCB, demolition, and construction activities on bridge projects were researched to determine the project cost data to use for the example.

5.2.1 Bridge Dimensions

As previously stated the bridge dimensions for the I-59 project were determined from the ALDOT plan set for Project No. BR-1059 (I-59 Collinsville). These dimensions were used to calculate individual lane-span dimensions (i.e. length, width, and area). A summary of the lane-span dimensions by lane span ID can be seen in
Table 5-2.

Table 5-2 Lane-Span Dimensions for Northbound/Southbound Bridge

Lane Span ID	Length (ft)	Existing Width (ft)	Existing Area(ft^2)	Post Construction Width(ft)	Post Construction Area(ft^2)
NBI1	56.83	12.58	714.9	19.38	1101.4
NBI2	56.00	12.58	704.5	19.38	1085.3
NBI3	56.00	12.58	704.5	19.38	1085.3
NBI4	56.83	12.58	714.9	19.38	1101.4
NBO1	56.83	20.58	1169.6	27.38	1556.0
NBO2	56.00	20.58	1152.5	27.38	1533.4
NBO3	56.00	20.58	1152.5	27.38	1533.4
NBO4	56.83	20.58	1169.6	27.38	1556.0
SBI1	56.83	12.58	714.9	19.38	1101.4
SBI2	56.00	12.58	704.5	19.38	1085.3
SBI3	56.00	12.58	704.5	19.38	1085.3
SBI4	56.83	12.58	714.9	19.38	1101.4
SBO1	56.83	20.58	1169.6	27.38	1556.0
SBO2	56.00	20.58	1152.5	27.38	1533.4
SBO3	56.00	20.58	1152.5	27.38	1533.4
SBO4	56.83	20.58	1169.6	27.38	1556.0

Note:
NBI(#) - Northbound inside (lane-span number)
NBO(#) - Northbound outside (lane-span number)
SBI(#) - Southbound inside (lane-span number)
SBO(#) - Southbound outside (lane-span number)

5.2.2 Cost Estimating

Cost estimating was performed for TCB, demolition, and construction. Bid prices and average values were used as a reference point for hypothetical cost values. Actual cost data collected on the I-59 project once constructed, most likely will vary from estimated bid pricing submitted by the contractor during project letting. All cost values reported herein, unless otherwise noted, include all material, labor, and equipment required to perform the activity under consideration. The cost values are not intended to predict the actual I-59 project costs, but rather give guidance as to how to process the actual values collected during the I-59 project for analysis.

For demolition and construction activities, the concept of a learning curve will be applied where appropriate for each bridge lane. "Many repetitive construction field operations exhibit a learning curve, over which the time or cost per cycle decreases as the cycle number increases"

(Everett and Farghal 1994). As construction continues the estimated cost of subsequent lane-spans are expected to lower due to an understood learning curve concept.

5.2.2.1 *Temporary Concrete Barrier: Cost Estimating*

To estimate temporary concrete barrier (TCB) cost, the overall bridge length was first calculated to be 225.6 ft (67.7 m). The price of a new ten foot concrete barrier was researched and determined to be $350 by the concrete barrier vendor DCC. To estimate the number of barriers required per row the bridge length was divided by the ten foot concrete barrier. It was determined that a single row of TCB required 23 concrete barriers. By multipling the number of barriers by the cost per barrier, the cost per row of TCB was determined to be $8,050/row.

In traditional construction sequencing only one row of TCB is required to create a work space and a traffic space for each bridge. The cost for installing and removing the total TCB row was estimated as $8,050. Each lane-span that is in a traditional construction sequence lane shares an equal portion of the $8,050. The actual cost for each lane-span being construction under traditional construction sequence is reported as $2,013.

In an accelerated construction sequence lane there are three rows of TCB required to separate the bridge into a work space and traffic space. Multiply the TCB cost per row of $8,050/row by the three rows of TCB equals a value of $24,150. This value is shared by each lane-span in the construction sequence lane. The actual cost reported for each lane-span in an accelerated construction sequence lane is $6,038. Table 5-3 summarizes the TCB cost estimation for the example problem.

Table 5-3 TCB Cost Estimating Summary

Construction Sequence	Lane TCB Cost	Lane-Span TCB Cost
Traditional (1 Row of TCB)	$8,050	$2,013
Accelerated (3 Rows of TCB)	$24,150	$6,038

5.2.2.2 *Demolition: Cost Estimating*

From the report 'Life-Cycle Cost Survey of Concrete Bridge Decks', "the average cost of removal and disposal of concrete decks is $9.19 per square foot" (Anido 2001). This value was used as a reference for estimating each lane-span's demolition cost.

The assumed demolition cost is $\$9.19/ft^2$ ($\$100.08/m^2$) multiplied by the area of the lane span. An assumed learning curve will be applied for a reduction in cost of the subsequent lane-span. The second and third lane-spans' construction will receive a 5% cost reduction, while the fourth construction lane span will receive a 10% reduction.

In accelerated construction sequence lanes, a reduction in cost will also be applied to each subsequent lane-span. However, it has been assumed that on a weekend closure only two lane-spans will be demolished in one weekend. Therefore, only the second constructed lane-span on each weekend will receive a 5% cost reduction from the learning curve.

Table 5-4 summarizes the demolition cost values developed for each lane-span by applying the average cost per square foot of $9.19/ft^2$ ($100.08/m^2$) and the appropriate learning curve percent cost reduction.

Table 5-4 Demolition Cost Development Based on Assumed Learning Curve Cost Reduction

NORTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane Span ID	Span Length (ft)	Existing Construction Area (ft^2)	Estimated ($/$ft^2$)	Learning Curve Reduction	Demolition Cost ($)
Exodermic	Traditional	CIP	NBI1	56.83	714.9	9.19	0%	6,570
			NBI2	56.00	704.5	9.19	5%	6,151
	Accelerated	CIP	NBO1	56.83	1169.6	9.19	5%	10,211
			NBO2	56.00	1152.5	9.19	0%	10,591
Steel Grid	Traditional	CIP	NBI3	56.00	704.5	9.19	5%	6,151
			NBI4	56.83	714.9	9.19	10%	5,913
	Accelerated	CIP	NBO3	56.00	1152.5	9.19	5%	10,062
			NBO4	56.83	1169.6	9.19	0%	10,749

SOUTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane Span ID	Span Length (ft)	Existing Construction Area (ft^2)	Estimated ($/$ft^2$)	Learning Curve Reduction	Demolition Cost ($)
NCHRP	Traditional	PC	SBI1	56.83	714.9	9.19	10%	5,913
			SBI2	56.00	704.5	9.19	5%	6,151
	Accelerated	PC	SBO1	56.83	1169.6	9.19	0%	10,749
			SBO2	56.00	1152.5	9.19	5%	10,062
Exodermic	Traditional	PC	SBI3	56.00	704.5	9.19	5%	6,151
			SBI4	56.83	714.9	9.19	0%	6,570
	Accelerated	PC	SBO3	56.00	1152.5	9.19	0%	10,591
			SBO4	56.83	1169.6	9.19	5%	10,211

5.2.2.3 *Construction: Cost Estimating*

Construction cost for concrete deck systems were research and "the average concrete deck cost was reported by twelve Department of Transportation's (DOT's) was $29.50 per square foot. The minimum cost reported was $20.00 per square foot and the maximum was $55.00 per square foot" (Anido 2001). When comparing the price of cast-in-place (CIP) to precast (PC) deck panels, it was found that PC panels can have an initial price 75% higher than CIP panel (Menard 2010). This information was used to estimate construction cost for the example problem.

Because no actual bid prices have been given for each deck system the following unit cost were assumed from the literature. Exodermic CIP decks were estimated at the average cost of $29.50 per square foot. Steel grid was assumed at the minimum cost of $20.00 per square foot. NCHRP was priced at the maximum cost of $55.00 per square foot. The Exodermic PC deck was estimated at a price of 75% higher than the Exodermic CIP deck with a value of $52.00 per square foot. This data is hypothetical and only intended to outline how real I-59 data should be collected and processed. Table 5-5 summarizes the assumed unit cost of each deck system.

Table 5-5 Assumed Deck System Construction Unit Cost

Deck System	Casting Technique	Construction Unit Cost ($/ft^2)
Exodermic	CIP	29.50
Steel Grid	CIP	20.00
NCHRP	PC	55.00
Exodermic	PC	52.50

Following unit cost estimation, the learning curve principle was again applied to develop construction cost for each lane-span. The learning curve reductions for each lane-span are the same for the construction cost as they were for the demolition cost. Table 5-6 summarizes the construction cost developed, based on the assumed unit cost and learning curve reduction.

Table 5-6 Construction Cost Development Based on Assumed Learning Curve Cost Reduction

NORTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane Span ID	Span Length (ft)	Post Construction Area (ft^2)	Estimated ($/$ft^2$)	Learning Curve Reduction	Construction Cost ($)
Exodermic	Traditional	CIP	NBI1	56.83	1101.4	29.50	0%	32,491
			NBI2	56.00	1085.3	29.50	5%	30,416
	Accelerated	CIP	NBO1	56.83	1556.0	29.50	5%	43,607
			NBO2	56.00	1533.4	29.50	0%	45,232
Steel Grid	Traditional	CIP	NBI3	56.00	1085.3	20.00	5%	20,621
			NBI4	56.83	1101.4	20.00	10%	19,825
	Accelerated	CIP	NBO3	56.00	1533.4	20.00	5%	29,133
			NBO4	56.83	1556.0	20.00	0%	31,120

SOUTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane Span ID	Span Length (ft)	Post Construction Area (ft^2)	Estimated ($/$ft^2$)	Learning Curve Reduction	Construction Cost ($)
NCHRP	Traditional	PC	SBI1	56.83	1101.4	55.00	10%	54,519
			SBI2	56.00	1085.3	55.00	5%	56,707
	Accelerated	PC	SBO1	56.83	1556.0	55.00	0%	85,580
			SBO2	56.00	1533.4	55.00	5%	80,115
Exodermic	Traditional	PC	SBI3	56.00	1085.3	52.50	5%	54,129
			SBI4	56.83	1101.4	52.50	0%	57,824
	Accelerated	PC	SBO3	56.00	1533.4	52.50	0%	80,498
			SBO4	56.83	1556.0	52.50	5%	77,606

Figure 5-3 summarizes the learning curve reduction percent for each lane-span for demolition and construction activity.

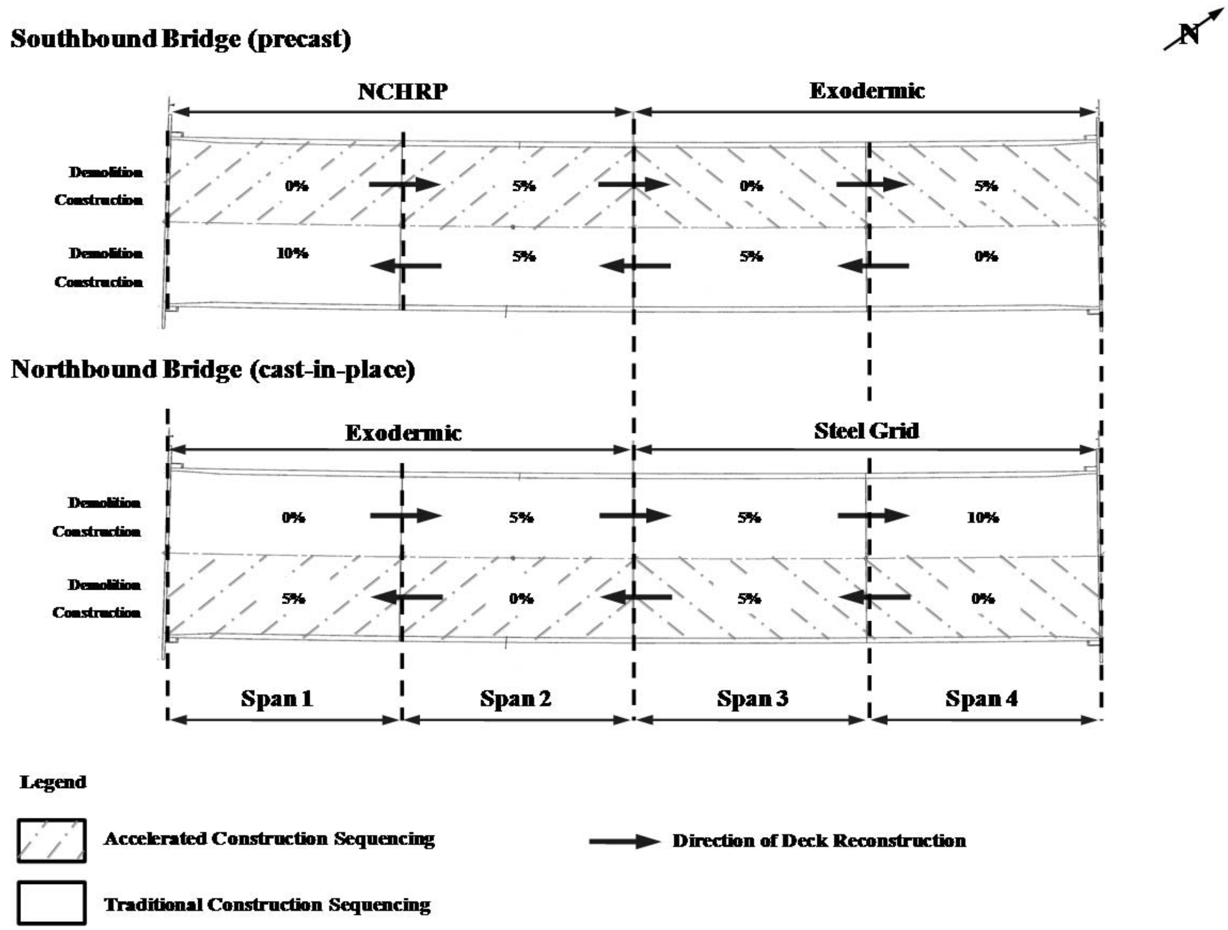


Figure 5-3 Summary of Learning Curve Cost Reduction for Each Lane Span.

