APPLICATION OF LEAN PHILOSOPHY TO ROUTINE INSPECTION OF BRIDGES

by

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ABSTRACT

It takes significant time, money, labor, and equipment to run a routine bridge inspection program. This work examines the application of Lean philosophy, originating from manufacturing, as a means to assess and suggest improvements regarding the efficiency of bridge inspections. Lean aims to maximize time on activities that add value to the final product and significantly reduce losses identified as waste. The bridge inspection process was first considered as a process flow and broken down into stages. Bridge inspection stages were defined in sequential order as: the review of documents in preparation for inspection; mobilization of equipment and personnel to the site; inspection time including the time spent on visual assessment, measurement, note taking, and photographing bridge elements; demobilization; and report writing. Data was collected by shadowing each stage of the inspection of 26 bridges. The bridges were of various types, sizes, and conditions. Three different inspection team leaders and four associate inspectors were shadowed, comprising six team combinations. In order to apply Lean philosophy to bridge inspection, a time log of all activities by stage was created and the activities were classified based on their value to the final product (an owner-approved bridge inspection report) by identifying value added, required non-value added, and non-value added activities. Findings from this research suggest that the mobilization/demobilization, inspection and report writing stages each claimed approximately one-third of the total routine inspection duration. Report writing time further increased to half of the total duration when inspectors' self-reported time on these activities was included. Furthermore, only 42% of total time spent on routine inspection of bridges was found to add value to the final output, an owner approved bridge inspection report. Different types of challenges

observed during the shadowed bridge inspections informed recommendations that are provided as suggestions for possible improvements in the efficiency of bridge inspection.

Chapter 1

INTRODUCTION

1.1 Motivation

There are more than 600,000 bridges in the US, all of which are routinely inspected. It takes significant time, money, labor and resources to inspect these bridges. Furthermore, many of these bridges have reached their design life. This fact contributes to US bridges being graded “C+” by the American Society of Civil Engineers (ASCE) Infrastructure Report Card of 2017 (ASCE, 2017). Inspection of older or poor condition bridges may be more demanding than inspection of bridges in better condition. Thus, understanding the efficiency of the time spent on the routine inspection of bridges may provide opportunities for reducing the cost and improving the quality of the bridge inspection process.

Lean is a management philosophy focused on efficiency. It was used for the first time in the 1950s by the Toyota Motor Corporation (hereafter, "Toyota" for brevity) and has been stated as the reason Toyota grew rapidly compared to more established companies (Ohno,1988). Lean studies all activities performed from the order of a product until delivery of the product to a customer. These activities are classified into work and waste activities. Activities that add value to a product are called work, while the ones that do not add value to a product are called waste. Through the identification of waste via this concept, new approaches to eliminate or reduce the time spent on these activities can be explored. Thus, the purpose of this research is to determine if Lean can be used to identify potential improvements in efficiency during the bridge inspection process.

1.2 Objective

The objective of this research is to identify the potential scope for improvements in the efficiency of the bridge inspection process, and accordingly providing recommendations to improve this efficiency. The ultimate goal is to provide savings in time, labor, and material resources during bridge inspection. Furthermore, improving the process of bridge inspection may reveal opportunities to improve environmental sustainability by eliminating wasted time and movement of inspection personnel and equipment, which is likely to reduce emissions. These aims are targeted at providing information that could guide state transportation agencies and other bridge owners to conduct more effective inspections at a lower cost. The specific audience is bridge inspectors and inspection managers.

1.3 Problem Statement

It is presumed that bridge inspections can be thought of as a process which has stages that consist of discrete groups of activities. This research attempts to answer:

- How many and what stages comprehensively describe the process of bridge inspection?
- How many and what activities make up a bridge inspection?
- Which of these activities add value and do not add value to the final bridge inspection report?
- How is time spent on different stages and activities that add value or do not add value?

- Are there differences in approaches and time taken between different bridge inspectors?

1.4 Scope

The scope of this research involves shadowing the inspection process of 26 different bridges. The term "shadowing" here refers to the procedure where a researcher accompanies an inspection crew to record inspection activities and the time spent on each of these activities. The approach developed in this research work identifies all inspection activities leading to an owner-approved inspection report. This approach records the duration of all bridge inspection activities and executes Lean analysis to identify and categorize activities by type of waste and work as well as the time spent on these activities. This scope includes all activities carried out by inspectors during the inspection process, which starts with preparing for the inspection of a bridge all the way through to submitting an owner-approved inspection report for the bridge. Scheduling of inspections and actions taken based on the inspection report findings (such as making decisions regarding and executing maintenance actions) are outside the scope of this research.

1.5 Thesis Organization

The organization of this thesis is as follows:

- Chapter 1, Introduction discusses the motivation, objectives, problem statement, scope, organization, and terminology used in the thesis.
- Chapter 2, presents the inspection background and literature review, Lean background and literature review, and justifies application of Lean philosophy during the routine inspection of bridges.

- Chapter 3, Methodology discusses the characteristics of the bridges whose inspections were shadowed, routine bridge inspection phases and stages, the data collection method, classification of activities based on inspection stages and value of inspection activities, significance of identification and elimination of waste, and a short summary of this chapter.
- Chapter 4, Results and discussions cover the inspection duration of bridges, recorded activities at different stages of inspection, categorization of activities based on the Lean concept, and a short summary of this chapter.
- Chapter 5, Conclusions discusses the summary of results, recommendations, and scope for future research.

1.6 Terminology

The following specific terminology were used in this research and are defined below. In some cases, inspection terms are specific to one or more agencies included in this work and may differ slightly from national terminology.

Activity	An individual action that consumes time.
Bridge clearance	The distance between the bridge deck and ground or water level.
Bucket truck	Truck with a bucket large enough for personnel, which provides access for hands-on inspection of bridge elements.
Chest wader	Long waterproof overalls with boots extending from foot to chest that are used by inspectors to wade in water.
Co-inspector	An inspector whose work is supervised by the team leader.
Defects waste	Mistakes which require corrective measures that consume additional time, effort, and cost.
Demobilization	Returning equipment from a bridge inspection site.
Hands-on inspection	Routine inspection characterized by the inspector being at a sufficiently small distance from all bridge elements that they

	can be touched and measured if needed. Hands-on inspection is a more detailed routine inspection than a visual inspection.
Inspectors	Personnel conducting bridge inspections.
Inventory waste	Activities that result in collecting information that has not been processed into a completed inspection report (waste).
Mobilization	Moving equipment to a bridge inspection site.
Motion waste	Movement of vehicles, equipment, inspectors, or the inspection report that does not directly add value to the final product.
Non-value added (NV) activity	Activities that do not add value to the final product and are not necessary to perform under the current operating procedures.
Over-processing waste	Duplicating effort or using a complex procedure instead of an available simple procedure for achieving the same goal.
Over-production waste	Duplication of products for which there is no destination for the produced material
Phases	Phases consist of one or more stages that have common goals during the inspection process: pre-inspection, inspection, and post-inspection phases.
Required non-value added (RNV) activity	Activities that are required to be performed considering current operating standards but do not add value to the final product.
Routine inspection	Scheduled inspection of bridges to evaluate the condition ratings of bridge elements through observations and measurements and to identify changes in bridge condition from previously recorded inspection reports.
Stage	Stages are a group of individual activities occurring during the inspection process typically occurring in a common location: review of documents, mobilization, inspection, demobilization, and report writing.
Team leader	Inspector with overall responsibility for inspection of a bridge, including completion and submission of the inspection report.
Time log data	The time consumed by an activity.
TPS	Toyota Production System also called Lean.

Transportation waste	Mobilization and demobilization to the bridge site.
UBIV	Under bridge inspection vehicle.
Value added (VA) activity	Value added activities add value to the final product and are classified as work.
Visual inspection	Routine inspection characterized by the inspector being at a sufficiently small distance from important locations of bridge elements such that they can be touched and measured if needed and having the ability to clearly observe all bridge elements.
Waiting waste	Idling of personnel or equipment.
Waste	Activities that are classified as non-value added or required non-value added which do not add value to the final product.
Work	Activities that add value to the final product.

Chapter 2

BACKGROUND AND LITERATURE REVIEW

This chapter covers the background and literature review of bridge inspection and the concept of Lean. It reviews research literature published on the existing practices and methods in routine bridge inspection followed by the application of Lean philosophy in other industries. This review mainly focused on service industries since bridge inspection is generally considered a service activity. Lastly, the significance of applying Lean philosophy to the routine inspection of bridges is considered.

2.1 Bridge Inspection Background and Literature Review

The first section provides a brief detail of bridge inspection programs that are used to evaluate the condition rating of bridges. Secondly, the literature review section presents research works that focused on increasing the efficiency of bridge inspections through effective quantitative and qualitative frameworks and advanced technological tools and programs.

2.1.1 Bridges' Inspection Programs

The American Society of Civil Engineers (ASCE) reports that almost four in ten bridges in the US are more than 50 years old and one in ten of the nation's bridges are rated as structurally deficient (ASCE, 2017). According to the United States Department of Transportation 2014 Statistics report, there are more than 260 million registered vehicles in the US (BTS, 2014) that drive on average 188 million times across structurally deficient bridges each day (ASCE, 2017). Figure 2.1 shows that 239,600 bridges out of 614,000 total bridges in the U.S. are more than 50 years of old. Thus, as the nation's bridge infrastructure continues to age and degrade, evaluation of bridges' condition ratings becomes increasingly significant to maintain a functional, safe and reliable transportation system.

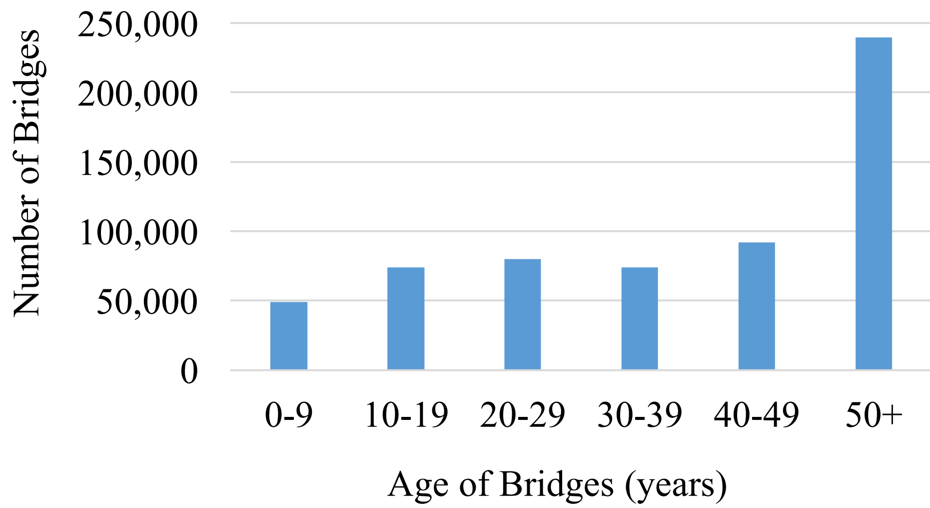

Figure 2.1: Age histogram of US bridges (adapted from ASCE, 2017)

After the collapse of the Silver Bridge at Point Pleasant, West Virginia in 1967, the US Congress was prompted to develop a national bridge inspection standard in the Federal-Aid Highway Act of 1968 (FHWA, 2012). The collapse of the bridge was due to a cleavage type crack failure developed at the north eyebar chain that resulted in the loss of 46 lives (Lichtenstein, 1993). National interest in safety, inspection, and evaluation of bridge condition increased after this tragic collapse. Thus, the National Bridge Inspection Standards (NBIS) came into existence in 1971 that created a national policy regarding inspection procedures, the frequency of inspections, qualification of personnel, inspection reports and maintenance of state bridge inventories. The NBIS national policy was implemented through manuals published by the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO). The Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges, and Bridge Inspector's Reference Manual (BIRM) were developed by the FHWA that set the standard for detailed guidance in evaluating and coding specific bridge data, and inspectors' training, respectively. The AASHTO Manual for Maintenance and Inspection of Bridges established a standardized framework to provide uniformity in the procedures for determining condition ratings and maintenance needs of bridges (FHWA, 2012).

The inspection activities, methods, and techniques vary depending on the type and condition of a bridge. Following are the different types of inspections stated by AASHTO (2016):

- Initial Inspection,
- Routine Inspection,
- In-Depth Inspection,
- Fracture-Critical Member Inspection,
- Underwater Inspection,
- Special Inspection, and
- Damage Inspection.

An initial inspection is the first inspection of a bridge which is also called an inventory inspection. The purpose of an initial inspection is to record bridge inventory data and establish the baseline condition rating of the bridge elements. Routine inspection is a scheduled inspection of bridges to evaluate the condition ratings of bridge elements through observations and measurements and to identify changes in bridge condition from previously recorded inspection reports. The interval between routine inspections is typically not to exceed 24 months. However, certain bridges may be routinely inspected over longer intervals of time with prior FHWA approval not exceeding 48 months (AASHTO, 2016). An in-depth inspection is the detailed, close-up inspection of bridge elements above or below the water level, conducted to identify possible deficiencies of a bridge that are not readily visible using routine inspection procedures. A fracture critical member inspection is the hands-on inspection of members identified as being fracture critical, which generally means there is not a redundant load path if the member were to fail. An underwater inspection is an inspection that generally requires diving or other appropriate techniques to evaluate condition ratings of underwater substructures and the surrounding channel. Special inspection procedures may be used to monitor a known or suspected deficiency of bridge elements. A damage inspection is an unscheduled inspection to evaluate the condition rating of a bridge damaged due to human factors such as truck collision or environmental events such as an earthquake or flooding.

This study focuses on the routine inspection of bridges because this is the most common type of inspection procedure. Routine inspection is conducted for more than 600,000 bridges in the US and requires continuous expenditure of labor and resources at a cost. Routine inspections are performed to identify any variation in bridges' elements condition from previous inspections and to ensure that bridges satisfy serviceability. Routine inspection is required to satisfy all requirements of the National Bridge Inspection Standards (NBIS, 1996). The routine inspection reports of bridges are regularly updated to the National Bridge Inventory (NBI) database by state and federal bridge agencies. Based on this data, funding and resources are allocated, reports are made to the US Congress and decisions pertaining to the bridge program are made by the FHWA. In addition to the condition rating of bridges, the NBI file includes information such as inspection frequency, geometry, sufficiency, age, location, functional classification, average daily traffic, improvement costs, material, design types, historical significance, structural deficiency, functional obsolescence and other details of bridges that are vital for maintaining bridge safety.

2.1.2 Routine Inspection Literature Review

2.1.2.1 Theoretical Frameworks for Inspection Intervals

Washer et al. (2016) proposed a new way for risk-based inspection that uses occurrence and consequence factors of a risk matrix. The goal was to improve safety and reliability of bridges and optimize the interval of bridge inspections. A reliability assessment panel comprising experts with knowledge of bridge design characteristics and performance history of bridges was assembled. The panel conducted an analysis using the current bridge elements' condition to support risk-based inspection, predicting future failure occurrence and serviceability of a bridge after 72 months. Using the proposed methodology, it becomes easier to perform a risk-based assessment of bridges to determine the ones that need a shorter interval of inspection and those needing longer intervals. Potential damage modes and associated safety consequences were analyzed using a simple risk matrix to identify the optimal inspection interval between 12 to 96 months instead of a uniform 24 months of routine inspection interval. This is a rational inspection strategy which can improve the efficiency of routine inspections.

Agarwal and Alampalli (2010) presents two studies to improve bridge inspection and management practices. The first study covers reliability assessment of New York State highway bridge inspection process based on quantitatively documenting the variability associated with the bridge inspection program. The research objective is to recommend improvements in areas of bridge inspection policy, procedure and required training of bridge inspectors to improve the consistency of inspection programs. The second study uses historical bridge inspection data to develop a deterioration curve based on the Weibull distribution approach to estimate the remaining life of bridge elements based on deterioration rate of these elements. The researchers include that at present, inspection methods are very constant throughout the life of bridges which can be improved based on the understanding of the lifecycle of the bridge and how it deteriorates (Agarwal & Alampalli, 2010).

Parr et al. (2009) proposed a two-phase procedure to establish a rational inspection interval for fracture critical bridges. The assessment procedure contains screening and scoring phases. In the screening part, if a fracture critical bridge passes all eight defined criteria, then the bridge is assigned to Category-II and may be inspected in the interval of equal to or more than 24 months. Else, the inspection interval may be equal to or less than 24 months where the bridge is assigned to Category-I. The scoring part ranks 12 performance factors of a bridge based on points. The resulting score correlates to an inspection interval in the range of 6 to 120 months for the fracture critical inspection of a bridge. The goal of this approach is to prevent both too infrequent inspections and too frequent inspections of a fracture critical steel bridge.

Yen et al. (2010) developed a two-phase heuristic approach that can enable bridge management agencies to schedule an optimal inspection plan for a group of bridges. The researchers implemented the practice on 68 bridges in Taiwan. In the first stage, a heuristic rule was established to identify a viable initial inspection route based on the bridges' size, location, distance, and connected paths. They developed a model that calculates the shortest path connecting every bridge along with assigning all bridges for inspection within an estimated 15 days of work. The second stage builds on the first stage and improves the initial route utilizing a genetic algorithm. Applying this novel approach resulted in significantly reducing the time of routine inspection of bridges where all 68 bridges were inspected in 13 days.

Orcesi and Frangopol (2010) analyzed the time-dependent safety of deteriorating bridges by applying a model using lifetime functions to structural systems. This function represents the probability that the structure will not fail before time *t* (Hoyland and Rausand 1994). After conducting elaborate case studies on steel bridges, they proposed an event-tree model in order to establish a probabilistic framework to help bridge agencies to find optimal risk-based inspection frequency for practical decision-making support. This assessment strategy considers each bridge component to ensure the overall safety of the bridge structure. This approach also considers the errors associated with various inspection processes. Additionally, the event-tree model was further used to identify effective inspection strategies that will simultaneously result in reducing the estimated inspection and maintenance costs along with the expected future failures.

2.1.2.2 Technological Tools

Use of various technologies and software has the potential to significantly increase the efficacy of assessing the structural condition of bridges. Such tools can also allow foreseeable problems to be anticipated and maintenance needs to be determined while minimizing safety hazards. The use of technologies such as drones (Gillins et al., 2016; Dubose, 2016), photogrammetry (Jauregui & White, 2005; Jáuregui et al., 2012; Bail & Hilton, 1985), virtual reality (Jáuregui & White, 2003; Jáuregui et al.2005), and software applications including database management systems are opening new avenues to strengthen existing bridge inspection methods.

Routine bridge assessment procedures and quality of visual inspection data can be further improved with the usage of unmanned, remotely controlled aerial vehicles, i.e., drones. Several studies have been carried out to examine the potential of drones as a safer and inexpensive means of bridge inspection for problems such as corrosion and distortion. Gillins et al. (2016) used drone technology to remotely inspect elements of a deck plate girder bridge in Oregon that was 675.4 m in length, making it one of the largest bridges in the region. The researchers reported that the high-resolution remote sensing images and videos collected through drones were similar to the visual inspection of bridge elements by inspectors at arm's length. For example, bolt patterns, rust stains, concrete spalling, a leaking joint, and cracks were easily identifiable. Moreover, drones readily captured the surroundings of the bridge including high-definition video of the upstream and downstream of the bridge, and inspect visible erosion of river banks. The researchers also explained that usage of drones improved safety and reduced the cost of bridge inspection by eliminating the need to close traffic lanes and utilize access equipment such as UBIVs, bucket trucks, and ladders. Dubose (2016) also conducted drone usage experiments with the

Minnesota Department of Transportation to determine the efficacy of using drones for inspections. Researchers found that drones can perform a wide variety of inspection activities that did not require hands-on physical inspection. Moreover, drones collected high-quality images and video footage of bridge element condition that later helped construct maps and 3D models of bridge elements.

Qualified bridge inspectors may use digital close-range photogrammetry measurement systems (Jauregui & White, 2005; Jáuregui et al. 2012; Bailes & Hilton, 1985). Photogrammetry is a 3D coordinate measuring technique that uses photographs to determine measurements. Special photogrammetric software along with high-resolution cameras are required to produce the 3D coordinates of the bridges' points of interest. Bailes and Hilton (1985) were among the first to carry out a bridge monitoring project including a condition survey and vertical deflection measurement through close-range photogrammetry. Later, Jauregui and White (2005) discuss photogrammetry instruments, procedures, and applications in routine bridge inspection, which allows a thorough examination of deterioration in locations where access is extremely difficult. The researchers strategically positioned high-end cameras in inaccessible or hard to reach locations and used digital programs to generate precise 3D image data of bridge elements that can provide the means for a safe and accurate measurement of a deteriorated area. In another study, Jáuregui (2012) evaluated the combined utilization of photogrammetry instruments such as a digital camera, image sensor and wide-angle lens in conjunction with the PhotoModeler Pro software for routine bridge inspection and historic bridge documentation. Their findings suggested that photogrammetry is an affordable and practical measurement option that provides sufficient accuracy.

Nowadays, modern software utilities such as QuickTime Virtual Reality (QTVR) and computerized bridge management software programs can greatly enhance the inspection and documentation process. The QTVR application allows recording and management of the inspection report in an interactive, virtual reality format by using multimedia techniques that provide a significant higher level of details than hand-written reports. Specifically, Jáuregui and White (2003) used QTVR and panoramic image creation utilities to simulate a virtual environment of the bridge site with supplementary descriptions that can be navigated off-site. This information can also be stored on external devices for later review. A separate study by Jáuregui et al. (2005) also explored the potentials of QTVR software to advance inspection practices in terms of review of previous inspection reports, automating the inspection and documentation process and the training of inspectors. Laird et al. (2010) investigated the innovative use of an integrated inspection and management program for the New Jersey Turnpike Authority to standardize the wide variety of bridge structure types, various consultant reports and required maintenance information. The software contributed to organizing the diverse array of inspection related information and greatly enhanced the documentation process by coordinating compartmentalized reports into a systematic whole.

Madanat and Lin (2000) investigated the application of sequential hypothesis testing methods, a statistical decision-making method, to assist technology-based decision support programs in selecting appropriate remedial activities and allocation of resources for bridges. The study presented factors influencing the decision-making process including precision of measurements, optimal sample size determination, and accuracy of inspector judgment. Researchers reported that the decision-making system is significantly influenced by the precision of measurements because the correct conclusion is reached more often as quantified by a smaller standard deviation of the measurement. Moreover, the accuracy of inspector judgment has a significant effect on the correctness of the conclusions of the decision-making method.

2.1.2.3 Reliability and Bridge Inspection

Phares et al. (2004) reported the results of examining the reliability and accuracy factors of routine bridge inspection procedures under an investigation initiated by The Federal Highway Administration (FHWA). The researchers found significant variability in all structural condition documentation including the number and types of field notes and photographs taken by the inspectors. In an FHWA investigation conducted by Moore et al. (2001), the 49 inspectors who participated in the experimental study had significantly different assessments of the condition ratings of bridge elements, resulting in significant variation between the expected inspection time and the actual time taken to complete the inspection process. The study also presented crucial evidence related to discrepancies in field inspection notes as well as the frequent omission of notes and photographs concerning important structural defects.

Estes and Frangopol (2003) examined the use of information collected from routine visual inspections to update the lifetime reliability of bridge condition ratings. Time-dependent reliability analysis that can predict future structural performance requires updated data sources from specific nondestructive evaluation methods which are expensive, time-consuming and require extensive resources to execute for a large number of bridges. Extensive data from visual routine inspections are systematically recorded in a bridge management system and are used primarily for decision making on all bridges in a network at regular intervals. However, such data are not suited for updating the lifetime reliability of bridge condition ratings. The researchers suggest revisions like segment-based inspections and conservative assumptions through which inspection results recorded in the PONTIS Bridge Management System can be effectively integrated into the reliability analysis of a specific bridge. The steel corrosion of a simply supported, nine-girder bridge in Colorado was used for this study. The previously recorded inspection model of steel corrosion is compared to visual inspection results collected by very experienced, experienced and inexperienced inspectors' inspection data. The researchers then discussed the limitations and necessary modifications to current practice for increased efficacy of routine inspection operations. They suggested the need for better communication between engineers who develop inspection systems and those who perform reliability analyses to maximize the effectiveness of inspection data (Estes & Frangopol, 2003).

2.2 Lean Background and Literature Review

The first two subsections provide a brief detail of Lean philosophy and its relation to Toyota Production System (TPS), respectively. Then, the literature review section presents research works that focus on the application of Lean philosophy to several manufacturing and services industries such as, construction, auto repair, precast-concrete fabrication and the health sector.

2.2.1 Lean Philosophy

The word "Lean" was used for the first time by researcher John Krafcik in 1988 referring to the Toyota Production Systems (TPS). Currently, the Lean concept is used widely as a management philosophy in both manufacturing and service industries. Lean philosophy (also called Lean thinking, Toyota Production Systems, Lean manufacturing, or Lean engineering) focuses on using less, such as less space, fewer workers and shorter production times than conventional mass production systems, to produce the same amount of output. Lean originally was used by Toyota to make smaller batch sizes of automobiles to better react to fluctuating market demand for product types while minimizing product defects (Ohno, 1988). The core methodology of Lean production systems can be applied to any industry, which results in forward thinking that exerts an overall positive impact on the development of our society (Womack et al, 1990).

It is important to understand the development of production systems in the auto industry where the concept of Lean originated. The three different types of production systems are illustrated in Table 2.1 (adapted from Womack et al, 1990) and their differences are briefly discussed in the domain of the auto industry which resulted in the development of Lean philosophy as a powerful management system.

Table 2.1: Auto Industry Production Systems (adapted from Womack et al, 1990)

	Craft Production	**Mass Production**	**Lean Production**
Country of origin	France	USA	Japan
Developed by	Panhard et Levassor	Ford	Toyota
Time Era	1880s	1915s	1950s
Production	Multiple types, Low	Limited types, High	Multiple types, High
Cost	High	Low	Low
Tools used	Basic tools and highly skilled labor	Advanced expensive machines, semi-skilled, uni-skilled or unskilled labor	Flexible/automated machines and multi-skilled workers

Craft production of automobiles uses basic tools and highly skilled human labor to produce a product. Examples of handcrafted products are handmade carpets and paintings. The nature of labor-intensive and time-consuming craft production work generates few products at an extremely high cost that is unaffordable to most people.

On the other hand, mass production employs uni-skilled (skilled in one particular domain), semi-skilled (partially skilled) and unskilled workers and advanced mechanical equipment for production of massive numbers of standardized items. The focus of mass production is on continued use of highly invested, expensive machines that will produce a bulk of uniformly standardized products and parts. This requires a large buffering area for proper storage of parts and extra labor to arrange stored products. The nature of a traditional mass production system results in lower cost but limited product options; a limited choice is not always appreciated by customers.

The Lean production system inherits its lower cost from mass production techniques and its flexibility in manufacturing to create multiple standard types of products from craft production. Lean manufacturing uses multi-skilled (skilled in many tasks) workers and highly flexible machines to produce varieties of products with high quality in small batch quantities.

2.2.2 Toyota Production System

Lean management philosophy originated from Toyota Production System (TPS). Taiichi Ohno was the first to develop this concept between 1948 and 1975, which is still employed by Toyota for vehicle production to this day. After the first oil crisis in 1973, Japanese growth collapsed but Toyota's earnings were sustained through those years more than other companies, which drew the attention of the world to the TPS (Ohno,1988).

Lean focuses on removal of non-value added waste activities from the entire work production timeline, from order placement to revenue generation (Ohno, 1988). The goal of TPS is to shorten the time between receiving an order and payment by the elimination of waste that includes wasting resources, time and labor effort. The seven types of TPS waste types that Lean philosophy seeks to eliminate are:

- transportation, i.e. movement of items more than required;
- inventory, i.e. holding onto material and information more than necessary;
- motion, i.e. movement of people that do not add value to a process;
- waiting, i.e. time spent waiting for the next process;
- overproduction, i.e. producing too much too soon;

- over-processing, i.e. processing more than required; and
- defect, i.e. errors and mistakes that require reworking.

2.2.3 Lean in Manufacturing and the Service Industry

The Lean concept originated from Toyota and its earlier application only focused on manufacturing automobiles and associated products. Now, Lean is also a highly used management philosophy in service contexts (Womack & Jones, 2005), which are the focus here as this is viewed as most similar to the bridge inspection process. Service companies have obtained significant improvement using Lean philosophy (Leite & Vieira, 2015). One of the reasons for such a success is its simplicity to eliminate issues related to waste from a work process across various activities associated with a particular industry. For example, service in a customer service call center was optimized by combining agent-assisted automation with Lean's waste reduction principles (Adsit, 2008).

The application of Lean philosophy can improve the efficiency within the service industry by reducing the amount of time spent on providing services. In addition to reducing overall time to provide the service, other benefits may result, including financial savings and reduced number of accidents. Service companies gained considerable profits by minimizing customers' time and effort along with prompt delivery of goods and services on demand (Womack & Jones, 2005; Piercy & Rich, 2009).

Womack and Jones (2005) reported the implementation of Lean principles in a car repair company in Portugal. The cumulative time consumed for repair services was analyzed pre and post implementation of Lean. Adopting Lean concepts increased the car technicians' value-added duration from 45% to 78% of total time, nearly doubling the production rate. Similarly, Piercy and Rich (2009) reported an average reduction in time of 53% to complete the request of customers in three call service companies after implementing minimal training of employees about Lean principles.

The Lean Six Sigma framework was developed by Shahada and Alsyouf (2012) who integrated Lean and Six Sigma techniques into one strategy and conceptualized a framework that can be applied in all industries. The Six Sigma is a business processes improvement technique which is based on the five phases: define, measure, analyze, improve and control. Each phase contains several steps in order to improve a process (Shahada and Alsyouf, 2012). Garza-Reyes et al. (2016) implemented Lean Six Sigma framework to improve port loading operations of a large iron ore producer by reducing its ship loading time. The result of using Lean philosophy saved more than 30% of loading time, which resulted in savings of $300,000 USD per year.

Kim et al. (2006) stated that in the health sector, the Lean concept provides powerful tools, a management philosophy and an accountability structure for working toward providing the best care possible to patients using available resources. Hospitals benefit from the implementation of Lean through improving delivery of health care to patients. Results of applying this concept in health care organizations have shown noticeable improvement in quality and efficiency of health care sector. For example, implementation of Lean at Park Nicollet Health Services in Minneapolis, Minnesota, reduced patients waiting time from 122 to 52 minutes at the urgent care clinic.

In the construction industry, 40% to 60% of labor activities are unproductive (Forbes & Ahmed, 2011). Another study on the application of Lean principles to a precast concrete fabrication company showed significant improvements in production with little capital investment and without changing technology or execution of operational methods (Ballard et al., 2002). Applying Lean changed the management philosophy and work structure, which led to enhanced workflow with maximized value and minimized waste; the managerial focus on production was shifted from a push driven system coming from the company to a pull driven system reacting to customer demand.

Erol et al. (2015) developed a simulation methodology using Monte Carlo probabilistic technique to compare the Lean and non-Lean construction process for residential buildings. The activities involved in the construction process were recorded and their optimistic, pessimistic, and most likely durations were obtained and analyzed. The application of Lean philosophy in construction process reduced project duration between 6% and 10%.

Garrett and Lee (2010) applied the Lean concept to the process of contractors submitting construction documentation to the construction field office for review and approval. To improve efficiency, Lean concepts such as just in time, visual controls, value stream mapping were used. Furthermore, the researchers specifically examined the application of value stream mapping (VSM). VSM is a Lean tool that visualizes all activities in a process using a current state map including value-added and non-value added actions. VSM identifies areas requiring improvement and develops a future state map incorporating these improvements. Actions like forwarding electronic versions of the submittal for review instead of paper-based documents, immediate entry of reviewed submittal documents to a database, early preparation of construction documents review processes and improving construction manager coordination by using emails considerably reduced process time by 25% and the number of activities by 37%.

Salem et al. (2006) conducted research demonstrating the usage of different Lean construction techniques for an Ohio-based general contractor. The study resulted in an average project plan completion rate (PPC) of 76% based on scheduled work which was 20% above the initial PPC prior to the implementation of the Lean techniques. Project work was also three weeks ahead of schedule and the cost was below budget. Sub-contractors and the general contractor were satisfied with the relationship among staff; no major injuries occurred, and the incident rate was below average for a similar project and the same company.

2.3 Application of Lean Philosophy to the Routine Inspection of Bridges

Existing research works about routine inspection of bridges and the application of Lean philosophy to service industries has been reviewed in this chapter. The literature review focused on bridge inspection shows that researchers have investigated new theoretical frameworks for inspection intervals (Washer et al., 2016; Agarwal & Alampalli, 2010; Parr et al., 2009; Yen et al., 2010; Orcesi & Frangopol, 2010), applied technological tools (Gillins et al., 2016; Dubose, 2016; Jauregui & White, 2005; Jáuregui et al., 2012; Bailes & Hilton, 1985; Jáuregui & White, 2003; Jáuregui et al., 2005); and considered the reliability of and resulting from the inspection process (Phares et al., 2004; Moore et al., 2001; Estes & Frangopol, 2003) to enhance the inspection completion rate in conjunction with reduced safety risks, costs, resources and time that can improve current bridge inspection procedures. Secondly, the literature review on Lean shows time and cost reduction by applying Lean philosophy to different service industries. Thus, Lean philosophy is a crucial management principle that should be emulated and adapted in more industries to make improvements. Routine bridge inspection, as a service, can be expected to benefit from adopting Lean principles similar to other service industries. However, Lean philosophy has not been explored in the domain of bridge inspection.

Chapter 3

METHODOLOGY

The inspection work of 26 bridges was shadowed. These bridges were inspected by inspection teams on 14 individual days. To understand the general pattern of bridge inspection work, the inspection activities and the time consumed during a day of work were recorded. A day of work, including a half hour lunch break, began at 7:00 am and continued until 3:00 pm, for a total duration of 8 hours. Thus, excluding the half hour lunch break, a total of 7.5 hours of bridge inspection activities were recorded per day. The methodology used during the bridge inspection shadowing is presented in this chapter.

3.1 Scope of Shadowing Bridge Inspection Process

The scope of this work focused on shadowing the inspection approaches of different team leaders during the inspection process of various types of bridges. The term “shadowing” here refers to the procedure where a researcher accompanies the bridge inspection crew to record bridge inspection activities. This includes logging the time taken on different activities and writing down observed challenges of the inspection.

The types of inspected bridges were steel girder, pre-stressed concrete box girder, reinforced concrete slab, timber bridges and culverts of different sizes and condition ratings, as shown in Table 3.1. A total of 26 bridges’ inspection work was shadowed, 23 of these bridges involved crossing over a body of water that required scouring measurement of water channels. The two steel girder bridges and one of the pre-stressed concrete girder bridges crossed over roadways that only required to measure their clearance from the road surface instead of collecting scouring data.

Table 3.1: Number of shadowed bridges, by structure and crossing type

Structure Type	Number of Shadowed Bridges	Number Bridges Above Water
Steel girder bridge	3	1
Pre-stressed girder bridge	8	7
Timber bridge	1	1
Reinforced concrete slab bridge	4	4
Culverts	10	10
Total	**26**	**23**

Figure 3.1 shows minimum condition ratings, deck areas and types of inspected bridges. These features are relevant to the time consumed by bridge inspections. In other words, a larger bridge with poor condition rating usually takes a longer time than a small bridge with a better condition rating. Condition ratings can range between 0 to 9, with a rating of 9 denoting the bridge is in excellent condition and a rating of 0 denoting the bridge has failed to meet its intended function and is closed to traffic (AASHTO, 2016). The horizontal axis of Figure 3.1 shows the logarithmic scale of bridges' deck area. The reason for use of a logarithmic scale instead of the actual area is the high variation between the deck area of the bridges shadowed in order to display all bridges in a single and compact view.

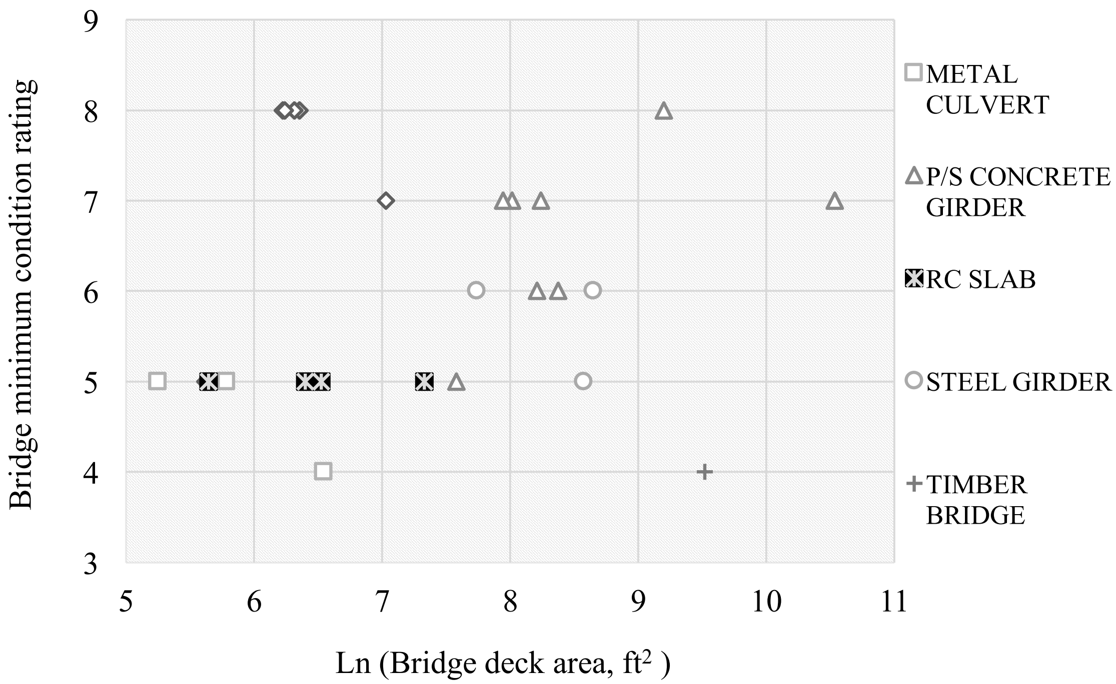

Figure 3.1: Minimum condition ratings, distribution of deck areas, and bridges' type

A bridge inspection team usually constitutes of a team leader and a co-inspector. The team leader undertakes full or partial responsibilities of selecting a bridge for inspection, reviewing previous inspection reports, performing the field inspection of bridge condition ratings, and preparing and submitting the final inspection reports. A co-inspector accompanies the team leader during bridge inspection, and assists in duties such as taking measurements, compiling notes, making copies of documents, checking scour of channel profiles and taking photos. The work of the co-inspectors is generally reviewed and supervised by team leaders. Shadowing the work of two people in detail was not possible by one researcher. Thus, the researcher shadowed and recorded time log data of the team leaders' inspection activities because they have the ultimate responsibility for the content of the bridge inspection reports.

The distribution of the shadowed inspection work between three team leaders is listed in Table 3.2. It illustrates the number of days and the total number of bridges inspected by each of the team leaders.

Table 3.2: Number of bridge inspections by team leaders

Shadowed Team Leaders	Days	Number of Bridges
TL1	5	6
TL2	5	10
TL3	4	10

3.2 Routine Bridge Inspection Phases and Stages

The shadowed bridge inspections are categorized into three phases, pre-inspection, inspection and post-inspection, as illustrated in Figure 3.2. While other agencies may adopt slightly different workflows, the tasks and sequence of those tasks are generally applicable to most of the inspection agencies. In this work, the pre-inspection phase is comprised of the review of inspection files and mobilization of equipment to the site. The inspection phase involves visual inspection, measurement, taking photographs and notes of the bridge elements' condition. The post-inspection phase includes demobilization of equipment and writing of the inspection report.

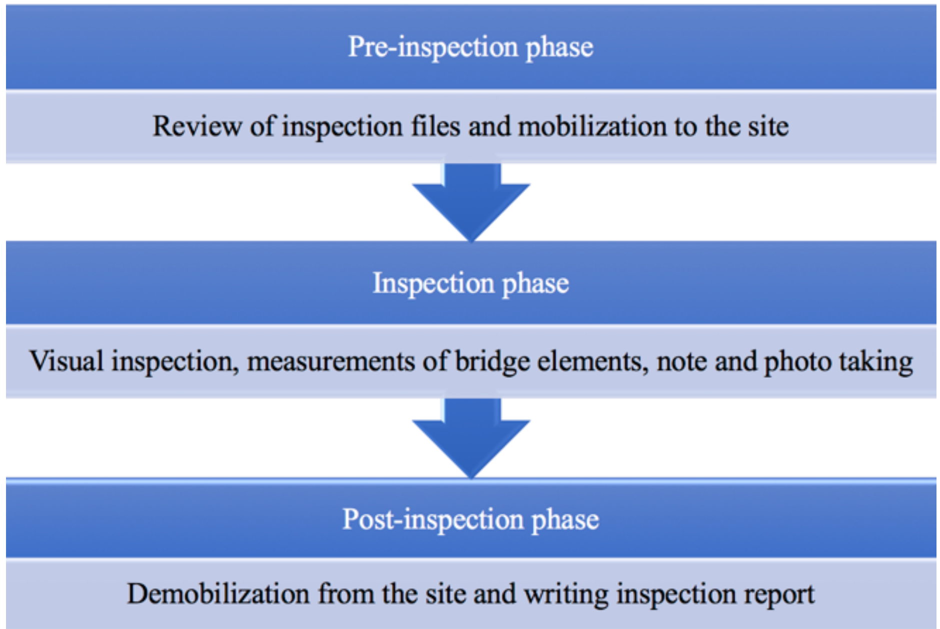

Figure 3.2: Routine inspection work flow

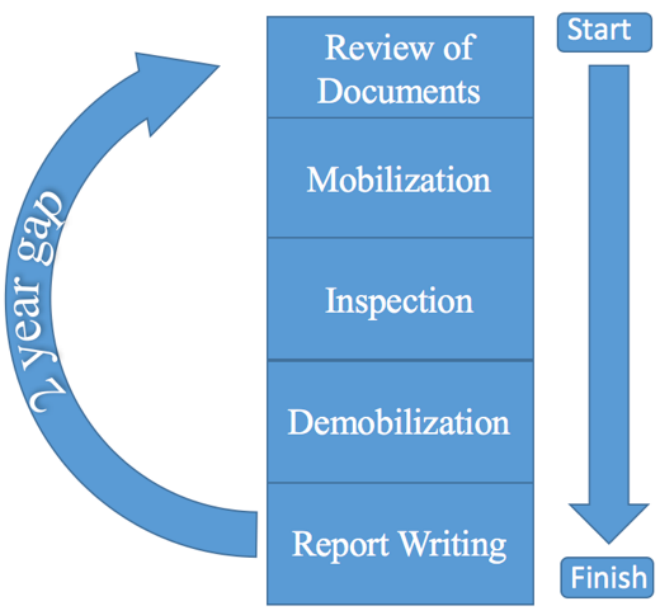

Figure 3.3: Inspection process flow

Further, routine inspection process flow is classified into five stages which are shown in Figure 3.3. The stages which occur in different phases of bridge inspection include review of previous inspection documents, mobilization to bridge site, inspection, demobilization from bridge site and report writing. The following discussion elaborates on the tasks completed by inspectors within each of these stages.