5.2.3 Schedule Estimating

Reasonable average activity durations for installation/rearrangement/removal of TCB, demolition, and construction were assumed for each bridge, lane-span, and deck system. Lane span-dimensions from

Table 5-2 were used as the estimating tool for calculating total time required for completing a particular activity.

5.2.3.1 *Temporary Concrete Barrier: Schedule Estimating*

TCB schedules were estimated for the time required to install, rearrange, and remove one row of TCBs. It was estimated that each activity: installation, rearrangement, and removal, would require 1 hour. In traditional construction sequencing only one row of TCB is required. For installation and removal it is estimated to take 2 total hours (e.g., 1 hour installation, 1 hour removal). This time will be shared by all four lane-spans equally and the reported TCB lane-span time will equal 0.5 hours.

During weekend accelerated construction sequencing three rows of TCB will be required, as well as rearrangements for individual lane-spans. The weekend closure scenario assumes that there is only one rearrangement for each lane-span constructed. Therefore, 4 total hours of rearrangement for the entire lane will be required. The total estimated TCB schedule for accelerated weekend scenarios is 10 hours (6 hours for installation/removal and 4 hours for rearrangement). The lane-span TCB duration reported will be ¼ the total lane TCB duration (i.e. 10 divided by 4 equals 2.5 hours per lane-span).

Table 5-7 TCB Schedule Estimating Summary

Construction Sequence	Lane TCB hours	Lane-Span TCB hours
Traditional (1 Row of TCB)	2	0.5
Accelerated (3 Rows of TCB)	10	2.5

5.2.3.2 *Demolition: Schedule Estimating*

The outside lane, using accelerated construction sequencing, of both the NB and SB bridges has larger areas than the inside lane areas, using traditional construction sequencing. The initial demolition time required for an inside lane-span using traditional construction sequencing was assumed to be 5 hours. This time included all cutting, jack hammering, and debris removal to prepare the lane-span for reconstruction. A learning curve of 0.5 hours was applied for the following two lane-spans for durations of 4.5 hours. The learning curve assumes that as the contractor repeats an operation he or she will become more efficient at that operation which results in requiring less time to complete the same activity. For the fourth lane-span an additional learning curve of 0.5 hours was applied, giving the fourth inside lane-span a demolition duration of 4 hours.

A learning curve was also applied to the outside lanes using weekend accelerated construction sequencing. During the weekend scenario it was estimated that only two lane-spans could be demolished over this period. For this reason, additional reduction in time from the learning curve will not be applied to the third and fourth lane-span. Each weekend will start the learning curve process over. The durations required for the first and second lane-spans, of weekend accelerated construction sequence lanes, are 9 and 8.5 hours respectively. The durations for the third and fourth lane-spans, which will occur on the second weekend, are also 9 and 8.5 hours respectively.

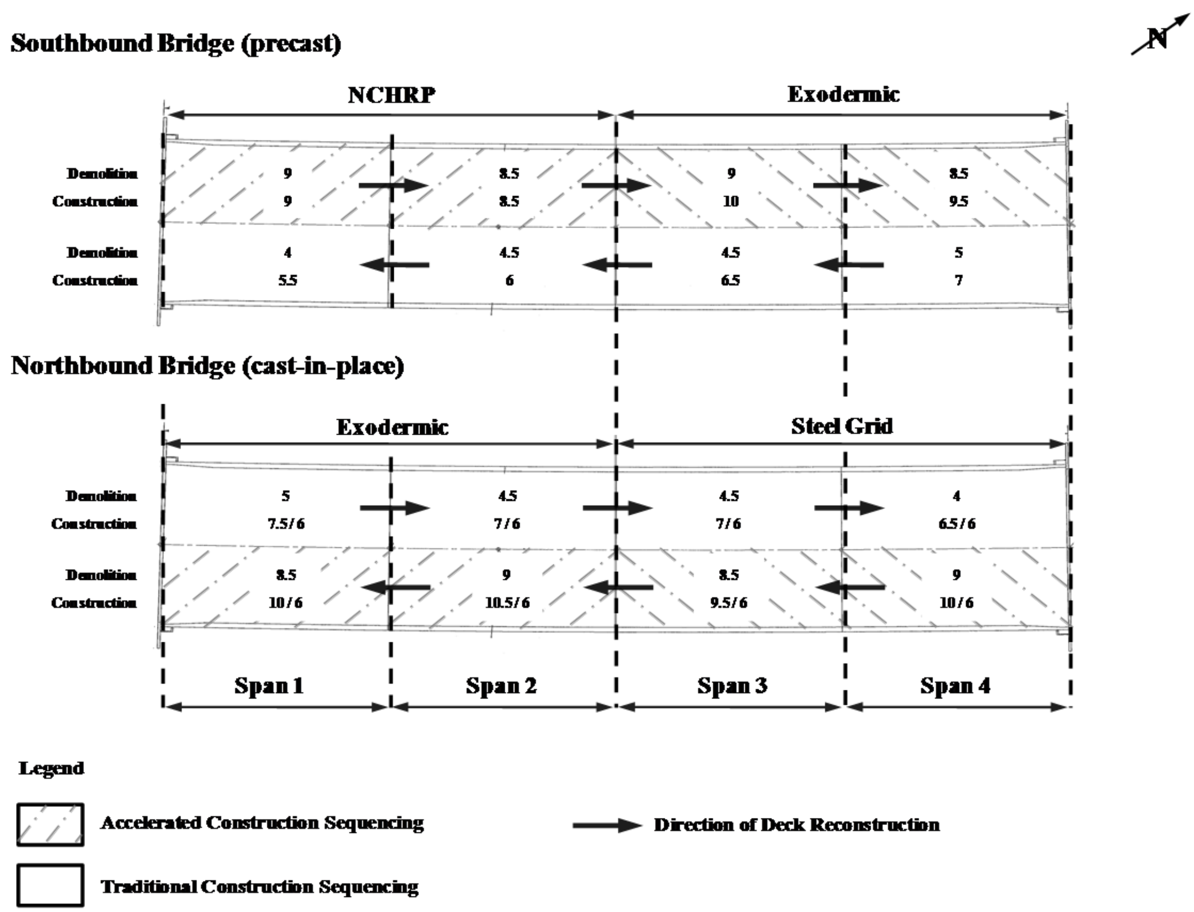
5.2.3.3 *Construction: Schedule Estimating*

Construction schedule estimating was accomplished by calculating the time needed for each deck system. Cast-In-Place (CIP) deck systems will require additional curing time after pouring concrete, while precast (PC) systems will not. The pour or placement time for each deck system was estimated in hours for both the traditional and accelerated construction sequence lanes. A ratio of the outside lane-span areas to the inside lane-span areas was used to estimate all pour or place times. The curing time regardless of deck system and lane-span was estimated at 6 hours. Table 5-8 shows all estimated construction times.

Table 5-8 Estimated Deck System Construction Schedules

Deck System	Casting Technique	Pour or Place Time (hrs)		Cure Time (hrs)
		Traditional	Accelerated	
Exodermic	CIP	7.5	10.5	6
Steel Grid	CIP	7	10	6
NCHRP	PC	6	9	
Exodermic	PC	7	10	

Figure 5-4 displays all schedule estimates calculated in this section by lane-span in a bridge plan view format. On the NB bridge the value of construction has two numbers. The first number indicates the pour time while the second number represents the curing time. The SB bridge is all PC and therefore does not have a curing time for any of the lane-spans. The arrows on the lane-spans identify the direction that work will progress.



Note: construction times reported for CIP methods is formatted as: (pour time/cure time)

Figure 5-4 Summary of Learning Curve Time Reduction for Each Lane-Span.

5.2.3.4 *Traffic Data: Value Estimating*

Before construction, traffic data volumes and speeds will be used in the example problem. The vehicle classification has been divided into passenger vehicles and trucks. Passenger vehicles represent a vehicle below 46.9 ft (14.2 m) in length while trucks represent a vehicle above 46.9 ft. (14.2 m) in length. These lengths were taken from the American Association of State Highway and Tranportation Officials (AASHTO) "Policy on Geometric Design of Highways and Streets".

During construction it is assumed that there will be no reduction in flow due to the low volumes experience on the I-59 roadway. However, an enforced work zone speed of 45 mph will be used to determine additional RUC. Volumes and speeds that will be used for traditional construction sequence lanes, that will have weekday closures, and accelerated construction sequence lanes, that will have weekend closures, can be seen on Table 5-9. The weekday value is estimated from a 24 hour period, while the weekend value is based on a 60 hour period.

Table 5-9 Northbound and Southbound Traffic Data by Work Closure Period

	Vehicle Volume			Speed (mph)	
	Passenger Vehicle	Truck	Total	Passenger Vehicle	Truck
Before Construction					
Weekday	3,987	2,082	6,069	75	77
Weekend	13,560	2,992	16,552	77	79
During Construction					
Weekday	3,987	2,082	6,069	45	45
Weekend	13,560	2,992	16,552	45	45

5.3 Data Collection Summary

The values estimated in the previous section for the example will be consolidated, summarized, and shown in Table 5-10. On the actual I-59 project these values will represent actual values collected over the course of the bridge reconstruction effort and no schedule or cost estimating will be required. Table 5-10 shows the bridge dimensions, cost, schedule, and traffic data for the example. The duration information will be used to develop hypothetical Gantt charts to be used throughout the example. The construction performance factors to be evaluated will also be developed from the data seen on Table 5-10.