In the pre-inspection phase, first comes the review of the documentation stage when inspectors review previous inspection records of a bridge, determine the equipment required for access to the bridge, and make copies of the inspection report pages that are used to compile draft handwritten notes at the site. In order to access the bridge for inspection, the access equipment could be an under-bridge inspection vehicle (UBIV), a bucket truck, ladder or a boat.

Next comes the mobilization stage. Based on the previous inspection report details, decisions regarding mobilization of access equipment to a bridge site are made. If a boat is required for the inspection of a bridge. Accordingly, a boat will be taken from inventory and attached to a truck for transportation to the site. A UBIV or a bucket truck are used as access vehicles to inspect bridges with higher clearance from the ground or water level and boat is used for inspection of bridges with lower clearance from water level. Figure 3.4 shows a truck and motor boat for the inspection of a bridge crossing over a waterway. Figures 3.5 and 3.6 illustrate a truck loaded with all the necessary inspection tools. The truck is loaded with all necessary inspection tools such as a ladder, scour measuring pole, chest waders, boots, carpenter ruler, hammer, flashlight, etc. The inspection team inspects the bridge elements' condition and collects scouring data of a channel profile using these tools. A flashlight is utilized if a part of the bridge is not clearly visible for inspection due to shadows and darkness.

The hammer is used for identification of delamination of the bridge elements, and a measuring tape is used to identify location and size of deterioration.

Figure 3.4: Bridge inspection motor boat attached to the inspection truck

Figure 3.5: Truck loaded with necessary inspection tools

Figure 3.6: Bridge inspection tools including measuring tape, hammer, flashlight etc.

During the inspection phase, inspectors rate the condition of each bridge element and take both measurements and photographs of bridge deterioration as well as necessary notes to support these ratings. They also compile channel scouring data of a bridge crossing over a body of water. In some cases, the inspectors wore chest waders to walk in channels and utilized a long scour measuring pole to measure the depth of a channel while simultaneously recording the data on a sketch sheet. In the case of some deep channels, inspectors used a boat and laser device for measuring the profile of a channel. A total of 23 shadowed bridges in this study crossed over the waterway and thus required collecting scouring data. Figure 3.7 shows inspector measuring scour detail of the channel using scour measuring pole. Simultaneously, scour details are recorded on a paper.

Figure 3.7: Inspector measuring scour detail of a channel

In the post-inspection phase, the demobilization stage involves driving back to the office and returning the access equipment and truck to the inventory. Lastly, in the report writing stage, inspectors primarily deal with organizing and storing inspection data along with making recommendations for the maintenance of inspected bridges. The inspection photos, written notes about the bridge elements' condition ratings, and scouring details of the channel profile are input into software, specifically AASHTOWare Bridge Management Software (BrM). This creates a report which complies with AASHTO's manual for bridge elements' inspection and National Bridge Inspection Standards (NBIS, 1996).

3.3 Data Collection Method

The method of bridge inspection data collection was prepared based on Taiichi Ohno's concepts of work sequence, activities, and standard inventory elements in his book "Toyota Production System" (Ohno, 1988). This emphasizes understanding the sequence of workflow, duration of activities, and presence of inventory in auto manufacturing to identify and eliminate waste activities. Similarly, data collection through bridge shadowing was designed to analyze all activities of the bridge inspection process, included those executed in the office, inspection site, and while commuting.

The detailed scheme of the research work was prepared to identify inspection activities and record time consumed by each of these activities during a day of bridge inspection work. Table 3.3 shows the sheet prepared and used by the researcher to collect inspection data while shadowing inspections, referred to as 'time log sheet'. This data collection method records the sequence of inspection stages and activities, total inspection time, each activities' duration, and necessary inspection equipment utilized. The time log sheet consists of six tables; a summary table was used to record the total duration of the five individual stages of inspection work. The remaining five tables were used to record inspection activities and their time log data for each stage of the bridge inspection process. In addition, the notes column is provided for writing observations and the equipment inventory used during the inspection.

Table 3.3: Time log sheet prepared for collection of inspection shadowing data

Review of Doc, Activities	Start time	End time	Total time	Notes

Mobilization, Activities	Start time	End time	Total time	Notes

Inspection, Activities	Start time	End time	Total time	Notes

Demobilization, Activities	Start time	End time	Total time	Notes

Report Writing, Activities	Start time	End time	Total time	Notes

Summary of Stages	Start time	End time	Total time	Notes
Review of Documents				
Mobilization				
Inspection				
Demobilization				
Report Writing				

3.3.1 Data Collection Locations

During a day of routine inspection, different types of activities take place in different locations such as the office, on the road while driving, and at the bridge inspection site. Therefore, activities from different phases and stages of bridge inspection occur in these different locations as demonstrated in Figure 3.8. This diagram details and clarifies the sequence and relationship of bridge inspection phases, stages, locations and process flow during routine bridge inspection of work. Bridge inspection stages consume time, labor, and resources in three locations; in the office, on the road, and at the bridge inspection site. Each of the stage's activities are individually recorded to understand the time consumption and determine the waste of resources involved. Resources used include inspection crew time, effort and inspection equipment. The review of documents and report writing stages generally occur in the office but sometimes occur during commuting or at the inspection site.

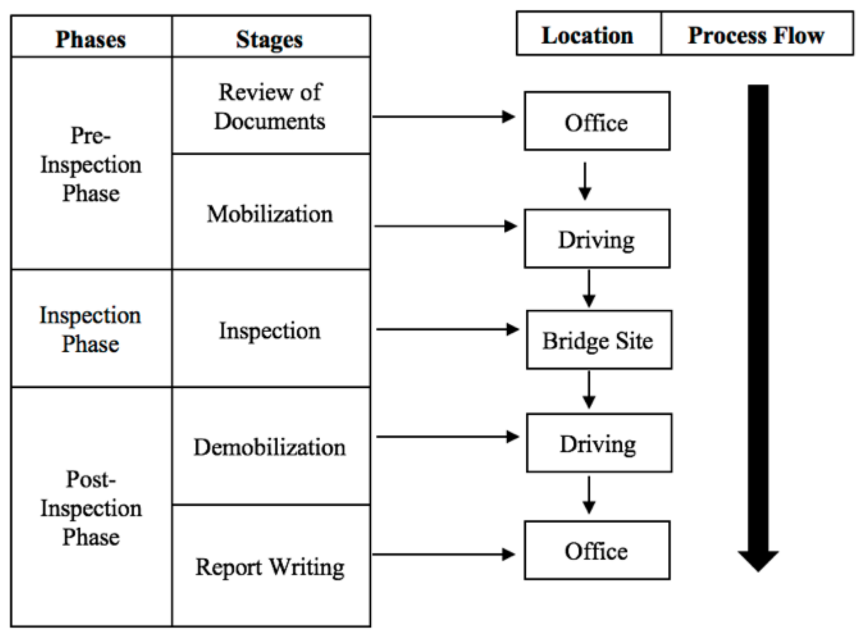

Figure 3.8: Relationship between phases, stages, and location of inspection process

3.3.2 Bridge Inspection Shadowing Process

Team leaders' inspection activities were recorded using the time log sheet illustrated in Table 3.3. The review of documents stage of bridge inspection started at 7:00 am and continued until the inspection team leaves the office for a bridge inspection site. After leaving the office, activities were recorded under the mobilization stage until the arrival of the inspection team to the bridge site. Upon arrival at the site, all inspection activities, their time log data, and other observations are categorized as the inspection stage and recorded in the inspection table of the time log sheet. Following departure from a site until returning to the office, all activities including time log data and observations are recorded in the demobilization table of the time log sheet. Finally, during the report writing stage, activities, their time intervals, and other notes are recorded when the inspection team returns to the office from an inspection site until the end of office work hours, i.e., at 3:00 pm. Sometimes team leaders took inspection report writing work home or completed the inspection report during a subsequent work day and self-reported total report writing time for that bridge to the researcher.

A stop watch on a mobile device was used to measure the continuous duration of inspection activities using the lap feature. The laps continue for the entire work day to record all activities. The end of one activity signaled the start of another activity. For example, Figure 3.9 shows a recording duration of bridge inspection activities on the site. Lap 1 to lap 7 are durations of individual activities recorded that in total covered 14 minutes and 4 seconds. For example, Lap 2 (4 minutes and 10 seconds) is recoded duration for visual inspection of a bridge element and Lap 3 (2 minutes and 7 seconds) is recorded duration for measurement of a deterioration.

Figure 3.9: Stop watch with lap feature for recording duration of inspection activities

3.4 Lean Classification of Activities

Figure 3.10 shows the Lean classification of activities. A group of actions that consume time in a process to complete a task is called an activity. Activities can be classified as work (activities that add value) or waste (activities that are non-value added or required non-value added). There are seven kinds of waste activities shown in Figure 3.10 (adapted from Ohno,1988), which need to be identified and eliminated from a process to enhance efficiency.

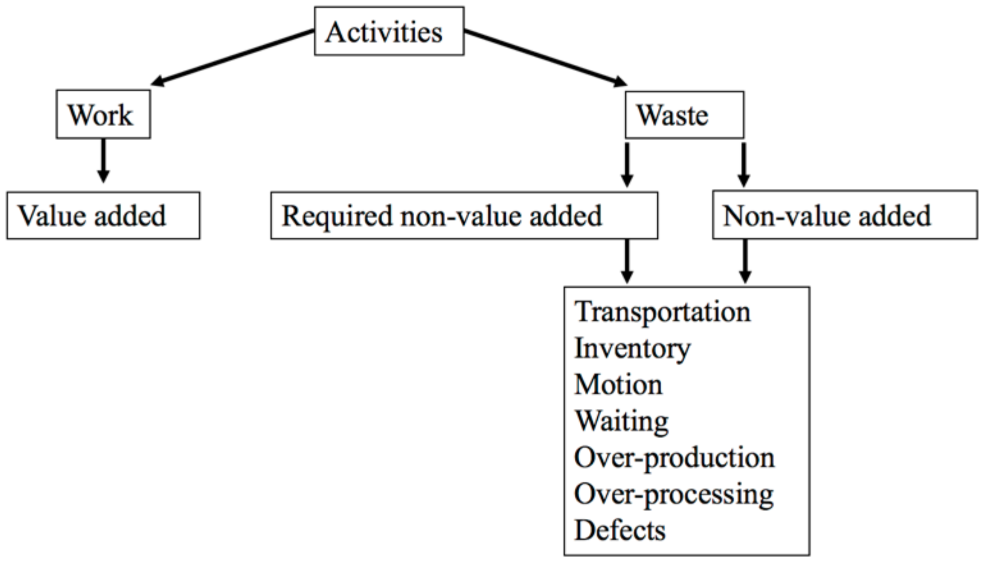

Figure 3.10: Lean classification of activities (adapted from Ohno,1988)

3.4.1 Classification of Data by Value

In order to apply Lean principles, the activities logged during the bridge inspections were classified by the value they add to the inspection process as follows:

- Value added (VA) activities are deemed significant work because they add value to the final product. For bridge inspection, value added activities are the conversion of inspectors' observations, measurements, and judgments about the bridge elements' condition into outputs of information communicated through an owner-approved inspection report.
- Required non-value added (RNV) activities are necessary to perform, but they do not add value to the ongoing procedures and are classified as waste. Hines and Rich (1997) use "required" to mean that the activity is necessary under the current standard operating procedures.

Bridge inspection examples of required non-value added activities include driving to the bridge site. In Lean philosophy, such activities should be recognized as waste and sought to be minimized; although such changes may require major changes to operating procedures and may not be possible immediately.

- Non-value added (NV) activities do not add value to the final product and are not necessary to perform under the current operating procedures (Hines and Rich 1997). Non-value added activities are waste that should be identified and eliminated from the work process. An example of a non-value added activity during a bridge inspection is taking a wrong turn while driving to the bridge site.

3.4.2 Classification of Data by Type of Waste

RNV and NV activities are both waste and these activities have been categorized into the seven types of waste defined in Table 3.4. It also provides examples of each of these types of waste that were observed during the shadowing of bridge inspections when applicable.

Table 3.4: Seven types of waste activities

Type of waste	Definition	Examples
Transportation	Mobilization and demobilization to the bridge site	-Driving to bridge site (RNV) -Walking to the bridge (RNV) -Taking or returning boat to/from inventory (RNV)
Inventory	Activities that result in collecting information that has not been processed into a completed inspection report	-Working on backlogged inspection reports(RNV)
Motion	Movement or excess activity of vehicles, equipment, inspectors, or the inspection report that does not directly add value to the final product	-Collecting and copying bridge inspection files (RNV) -Positioning and movement of bucket truck (RNV)
Waiting	Idling of personnel or equipment	-Waiting for computer to be available for entering data (NV) -Repositioning traffic control (NV)
Over-processing	Duplicating efforts or using a complex procedure instead of an available simple procedure for achieving the same goal	-Manually documenting photo sequence in a notebook on the bridge site, then copying the bridge photos from a camera to a computer and later, matching the bridge elements' condition to the photos while entering the inspection report on a computer (RNV)
Overproduction	Duplication of products for which there is no destination for the produced material	-Taking a surplus number of photos of a bridge element on the inspection site (NV)
Defects	Mistakes which require corrective measures that consume additional time, effort, and cost.	- Malfunctioning of inspection tools (NV) - Returning to the site to take photographs of forgotten bridge elements (NV)

3.5 Significance of Identification and Elimination of Waste

Lean is a continuous improvement process. The continuous improvement process is characterized by consistent efforts to identify and eliminate waste activities, which gradually improves the process of a company. Lean requires a cultural shift of employee mindsets and commitment from management to adopt an ongoing continuous improvement process within a company. A key factor in this initiative involves the identification and elimination of work structure and activities that act as hindrances to achieving superior end results, otherwise known as waste.

The efficiency and quality of the bridge inspection process cannot be understood by simply looking at the final inspection report. Lean is highly regarded as a unique business improvement framework owing to Taichi Ohno's systematic method of waste minimization within an organization without sacrificing the end quality of production. In fact, Toyota Production Systems is renowned for its steady focus on reduction of counterproductive and ineffectual processes to improve customer value. To understand the role and function of the overall inspection process and each inspection activity, the researcher carefully observed, through shadowing, all inspection activities of an inspection crew. These observations were used to identify potential waste activities that can be removed from the bridge inspection process to enhance the efficiency of inspections.

3.6 Summary

The described methodology was used to collect data for this research work. A total of 26 bridges' inspection work is shadowed and Lean principles are used to analyze data. The recorded activities and their time log data based on Sections 3.3 detail are briefly listed in Table 4.5 of Chapter 4. Appendix-A can be referenced for all recoded inspection activities and their time log data. Value and waste-based classification of recorded activities are conducted in the Sections 4.3 of Chapter 4, using the value and waste definitions provided in Section 3.4.

Chapter 4

RESULTS AND DISCUSSIONS

Lean philosophy is applied to determine the efficiency of routine inspection of bridges. The results obtained from the application of Lean philosophy to the routine inspection of bridges is presented in this chapter. It discusses routine inspection time variability based on different variables in Section 4.1, categorization of recorded activities based on different stages of inspection in Section 4.2, categorization of activities based on Lean concept in Section 4.3, and a summary of this chapter in Section 4.4. In Section 4.1, differences in routine inspection time of bridges are compared by the following variables: a) the size of bridges; b) the types of bridges; c) the condition ratings of the bridges; d) the team leaders' inspection approaches; e) the channel requirement of scour data collection; f) the months of bridge inspections. In Section 4.2, the routine inspection time consumption by various stages of inspection including review of documents, mobilization, inspection, demobilization, and report writing is presented. Furthermore, considering the principles of Lean, the recorded routine inspection activities are classified into either work or one of the seven of waste types in Section 4.3. The time taken for these activities was measured, analyzed and presented as time spent on work (value added) versus waste (includes non-value added and required non-value added waste). The effect of the differences in these variables on the total routine inspection time is discussed.

4.1 Inspection Duration

The routine inspection duration of bridges may vary by the type, size, condition ratings of bridges, inspection crew, inspection month and scour data. Table 4.1 reports the recorded inspection duration of bridges with different characteristics. In the sequence from left to right, the first column shows the sequence number of the 26 inspected bridges which were inspected by three different team leaders. The inspection work of these bridges was typically shadowed a few days per week in months of September, October, and November. These shadowed bridges were of different types, which included culvert, reinforced concrete (R/C) slab, steel girder, pre-stressed (P/S) concrete girder and timber bridges. They were of different sizes with deck area ranging from 190 ft^2 (19ft length) culvert to 37,548 ft^2 (840ft length) P/S concrete girder bridge along with their minimum condition ratings ranging between 4 to 8. The access equipment used to inspect these bridges are also listed in the table. Most of the shadowed bridges crossed over a stream or creek that required channel scour measurements. Thus, chest waders and a boat were usually used by the inspectors to collect scour data.

There are three types of times discussed in this chapter: total time, inspection time and field time. The recorded duration of all activities conducted in a day of routine inspection of bridges except half hour of lunch break is referred to as "total time" and used in Sections 4.2,4.3 and 4.4 that is used for Lean analysis of inspections duration. The term "inspection time" refers to the duration of an inspection excluding driving to and from the bridge site because driving time depends on the location of a bridge and it cannot be used to show the variability of inspection time for bridges by other characteristics. "Field time" refers to recorded duration of particular activities at the bridge site such as visual inspection of bridge elements, measurement of bridge elements' deterioration by means of tape or carpenter ruler, checking clearance of a bridge or channel scour depth, and taking photos of a bridge. Table 4.1 reports the recorded total time, inspection time and field time for routine inspection duration of bridges.