Table 5-10 Northbound/Southbound Bridge Summary Raw Data Table

NORTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane Span ID	Span Length (ft)	Construction Area (ft^2)		Cost ($)			Schedule (hrs)			Traffic Data
					Exist	Post	TCB	Demo	Const	TCB	Demo	Const	Vehicle Volume
Exodermic	Traditional	CIP	NBI1	56.83	714.9	1101.4	2,013	6,570	32,491	0.50	5.00	13.50	6,512
			NBI2	56.00	704.5	1085.3	2,013	6,151	30,416	0.50	4.50	13.00	6,512
	Accelerated	CIP	NBO1	56.83	1169.6	1556.0	6,038	10,211	43,607	2.50	8.50	16.00	7,518
			NBO2	56.00	1152.5	1533.3	6,038	10,591	45,232	2.50	9.00	16.50	7,518
Steel Grid	Traditional	CIP	NBI3	56.00	704.5	1085.3	2,013	6,151	20,621	0.50	4.50	13.00	6,512
			NBI4	56.83	714.9	1101.4	2,013	5,913	19,825	0.50	4.00	12.50	6,512
	Accelerated	CIP	NBO3	56.00	1152.5	1533.3	6,038	10,062	29,133	2.50	8.50	15.50	7,518
			NBO4	56.83	1169.6	1556.0	6,038	10,749	31,120	2.50	9.00	16.00	7,518

SOUTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane Span ID	Span Length (ft)	Construction Area (ft^2)		Cost ($)			Schedule (hrs)			Traffic Data
					Exist	Post	TCB	Demo	Const	TCB	Demo	Const	Vehicle Volume
NCHRP	Traditional	PC	SBI1	56.83	714.9	1101.4	2,013	5,913	54,519	0.50	4.00	5.50	5,153
			SBI2	56.00	704.5	1085.3	2,013	6,151	56,707	0.50	4.50	6.00	5,153
	Accelerated	PC	SBO1	56.83	1169.6	1556.0	6,038	10,749	85,580	2.50	9.00	9.00	5,655
			SBO2	56.00	1152.5	1533.3	6,038	10,062	80,115	2.50	8.50	8.50	5,655
Exodermic	Traditional	PC	SBI3	56.00	704.5	1085.3	2,013	6,151	54,129	0.50	4.50	6.50	5,153
			SBI4	56.83	714.9	1101.4	2,013	6,570	57,824	0.50	5.00	7.00	5,153
	Accelerated	PC	SBO3	56.00	1152.5	1533.3	6,038	10,591	80,498	2.50	9.00	10.00	5,655
			SBO4	56.83	1169.6	1556.0	6,038	10,211	77,606	2.50	8.50	9.50	5,655

Note:
*Exist – Existing Construction Area
*TCB – Temporary Concrete Barrier
*Demo = Demolition
*Const = Construction

5.4 Analysis Techniques

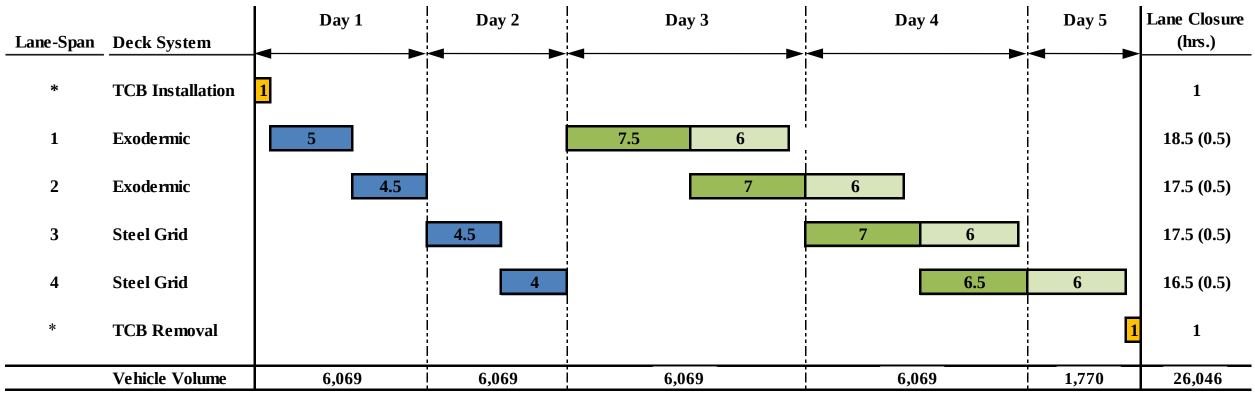
The raw data summarized in Table 5-10 will be used to compute the construction performance factors to be analyzed. Gantt charts will be created from the scheduling information to help understand and evaluate the different closure scenarios that will be examined. The inside lanes using traditional construction sequencing will be under construction during a typical weekday closure schedule. The outside lanes being constructed under accelerated construction sequencing will be evaluated with a weekend closure scenario.

The formulas and methodology for creating the Gantt charts and construction performance factors have been described in detail in Chapter 4.

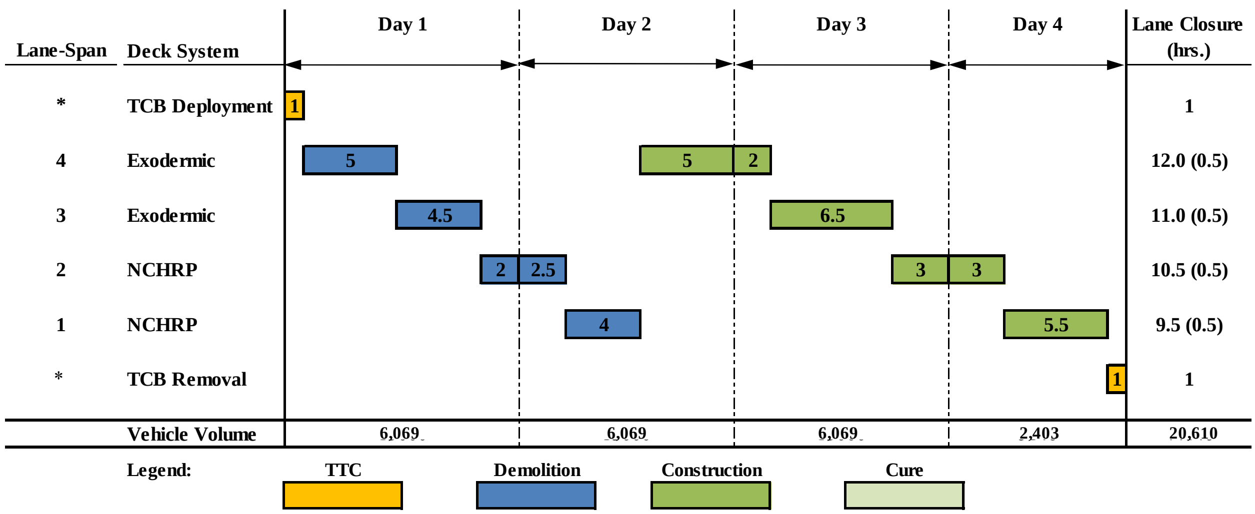
5.4.1 Gantt Charts

For the construction schedule developed in the raw data for this example problem Gantt charts have been created. Traditional construction sequencing was assumed to occur on weekdays using a closure from the beginning of the project until the finish of the project. Accelerated construction sequencing was assumed to be performed on weekends and uses non-peak travel periods to intermittently close lanes for reconstruction while reopening lanes during peak travel periods.

A 12 hour work period during the week and a 24 hour work period on the weekends were assumed. One of the limiting factors to the work schedule was the casting technique. Cast-in-place (CIP) construction techniques require a 6 hour cure time. This additional cure time limited the ability of the accelerated construction sequence to be performed during any other closure period other than weekends.
From the raw data on Table 5-10 the following Gantt charts were created. The charts highlight the effect that different bridge deck replacement methods have on the total project schedule. The numbers displayed on the bars represent the scheduled time required to complete the activity under consideration. The far right column indicates the lane closure time for each lane-span in hours. The number in parenthesis next to the lane closure time is the shared time for TCB installation and removal. On the bottom of each chart the corresponding vehicle volume is reported for each work period. For traditional construction sequencing on the inside lanes, the work period is 12 hours, however the lane closure is for 24 hours. For accelerated construction sequencing on the outside lanes, the work period and the lane closure period are the same since the lane is reopened to traffic once construction is completed on a lane-span. Figure 5-5 shows the Gantt charts for the traditional construction sequence lanes of the example problem. Figure 5-6 show the Gantt charts for the accelerated construction sequence lanes of the example problem.



(a) Northbound Bridge, Inside Lane, Cast-in-place.

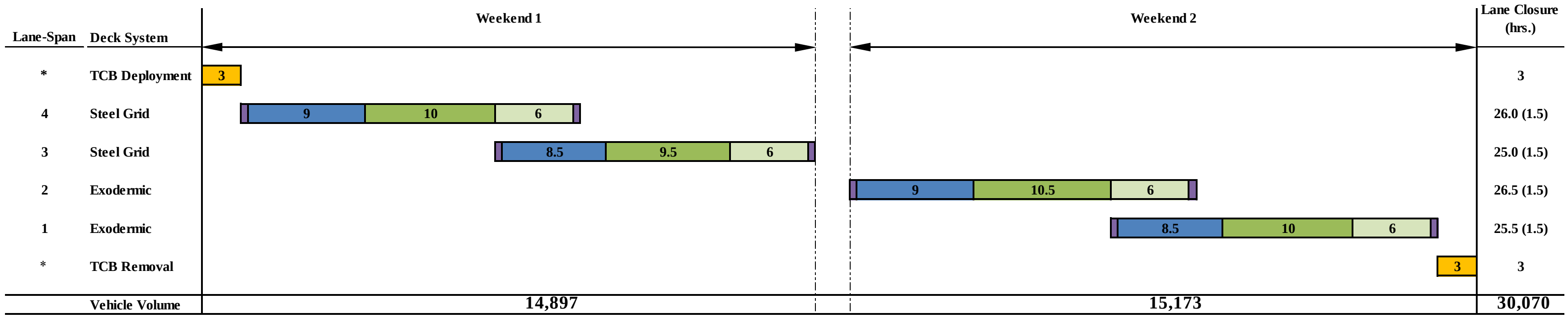


(b) Southbound Bridge, Inside Lane, Precast.

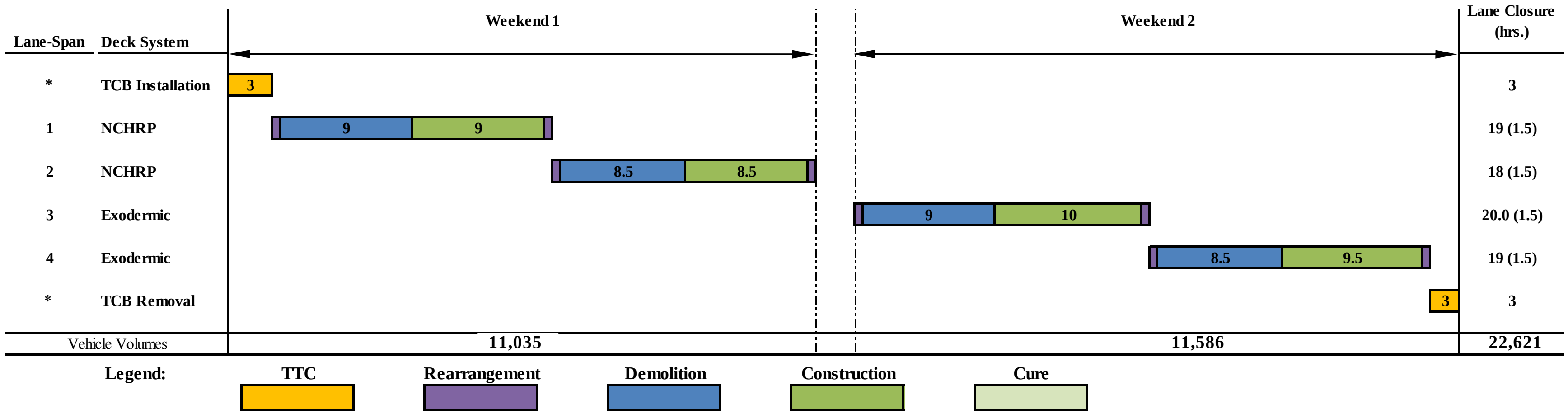
Note:

* The work period for this example is a 12 hour work day
* Only work activity is shown, but each day represents a 24 hour lane closure unless noted otherwise
* Number in parenthesis in the 'Lane Closure' column are shared TCB values

Figure 5-5 Traditional Construction Sequencing Gantt Charts with Weekday Closure.



(a) Northbound, Outside Lane, Cast-in-place.



(b) Southbound, Outside Lane, Precast.

Note:
* The work period for this example is an around the clock schedule
* Only work activity is shown, but each day represents a 24 hour lane closure unless noted otherwise
* Number in parenthesis in the 'Lane Closure' column are shared TCB values

Figure 5-6 Accelerated Construction Sequencing Gantt Charts with Weekend Closure.

On Figure 5-5 and Figure 5-6 the effect of the additional curing time of the CIP casting techniques can be seen on the total project duration. It is important to remember that the accelerated lane-spans have a slightly larger area than the traditional lane-spans and therefore have a larger scheduled time. The production rates calculated in the following section will provide a better indication as to the effect that construction sequence had on the total lane closure and schedule.

5.4.2 Normalizing Collected Data

The compiled raw data on Table 5-10 must be normalized for nested analysis of variance (ANOVA) statistical testing. Using the bridge dimensions and values found in the American Association of State Highway and Tranportation Officals (AASHTO) publication,"User and Non-User Benefit Analysis For Highways" the construction performance factors: (1) unit cost, (2) production rate, and (3) RUC were calculated. For the example problem the following values were assumed from "User and Non-User Benefit Analysis For Highways" for passenger vehicles and trucks and can be seen on Table 5-11. These values are hypothetical and may not be appropriate for the actual I-59 project.