Furthermore, the inspection time spent on inspection per 1000 ft^2 deck area of a bridge is called normalized inspection time, and field time per 1000 ft^2 deck area of a bridge is called normalized field time. The normalized inspection time and normalized field time are reported to understand how the inspection time differs for bridges with the same deck size. Inspection time and normalized inspection time are used in Section 4.1, 4.1.1, 4.1.2 and 4.1.3 of this chapter to show inspection time and normalized inspection time variability of routine inspections of bridges based on different variables. However, field time and normalized field time are only used in Section 4.1.3 to show field time and normalized field time variability of routine inspections based on the shadowed inspection work of three team leaders

Table 4.1: Recorded total time and field time of routine inspections

No	Inspection date	Team leader	Type of bridge	Access equipment	Collection of scouring data	Minimum condition rating	Deck area (ft^2)	Total time (min)	Inspection time (min)	Normalized inspection time (min/ 1000 ft^2)	Field time (min)	Normalized field time (min/1000 ft^2)
1	Early September	TL 1	R/C slab	Chest wader	Yes	5	282	474	333.6	1182.9	56.3	199.6
2	Early September	TL 1	Steel girder	Ladder	No	6	5689.8	455	417	73.3	176.4	31
3	Early September	TL 2	Concrete culvert	Chest wader	Yes	5	288	199	161.1	559.4	31	107.6
4	Early September	TL 2	R/C slab	Chest wader	Yes	5	1522.5	245.2	210.2	138	49.1	32.2
5	Early September	TL 2	Concrete culvert	Chest wader	Yes	8	573.9	319.8	272.8	475.3	67.1	116.9
6	Early September	TL 2	Concrete culvert	Chest wader	Yes	5	275.3	183.2	117.2	425.8	16	58.1
7	Early September	TL 1	Timber bridge	Boat, chest wader	Yes	4	13634	473	373	27.4	134	9.8
8	Early September	TL 1	Steel girder	Bucket truck	No	5	5280	466	379	71.8	120	22.7
9	Middle Of October	TL 2	R/C slab	Boat	Yes	5	682	206	157	230.2	55.5	81.4
10	Middle Of October	TL 2	P/S concrete girder	Boat	Yes	5	1958	266.1	203.1	103.7	76.8	39.2
11	Middle Of October	TL 3	Steel girder	Boat	Yes	6	2300	193.5	185.5	80.7	61.6	26.8
12	Middle Of October	TL 3	Concrete culvert	Boat	Yes	8	505	225.6	158.6	314.1	16.1	31.9
13	Middle Of October	TL 3	Concrete culvert	Chest wader	Yes	7	1131.6	181.1	169.1	149.4	15.5	13.7
14	Middle Of October	TL 3	Metal culvert	Chest wader	Yes	4	693.4	283.1	246.1	354.9	16.8	24.2
15	Middle Of October	TL 2	P/S concrete girder	Boat	Yes	7	37548	478.8	442.8	11.8	81.1	2.2
16	End Of October	TL 3	P/S concrete girder	Boat	Yes	7	3021.5	124	106	35.1	19.5	6.5
17	End Of October	TL 3	P/S concrete girder	Boat	Yes	6	4343.2	171	119	27.4	52	12
18	End Of October	TL 3	P/S concrete girder	Boat	Yes	7	3780	171	95	25.1	38	10.1
19	End Of October	TL 1	Concrete culvert	Chest wader	Yes	8	552.7	288.5	256.5	464.1	56	101.3
20	End Of October	TL 1	Concrete culvert	Chest wader	Yes	8	512.5	191.6	148.6	289.9	48.5	94.6
21	End Of October	TL 2	R/C slab	Chest wader	Yes	5	601.2	213.7	178.7	297.2	15	25
22	End Of October	TL 2	Metal culvert	Chest wader	Yes	5	325.8	75.9	65.9	202.3	22.4	68.8
23	End Of October	TL 2	Metal culvert	Chest wader	Yes	5	190	157.5	141.5	744.7	8	42.1
24	End Of November	TL 3	P/S concrete girder		No	8	9885.9	152.8	139.8	14.1	30.3	3.1
25	End Of November	TL 3	P/S concrete girder	Boat	Yes	7	2818.4	121.8	93.8	33.3	22.5	8
26	End Of November	TL 3	P/S concrete girder	Boat	Yes	6	3667.6	200.8	182.8	49.8	40.8	11.1

The collected data shown in Table 4.1 is arranged and plotted in graphs to illustrate the variation of both the inspection time and the normalized inspection time of routine inspections based on different variables. Many variables affect the total routine bridge inspection duration; the following graphs do not necessarily reflect the degree of influence of the variable being graphed as the statistical correlation between different variables was not assessed.

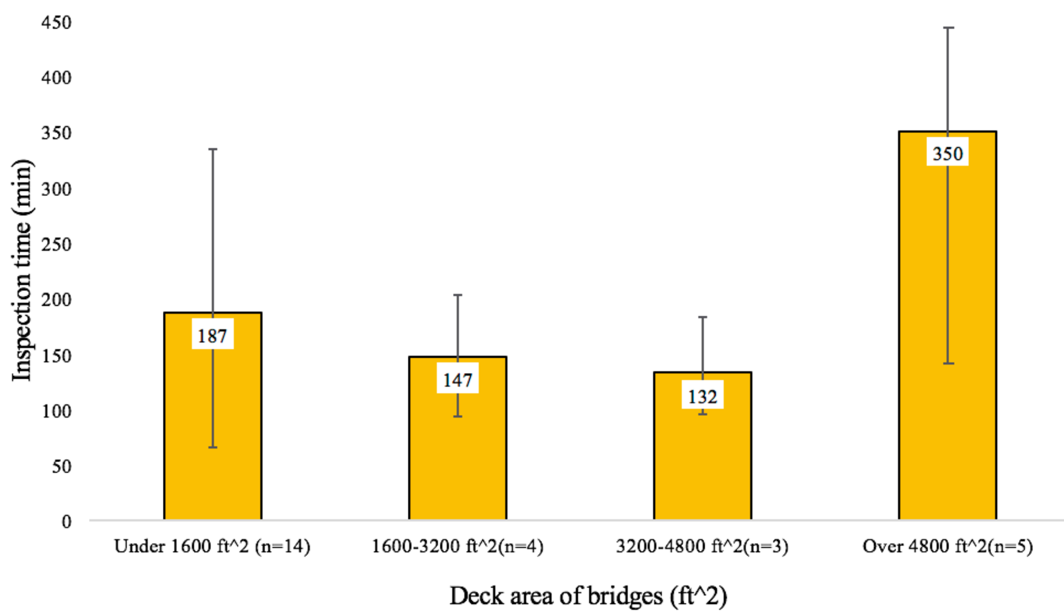

Figure 4.1: Average inspection time of bridges by different ranges of deck areas (error bars represent range of values)

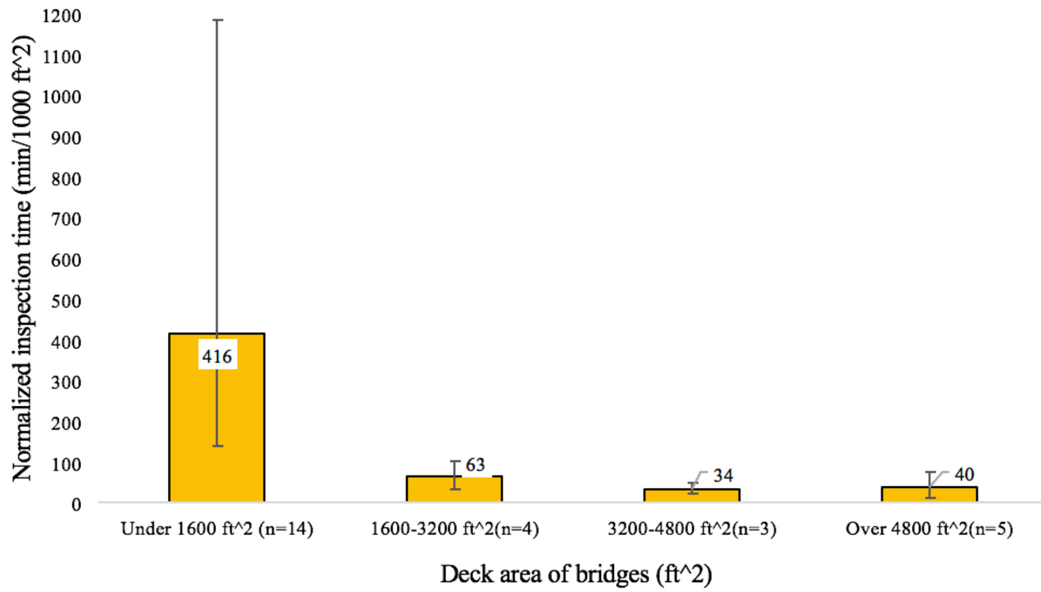

Figure 4.2: Average normalized inspection time of bridges by different range of deck areas (error bars represent range of values)

Figure 4.1 and Figure 4.2 demonstrate the inspection time and normalized inspection time of inspected bridges sorted based on their deck area. The total number of bridges (n) used for calculating these average values is also illustrated at bottom of the graphs. The deck area of bridges is classified into four categories: under 1600 ft^2, 1600 – 3200 ft^2, 3200 – 4800 ft^2, and over 4800 ft^2. All under 1600 ft^2 classified bridges are culvert and reinforced concrete slab type of bridges totaling 14 bridges and the remaining 12 bridges are pre-stressed concrete girder and steel girder bridges alongside a timber bridge. It can be noticed from Figure 4.1 that the bridges with an area over 4800 ft^2 consumed on average the highest duration for inspection compared to the ones with smaller size. However, when normalized inspection time is considered which is shown in Figure 4.2, the bridges (culverts and R/C slab bridges) under 1600 ft^2 consumed on average the highest normalized inspection time compared to the ones with larger size.

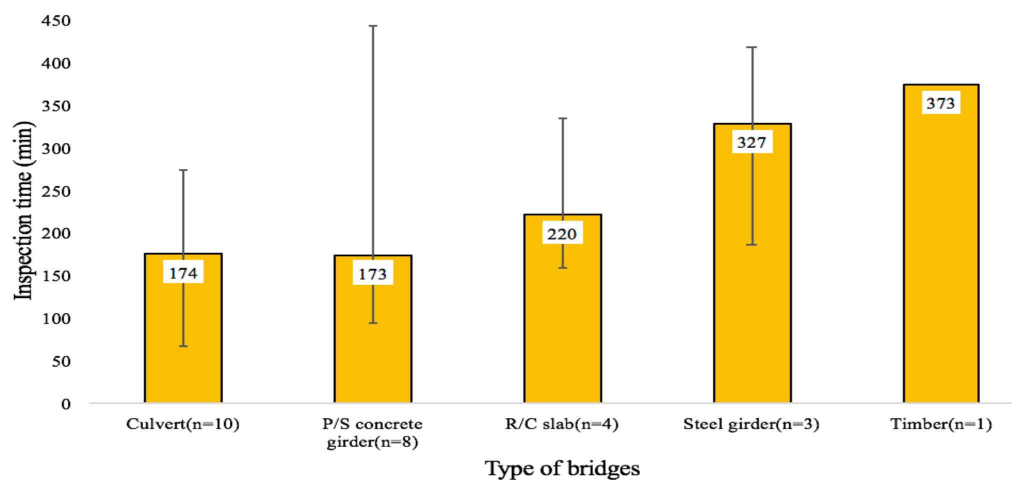

Figure 4.3: Average inspection time of bridges by different types (error bars represent range of values)

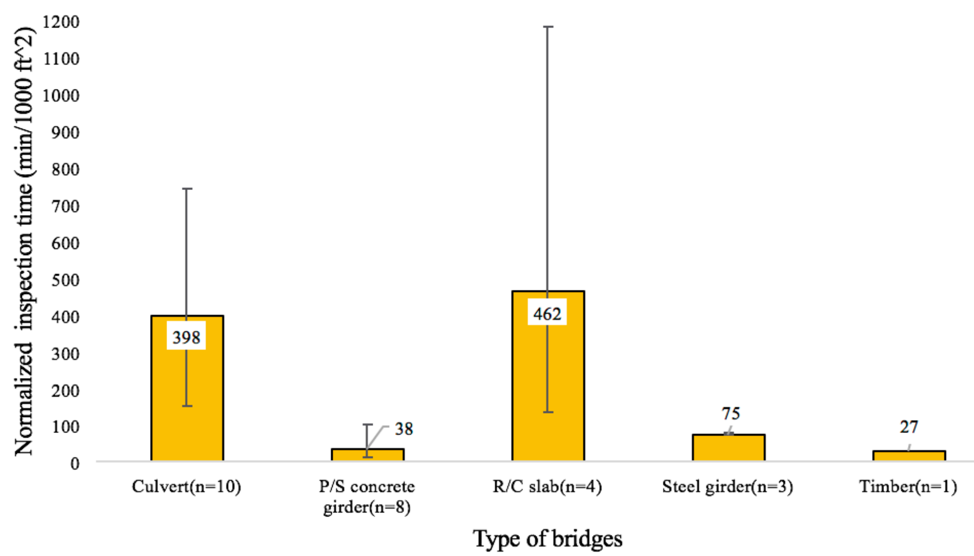

Figure 4.4: Average normalized inspection time of bridges by different types (error bars represent range of values)

Inspection time and normalized inspection time of different types of bridges are shown in Figure 4.3 and Figure 4.4, respectively. Their maximum, minimum and average durations are illustrated by error bars. Since inspection work of a single timber bridge was shadowed, there is no maximum and minimum variance for the timber bridge category. Comparing inspection time of the remaining four types of bridges shown in the plotted graph of Figure 4.3, the steel girder bridges consumed the highest average inspection time and pre-stressed concrete girder bridges consumed the lowest average of inspection time for routine inspection of bridges. One of the reasons for this variation may be due to the presence of multiple members in steel structures like bracing that makes inspection work more laborious as compared to concrete structures and culverts. On the other hand, it can be noticed from Figure 4.4 that culverts and R/C slab type of bridges consumed on average longer normalized inspection time compared to other types of bridges.

Condition ratings are used to evaluate existing physical condition of the deck, superstructure, and substructure components of a bridge compared to their initial as-built condition. The condition evaluation also includes channel scour detail and culverts' physical conditions. Condition ratings in the range of 1 to 9 are used as a guide in evaluating bridge components, culverts, and channels. The given range is described as– 1 is failure condition, 2 is critical condition, 3 is serious condition, 4 is poor condition, 5 is fair condition, 6 is satisfactory condition, 7 is good condition, 8 is very good condition and 9 is excellent condition of bridges, culverts, and channels (FHWA, 1995).

The inspection time and normalized inspection time is sorted based on the minimum condition ratings of bridges and plotted in Figure 4.5 and Figure 4.6, respectively. The condition ratings of the inspected bridges varied between the range of 4 (poor condition) to 8 (very good condition). It can be noted from the graph in Figure 4.5 that the bridges with the condition ratings of 4 consumed comparatively more inspection time than the bridges with condition ratings in the range of 5 to 8. However, Figure 4.6 shows that the bridges with condition ratings of 5 consumed more normalized inspection time compared to other bridges. Since there are only 2 bridges with condition ratings of 4 along with the possible influence of multiple variables on inspection duration, the significance of this variation is unknown.

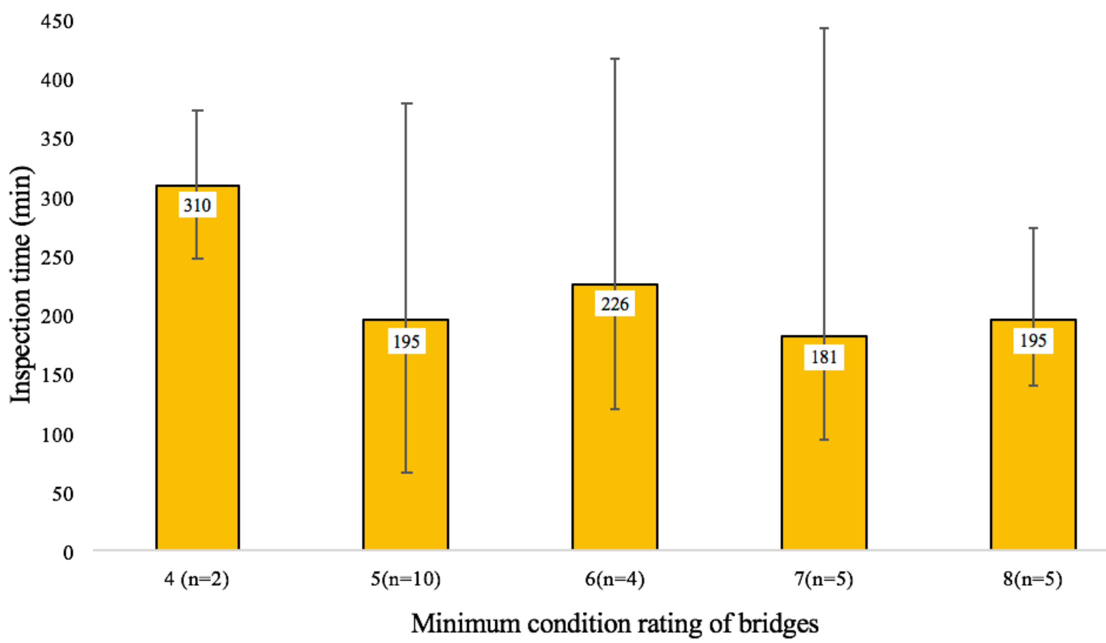

Figure 4.5: Average inspection time of bridges by minimum condition rating of bridges (error bars represent range of values)

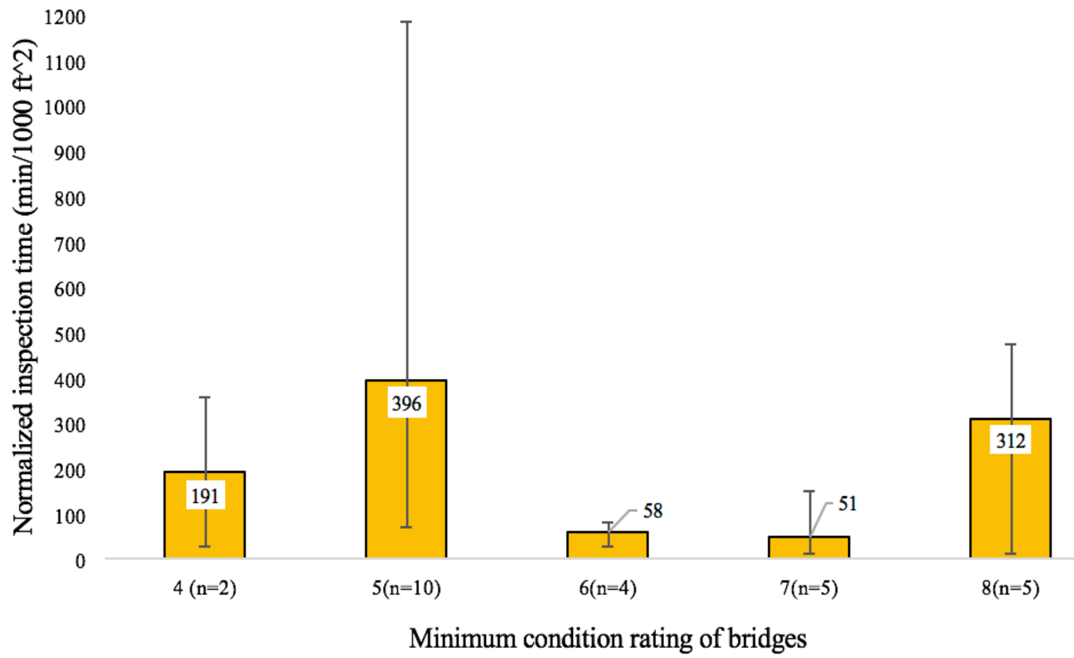

Figure 4.6: Average normalized inspection time of bridges by minimum condition rating of bridges (error bars represent range of values)

The inspections of these bridges were conducted by three inspection teams. Each team consisted of a junior inspector and a team leader. The team leader had more than 5 years of inspection experience and was mainly responsible for the core inspection duties such as reviewing previous inspection reports, performing the field inspection of bridge condition ratings, and preparing and submitting the final inspection reports. As it was not possible to comprehensively shadow both members of the inspection team, only the team leaders were shadowed. Specifically, three different team leaders were shadowed.

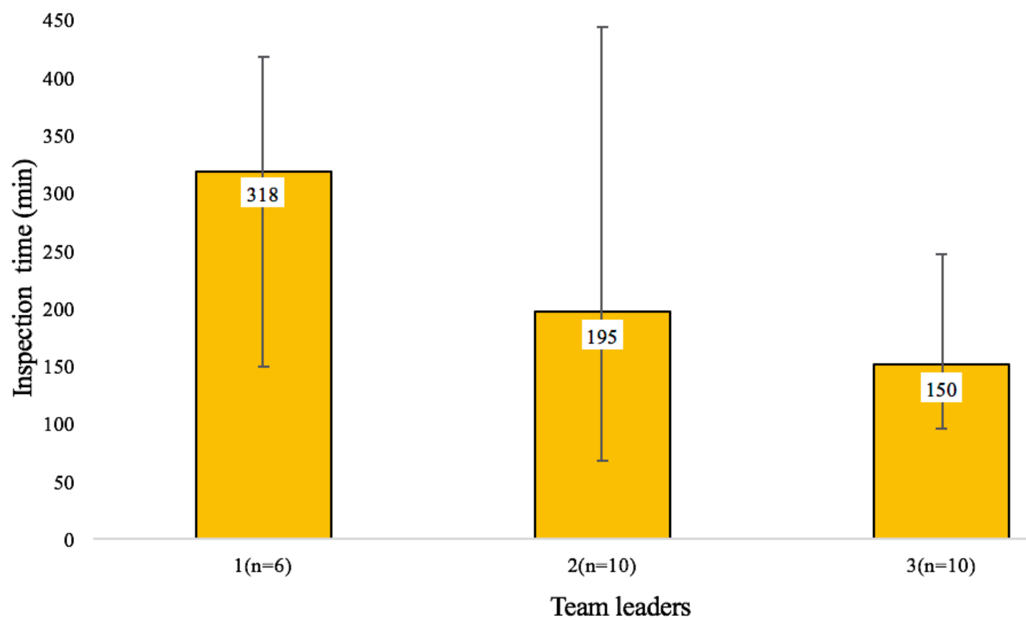

Figure 4.7: Average inspection time of bridges by different team leaders (error bars represent range of values)

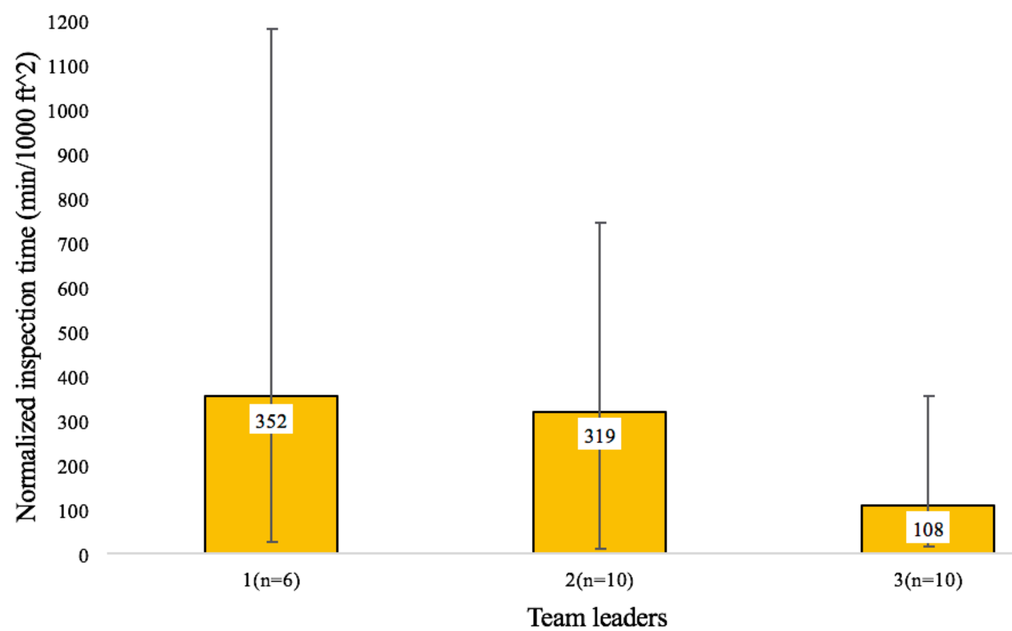

Figure 4.8: Average normalized inspection time of bridges by different team leaders (error bars represent range of values)

Figure 4.7 and Figure 4.8 show the minimum, maximum and average of total inspection time and normalized inspection time by three different team leaders, respectively. On average, more than 50% variation can be observed between routine inspection duration of team leader-1 and team leader-3 but it should be recognized that different bridges of different sizes and conditions were inspected, which contributes to the variation. For example, team leader-1 inspected six bridges in five inspection days that include a timber, reinforced concrete slab, two culverts, and two steel girder type bridges. On the other hand, team leader-3 inspected ten bridges in four inspection days that included a steel girder, six pre-stressed concrete girder and three culvert types of bridges. Furthermore, team leader-1 inspected bridges in the early months of autumn whereas team leader-3 inspected bridges in the last months of autumn when the temperature was comparatively colder. Thus, the differences in average inspection time between team leaders may not exist but may instead reflect differences in the time of year, type and condition ratings of inspected bridges.

The inspected bridges that crossed over a water body required channel profile measurements to assess possible scour. Thus, the shadowed bridges are classified based on the collection of scour data as shown in Figure 4.9 and Figure 4.10. Considering the difference between the maximum and the minimum recorded duration of the bridges, the ones in need of scour data collection have larger variation compared to other bridges. The average inspection time of bridges crossing over a water body is lower than the ones crossing over a roadway. In another hand, normalized inspection time of bridges crossing over a water body is higher compared to the ones crossing over a roadway. The reason is most likely due to smaller size bridges crossing over channels and other characteristics of the bridges.

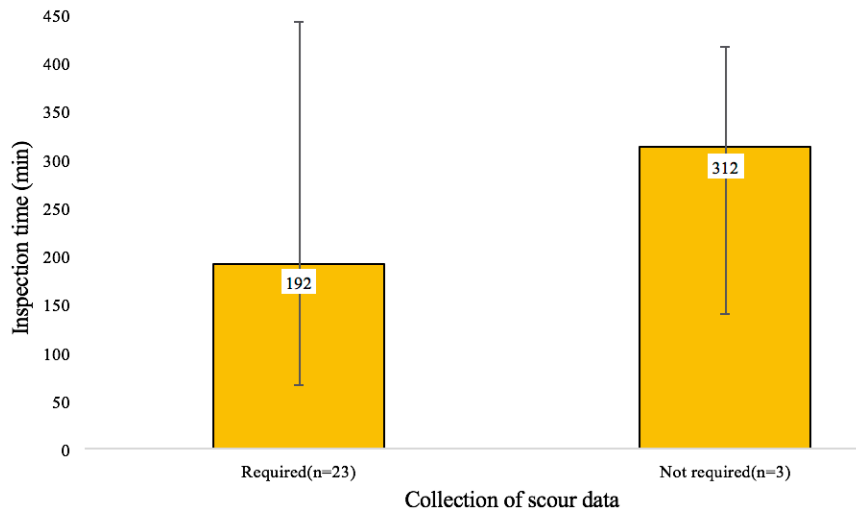

Figure 4.9: Average inspection time for bridges by scour data collection requirement (error bars represent range of values)

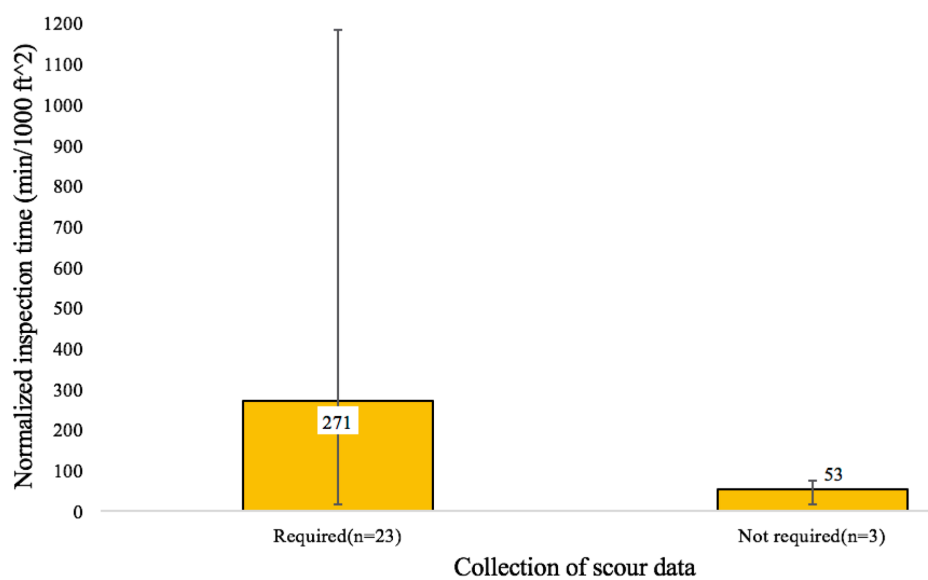

Figure 4.10: Average normalized inspection time for bridges by scour data collection requirement (error bars represent range of values)

The bridges' inspection season starts from early February and continues to the end of November (inspection season can vary based on geographical locations). The researcher shadowed bridge inspections in the last three months of the inspection season: September, October, and November. The terms early, mid and end for months correspond to the first ten, middle ten and remaining days of a month, respectively. The change in inspection time and normalized inspection time due to different months are notable from Figure 4.11 and Figure 4.12. It can be noticed from the plotted graph that, on average, the duration spent on inspection of bridges in early September is approximately twice the duration in late November. The significance of this variation is unknown since multiple of variables in combination can influence the inspection time of bridges.

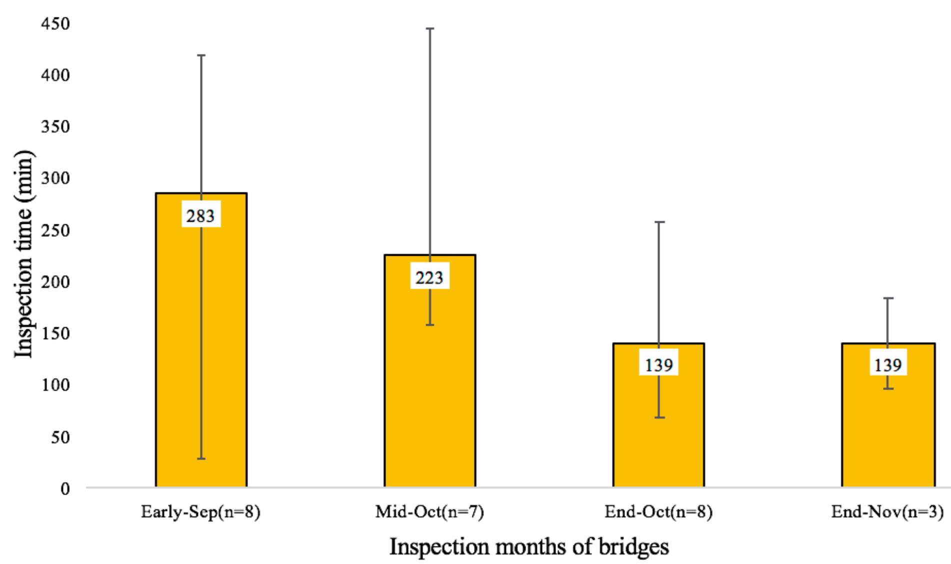

Figure 4.11: Average inspection time for bridges by different months (error bars represent range of values)

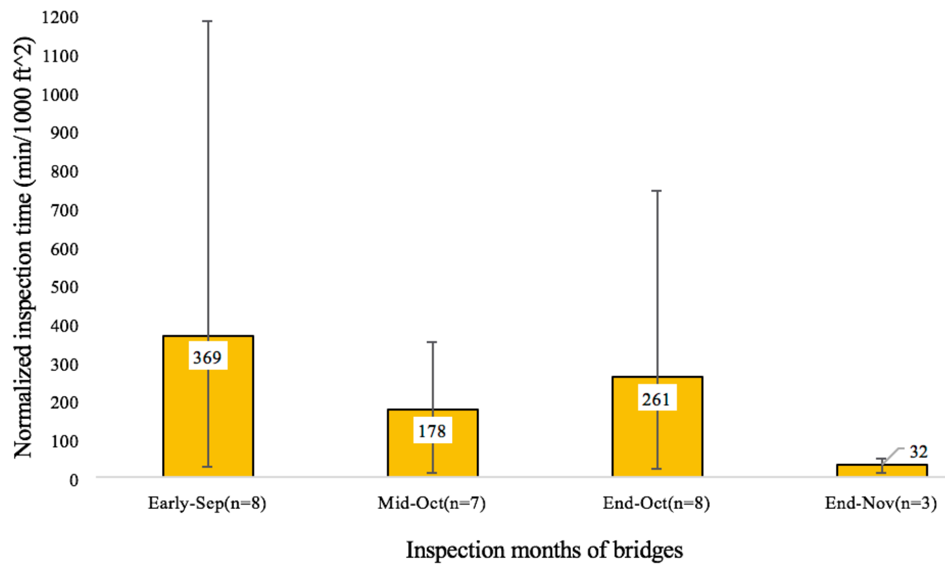

Figure 4.12: Average normalized inspection time for bridges by different months (error bars represent range of values)

Furthermore, section 4.1.1, 4.1.2 and 4.1.3 elaborate on the influence of size, condition ratings and type of bridges, team leaders and seasonal (inspection months) variables on routine bridge inspections.

4.1.1 Inspection Duration Based on Condition Rating and Size of Bridges

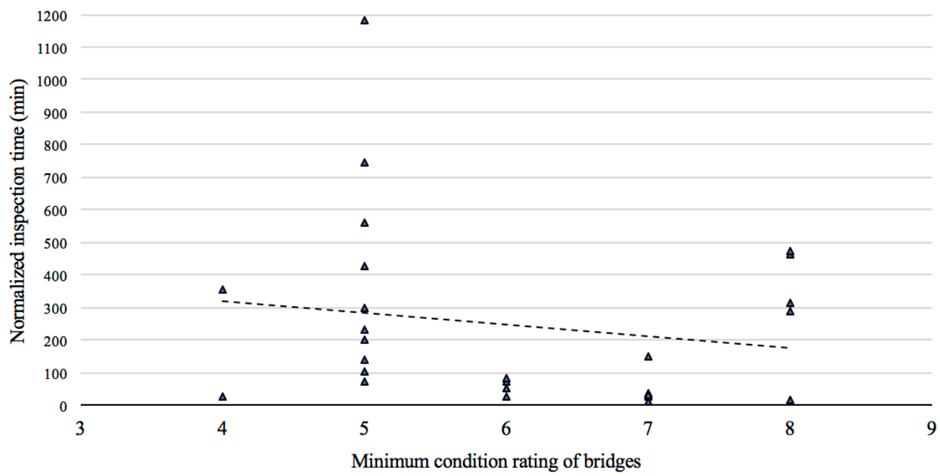

Figure 4.13: Trend line for normalized inspection time of bridges with different condition ratings.

The graph in Figure 4.13 illustrates the amount of normalized inspection time taken to inspect bridges with different condition ratings. A linear trend line of normalized inspection time (per 1000 ft^2 deck area) as a function of bridge condition rating is included. This is intended for illustrative purposes only; a strictly linear relationship between these two variables is not expected, especially given the possible influence of other variables such as bridge types and inspectors. The trend line demonstrates an increase in inspection duration with a decrease in condition rating. On average, the duration increased by 35 minutes per 1000 ft^2 when condition ratings decrease by one unit. In other words, the slope of the trend line is 35 minutes per condition rating as shown the trend line function for normalized inspection time in Equation 4.1.

$$T = \frac{175 \text{ x A}}{1000} + 35\ (8 - C) \qquad (4.1)$$

T, Normalized inspection time in minutes
A, Deck area of bridge in ft^2
C, Minimum condition rating of a bridge

Figure 4.13 also shows a noticeable variation in time consumption for different condition ratings. Considering the data, the minimum duration consumed for a condition rating of 4 is 25 minutes per 1000 ft^2 and the maximum duration for condition ratings of 5 and 8 are 1200 and 500 minutes per 1000 ft^2, respectively. However, it is not clear that deck area and condition ratings are the only or most significant factors that influence normalized inspection time of bridges

4.1.2 Inspection Duration Based on Types of Bridges

There are different types of bridges that are routinely inspected. The difference in materials and structure types can result in variation in bridges' inspection duration. Figure 4.14 illustrates the variation in inspection time of all 26 inspected different types of bridges. It can be noted from the graph that the maximum average inspection time for bridge inspections is consumed by steel girder type of bridges. The average minimum inspection time is consumed by pre-stressed concrete girder bridges. Condition rating of bridges and team leaders who inspected these bridges are also illustrated in the graph which is discussed in detail in Section 4.1.1, and 4.1.3 of this chapter, respectively.

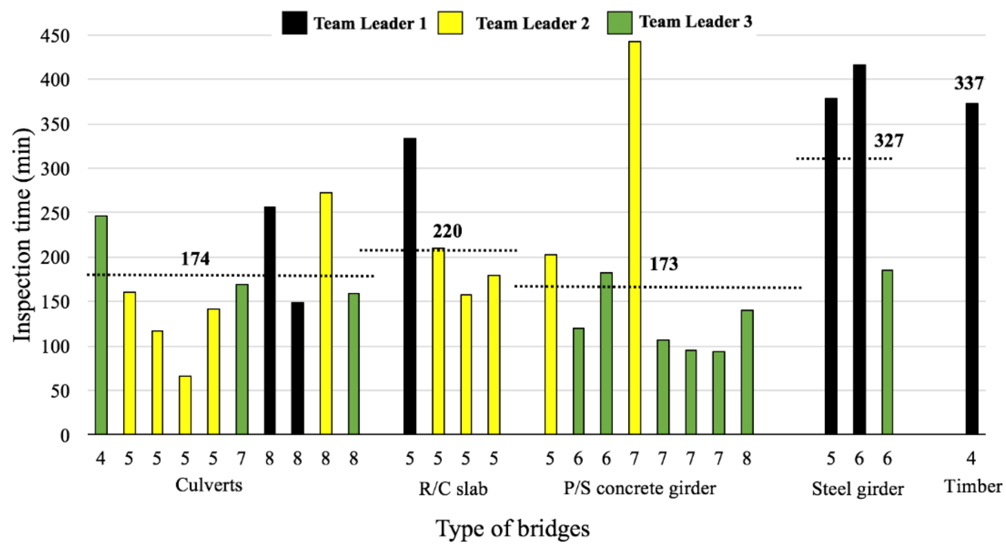

Figure 4.14: Inspection time by different types of bridges, average time denoted by dotted line

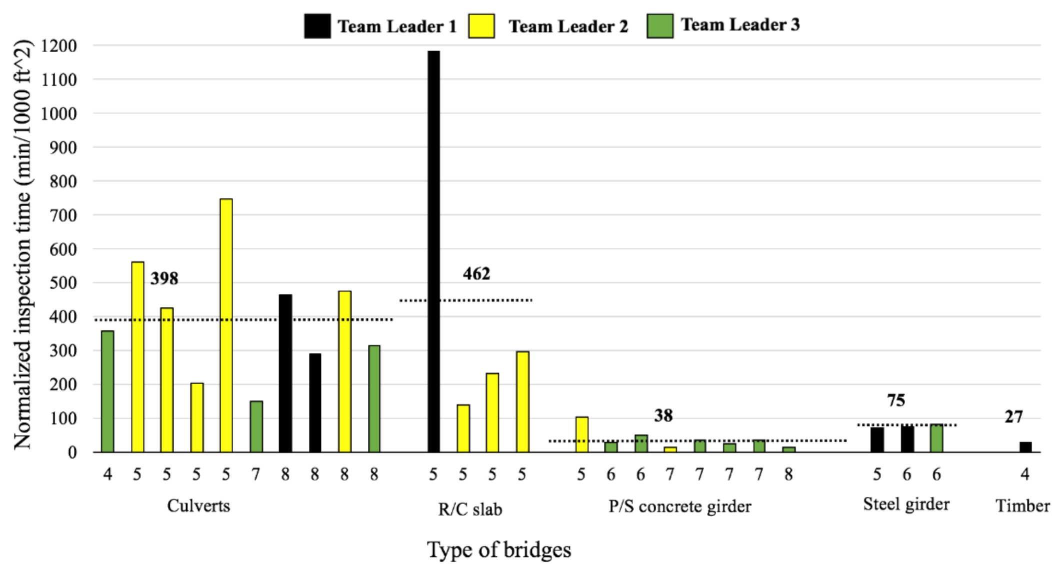

Figure 4.15: Normalized inspection time by different types of bridges, average time denoted by dotted line

Furthermore, normalized inspection time by bridge type is shown in Figure 4.15. It is observed that the reinforced concrete (R/C) slab bridge with the average of 462 minutes is the maximum average normalized inspection time spent. The second most duration is consumed by culverts with an average of 398 minutes normalized inspection time. On the other hand, the timber bridge only consumed 27 minutes normalized inspection time, which was the minimum average normalized duration. This bridge is relatively large and when the duration is viewed in total, this bridge is not an outlier because it is not subject to vehicular traffic. The averages of normalized inspection time for concrete and steel girder bridges are only 38 and 75 minutes, respectively.

The average normalized inspection time shows similar results for culverts and for reinforced concrete slab bridges, which are mainly used for short spans. On the other hand, the average duration of steel and P/S concrete girder shows similar results, which are medium and long span bridges. The average condition rating of six for culvert and slab type of bridges is similar to average condition rating of P/S concrete and steel girder bridges along a timber bridge that means based on Equation 4.1 (normalized inspection time), these bridges should consume on average same duration, 245 minutes. However, culverts and slab have consumed on average 430 minutes (more duration than the expected) and P/S concrete and steel girder bridges have consumed on average 46 minutes (less than the expected). That presence existence of variance between expected and actual spent normalized inspection time between different types of bridges.

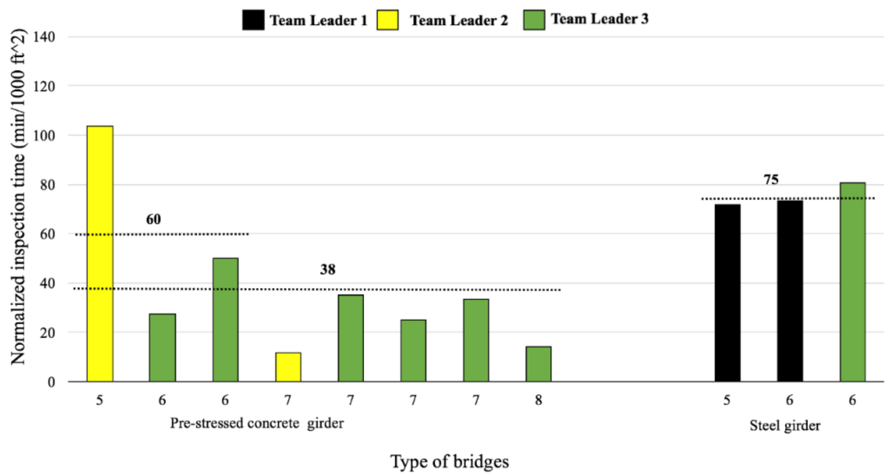

Figure 4.16: Normalized inspection time by P/S concrete and steel girder bridges, average time denoted by dotted line

The graph shown in Figure 4.16 illustrates the difference in normalized inspection time between the pre-stressed concrete girder and steel girder bridges. The average normalized inspection time of steel girder bridges is higher compared to pre-stressed concrete girder bridges. Considering the condition ratings of pre-stressed concrete bridges, two different average inspection time values are calculated. First, the average inspection time for all ten pre-stressed concrete girder bridges is specified at 38 minutes, but some of these bridges have better condition than the population of steel girder bridges considered here. Thus, the average normalized time for three pre-stressed concrete girder bridges with condition ratings matching those of the steel bridges in this population (5, 6 and 6) is calculated as 60 minutes, Thus, when bridge condition and size are considered, the average normalized time consumed by steel girder bridges (75 minutes) is more compared to pre-stressed concrete girder bridges. In addition, when comparing inspection duration of two pre-stressed concrete girder bridges and a steel girder bridge with condition ratings of 6 inspected by the same team leader (team leader-3), it can be noticed from the graph and details that the steel girder bridges consumed more duration than pre-stressed concrete girder bridges. One of the reasons for this variation may be due to the presence of multiple members in steel structures like bracing that makes inspection work more laborious as compared to concrete structures and culverts.