Table 5-11 Assumed RUC Calculation Values

	Passenger Vehicle	Truck
Finance Rate	0.10	0.10
Percentage of Hourly Wage	50%	100%
Average Hourly Wage($)	18.56	20.23
Average Vehicle Occupancy	1.3	1.05
Speed Before Closure (mph)		
Weekday	75	77
Weekend	77	79
Speed After Closure (mph)	45	45
Other Operating Cost per Mile($/mile)	0.04	0.05
Vehicle Life (years)	10	8
Vehicle Cost ($)	20,000	60,000
Salvage Value at End of Life ($)	2,000	5,000
Insurance per Year ($)	1,000	1,500
Cargo Value($)		200,000

All equations, 4-1 through 4-15, used to calculate the construction performance factors can be found in in Chapter 4. Example calculation for the Exodermic Traditional CIP bridge deck replacment method with lane-span ID NBI1 have been provided and are shown below.

The TCB unit cost was calculated using equation 4-1 seen below:

$$\text{TCB Unit Cost}\left(\frac{\$}{\text{ft}}\right) = \frac{\text{TCB Cost (\$)}}{\text{Lane-Span Length (ft)}} = \frac{2{,}013}{56.83} = 35.42 \tag{4-1}$$

Demolition unit cost will be calculated as the total cost for demolition of an individual lane-span divided by the area of existing deck of the lane-span under consideration. Demolition unit cost was calculated with equation 4-2 below:

$$\text{Demolition Unit Cost}\left(\frac{\$}{\text{ft}^2}\right) = \frac{\text{Demolition Cost (\$)}}{\text{Existing Lane-Span Area (ft}^2\text{)}} = \frac{6{,}750}{714.9} = 9.19 \tag{4-2}$$

Construction unit cost will be calculated as the total cost required to construct the lane-span under consideration with the appropriate deck system and can be seen in equation 4-3 below:

$$\text{Construction Unit Cost}\left(\frac{\$}{\text{ft}^2}\right) = \frac{\text{Construction Cost (\$)}}{\text{Post Lane-Span Area (ft}^2\text{)}} = \frac{32{,}491}{1101.4} = 29.50 \tag{3}$$

TCB production rate was calculated as the linear length of a lane-span divided by the total duration of time spent installing or removing TCB for the lane-span in question and is shown in equation 4-4 below:

$$\text{TCB Production Rate}\left(\frac{\text{ft}}{\text{hr}}\right) = \frac{\text{Lane-Span Length (ft)}}{\text{TCB Duration (hr)}} = \frac{56.83}{0.50} = 113.7 \tag{4-4}$$

Demolition production rate will be determined by dividing the existing lane-span area by the total duration spent on the demolition process of a single lane-span. Demolition production rate can be seen in equation 4-5 below:

$$\text{Demolition Production Rate}\left(\frac{\text{ft}^2}{\text{hr}}\right) = \frac{\text{Existing Lane-Span Area (ft}^2\text{)}}{\text{Demolition Duration (hr)}} = \frac{714.9}{5.00} = 143.0 \tag{4-5}$$

Construction production rate is calculated by dividing the post construction area by the total duration of the construction period for each lane-span and is shown in equation 4-6 below:

$$\text{Construction Production Rate}\left(\frac{\text{ft}^2}{\text{hr}}\right) = \frac{\text{Post Lane-Span Area (ft}^2\text{)}}{\text{Construction Duration (hr)}} = \frac{1101.4}{13.50} = 81.6 \tag{4-6}$$

The RUC was calculated using equations 4-7 through 4-14. The following template, shown in Figure 5-7, demonstrates how the equations were used to calculate a lane-span RUC for the lane-span ID NBI1. Table number on the RUC template refer to the “User and Non-User Benefit Analysis for Highways” AASHTO publication.

Road User Cost Estimating

General Information	
Project	I-59 Project
Date	24-Feb
Analysis Year	2011

Site Information	
Segment (ft)	225.66
Period of Closure	Weekday
Volume (veh)	22,621
Percent Passenger Cars (%)	66.0%
Percent Heavy Vehicles (%)	34.0%

Inputs

Finance Rate: **0.10**

Passenger Vehicles		Trucks	
Percentage of hourly wage (Table 5-1)	50%	Percentage of hourly Wage (Table 5-1)	100%
Average hourly wage (Table 5-2)	$18.56	Average hourly wage (Table 5-2)	$20.23
Average vehicle occupancy	1.3	Average vehicle occupancy	1.05
Speed before closure (mph)	77	Speed before closure (mph)	79
Speed during closure (mph)	45	Speed during closure (mph)	45
Other Operating Costs per Mile (Table 5-4) (tires, maintenance, etc.)	0.040	Other Operating Costs per Mile (Table 5-4) (tires, maintenance, etc.)	0.050
Vehicle Life (years)	10	Vehicle Life (years)	8
Vehicle Cost ($)	$20,000	Vehicle Cost ($)	$60,000
Salvage Value at End of Life	$2,000	Salvage Value at End of Life	$5,000
		Cargo Value	$200,000
Insurance per Year (Table 5-4):	$1,000	Insurance per Year (Table 5-4):	$1,500

Calculations

Autos		Trucks	
Value of time per vehicle hour ($/veh-hr): (wage X percentage X occupancy)	$12.06	Value of time per vehicle hour ($/veh-hr): (wage X percentage X occupancy)	$21.24
Amortized cost per vehicle hour ($/veh-hr): A = (i*(P*(1+i)^n)-F)/((1+i)^n)-1)/8760	$0.357	Amortized cost per vehicle hour ($/veh-hr): A = (i*(P*(1+i)^n)-F)/((1+i)^n)-1)/8760	$1.234
Insurance cost per vehicle hour($/veh-hr): (Insurance per year / 8760)	$0.114	Insurance cost per vehicle hour($/veh-hr): (Insurance per year / 8760)	$0.1712
		Inventory cost per vehicle hour($/veh-hr): (Cargo value X finance rate / 8760)	$2.2831
Total cost per vehicle hour ($/veh-hr):	$12.54	Total cost per vehicle hour ($/veh-hr):	$24.9298
Travel time before closure (sec)	1.998	Travel time before closure (sec)	1.948
Travel time during closure (sec) (Segment / 5280) X (3600 / Speed)	3.419	Travel time during closure (sec) (Segment / 5280) X (3600 / Speed)	3.419
Cost per vehicle before closure ($/veh)	$0.0070	Cost per vehicle before closure ($)	$0.0135
Cost per vehicle during closure($/veh) (Total cost per vehicle hour / 3600)*(delay)	$0.0119	Cost per vehicle during closure($) (Total cost per vehicle hour / 3600)*(delay)	$0.0237
Realized cost per vehicle ($/veh) (cost after closure - cost before closure)	$0.0049	Realized cost per vehicle ($/veh) (cost after closure - cost before closure)	$0.0102

Results

RUC from Autos for lane($) (Realized Cost X Volume X Percentage)	$73.87	RUC Trucks for lane ($) (Realized Cost X Volume X Percentage)	$78.37

Total RUC for Lane ($) **$152.24**

Figure 5-7 RUC Template For Lane-Span NBI1.

It is shown in Figure 5-7 that the total lane RUC was determined to be \$175.29. To calculate the RUC for the lane-span we will apply equation 4-15.

$$\text{Lane-Span RUC (\$)} = \left(\frac{\text{Lane-Span Duration (hr)}}{\text{Total Lane} - \text{Span Duration (hr)}} \right) \times \text{Lane RUC (\$)} \tag{4-15}$$

$$\text{Lane-Span RUC (\$)} = \left(\frac{19}{72} \right) \times 175.29 = 46.26$$

All calculated construction performance factors for all bridge deck replacement methods have been summarized in Table 5-12

Table 5-12 Northbound/Southbound Bridge Construction Performance Factors

NORTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane Span ID	Span Length (ft)	Construction Area (ft^2) Exist	Construction Area (ft^2) Post	Unit Cost TCB ($/ft)	Unit Cost Demo ($/$ft^2$)	Unit Cost Const ($/$ft^2$)	Production Rate TCB (ft/hr)	Production Rate Demo (ft^2/hr)	Production Rate Const (ft^2/hr)	RUC ($)
Exodermic	Traditional	CIP	NBI1	56.83	714.9	1101.4	35.42	9.19	29.50	113.7	143.0	81.6	46.26
			NBI2	56.00	704.5	1085.3	35.95	8.73	28.03	112.0	156.6	83.5	43.82
	Accelerated	CIP	NBO1	56.83	1169.6	1556.0	106.25	8.73	28.03	22.7	137.6	97.3	50.13
			NBO2	56.00	1152.5	1533.3	107.82	9.19	29.50	22.4	128.1	92.9	51.99
Steel Grid	Traditional	CIP	NBI3	56.00	704.5	1085.3	35.95	8.73	19.00	112.0	156.6	83.5	43.82
			NBI4	56.83	714.9	1101.4	35.42	8.27	18.00	113.7	178.7	88.1	41.39
	Accelerated	CIP	NBO3	56.00	1152.5	1533.3	107.82	8.73	19.00	22.4	135.6	98.9	49.20
			NBO4	56.83	1169.6	1556.0	106.25	9.19	20.00	22.7	130.0	97.3	51.06

SOUTHBOUND

Deck System	Construction Sequence	Casting Technique	Lane Span ID	Span Length (ft)	Construction Area (ft^2) Exist	Construction Area (ft^2) Post	Unit Cost TCB ($/ft)	Unit Cost Demo ($/$ft^2$)	Unit Cost Const ($/$ft^2$)	Production Rate TCB (ft/hr)	Production Rate Demo (ft^2/hr)	Production Rate Const (ft^2/hr)	RUC ($)
NCHRP	Traditional	PC	SBI1	56.83	714.9	1101.4	35.42	8.27	49.50	113.7	178.7	200.3	30.82
			SBI2	56.00	704.5	1085.3	35.95	8.73	52.25	112.0	156.6	180.9	33.91
	Accelerated	PC	SBO1	56.83	1169.6	1556.0	106.25	9.19	55.00	22.7	130.0	172.9	37.81
			SBO2	56.00	1152.5	1533.3	107.82	8.73	52.25	22.4	135.6	180.4	35.97
Exodermic	Traditional	PC	SBI3	56.00	704.5	1085.3	35.95	8.73	49.87	112.0	156.6	167.0	35.45
			SBI4	56.83	714.9	1101.4	35.42	9.19	52.50	113.7	143.0	157.3	38.53
	Accelerated	PC	SBO3	56.00	1152.5	1533.3	107.82	9.19	52.50	22.4	128.1	153.3	39.65
			SBO4	56.83	1169.6	1556.0	106.25	8.73	49.88	22.7	137.6	163.8	37.81

Note:
*Exist – Existing Construction Area
*TCB – Temporary Concrete Barrier
*Demo - Demolition
*Const - Construction

5.4.3 Nested ANOVA

Nested ANOVA was performed on each of the seven construction performance factors in Table 5-12. There are three sub-factors in unit cost: TCB unit cost, demolition unit cost, and construction unit cost; three sub-factors in production rate: TCB production rate, demolition production rate, and construction production rate; and one cost factor in RUC. The null hypotheses (H_0) tested that the mean value of the construction performance factor in question, regardless of path selected to the deck system level, was equal. This is to say that the bridge deck replacement methods had no statistical significant effect on the mean value of the factor being tested and either method could be selected for similar results. The alternative hypothesis (H_a) tested that the path selected does result in a statistical significant difference in the mean value of the construction performance factor in question. P-values were used to prove or fail to prove the hypotheses. A p-value of 0.05 or smaller was identified as having a statistical significant difference on the mean value of the performance factor. An R^2 value of 0.60 or larger was an acceptable goodness-of-fit of the model. Table 5-13 shows the hypotheses and construction performance factors that were tested with a nested ANOVA.

Table 5-13 Example Nested ANOVA Null and Alternative Hypothesis Test for Construction Performance Factors

Construction Performance Factor	Null Hypothesis (H_0)	Alternative Hypothesis (H_a)
1. TCB Unit Cost	$\mu_1 = \cdots = \mu_8$	not all μ_i are equal
2. Demolition Unit Cost	$\mu_1 = \cdots = \mu_8$	not all μ_i are equal
3. Construction Unit Cost	$\mu_1 = \cdots = \mu_8$	not all μ_i are equal
4. TCB Production Rate	$\mu_1 = \cdots = \mu_8$	not all μ_i are equal
5. Demolition Production Rate	$\mu_1 = \cdots = \mu_8$	not all μ_i are equal
6. Construction Production Rate	$\mu_1 = \cdots = \mu_8$	not all μ_i are equal
7. RUC	$\mu_1 = \cdots = \mu_8$	not all μ_i are equal

Each test produced an ANOVA model report with an interaction tree diagram. From the results, conclusions were drawn to the effect that a bridge deck replacement method had on the overall mean of the construction performance factor being tested.

5.4.3.1 *TCB: Unit Cost*

The construction performance values that were tested in a nested ANOVA for TCB unit cost have been summarized on Table 5-14. These values were taken directly from Table 5-12.

Table 5-14 TCB Unit Cost

Deck System	Construction Sequence	Casting Technique	Lane-span ID	TCB Unit Cost ($/ft)
Exodermic	Traditional	CIP	NBI1	35.42
			NBI2	35.95
	Accelerated	CIP	NBO1	106.25
			NBO2	107.82
Steel Grid	Traditional	CIP	NBI3	35.95
			NBI4	35.42
	Accelerated	CIP	NBO3	107.82
			NBO4	106.25
NCHRP	Traditional	PC	SBI1	714.9
			SBI2	704.5
	Accelerated	PC	SBO1	1169.6
			SBO2	1152.5
Exodermic	Traditional	PC	SBI3	704.5
			SBI4	714.9
	Accelerated	PC	SBO3	1152.5
			SBO4	1169.6

From the ANOVA test the following model report, Table 5-15, was created.

Table 5-15 TCB Unit Cost Nested ANOVA Model Report from SAS Software

Source	DF	Sum of Squares	Mean Square	F-Value	P-value
Model	7	20365.4309	2909.3473	4274.56	<.0001
Error	8	5.4450	0.6806		
Corrected Total	15	20370.8758			

R^2	Coeff Var	Root MSE	Mean
0.9997	1.1561	0.8250	71.36

Source	DF	Type I SS	Mean Square	F-value	P-value
Casting Technique	1	0.0001	0.0001	0.00	0.9930
Construction Sequence	2	20365.4306	10182.7153	14961.0	<.0001
Deck System	4	0.00023	0.0001	0.00	1.0000

The ANOVA test fails to prove that the casting technique and deck system selected have a statistically significant impact on the TCB unit cost. The test proves that construction sequence has a statistical significant impact on the mean value of the TCB unit cost, with a reported p-value of <.0001. The R^2 value is very high at 0.9997, suggesting that the statistical model explains the given data well. For the 16 TCB unit cost values tested, the overall mean reported was $71.36/ft ($235.49/m).

An interaction tree diagram, Figure 5-8, was created to give reference to the magnitude of values being reported by the ANOVA test. The test suggests that the strongest impact on TCB unit cost comes from the construction sequence selected. In Figure 5-8 we see at the construction sequence level that the average mean value of TCB unit cost for a traditional construction sequence lane is $35.68/ft ($117.74/m). The average mean value of the accelerated construction sequence lane at the same level is $107.03/ft ($353.20/m. The accelerated construction sequence TCB unit cost is on average $71.35/ft ($235.46/m) higher than the traditional construction sequence.). The ratio of accelerated TCB unit cost to traditional TCB unit cost is 3:1, which is to be expected because the accelerated construction sequence lane requires three TCB rows to perform intermittent lane closures, while traditional construction sequencing only uses one row of TCB.

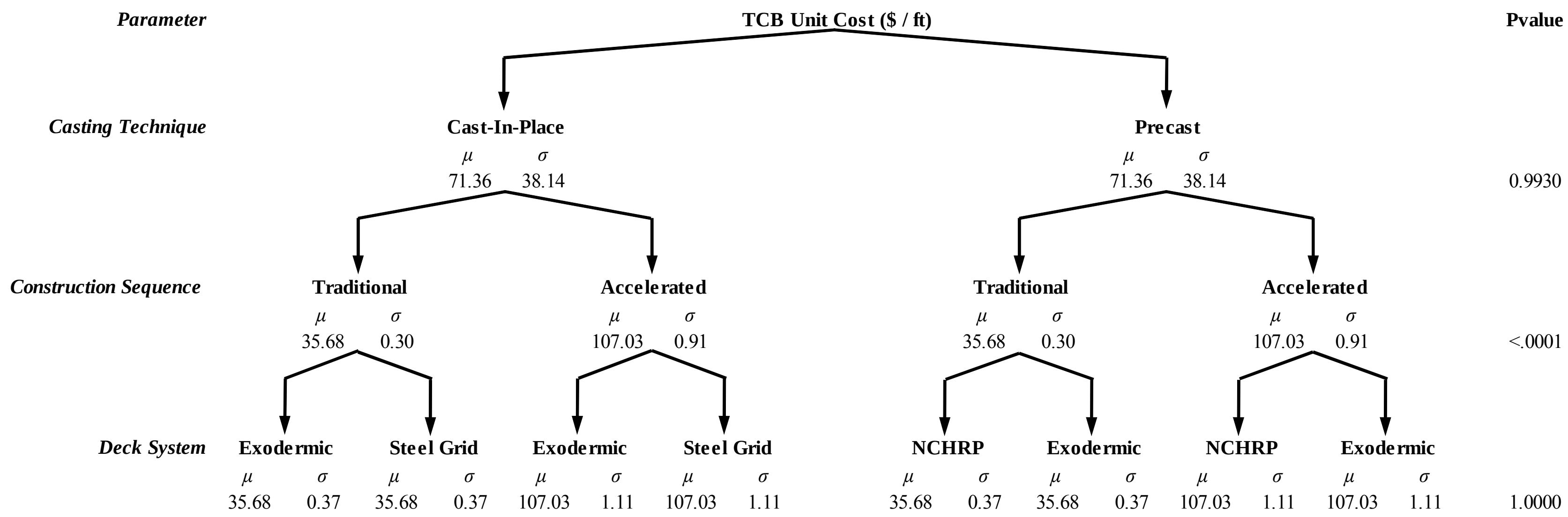


Figure 5-8 TCB Unit Cost Interaction Tree Diagram.

5.4.3.2 *Demolition: Unit Cost*

The values used for demolition unit cost are drawn directly from Table 5-12 which is the summary of the construction performance factors. Table 5-16 shows only the demolition unit costs.

Table 5-16 Demolition Unit Cost

Deck System	Construction Sequence	Casting Technique	Lane-span ID	Demolition Unit Cost ($/ft^2)
Exodermic	Traditional	CIP	NBI1	9.19
			NBI2	8.73
	Accelerated	CIP	NBO1	8.73
			NBO2	9.19
Steel Grid	Traditional	CIP	NBI3	8.73
			NBI4	8.27
	Accelerated	CIP	NBO3	8.73
			NBO4	9.19
NCHRP	Traditional	PC	SBI1	8.27
			SBI2	8.73
	Accelerated	PC	SBO1	9.19
			SBO2	8.73
Exodermic	Traditional	PC	SBI3	8.73
			SBI4	9.19
	Accelerated	PC	SBO3	9.19
			SBO4	8.73

From the ANOVA test the following model report, Table 5-17, was generated.

Table 5-17 Demolition Unit Cost Nested ANOVA Model Report from SAS

Source	DF	Sum of Squares	Mean Square	F-Value	P-value
Model	7	0.6348	0.0907	0.86	0.5741
Error	8	0.8464	0.1058		
Corrected Total	15	1.4812			

R^2	Coeff Var	Root MSE	Mean
0.4286	3.6774	0.3253	8.85

Source	DF	Type I SS	Mean Square	F-value	P-value
Casting Technique	1	0.0000	0.0000	0.00	1.0000
Construction Sequence	2	0.2116	0.1058	1.00	0.4096

Deck System	4	0.4232	0.158	1.00	0.4609

At a p-value threshold of 0.05 the ANOVA model fails to prove that any of the bridge deck replacement methods have a statistically significant impact on the demolition unit cost.

This model may be explained from the low learning curve factors applied to the lanes. In real construction a higher reduction learning curve may occur that will result in greater deviation to the demolition unit cost. It can also be seen in this example, as would be expected, that the demolition unit cost is completely insensitive to the replacement method casting technique with a p-value of 1.0000.

The demolition unit cost interaction tree diagram can be seen in Figure 5-9.

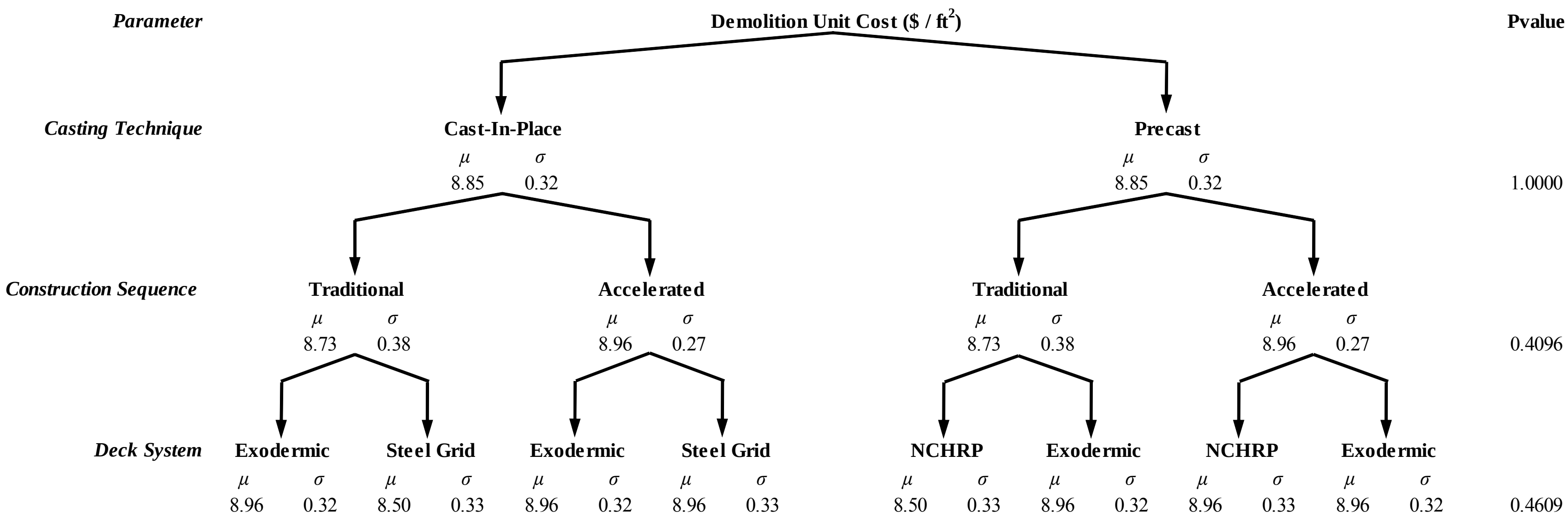


Figure 5-9 Demolition Unit Cost Interaction Tree Diagram.

5.4.3.3 *Construction: Unit cost*

Table 5-12, construction unit cost were used for nested ANOVA. The construction unit costs have been summarized on Table 5-18.

Table 5-18 Construction Unit Cost

Deck System	Construction Sequence	Casting Technique	Lane-span ID	Construction Unit Cost ($/ft^2)
Exodermic	Traditional	CIP	NBI1	29.50
			NBI2	28.03
	Accelerated	CIP	NBO1	28.03
			NBO2	29.50
Steel Grid	Traditional	CIP	NBI3	19.00
			NBI4	18.00
	Accelerated	CIP	NBO3	19.00
			NBO4	20.00
NCHRP	Traditional	PC	SBI1	49.50
			SBI2	52.25
	Accelerated	PC	SBO1	55.00
			SBO2	52.25
Exodermic	Traditional	PC	SBI3	49.87
			SBI4	52.50
	Accelerated	PC	SBO3	52.50
			SBO4	49.88

The ANOVA model report, Table 5-19, for construction unit cost was created from the ANOVA analysis.

Table 5-19 Construction Unit Cost of Nested ANOVA Model Report from SAS

Source	DF	Sum of Squares	Mean Square	F-Value	P-value
Model	7	3300.9580	471.5654	214.18	<.0001
Error	8	17.6141	2.2018		
Corrected Total	15	3318.5721			

R^2	Coeff Var	Root MSE	Mean
0.9947	3.9254	1.4384	37.80

Source	DF	Type I SS	Mean Square	F-value	P-value
Casting Technique	1	3099.4273	3099.4273	1407.71	<.0001
Construction Sequence	2	4.2950	2.1475	0.98	0.4178
Deck System	4	197.236	49.3089	22.40	0.0002

The ANOVA test fails to prove that construction sequence has a statistically significant impact on the construction unit cost. The test does prove that the casting technique and deck system have statistically significant impacts on the construction unit cost with a p-value of <.0001 and 0.002 respectively. The R^2 value is 0.9947, which indicates the model represents the given data well. The mean value for the 16 construction unit costs tested was \$37.80/ft^2 (\$411.64/m^2).

The construction unit cost interaction tree diagram was created from the analysis and can be seen in Figure 5-10. At the casting level the calculated mean construction unit cost for CIP and PC is \$23.88/ft^2 (\$260.05/m^2) and \$51.72/ft^2 (\$563.23/m^2) respectively.