4.1.3 Inspection Duration Based on Team Leader

The bridges' inspection time varies by team leaders. It is important to understand how team leaders execute their inspection activities. It is commonly observed that team leaders often develop personalized approaches and differing techniques to inspect bridges. To comprehend the way team leaders operate, the researcher shadowed inspection work of three different team leaders. Figure 4.17 shows the average inspection time of bridges sorted by team leaders. It can be noted from the graphs that there is more than 50% difference between the average inspection duration of team leader-1 compared to team leader-3.

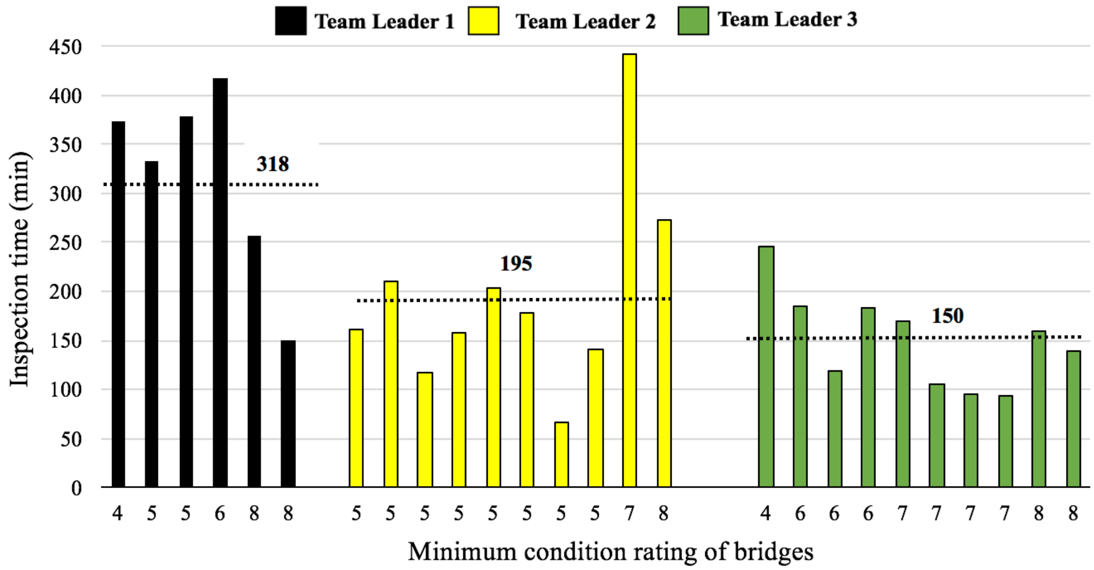

Figure 4.17: Inspection time by different team leaders, average time denoted by dotted line

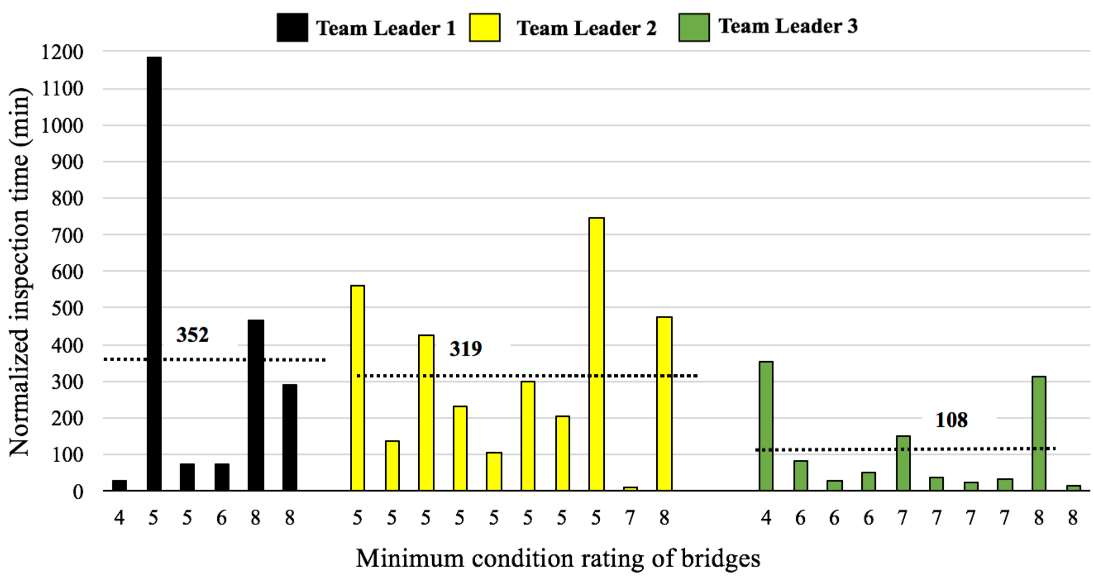

Figure 4.18: Normalized inspection time by different team leaders, average time denoted by dotted line

This variation can be further explained based on the normalized inspection time which is shown in Figure 4.18. The graph shows that the average normalized inspection time spent on the inspection of bridges by team leader-1 and team leader-2 is 90% in the same range; however, the average normalized inspection time spent by team leader-3 is far less. Specifically, on average, team leader-3 spent one-third of the normalized time of team leader-1 and team leader-2 on inspections. There are possibly many variables such as the type of inspected bridges, condition ratings of bridges, and other variables, which can influence inspection duration of bridges. Therefore, it is unclear from shown graphs whether one team leader is working efficiently compared to others.

Figure 4.19 shows five graphs that collectively report the presence of variation between field times spent on inspection of bridges by different team leaders. Each graph shows differences in the inspection procedure used by each team leader. The average field time reflects the duration of inspection activities at bridge sites such as: visual inspection of bridge elements, measuring deterioration of bridge elements by tape or carpenter ruler, taking photographs, checking clearance of bridges or channel scour depth. A larger bridge can take a longer time compared to a smaller bridge. Thus, the average field time per 1000 ft^2 deck area, normalized field time, is also provided. The normalized field time shows the presence of the variance between team leaders' inspections. The variation in normalized field time may also be influenced by condition ratings of inspected bridges. Thus, the average minimum condition ratings of the inspected bridges by three team leaders are calculated and shown in Figure 4.19. It can be noticed that the difference in the team leaders inspected bridges condition ratings is on average 15%. In addition, the average number of bridge photos taken and the bridges inspected per day by team leaders are recorded and shown in graphs. The graph with number of photos taken demonstrates that team leader-1 took more photos than team leader-2 and team leader-3. On the other hand, team leader-3 inspected more bridges per day compared to other team leaders. However, team leader-2 with inspection rating of two bridges per day has taken 11 photos and maintained middle values in comparison to the other team leaders.

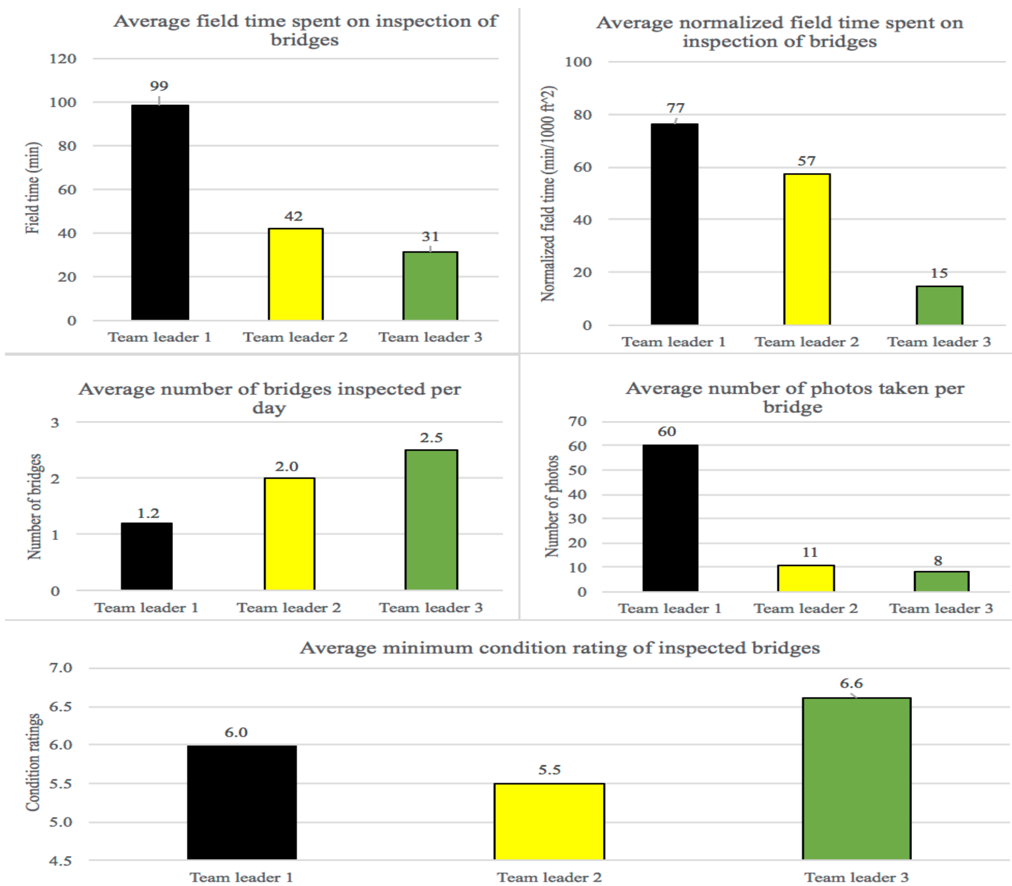

Figure 4.19: Average field time, normalized field time, number of bridges inspected per day, photos taken and condition ratings of bridges

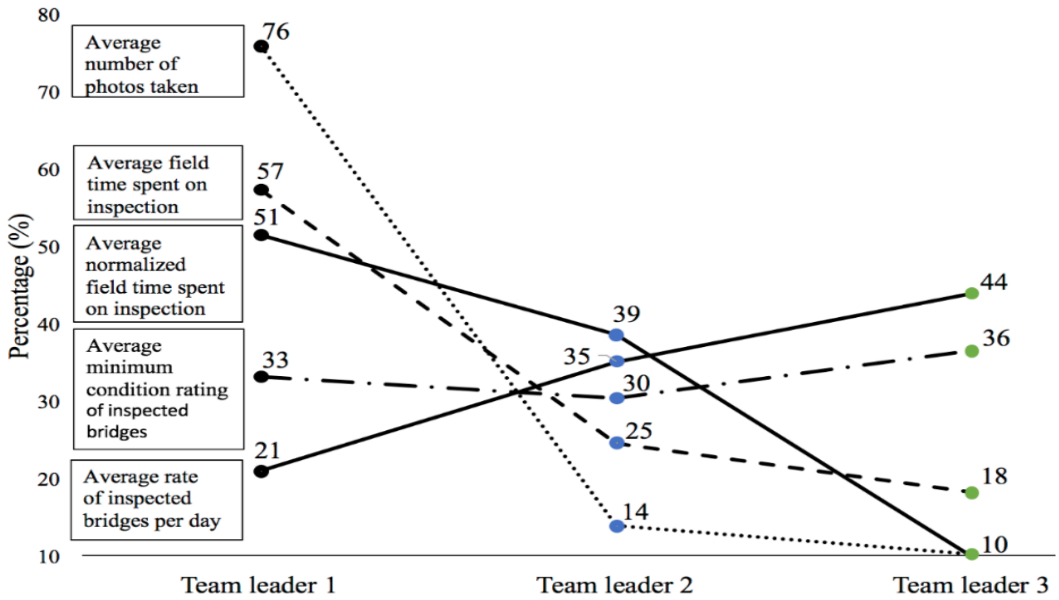

Figure 4. 20: Comparison of team leaders' inspection approach in percentage

Furthermore, the percentage graph of Figure 4.20 was plotted to show the variation of the five variables of Figure 4.19 by team leaders. The percentage is based on the aggregated field time, normalized time, number of photos taken, condition ratings of inspected bridges and number of inspected bridges per day by the three team leaders for overall 26 bridges. The percentage scale graph can easily compare all five variables in a single view. On average, the minimum condition ratings of the inspected bridges are approximately in constant range for all three team leaders. Team leader-1 takes the highest percentage of photos per bridge (percent relative to the sum of the average of all team leaders' photos) and inspects the lowest number of bridges per day in contrast to the two other team leaders. Consequently, the average time spent on inspection of a single bridge is the highest percentage for team leader-1. On the other hand, team leader-3 takes the lowest percentage of photos and inspects the highest number of bridges per day compared to the two other team leaders that results in an average less time consuming to evaluate bridges' condition ratings. Team leader-2 took 14% of the photos alongside inspection rate of 35% of bridges (total percent of team leaders' average inspected bridges) that consumed a medium amount of inspection time relative to other team leaders.

Hence, team leaders develop their unique approaches and they need to share their best practices about effective inspection techniques with each other. In addition, the approaches taken by team leaders need to be evaluated to select the best approach for training prospective inspectors to efficiently utilize inspection time.

4.1.4 Number of Bridges Inspected Per Day

On a day of routine inspection of bridges, team leaders take the decision on the number of bridges that need to be inspected and accordingly, inspections are conducted. Thus, to understand how many bridges were inspected per day by each of the shadowed team leaders, Figure 4.21 can be referred. It illustrates total time for routine inspection of each bridge on the vertical axis and the number of routine inspection days on the horizontal axis. The total time of a day of bridge inspection work is distributed among the number of bridges inspected per day. A total of 26 bridges were inspected by three team leaders in 14 individual workdays. The researcher shadowed the bridge inspections from 7:00 am to 3:00 pm and on average, recorded 465 minutes of the routine inspections' duration per day.

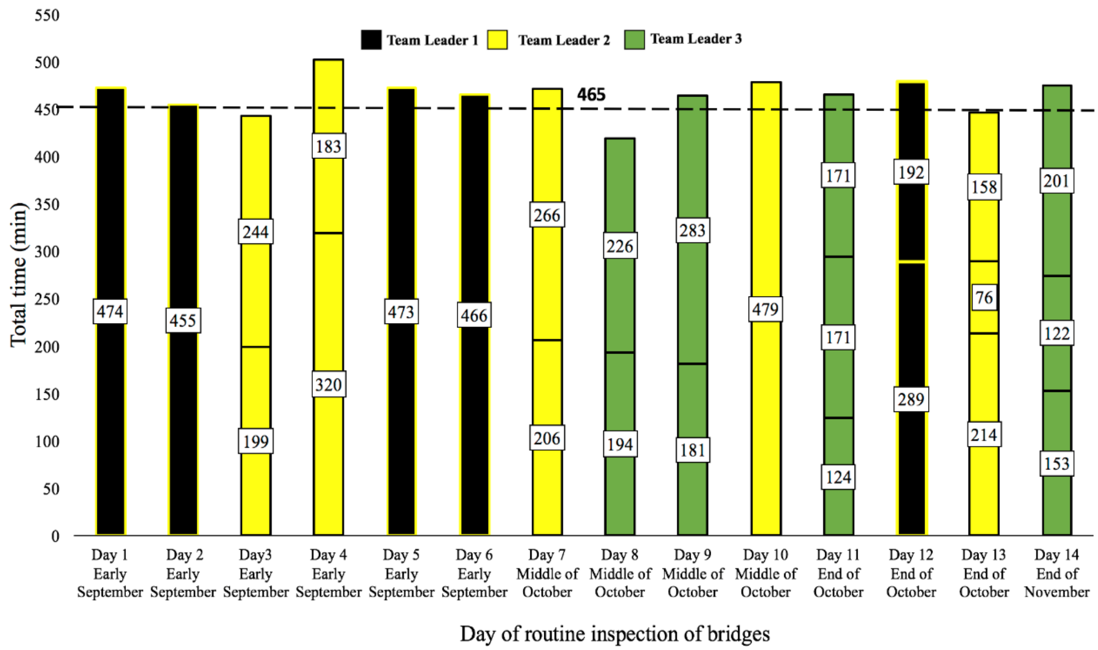

Figure 4.21: Recorded total time and number of bridges inspected per day

The number of inspected bridges varied between one to three per day. The number of bridges evaluated on each day is shown in the stacked column graph of Figure 4.21. There is a notable surge in the number of inspected bridges per day from September to November. In early September, team leaders inspected one or two bridges per day but towards the end of November, they inspected three bridges per day. Multiple variables such as type, condition ratings, and size of bridges can lead to the variation in inspections. However, the correlation and significance of any specific variable are not within the scope of this research work; rather this work defines all possibly relevant variables.

4.2 Categorization of Activities Based on Inspection Stages

Figure 4.22 presents the workflow for routine bridge inspection in terms of the five stages that are most often repeated after an interval of two years for each bridge. Bridge inspection activities have been categorized into these five main stages of inspection: review of documents, mobilization, inspection, demobilization and report writing. The performed activities during these five stages, their duration and observed details of inspection process were recorded. These activities occurred at the office, while commuting, and at the bridge inspection site.

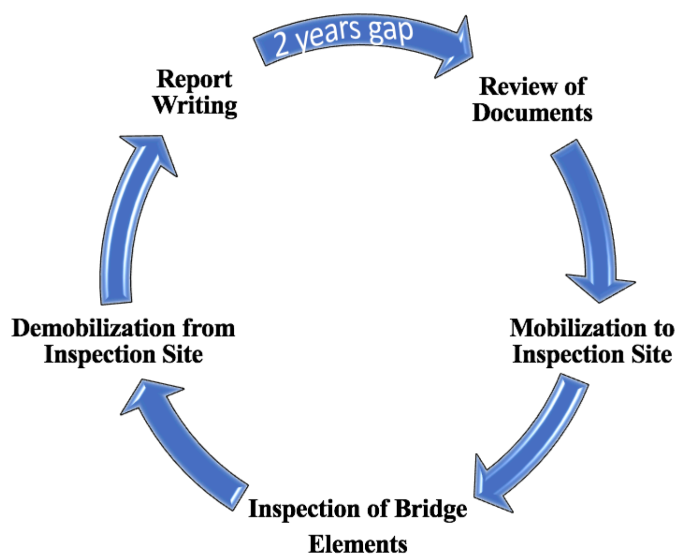

Figure 4.22: Process flow corresponding to different stages of routine inspection

The stages of the inspection process consist of several activities. During shadowing bridge inspections, 52 individual activities were recorded. These activities are listed in Table 4.2 which are sorted based on their time consumption from maximum to minimum duration with a sequential order of 1 to 52. The Lean classification of these activities based on value (value added, required non-value added, non-value added) will be described in detail in Section 4.4 of this chapter. Most of the listed activities are common to all 26 inspected bridges but some activities are unique to individual bridges. For example, Activity #50 (waiting due to malfunction of digital scour measuring device) did not occur during many inspections because most of the time the scour-meter was working at the inspection site, but Activity #10 (taking photos of bridges) is common to all inspections. It is important to record all the activities involved in the inspection of bridges in order to have a complete description of the time involved in the inspection.