These results support the cost estimating for this example problem. It was initially assumed that PC had a higher unit cost, 75% mark up, than CIP and it should be expected that the ANOVA supports this assumption. Likewise, the estimated unit costs for the deck systems are reflected in the ANOVA output. It was assumed that the lowest unit cost deck system was a steel grid, followed by the moderately priced Exodermic, and final the most expensive NCHRP.

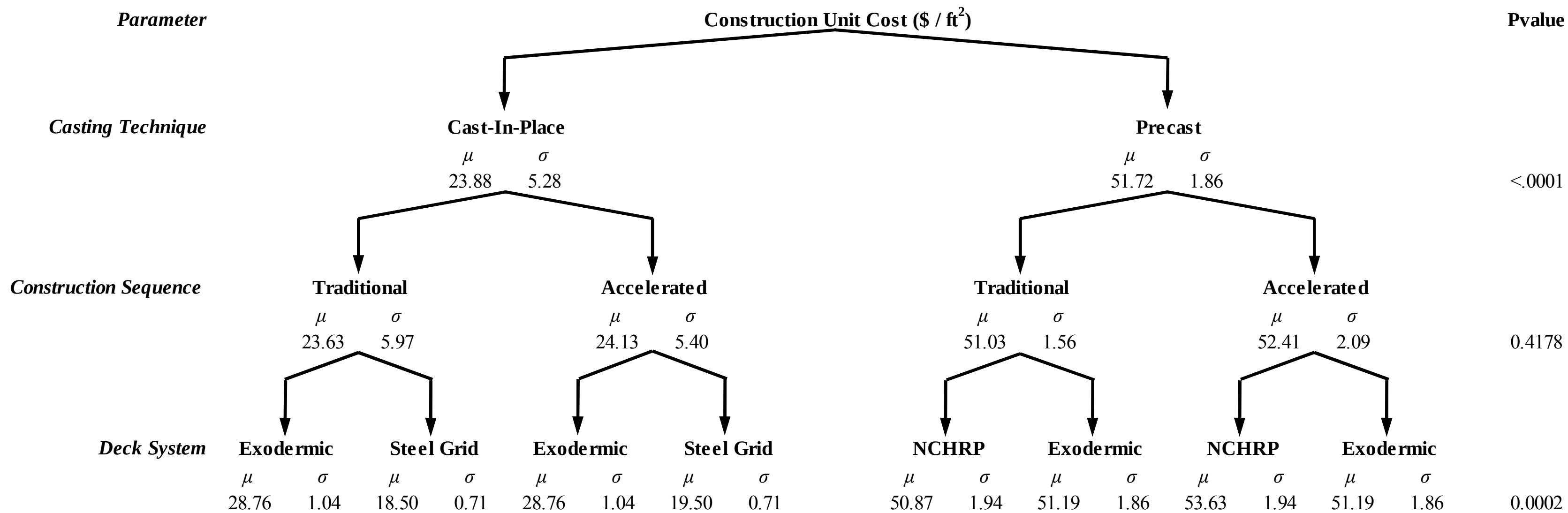


Figure 5-10 Construction Unit Cost Interaction Tree Diagram.

5.4.3.4 *TCB: Production Rate*

The TCB production rate values in Table 5-12 were analyzed in the nested ANOVA. A summary of theses TCB production rate values are shown in Table 5-20.

Table 5-20 TCB Production Rates

Deck System	Construction Sequence	Casting Technique	Lane-span ID	TCB Production Rate (ft/hr)
Exodermic	Traditional	CIP	NBI1	113.7
			NBI2	112.0
	Accelerated	CIP	NBO1	22.7
			NBO2	22.4
Steel Grid	Traditional	CIP	NBI3	112.0
			NBI4	113.7
	Accelerated	CIP	NBO3	22.4
			NBO4	22.7
NCHRP	Traditional	PC	SBI1	113.7
			SBI2	112.0
	Accelerated	PC	SBO1	22.7
			SBO2	22.4
Exodermic	Traditional	PC	SBI3	112.0
			SBI4	113.7
	Accelerated	PC	SBO3	22.4
			SBO4	22.7

The ANOVA model report can be seen in Table 5-21.

Table 5-21 TCB Production Rate Nested ANOVA Model Report from SAS

Source	DF	Sum of Squares	Mean Square	F-Value	P-value
Model	7	32616.3600	4659.4800	6254.34	<.0001
Error	8	5.9600	0.7450		
Corrected Total	15	32622.3200			

R^2	Coeff Var	Root MSE	Mean
0.9998	1.2749	0.8631	67.7

Source	DF	Type I SS	Mean Square	F-value	P-value
Casting Technique	1	0.0000	0.0000	0.00	1.0000
Construction Sequence	2	32616.3600	16308.1800	21890.2	<.0001
Deck System	4	0.0000	0.0000	0.00	1.0000

The ANOVA model report fails to prove that the casting technique and deck system methods have a statistically significant impact on the TCB production rate. The results suggest that the construction sequence does have a statistically significant effect on the mean TCB production rate. The R^2 value of 0.9998, suggest a model that represents the given data well. The reported mean value for the 16 TCB production rate values is 67.7 ft/hr (20.5 m/hr).

The magnitude of the TCB production rates can be seen on the interaction tree diagram displayed in Figure 5-11. The TCB production rate at the construction sequence level is 112.8 and 22.6 ft/hr (34.2 and 6.8 m/hr) for traditional and accelerated construction sequencing, respectively. The traditional construction sequence mean TCB production rate is 90.2 ft/hr (27.3 m/hr) greater than the accelerated construction sequence.

These results are expected because, by design the TCB production rates are insensitive to, not a function of, casting technique and deck system. The production rates are dependant only on the construction sequence which uses one row of TCB for traditional and three rows of TCB for accelerated construction sequencing.

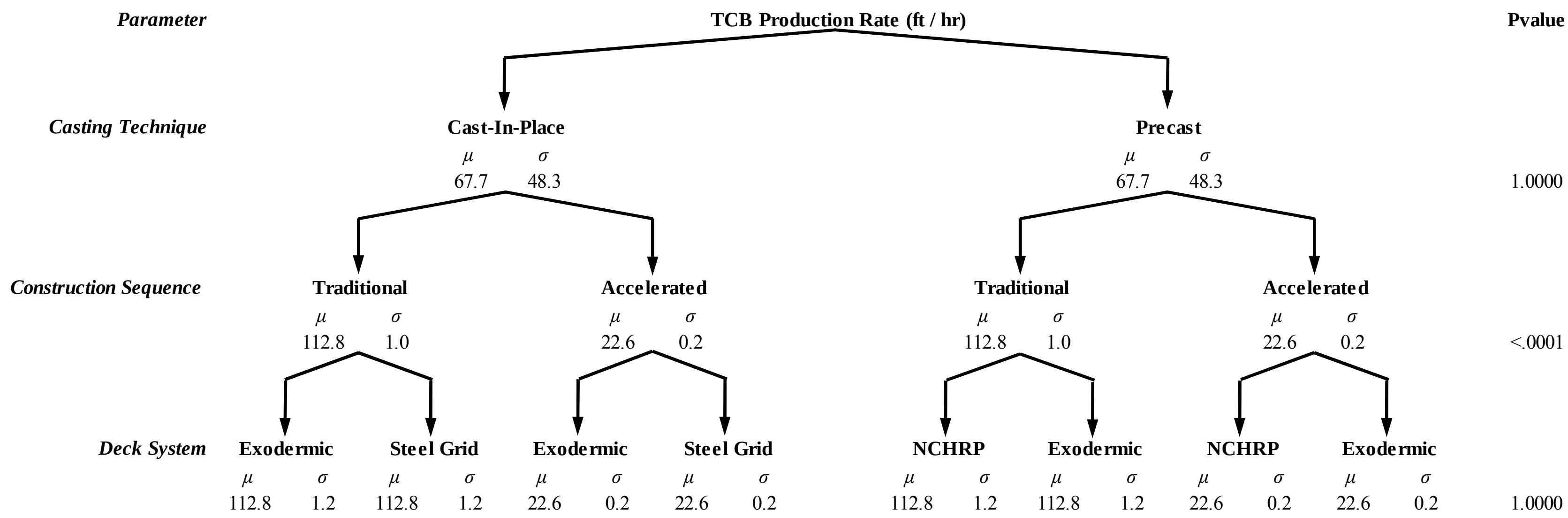


Figure 5-11 TCB Production Rate Interaction Tree Diagram.

5.4.3.5 *Demolition: Production Rate*

Demolition production rate values that were used for nested ANOVA testing can be seen in Table 5-22. These values have been taken directly from Table 5-12.

Table 5-22 Demolition Production Rates

Deck System	Construction Sequence	Casting Technique	Lane-span ID	Demolition Production Rate (ft^2/hr)
Exodermic	Traditional	CIP	NBI1	143.0
			NBI2	156.6
	Accelerated	CIP	NBO1	137.6
			NBO2	128.1
Steel Grid	Traditional	CIP	NBI3	156.6
			NBI4	178.7
	Accelerated	CIP	NBO3	135.6
			NBO4	130.0
NCHRP	Traditional	PC	SBI1	178.7
			SBI2	156.6
	Accelerated	PC	SBO1	130.0
			SBO2	135.6
Exodermic	Traditional	PC	SBI3	156.6
			SBI4	143.0
	Accelerated	PC	SBO3	128.1
			SBO4	137.6

Table 5-23 shows the ANOVA model report and statistics for the demolition production rates.

Table 5-23 Demolition Production Rate Nested ANOVA Model Report from SAS

Source	DF	Sum of Squares	Mean Square	F-Value	P-value
Model	7	3320.4900	474.3557	4.77	0.0215
Error	8	794.9800	99.3725		
Corrected Total	15	4115.4700			

R^2	Coeff Var	Root MSE	Mean
0.8068	6.8383	9.9686	145.7

Source	DF	Type I SS	Mean Square	F-value	P-value
Casting Technique	1	0.0000	0.0000	0.00	1.0000
Construction Sequence	2	2683.2400	1341.6200	13.50	0.0027
Deck System	4	637.2500	159.3125	1.60	0.2639

The ANOVA fails to prove that casting technique and deck system has a statistically significant effect on the mean demolition production rate. Only the construction sequence has a statistically significant effect on the mean of the demolition production rate. The R^2 value of 0.8068, suggests the model represents the given data well. The overall mean demolition production rate for the 16 values analyzed was reported as 145.7 ft^2/hr (13.4 m^2/hr).

The interaction tree diagram, illustrated in Figure 5-12, shows the magnitude of the mean demolition production rates at each bridge deck replacement method's level. The mean demolition production rate at the construction sequence level is 158.7 and 132.8 ft^2/hr (14.6 and 12.2 m^2/hr) for traditional and accelerated construction sequences, respectively.

It should be expected that the traditional construction sequence lane would have a higher production rate than the accelerated construction sequence lane, because of the assumed learning curve and the sequential progression of demolition activities. In the traditional construction sequence lane, demolition occurs from the first lane-span to the fourth lane-span reaching a maximum demolition cost reduction of 10% from the learning curve. In the accelerated construction sequence, the learning curve only allows the cost reduction to reach a maximum of 5%, because of the intermittent closures.

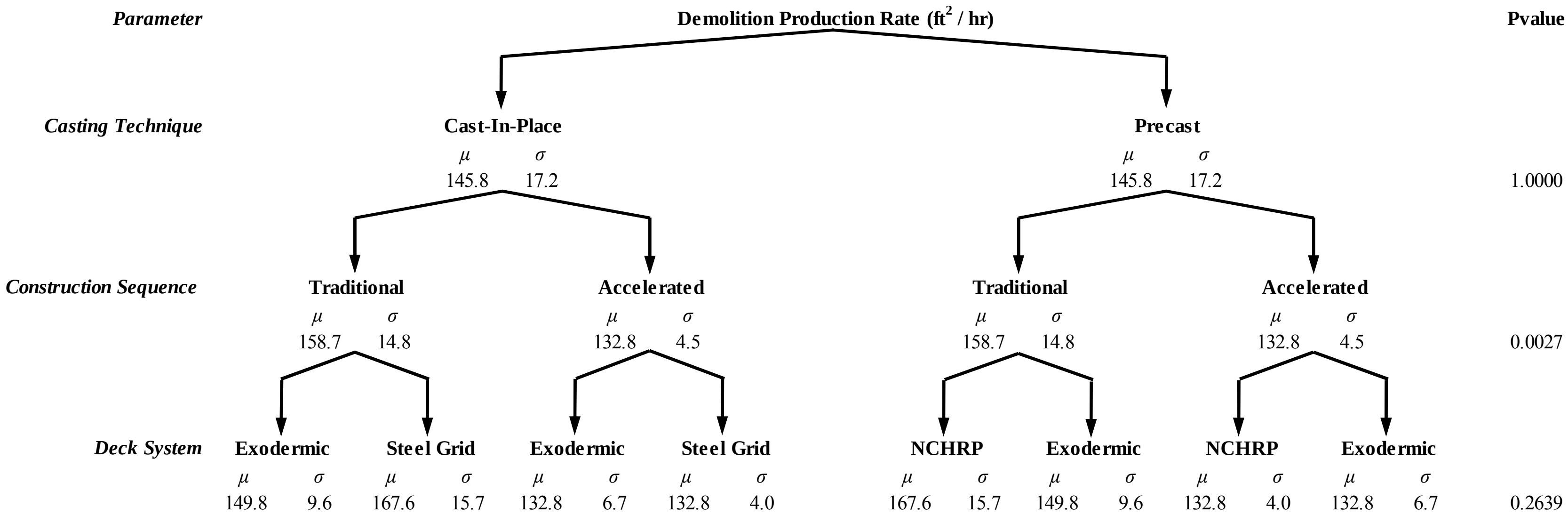


Figure 5-12 Demolition Production Rate Interaction Tree Diagram.

5.4.3.6 *Construction: Production Rate*

The construction production rate values that were analyzed in this section were gathered from Table 5-12. The values analyzed have been displayed in Table 5-24.

Table 5-24 Construction Production Rates

Deck System	Construction Sequence	Casting Technique	Lane-span ID	Construction Production Rate (ft^2/hr)
Exodermic	Traditional	CIP	NBI1	81.6
			NBI2	83.5
	Accelerated	CIP	NBO1	97.3
			NBO2	92.9
Steel Grid	Traditional	CIP	NBI3	83.5
			NBI4	88.1
	Accelerated	CIP	NBO3	98.9
			NBO4	97.3
NCHRP	Traditional	PC	SBI1	200.3
			SBI2	180.9
	Accelerated	PC	SBO1	172.9
			SBO2	180.4
Exodermic	Traditional	PC	SBI3	167.0
			SBI4	157.3
	Accelerated	PC	SBO3	153.3
			SBO4	163.8

From the nested ANOVA test the following model information was reported.

Table 5-25 Construction Production Rate Nested ANOVA Model Report from SAS

Source	DF	Sum of Squares	Mean Square	F-Value	P-value
Model	7	28253.5775	4036.2254	94.46	<.0001
Error	8	341.8200	42.7275		
Corrected Total	15	28595.3975			

R^2	Coeff Var	Root MSE	Mean
0.9880	4.9827	6.5366	131.19

Source	DF	Type I SS	Mean Square	F-value	P-value
Casting Technique	1	26634.2400	26634.2400	623.35	<.0001
Construction Sequence	2	462.7625	231.3813	5.42	0.0326
Deck System	4	1156.5750	289.1438	6.77	0.0111

The results show that the construction production rate is statistically affected by all of the bridge deck replacement methods. The overall mean of the 16 construction production rates analyzed for the given data is 131.9 ft^2/hr (12.1 m^2/hr).

The interaction tree diagram was created from the construction production rates on Table 5-24 and can be seen on Figure 5-13. The lowest p-value was seen at the casting technique level with a value of <0.0001. The mean value of the construction production rates, at the casting technique level, is 90.4 and 172.0 ft^2/hr (8.3 and 15.8 m^2/hr) for CIP and PC respectively. PC lane-spans were built on average at a rate of 81.6 ft^2/hr (7.5 m^2/hr) faster than CIP lane-spans. It is expected that the PC casting technique would have a higher production rate than the CIP casting technique because of the assumed 6 hour curing time for CIP methods.

The deck system with the highest construction production rate is a NCHRP deck system built with a traditional construction sequence using a PC casting technique with a production rate of 190.6 ft^2/hr (18.0 m^2/hr). The deck system with the lowest construction production rate is the Exodermic deck system built with a traditional construction sequence using a CIP casting technique with a production rate of 82.5 ft^2/hr (7.8 m^2/hr).

The results of the ANOVA test support the schedule estimating assumptions. It was assumed that the NCHRP deck system had the lowest total duration of 6 and 9 hours, for the traditional and accelerated lanes respectively. The Exodermic deck system was assumed to require the longest duration with a CIP casting technique of 7.5 and 10.5 hours respectively.

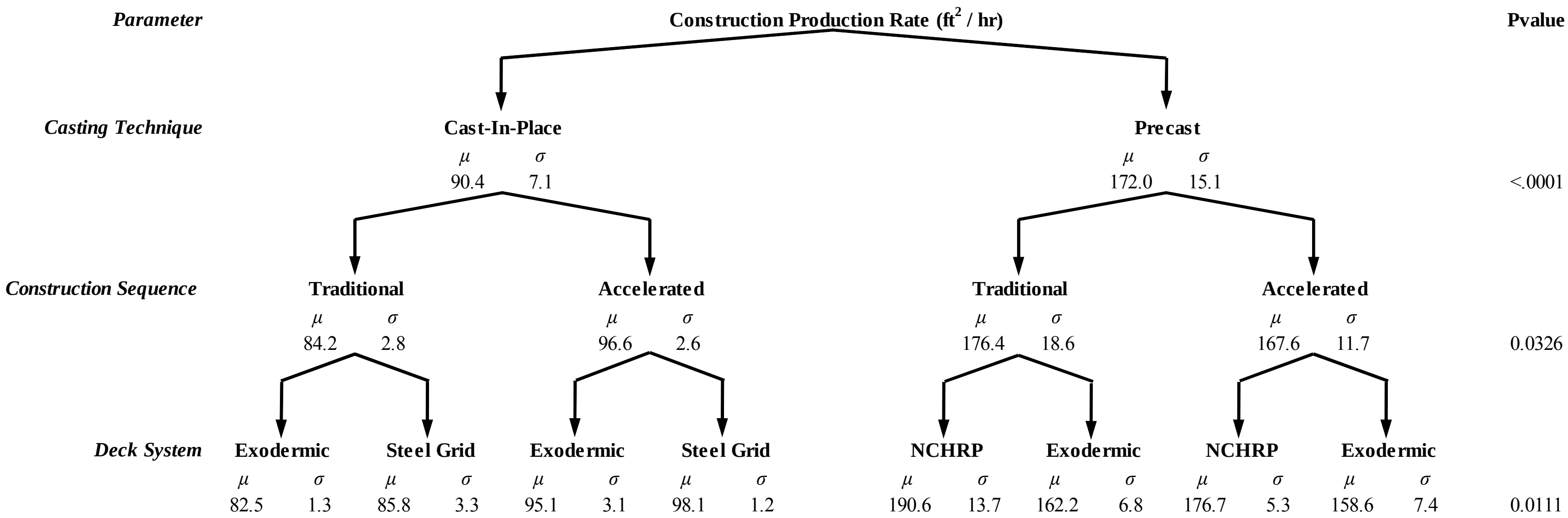


Figure 5-13 Construction Production Rate Interaction Tree Diagram.

5.4.3.7 *Road User Cost*

RUC values that were used for nested ANOVA testing can be seen in Table 5-26. These values have been taken directly from Table 5-12 which summarized the calculated RUC for each lane-span.

Table 5-26 Estimated Road User Cost (RUC) Values per Deck System

Deck System	Construction Sequence	Casting Technique	Lane-span ID	RUC ($)
Exodermic	Traditional	CIP	NBI1	46.26
			NBI2	43.82
	Accelerated	CIP	NBO1	50.13
			NBO2	51.99
Steel Grid	Traditional	CIP	NBI3	43.82
			NBI4	41.39
	Accelerated	CIP	NBO3	49.20
			NBO4	51.06
NCHRP	Traditional	PC	SBI1	30.82
			SBI2	33.91
	Accelerated	PC	SBO1	37.81
			SBO2	35.97
Exodermic	Traditional	PC	SBI3	35.45
			SBI4	38.53
	Accelerated	PC	SBO3	39.65
			SBO4	37.81

Table 5-27 shows the ANOVA model report and statistics for the RUC.

Table 5-27 RUC Nested ANOVA Model Report from SAS

Source	DF	Sum of Squares	Mean Square	F-Value	P-value
Model	7	623.8538	89.1219	31.98	<.0001
Error	8	22.2917	2.7864		
Corrected Total	15	646.1455			

R^2	Coeff Var	Root MSE	Mean
0.9655	4.0005	1.6692	41.7262

Source	DF	Type I SS	Mean Square	F-value	P-value
Casting Technique	1	480.9249	480.9249	172.59	<.0001
Construction Sequence	2	111.3586	55.6793	19.98	0.0008
Deck System	4	28.1279	7.8925	2.83	0.0981

The analysis fails to prove that the deck system selected has a statistically significant impact on the RUC with a confidence interval of 95%. The ANOVA does prove that the casting technique and the construction sequence does statistically affect the total RUC. The R^2 value for the model was 0.9655 suggesting that the model fits the given data well.

From the RUC values on Table 5-26 the following RUC interaction tree diagram was created and can be seen in Figure 5-14. The largest RUC, $50.60, was associated with an accelerated construction sequence and a CIP casting technique.

The traditional construction sequence was performed on weekdays, while the accelerated construction sequence was performed on weekends. From the traffic data collected at the site, it was determined that weekdays have an average lower vehicle volume than weekends for this example location. In some rural locations passenger vehicle volumes can increase on weekends while truck volumes decrease (Hallenbeck, 1997). Being that I-59 is a rural location higher vehicle volumes were experienced on the expected lower vehicle volume weekends. This result suggests that regional factors must be accounted for when selecting the period to apply accelerated construction sequences. In rural locations weeknights may be a better option for accelerated construction sequencing than weekends, because of the higher weekend vehicle volume attributed to an a rural area.

The CIP casting technique required longer total lane closure duration than the PC casting technique because of the additional 6 hour curing time. This additional time resulted in more vehicles that experienced delay due to the construction effort, which results in a higher RUC.

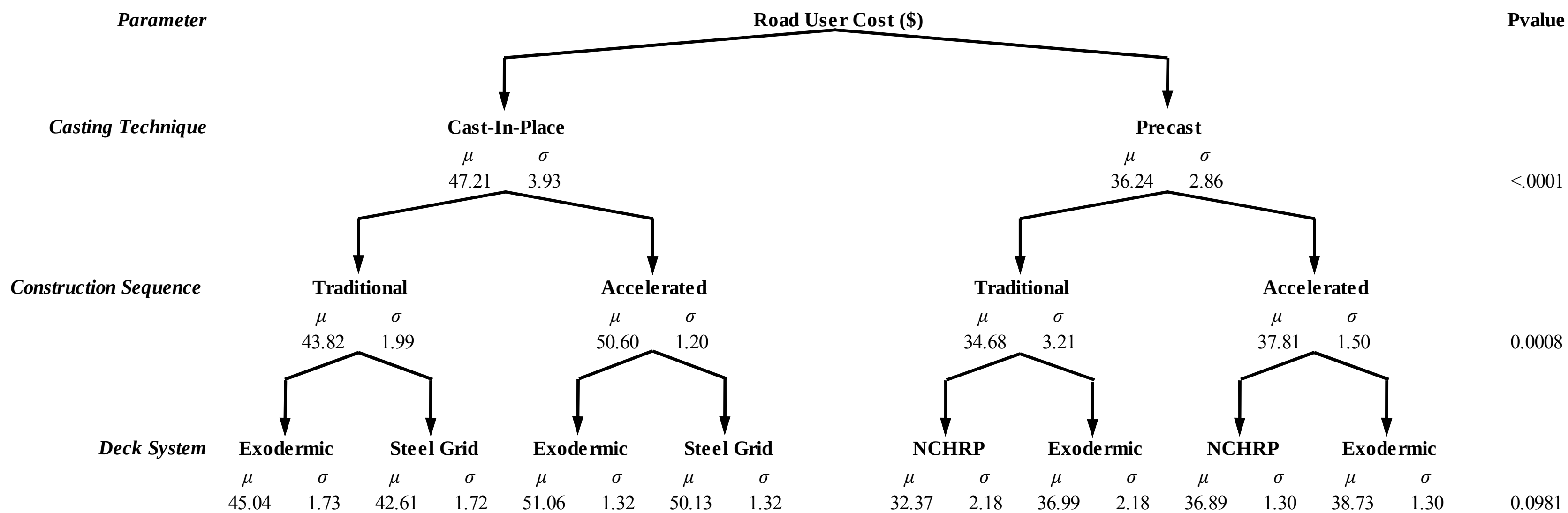


Figure 5-14 RUC Interaction Tree Diagram.