Table 4.2: Shadowed inspection activities

Activity	Activity Description	Classification Based on Value	Stage	Total time (min)
1	Driving to bridge	RNV	Mobilization	696
2	Visual inspection of bridge elements	VA	Inspection	675
3	Entering inspection report data of a bridge inspected on the same day	VA	Documentation	526
4	Driving back to office	RNV	Demobilization	467
5	Checking clearance of a bridge or scouring detail of a channel	VA	Inspection	345
6	Communicating, non-work related	NV	Documentation	312
7	Entering inspection report data of a bridge that was inspected on a previous day	RNV	Documentation	211
8	Browsing internet, non-work related	NV	Documentation	208
9	Taking a boat from inventory and handling it	RNV	Mob/Dem	164

	during mobilization and demobilization			
10	Taking photos of bridges	VA	Inspection	163
11	Writing down sequential order of photographs in notebook	RNV	Documentation	162
12	Discussion about inspected bridges among inspection team and manager	VA	Inspection	148
13	Taking field notes	VA	Documentation	145
14	Determining percentage of bridge deterioration measuring its location	VA	Inspection	143
15	Examining drawings and reviewing previous report of a bridge	VA	Review of doc	136
16	Adding comments to condition rating of bridge elements	VA	Documentation	126
17	Walking around bridge site for inspection purposes	RNV	Inspection	123
18	Getting ready, including collecting documents, camera as well as checking bridge inspection schedule and weather	RNV	Mob/Dem	114
19	Waiting in truck at parking lot before driving to a bridge	NV	Mobilization	108
20	Putting on and taking off boots and chest waders for inspections in water	RNV	Mob/Dem	103
21	Walking between parking lot and office	RNV	Mob/Dem	97
22	Creating bridge elements' inventory list on a paper and making a digital copy later for initial inspection of a bridge	RNV	Documentation	83
23	Review of previous inspection report	VA	Documentation	69

24	Locating and filling out traffic form needed for obtaining permission to block/redirect traffic	NV	Mobilization	67
25	Taking and returning of necessary inspection tools from truck such as ladder, ruler, and measuring tape	RNV	Mob/Dem	60
26	Driving boat to bridge	RNV	Mob/Dem	57
27	Missing a direction or a turn to bridge site and checking the paper map to find location	NV	Mobilization	49
28	Waiting for the completion of another agency's inspection for traffic control reasons	NV	Inspection	45
29	Making copies of element condition ratings page and scouring sketch detail of previous inspection	RNV	Review of Doc	44
30	Modifying scour measuring stick	NV	Inspection	41
31	Adding comments to pictures and specifying location of deterioration while typing inspection report	VA	Documentation	36
32	Being misdirected to site because of using outdated maps	NV	Mobilization	35
33	Positioning and movement of bucket truck	RNV	Mob/Dem	31
34	Searching for bridge drawings to check bridge elements detail, someone misplaced	NV	Review of Doc	27
35	Shifting positions of traffic signs to different locations to redirect traffic as needed	RNV	Inspection	25

36	Refueling of vehicle	RNV	Mob/Dem	25
37	Returning to previously inspected bridge site to inspect and collect missed images of elements	NV	Inspection	24
38	After reviewing previous report at the bridge site calling manager on phone to find immediate answer to queries about the bridge	NV	Inspection	23
39	Searching for inspection files in office and arranging inspection files	NV	Review Doc	23
40	Excessively removing vegetation around the bridge	NV	Inspection	21
41	Filling out form for requesting maintenance of a bridge	VA	Documentation	21
42	While writing inspection report on the computer, matching photographs to deterioration detail	RNV	Documentation	18
43	Refilling water cooler and emptying garbage bin from vehicle	RNV	demobilization	13
44	Copying pictures from camera to computer	RNV	Documentation	11
45	Returning to truck to retrieve forgotten documents or equipment	NV	Demobilization	11
46	Placing equipment in a new truck because the original one required maintenance	RNV	Mobilization	10
47	Checking high tide level under bridges to decide whether inspection operations can be carried out	NV	Mob/Dem	8

48	Returning to office to obtain forgotten documents or equipment	NV	Mobilization	7
49	Washing boat at fresh water lake to clean salt water from its engine	RNV	Demobilization	5
50	Waiting due to malfunction of digital scour measuring device	NV	Inspection	4
51	Rectifying mistake, such as correcting bridge ID while communicating with traffic agency through email	NV	Review of doc	3
52	Obtaining directions to bridge locations from office computer	RNV	Review of doc	2

4.3 Categorization of Activities Based on Lean Analysis

The recorded inspection activities in Table 4.2 are sorted into Table 4.3 that was developed to demonstrate an overall relationship between the inspection process and basic Lean principles. It includes the five stages of the bridge inspection process (organized vertically) as well as work and seven types of waste activities (organized horizontally). The classification of recorded activities is conducted based on the Lean definition of seven types of waste and work activities that were described in Section 3.4. The serial numbers from 1 to 52 represent recorded activities that are inserted into the table because of space limitations; refer to Table 4.2 for the descriptions of each of these activities. Specific font styles are used to illustrate value based classification of these activities: value added activities are shown with bold fonts, non-value added activities are shown with underline italic fonts and required non-value added activities are shown with regular fonts.

Table 4.3: Lean table for categorization of bridge inspection activities

BRIDGE INSPECTION STAGES	LEAN CATEGORIZATION OF ACTIVITIES							
	Over-produc-tion	Inventory	Defects	Over-processing	Waiting	Motion	Transport-tion	Work
Review of Documents		7	*34, 51*	*39*		29	52	**15**
Mobilization			*32, 48, 27*	*24*	*19*, 36	18, 20 25, 33 46, *47*	9, 4, 26, 1, 21	
Inspection			*28 ,37, 38, 50*	*30, 40*	35		17	**2, 5 10, 12 14**
Demobilization			*45*		36	18, 20 25, 33 43, *47*	9, 26, 49, 21	
Report Writing				22, 42, 44, 11	*6, 8*	*6, 8*		**3, 13 16, 23 31, 41**

Non-value added Required non-value added **Value added**

During the analysis and classification of the 52 recorded routine inspection activities, the following questions were addressed:

- In which stage of inspection has the certain activity occurred?
- Is the activity work or waste based on Lean definitions?
- If it is a waste, which type of waste is it?
- If it is a waste, what is the value of this activity (non-value added or required non-value)?

This table was used to connect Lean philosophy to the stages of bridge inspection. It depicts the bridge inspection process flow and Lean concepts in a single view. It was used as a management tool in this study to visualize Lean principles and accordingly, compare and classify all recorded bridge inspection activities. This table can also be used for Lean analysis in other industries.

4.3.1 Time Analysis of Classified Activities

Table 4.4 Percentage of consumed duration by categories of bridge inspection activities

Stage	Waste							Sum of Waste	Work	Stage
	Over-production	Inventory	Defects	Over-processing	Waiting	Motion	Transporta-tion			
Review of Documents	0	0	0.5	0.4	0	0.7	0.0	1.6	2.2	3.9
Mobilization	0	0	1.5	1.1	2.0	2.8	14.1	21.4	0.0	21.4
Inspection	0	0	1.6	1.0	0.4	0	2.0	5.0	24.3	29.3
Demobilization	0	0	0.2	0	0.2	2.8	10.5	13.7	0.0	13.7
Report Writing	0	3.5	0	4.5	3.5	5.1	0	16.5	15.2	31.7
Total	0.0	3.5	3.7	7.0	6.1	11.4	26.7	58.3	41.7	100.0

After classification of inspection activities based on inspection stages and Lean concepts, the duration consumed by the various work and waste activities in each stage was added and their percentage distribution is shown in Table 4.4. The percentage is specified based on total time of all 52 listed activities of routine inspections for 26 bridges in 14 individual workdays. In other words, excluding half hour of inspectors' lunch break duration remaining a day of routine bridge inspection duration is analyzed using Lean principles. The percentage scale is useful for better demonstration of the routine inspection duration by different stages of inspections, work (value added) and waste (non-value added and required non-value added) type of activities of the bridge inspection process.

Table 4.4 shows that 41.7% of the total time is spent on work (as classified by Lean philosophy), consisted of 24.3% of the total time spent on inspection stage, 15.2% of total time spent on report writing stage, and 2.2% of the total time spent on review of documents stage. It can be noticed from the table that among seven types of waste activities, transportation accounts for the largest percentage of waste (26.7% of total time), which mainly occurs during mobilization and demobilization stages.

Table 4.5: Seven most time consuming routine bridge inspection activities

Activity	Details of Activity	Stage	Classification Based on Waste & Work	Classification Based on Value	Total Time (min)	Daily Time (min)	Percent (%)	Total (%)
1	Driving to bridge	Mobilization	Transportation	RNV	696.0	49.7	11.5	11.5
2	Visual inspection of bridge elements	Inspection	Work	VA	675.0	48.2	11.1	22.6
3	Entering inspection report data of a bridge inspected on the same day	Documentation	Work	VA	526.3	37.6	8.7	31.3
4	Driving back to office	Demobilization	Transportation	RNV	467.0	33.4	7.7	39.0
5	Checking clearance of a bridge or scouring detail of a channel	Inspection	Work	VA	345.0	24.6	5.7	44.6
6	Communicating, non-work related	Documentation	Waiting/Motion	NV	312.3	22.3	5.1	49.8
7	Entering inspection report data of a bridge that was inspected on a previous day	Documentation	Inventory	RNV	211.0	15.1	3.5	53.3

The seven most time-consuming activities consumed more than 50% of the total time during the inspection of bridges. These seven activities are listed in order from the most to the least time-consuming in Table 4.5. Refer to Appendix A for a complete list of recorded activities and their duration. Of the top seven most time-consuming activities, 25.5%, 22.7%, and 5.1% percent of the duration spent were value added(VA), required non-valued added(RNV), and non-valued added(NV), respectively.

Driving the inspection crew and equipment to the bridge site (1, where parenthetical numbers in this discussion refer to the activity number as reflected in Table 4.2) was the activity that took the most of the total time. Driving back to the office (4) was also one of the most time-consuming activities, but retracing the route and returning to the office typically took less time than driving to the site. It is required to drive to and from the bridge site and back to the office but these activities do not add value to the bridge inspection work output of the final inspection report. Thus, mobilization and demobilization activities are classified as required non-value added and transportation waste. It was also observed that inspectors generally relied on paper maps and errors sometimes arose because of this process, revealing the potential for reducing the amount of duration spent on transportation waste.

Visual inspection of bridge elements (2) and checking clearances of a bridge and scour detail of a channel (5) are directly related to bridge evaluation and are thus, value added work. The total time spent on these two activities is 16.8% of the total inspection time. Creating an inspection report for a shadowed bridge (3) and creating an inspection report for a bridge in the inspector's backlog (7) both encompass creating inspection reports and are productive activities. However, 3 is classified as value added work because it relates to creating the report for a bridge inspection that was shadowed on the same day. In contrast, 7 is classified as required non-value added inventory type of activity. There are two reasons for this classification. One was based on the research logistics, meaning that the time was logged for the reporting, but there was no bridge inspection site visit with which to associate it. Thus, it was waste relative to the inspection plan for the present day. The second reason was based on the decrease in efficiency that may result from postponing the creation of the report due to the possibility of details being harder to mentally or physically retrieve as time passes.

4.3.2 Results by Stages of Inspection

The total time distribution among all five stages of bridge inspection process is expressed in Figure 4.23 on a percentage scale. On average, the largest percentage of the bridge inspection total time, 31.7%, is spent on the report writing stage. The inspection stage, with an average of 29.3% of the total time, is the second most time-consuming stage. Considering mobilization and demobilization stages together, they consumed 35% of the total time. Review of documents stage represented 3.9% of the total time of the routine inspections. Thus, on average, roughly one-third of the total time was spent on each of report writing stage, mobilization and demobilization stages combined, and inspection stage at the bridge site.

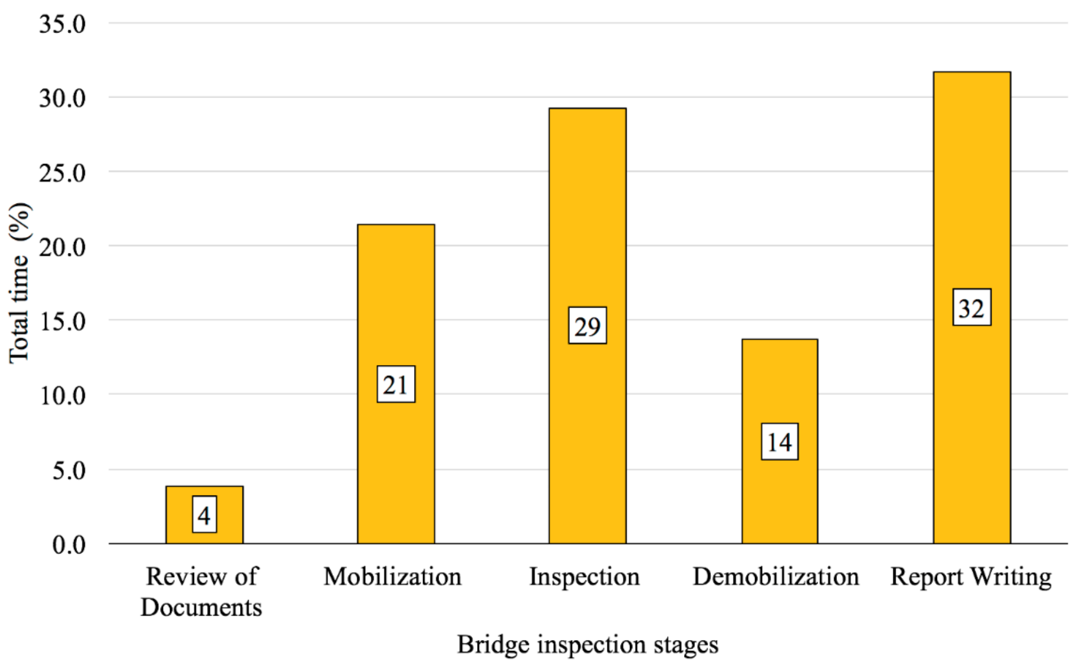

Figure 4.23: Total time distribution among different stages of routine inspections

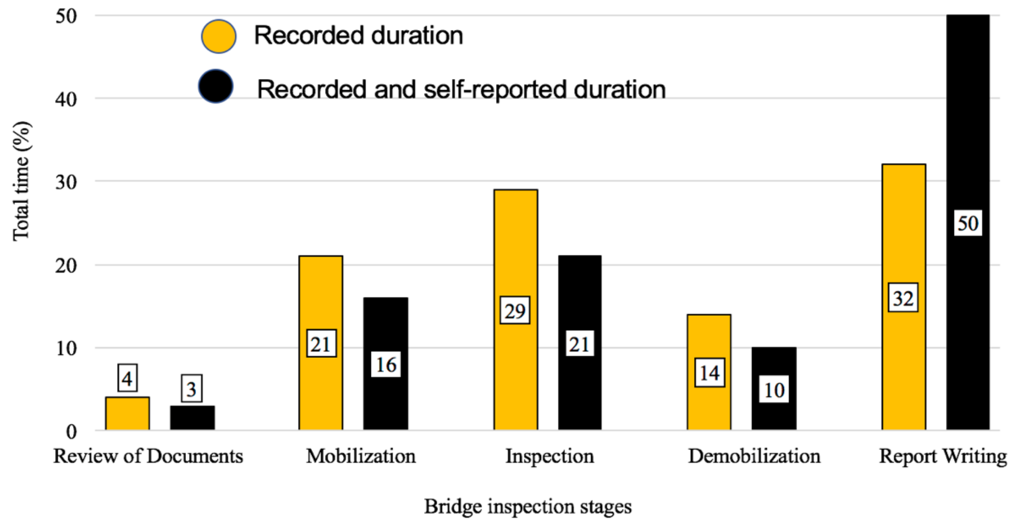

Figure 4.24: Comparison of total time distribution between stages of routine inspections

Furthermore, it is noted that shadowing took place on discrete work days scheduled from 7:00 am to 3:00 pm; it was often the case that report writing happened outside of this time frame and was, thus, not directly recorded by the researcher. In these situations, the inspectors self-reported the amount of duration spent on report writing. If this duration is included in the total time, the duration spent on report writing increases to an average of 50% of the total time for routine bridge inspection, illustrated in Figure 4.24. In other words, including self-reported time, which has no verifiability and likely less precision, the report writing stage consumed more than twice the duration of the inspection of bridge elements at the site (which accounts for 21% of the total time including self-reported time). However, for consistency, the self-reported duration is not included in the data analysis that follows unless otherwise noted.

4.3.3 Results by Value

The duration consumed by all five stages of bridge inspection and their valuation (by categorizing each activity as value added, required non-value added, or non-value added as defined above) is depicted in Figure 4.25. Here one of the most significant observations is that while the report writing stage represents the largest percentage of the total time, less than half of this duration adds value to the inspection report. Furthermore, this stage also contains the highest percentage of non-value added duration (relative to the total time and relative to the duration per stage), with 8.6% of the total time being represented by non-work related communication and browsing the internet while waiting on the computers containing the bridge reporting software and as personal habits of individuals. Non- work related communication claims the largest share with 5.1% of total time while non-work related browsing the internet represents 3.5% of total time. The report writing stage also exhibits 8% of required non-value added duration (relative to the total time of all stages) that represents the activities such as writing down the sequential order of photographs in the record book, entering inspection report of a bridge that was inspected on previous days in a computer, etc.

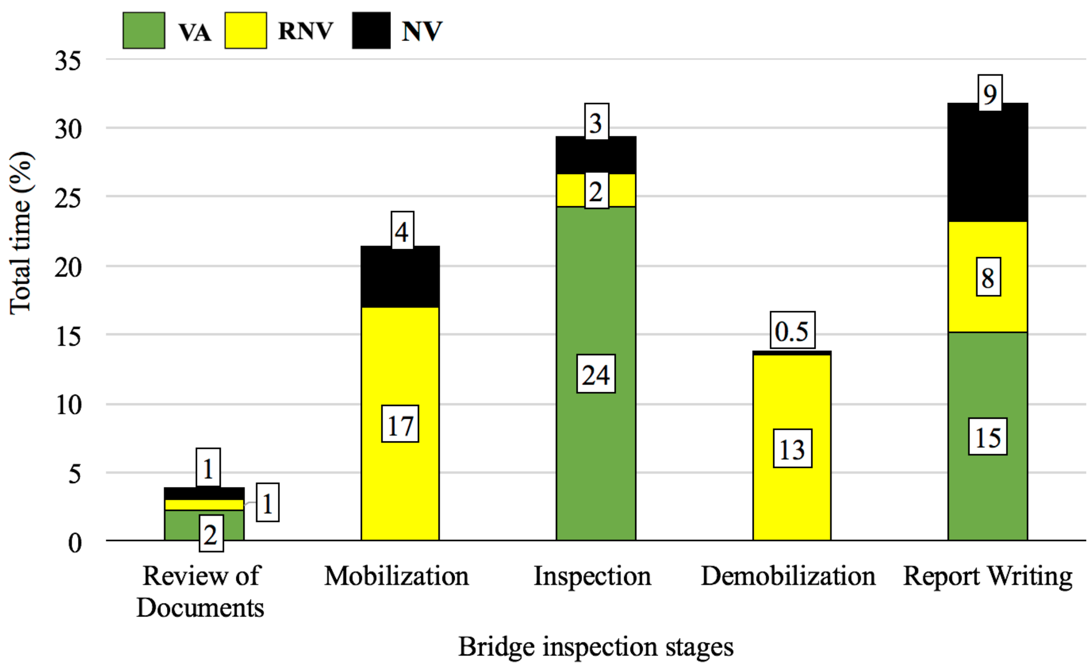

Figure 4.25: Valuation of routine inspection duration, relative to total time consumed by the five stages of the bridge inspection process

During the inspection stage, 29.3% of total time is consumed, with 24.3% of duration relative to the total time adding value to the inspection stage. A total of 2.6% and 2.4% of duration are non-value added and required non-value added, respectively. Thus, comparing the waste relative to the work in the inspection stage, this is the most efficient stage of inspection with 83% of the duration spent on the inspection stage being value added.

Together, the mobilization and demobilization stages consumed a total of 35% of the total time, with the entirety of this duration being waste. 30% of the total time is represented by required non-value added activities, which is mainly driving to and from the bridge sites. However, the mobilization stage also contained the second highest percentage of non-value added activities amongst all the stages which represented 4.4% of the total time. Waste activities during mobilization and demobilization include waiting in the truck at a parking lot before driving to a bridge, missing direction to the bridge site and consequently, checking the paper map to find location, etc.

The review of documents stage consumed the least duration among all five stages of routine inspection. Considering the value-added activities (VA) relative to waste in this stage, this stage is also relatively ineffectual, with nearly half of the duration spent in this stage being either required non-value added (RNV) or non-value added (NV). Instances may include review of previous inspection reports of a bridge (VA), writing down sequential order of photographs in notebook (RNV) and modifying measuring tools inside the office before departure to site (NV). For example, a team leader of inspection crew used a colored tape to cover a scour measuring pole which was unnecessary activity and thus waste. Later, the tape was removed from the pole before it was used on site and thus the duration spent on this activity did not add any value to the inspection process.

The pie charts in Figure 4.25 present the percentage of value added (VA), required non-value added(RNV), and non-value added (NV) duration consumed in each of the five stages of bridge inspection process. In the review of documents stage, 58% of total duration adds value. In this stage, 22% of duration is spent on non-value added activities and 20% duration is spent on required non-value added activities. Both mobilization and demobilization stages do not include any value added duration. In these stages, the total duration is mainly consumed by required non-value added activities comprising 79% and 98% of the duration spent in these stages, respectively. It can be observed from the pie charts that the highest proportion of value added activities occur during the inspection stage, which consumes 83% of duration in this stage. In the report writing stage, 48% of total duration adds value. Compared to the other stages, the report writing stage consists of the most non-value added duration, which is 27% of the duration at this stage. The remaining 25% of duration spent in the report writing stage is consumed by required non-value added activities.