5.4.4 Summary of Nested ANOVA

A summary of the p-values for each construction performance factor tested can be seen in Table 5-28. A p-value of 0.05 or less was used to determine if a bridge deck replacement method had a statistically significant impact on the mean of the construction performance factor in question.

Table 5-28 I-59 Example Bridge Deck Replacement Methods Effect on Construction Performance Factors P values

Bridge Deck Replacement Method	P-Values						
	Unit Cost			Production Rate			RUC
	TCB	Demo	Const	TCB	Demo	Const	
Casting Technique	0.9930	1.0000	<.0001	1.0000	1.0000	<.0001	<.0001
Construction Sequence	<.0001	0.4096	0.4178	<.0001	0.0027	0.0326	0.0008
Deck System	1.0000	0.4609	0.0002	1.0000	0.2639	0.0111	0.0981

Note:
*P value of 0.05 or less indicates a statistically significant effect on the mean value.

From the nested ANOVA results, unit cost of the TCB was only affected by the construction sequence. It required three rows of TCB for accelerated construction sequence, while in traditional construction sequence it only required one row of TCB. The demolition unit cost was mostly unaffected by all three of the bridge deck replacement methods. The construction unit cost was affected by the casting technique and the deck system selected.

The production rates of TCB and demolition were controlled by the construction sequence. This was a result of the assumed learning curves for the example project. The traditional construction sequence was allowed to reach a maximum cost reduction of 10%, while the accelerated construction sequence only reached 5%. The construction production rate was affected by all three bridge deck replacement methods. The results of the ANOVA reflected the assumed schedule of each deck system and the learning curve applied for raw data estimation.
RUC was affected by the casting technique and construction sequence. CIP casting techniques had higher RUC than PC, because it required a longer lane closure period for the curing time. The traditional construction sequence had a lower RUC than the accelerated construction sequence because weekend vehicle volumes were typically higher than weekday volumes for this rural location.

Based on the results of this hypothetical I-59 example problem, as a practitioner selecting the most viable bridge deck replacement method for this location, one could suggest that a steel grid cast-in-place traditional method would be best for construction. The steel grid deck system had the lowest unit cost of construction of the 3 deck systems with a moderate production rate. The CIP casting technique had a lower production rate than the PC casting technique but also a lower unit cost. The traditional construction sequence overall had a higher production rate and a lower RUC than the accelerated construction sequence. The traditional construction sequence having a lower RUC than the accelerated construction sequence was due to the attribute of a rural bridge having higher weekend vehicle volumes than the weekday. In some cases, rural location may have higher vehicle volumes on the weekend than on the weekday, opposed to urban locations that typically have lower vehicle volumes on the weekends.

The deciding factor between selecting a traditional or accelerated construction sequence and a CIP or PC casting technique would be based on the relative vehicle volume and length of the bridge under consideration, along with regional attributes of the project location. The example problem used a rather small bridge, 225.6 ft (68.4 m), with very low vehicle volumes located in a rural location. Because the I-59 location was rural the benefits of using accelerated construction sequencing on a weekend work schedule were not realized and the traditional construction sequence resulted in a lower traffic impact and lower RUC.

5.5 Summary of I-59 Example Project

For the example problem, hypothetical data was created to outline the steps created in the methodology and analysis of this report. Using the hypothetical data, with the methodology created, it was demonstrated how the effects of bridge deck replacement methods on construction performance factors could be analyzed. From the ANOVA model reports and interaction tree diagrams, inferences were made to highlight the strengths and weakness of each bridge deck replacement method.

The analysis can be used to help determine the most viable bridge deck replacement methods to be used on future bridge projects. The primary variables, from the example results, were the regional location, vehicle volume, and length of the bridge under consideration. Rural location may have higher vehicle volumes on a weekend, which make accelerated construction sequencing with weekend scheduling ineffective at alleviating associated traffic impacts. Alternatively, urban locations typically have lower vehicle volume weekend periods and accelerated construction sequences performed over that period has the potential to result in a lower traffic impacts and RUCs. Longer bridges with overall higher vehicle volumes will result in a high RUC and methods with higher production rates that come with higher unit cost could be more beneficial. Shorter bridges with low vehicle volumes will result in a lower RUC and methods with lower production rates that come with lower unit cost can also be considered. As a practitioner, bridge deck replacement method selection must be determined on the total project cost, schedule, and traffic impact. Low vehicle volume projects will not always warrant accelerated construction methods that come with a higher cost of construction. However, high vehicle volume projects can have a high RUC that could offset the associated cost of construction and accelerated construction methods may be more beneficial where applicable based on regional attributes of the project (i.e. rural or urban).

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

Deteriorating U.S. bridge infrastructure combined with traffic volume growth and increased user demand has led many engineers to explore new construction methods for replacing or rehabilitating infrastructure elements that minimize construction related impacts (i.e., travel time delays, congestion, and increases in road user costs (RUCs)). A better understanding is needed of the interaction of accelerated construction techniques on the overall cost, schedule and related traffic impacts. This information will allow practitioners to make sound engineering decisions on which accelerated bridge construction techniques should be employed on future bridge project

A bridge deck replacement project has been proposed for I-59 in Collinsville, AL. The bridge is 225.6 ft (68.4 m) in length with an AADT of 13,420 (ALDOT, 2011). The purpose of this research was to develop a framework that will be used to evaluate the impact of different accelerated bridge deck replacement methods from a construction perspective based on the total project cost, schedule, and traffic impact on the I-59 projects.

Before formulating a methodology for measuring the effects of bridge deck replacement methods on the construction performance factors: unit cost, production rate, and RUC, a thorough literature review was performed. The literature review identified, described, evaluated, and critically assessed pertinent literature on the current deck systems, methods, technologies, and analysis techniques available for assessing bridge deck replacement methods.

The knowledge gleaned from the literature review was applied to create a methodology for statistically evaluating the effects that a particular bridge deck replacement method's deck system, construction sequence, and casting technique have on the three specified construction performance factors: (1) unit cost, (2) production rate, and (3) RUC. Steps for data collection, normalizing the data, and analysis of the data were outlined. Tables were developed to aid in the collecting and organizing of the data.

Delays associated with the development of the plan set, bid package, and unforeseen site conditions on the I-59 project prevented the methodology from being applied to the actual project. As a result, a hypothetical example problem of the I-59 project was developed to demonstrate the applicability of the methodology. The results of the analyses performed are reported to showcase how the methodology could be used to select the most viable bridge deck replacement method to use on a future project based upon regional constraints and agency priorities. This example problem assumed hypothetical data and should only be used as a reference that demonstrates the analysis framework for the actual I-59 project.

Based on the hypothetical data in the example problem, it was identified that regional classification, vehicle volume, and bridge length are large contributing factors to the overall

RUC and selection of a bridge deck replacement method. In the example it was demonstrated that accelerated construction sequence on a weekend schedule may not be a viable selection for rural location. Urban locations typically have lower weekend vehicle volumes than weekday vehicle volumes and could benefit from weekend accelerated construction sequencing.

For ideal urban location such as Birmingham, AL, with lower weekend vehicle volumes, one disadvantage of using accelerated construction sequencing with PC casting techniques is that while it achieves a shorter total project duration, which keeps RUC low, it comes with an average higher overall unit cost for the project. It may not be financially justifiable to select accelerated construction methods to keep RUC low on all projects. If a project does not have high vehicle volumes traditional construction methods may be a better option. Traditional methods on low vehicle volume roadways can keep the overall project cost low with little impact to the RUC. As a practitioner the most critical components to use during decision making are the RUC and the construction cost. Determining when RUC offsets the cost of construction will enable proper bridge deck replacement method selection for a project based on project-specific constraints.

6.2 Recommendations

This research only considered direct RUCs such as value of time, and operating and ownership cost. Depending on the location, there are many more factors that can contribute to the overall RUC. Such examples include additional wear and tear of detour roadways from vehicles selecting alternative routes or the monetary loss businesses experience from exposure, due to new route selection by vehicles, increased crash risk associated with the presence of the work zone, and health cost due to increased emissions. These factors have the potential to increase the total RUC of a construction project and research should be conducted into adding these elements into the total RUC.

From the results of the example problem and knowledge gained from this report, future research should be conducted in the area of RUC on different vehicle volumes and length bridges. Because the vehicle volume and length of the bridge plays such an important part in determining the overall RUC and therefore when that cost is justifiable for selecting accelerated construction methods, better understanding of the vehicle volumes and bridge length is required. A sensitivity analysis study should be conducted comparing the effect of vehicle volumes against RUC to determine at what magnitude of vehicle volume, RUC offsets the increased unit cost accompanied with accelerated construction methods. Likewise, a study comparing the bridge length to the RUC would show at what bridge length accelerated construction methods become an alternative to justifiably keep RUC low.

In the example RUC values were estimated from the AASHTO publication (i.e. value of time, amortized cost, insurance cost). These values may not apply to future bridge projects in different regions. Research should be performed to determine appropriate values for a project based on region or site specific attributes. Then a sensitivity analysis should be performed to determine the effects of the assumed values on the overall result of the RUC.

To model the nested ANOVA, the bridge deck replacement methods had to be assigned to three levels. The results of the ANOVA test are unique to the design of the levels. Future research can be conducted on similar projects by assigning the bridge deck replacement methods to different levels in the model and seeing how the results are affected. By having a set of results for various models the information will be more transferable to future projects.

The future research with the methodology outlined throughout this report would help in creating a more accurate model for predicting the effects that bridge deck replacement methods will have on the total project cost, schedule, and traffic impact. This will give practitioners an effective tool to use during the decision making process when selecting accelerated bridge deck replacement methods on future bridge projects.

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Appendix A:
Road User Cost Template

Road User Cost Estimating

General Information

Project	
Date	
Analysis Year	

Site Information

Segment (ft)	
Period of Closure	
Volume (veh)	
Percent Passenger Cars (%)	
Percent Heavy Vehicles (%)	

Inputs

Finance Rate:

Passenger Vehicles

Percentage of hourly wage (Table 5-1)	
Average hourly wage (Table 5-2)	
Average vehicle occupancy	
Speed before closure (mph)	
Speed during closure (mph)	
Other Operating Costs per Mile (Table 5-4) (tires, maintenance, etc.)	
Vehicle Life (years)	
Vehicle Cost ($)	
Salvage Value at End of Life	
Insurance per Year (Table 5-4):	

Trucks

Percentage of hourly Wage (Table 5-1)	
Average hourly wage (Table 5-2)	
Average vehicle occupancy	
Speed before closure (mph)	
Speed during closure (mph)	
Other Operating Costs per Mile (Table 5-4) (tires, maintenance, etc.)	
Vehicle Life (years)	
Vehicle Cost ($)	
Salvage Value at End of Life	
Cargo Value	
Insurance per Year (Table 5-4):	

Calculations

Autos

Value of time per vehicle hour ($/veh-hr): (wage X percentage X occupancy)	
Amortized cost per vehicle hour ($/veh-hr): A = (i*(P*(1+i)^n)-F)/((1+i)^n)-1)/8760	
Insurance cost per vehicle hour($/veh-hr): (Insurance per year / 8760)	
Total cost per vehicle hour ($/veh-hr):	

Trucks

Value of time per vehicle hour ($/veh-hr): (wage X percentage X occupancy)	
Amortized cost per vehicle hour ($/veh-hr): A = (i*(P*(1+i)^n)-F)/((1+i)^n)-1)/8760	
Insurance cost per vehicle hour($/veh-hr): (Insurance per year / 8760)	
Inventory cost per vehicle hour($/veh-hr): (Cargo value X finance rate / 8760)	
Total cost per vehicle hour ($/veh-hr):	

Autos

Travel time before closure (sec)	
Travel time during closure (sec) (Segment / 5280) X (3600 / Speed)	
Cost per vehicle before closure ($/veh)	
Cost per vehicle during closure($/veh) (Total cost per vehicle hour / 3600)*(delay)	
Realized cost per vehicle ($/veh) (cost after closure - cost before closure)	

Trucks

Travel time before closure (sec)	
Travel time during closure (sec) (Segment / 5280) X (3600 / Speed)	
Cost per vehicle before closure ($)	
Cost per vehicle during closure($) (Total cost per vehicle hour / 3600)*(delay)	
Realized cost per vehicle ($/veh) (cost after closure - cost before closure)	

Results

RUC from Autos for lane($) (Realized Cost X Volume X Percentage)	
RUC Trucks for lane ($) (Realized Cost X Volume X Percentage)	
Total RUC for Lane ($)	

Note:
*i = Finance Rate
*P = Vehicle Cost
*n = Vehicle Life
*F = Salvage Value at End of Life
*8760 = Number of hours in one year