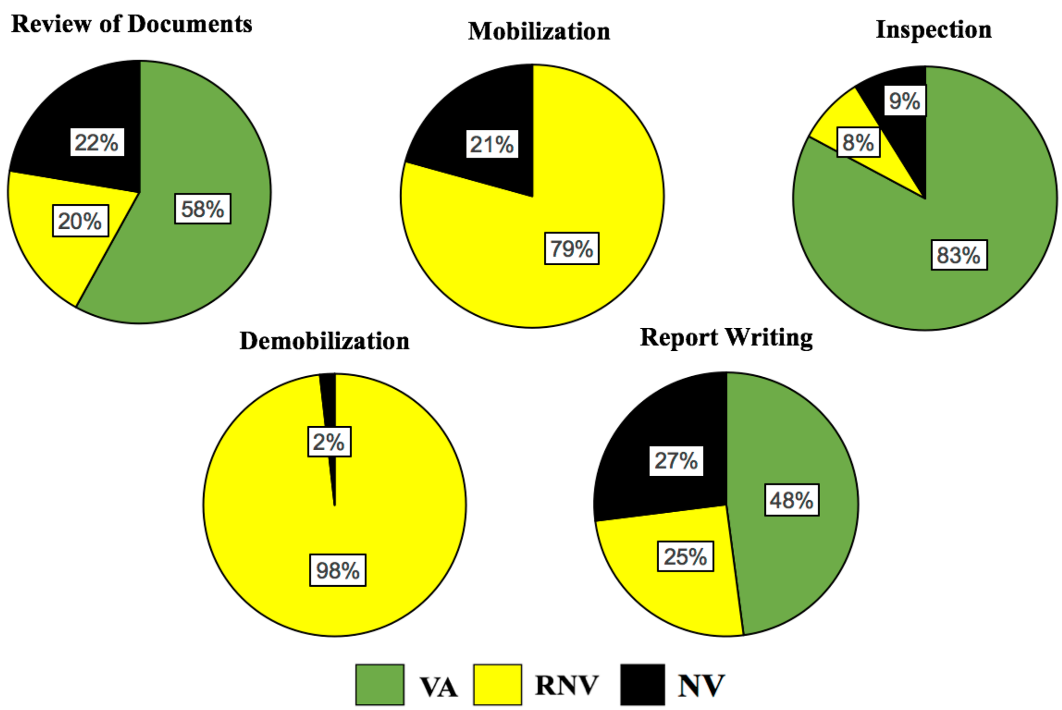

Figure 4.26: Valuation of duration, relative to consumed duration in each of the five stages

The bar graphs and pie charts for the five stages of bridge inspection (in Figures 4.25 and 4.26) illustrate value based classification of activities to identify how efficiently total time is spent on each of these five stages. Considering the time distribution among the five stages of bridge inspection process, the report writing stage consumed the maximum proportion of total time. This stage also has the highest percentage of non-value added time relative to the total time (8.6%). Hence, one opportunity for improving bridge inspection efficiency is to eliminate or decrease the duration of waste activities from the report writing stage. Mobilization and demobilization stages consumed a total of 35% of the bridge inspection workday. Coordinating the scheduling of bridge inspection work by location might enable the inspection team to inspect multiple bridges within close proximities in a single workday, saving significant commuting time.

4.3.4 Results by Type of Waste

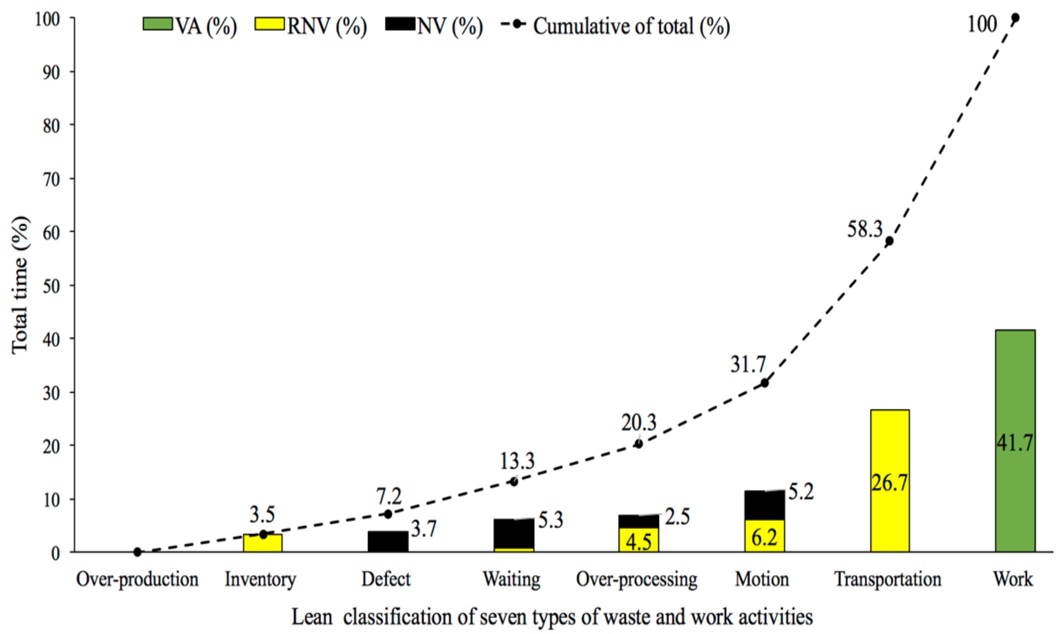

Figure 4.27: Valuation and total time consumption of seven types of waste and work activities, and their cumulative duration

All seven types of waste defined by Lean were observed while shadowing the bridge inspections. However, it was not possible to log the time for the over-production waste observed, specifically taking surplus photographs. Through simple shadowing, it was not possible to differentiate when taking photographs was in excess or was a value-added activity. Therefore, Figure 4.27 presents the duration associated with the remaining six types of waste and work activities. Among these waste types, the maximum duration is consumed by transportation waste for 26.7% of a day of bridge inspection. Transportation mainly constitutes the mobilization and demobilization stages of the inspection process that is required to be performed but it does not add any value to inspection work. Motion waste accounts for the second leading type of waste with 11.4% a day of bridge inspection. Over-processing, waiting, defect and inventory wastes consumed 7.0%, 6.1%, 3.7% and 3.5% of total a day of bridge inspection, respectively. Only 41.7% of a day of bridge inspection was spent on work activities that add value to the inspection process and the remaining 58.3% was spent on waste or non-value added activities.

4.4 Summary

This chapter systematically classified all bridge inspection activities based on Lean philosophy and illustrated the variations in inspection time based on different variables. Figure 4.28 presents a summary of the total time spent on all waste and work related activities in order to facilitate the intended goal of this research, to improve existing routine bridge inspection practices through the application of Lean. Specifically, Figure 4.28 illustrates the categorization of the time spent on bridge inspection activities into types of waste and work in the left bar and based on value in the right bar of the graph.

The right bar of the graph shows that 41.7% of bridge inspection time adds value to the inspection process. The activities that add value to the inspection process are categorized as ‘work activities’. The duration of required non-value added activities (41.6% of the total time) is approximately the same as the duration of value added activities. Non-value added activities consumed 16.7% of the total time. Together, 58% of total time is consumed by non-value added and required non-value added waste type of activities.

The left bar of the graph shows that transportation consumes more than a quarter of the total time. Motion and over-processing are the second and third most time-consuming types of waste, respectively.

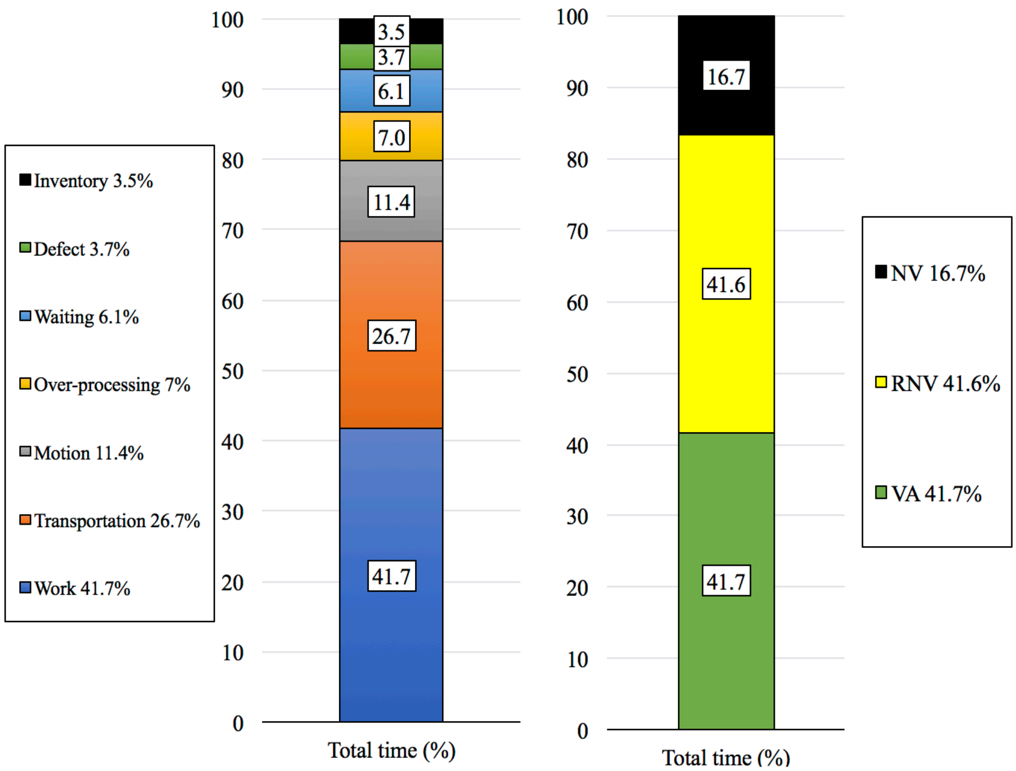

Figure 4.28: Lean classifications of bridges’ inspection time, based on waste and work (left), on value (right)

Table 4.6: Three most time-consuming activities for each value

Activity	Details of activity	Classification Based on Waste & Work	Classification Based on Value	Percent (%)
2	Visual inspection of bridge elements	Work	VA	11.1
3	Entering inspection report data of a bridge inspected on the same day	Work	VA	8.7
5	Checking clearance of a bridge or scouring detail of a channel	Work	VA	5.7
1	Driving to bridge	Transportation	RNV	11.5
4	Driving back to office	Transportation	RNV	7.7
7	Entering inspection report data of a bridge that was inspected on a previous day	Inventory	RNV	3.5
6	Communicating, non-work related	Waiting/Motion	NV	5.1
8	Browsing internet, non-work related	Waiting/Motion	NV	3.4
19	Waiting in truck at parking lot before driving to a bridge	Waiting	NV	1.8

Since inspection activities are classified based on value, Table 4.6 was prepared to illustrate the top three most time-consuming activities for value added, required non-value added and non-value added activities. The first three listed activities, visual inspection of bridge elements, entering inspection report data of a bridge that inspected on the same day, and checking clearance of a bridge or scour detail of a channel, add value to the inspection process and together consumes 25% of the total time. The most time-consuming work activity that adds value to the inspection process is visual inspection of bridge elements at site, comprising 11% of the total time. The second three listed activities, driving to or from bridge sites and entering inspection report data of a bridge that was inspected on a previous day are required to be conducted but they do not add value to inspection and together consume 23% of the total time. The highest percentage of required non-value added duration is spent on commuting to and from a bridge site, which are transportation waste activities comprising 19% of the total time. The last three activities, waiting, communication and browsing the internet about non-work related topics that do not add any value to inspection process and consume 10% of the total time. The highest percentage of non-value added time is spent on communication about topics not related to work, which can be motion or waiting type of waste and consumes 5% of the total time.

It is found that in total 42% of total time adds value to the inspection process. The duration of waste activities of the bridge inspection process is 58% of the total time recorded, which agrees with the range of 40-60% of nonproductive time reported for the construction industry by Forbes and Ahmed (2011). In another study, Womack and Jones (2005) implemented the Lean concept in a car repair company in Portugal. The cumulative value added time consumed by car technicians for repair services was reported as 45% prior to the implementation of Lean principles, which is similar to the 42% of value added time of bridge inspection work reported in this research. The researchers reported a surge in efficiency from 45% to 78% of total value added time after applying Lean concepts to the service company's work operations.

There is a widely available scope to improve routine bridge inspection efficiency when 58% of routine inspection duration is not value added. Required non-value added activities comprise a significant portion of this scope. Thus, reducing the duration of the required non-value added activities and non-value added waste activities from the inspection process can significantly contribute to the improvement of the inspection efficiency of bridges.

Chapter 5

CONCLUSIONS

The routine inspection of bridges is performed every two years for more than 600,000 bridges in the US, requiring continuous effort, resources, and cost. Several researchers have contributed significantly to improve the existing routine inspection practices. This research explored the effectiveness of applying Lean principles to this domain which had not been explored hitherto. Firstly, this chapter provides a summary of Lean analysis applied to routine bridge inspections. This research has identified the available potential for improving the efficiency of routine inspection of bridges within the framework of Lean philosophy and the focus has been on identifying waste activities, i.e., defining problems hindering the efficiency of routine inspection. Secondly, in Section 5.2 potential recommendations are provided to improve the efficiency of routine inspections by elimination or reduction of time spent on non-value added and required non-value added waste activities. Lastly, the scope for possible future research is discussed.

5.1 Summary

The goal of this research work was to conduct a Lean analysis of routine bridge inspection. Twenty-six routine bridge inspections were shadowed towards fulfilling this aim. Results showed that only 42% of inspection duration adds value to inspection work, 41% is required non-value added, and 17% of the duration does not add any value to the targeted outcome of an owner-approved inspection report.

The recorded duration of required non-value added and non-value added activities during the bridge inspection process i.e., 58% of the total duration, agrees with the range of 40-60% of the nonproductive duration observed in the construction industry as reported by Forbes and Ahmed (2011). Similarly, the 42% value added duration of inspection work activities agrees with the 45% value added duration of a car service company. After implementing the Lean concept and removing waste activities from a car service process, the value-added time of car technicians increased from 45% to 78%(Womack & Jones,2005). These findings also suggest the potential for improving bridge inspection efficiency, which may significantly decrease inspection time and cost.

The routine bridge inspection process was described by five stages (review of documents, mobilization, inspection, demobilization and report writing). Of the five stages of bridge inspection considered in this work, the largest amount of duration was spent on the report writing stage (32%, approximately one-third of the total time). This percentage further increases to nearly half of the total time for routine inspection if inspectors' self-reported time is included, which occurred when the report writing was completed outside of office hours or spread across multiple days. The report writing process includes activities such as writing comments about the condition of the bridge elements alongside inserting and matching photos for element deterioration within the report. The greatest number of non-value added activities also occur at the report writing stage, such as non-work related browsing the internet and leisurely communicating with colleagues. Thus, focusing on improving the efficiency of the documentation stage of bridge inspection is significant.

Mobilization and demobilization stages combined consumed 35%, or in other words, approximately one-third as well, of total time for routine inspection. Transportation to and from the bridge site is a required non-value added activity; using current operating procedures, it is not easy to decrease this duration consumption. The duration spent on actual inspection at the bridge site represented approximately the remaining one-third of the total time. Inspection stage mainly includes value added activities. It is noteworthy that only 4% of the total time was spent on review of documents in the pre-inspection phase. More preparation during review of documents especially regarding work planning and division of tasks amongst inspectors may in some cases positively impact the efficiency of mobilization/demobilization and inspection at the bridge site.

Considering the seven types of waste considered in the Lean analysis of activities, transportation was the largest category of waste, accounting for a total of 27% of total routine inspection duration. Motion was the second largest category of waste representing 11% of total routine inspection duration. Waste activities of over processing, waiting, defect and inventory consumed 7%, 6%, 4% and 3% of total inspection duration, respectively (Figure 4.27).

5.2 Recommendations

The following recommendations come from observations and subsequent analyses of routine bridge inspection work through the lens of Lean principles. Considering the significant amount of required non-value added and non-value added time spent on the mobilization and demobilization stages and that the greatest amount of waste occurred from transportation activities, it is recommended to focus more attention and effort on reducing the commuting time to bridge sites. Possible ways to achieve this include maximizing the opportunities of long distance driving by scheduling multiple bridge inspections on the same workday based on geographical proximity. This initiative would ideally be coupled with allowing inspectors flexibility in their daily working hours so that once the commuting distance had been traveled, multiple bridges could potentially be inspected in that area in a single day without concern for exceeding an eight-hour work day. This incentive would be beneficial for the inspectors by avoiding the wasted time of driving the same route repeatedly; additionally, some inspectors may prefer to accrue time to be taken off on other days.

Another strategy for decreasing driving time is for inspectors to start from decentralized office locations, such that the maximum distance needed to reach any given bridge is automatically reduced. This idea would need to be assessed against other potential compromises in efficiency resulting from having additional locations to support. Lastly, it was observed that the inspection crews shadowed in this work often depended on paper-based maps for directions that led to misdirection and loss of time. In contrast, the use of GPS navigation on mobile devices would likely decrease commuting time to bridge sites.

The second largest type of waste was due to motion. Using drones, also called Unmanned Aerial Vehicles (UAVs), for inspection can be an effective option for reducing motion waste by inspecting hazardous and inaccessible areas of a bridge. The Minnesota Department of Transportation (MnDOT) has used UAVs for inspection of bridges to study the effectiveness of utilizing drones to reduce bridge inspection cost (MnDOT, 2015). Using drones may also improve inspector safety and the quality of photographs. UAVs cannot perform inspections independently but can be used by bridge inspectors as a tool to view and assess bridge element conditions. UAVs can quickly identify deteriorations in hard to access elements of a bridge. The inspector operating drones needs to be licensed per Federal Aviation Administration (FAA) regulations (FAA, 2014).

The report writing stage consumed the most time among all five stages of inspection. 17% of the time spent in this phase was non-value or required non-value added. Most of this time was spent on non-work related activities, such as communication and using the internet for personal purposes. Report writing time (can be decreased if the documentation process is synchronized with the inspection of bridge elements at the site. Specifically, if inspectors can simultaneously evaluate and report the condition rating of bridge elements at the inspection site, time would likely be saved. Recent technological developments such as mobile tablet devices and other digital tools have paved the way to easily collect data for quick documentation of inspection report details at the bridge site. Using digital tools such as speech to text applications would possibly reduce time taken to duplicate handwritten notes made at the inspection site into a formal electronic format in the office used currently.

In the inspection stage at the bridge site, the majority of activities mainly add value to the inspection process. However, time saved by elimination of waste activities in other stages can be allotted to the inspection of a greater number of bridges in a single trip to one geographic region with multiple bridge inspection sites. Since review of documents presently claims only 2% of value added duration, spending more time for this stage may enhance the overall inspection process through improved work planning and division of tasks amongst inspectors during the inspection and demobilization/mobilization stages.

Identifying waste is only the first step to applying Lean principles. Lean is a continuous improvement process that requires training inspectors about Lean culture; inspector buy-in to continue the process of identifying and eliminating the seven types of waste during inspection work is essential to the success of this approach. A management-level commitment to establishing Lean as a work culture is required to see steady improvement in performance (Ohno, 1988).

In conclusion, this research work applied Lean philosophy to study the routine inspection process of 26 bridges. It is found that two-thirds of the time spent on these routine bridge inspections was consumed by non-valued added or waste activities. Inspection efficiency of bridges can be almost doubled if these type of waste activities are mitigated or eliminated from the inspection process**.**

5.3 Scope for Future Research

The outcome of the present study can be used as a baseline to compare the efficiency of new strategies and technical solutions that may be implemented for enhancing the efficiency of routine bridge inspection. Future research may also involve studying how to best encourage Lean culture for bridge inspection teams and to measure if changes are observed in bridge inspection efficiency after the adoption of Lean culture.

Presently, bridge inspections are scheduled based on pre-decided inspection date of bridges instead of considering their locations. Thus, to improve efficiency, efforts could be made to develop an optimized master schedule attuned to the geographical location of bridges, estimated inspection stage time, and equipment needs for the bridges. Documentation of inspection reports consumes most of the total routine bridge inspection duration; there is a need for research work to develop a framework which can easily synchronize documentation for inspection report writing along with the inspection of bridge elements on inspection site.

For many decades, routine bridge inspection procedures have been largely depended on to ensure serviceability and safety of bridges across nation that are regularly used by millions of commuters every day. Considering importance of the service that routine bridge inspection provides, it becomes crucial for researchers to engage in continuous investigative endeavors to perfect existing inspection practices and improve efficiency of routine bridge inspection. As such, this research found Lean analysis to be an effective way to identify areas that need improvement during the routine bridge inspection process.

REFERENCES

American Society of Civil Engineers (ASCE). (2017). “2017 report card for America’s infrastructure; bridges.” Retrieved May 27, 2017, from https://www.infrastructurereportcard.org/cat-item/bridges

American Association of State Highway and Transportation Officials (AASHTO). (2016). “Manual for Bridge Evaluation.” Interim Revisions - 4.1 General. America’s infrastructure; bridges. (pp. 4-4)

Agrawal, A., and Alampalli, S. (2010). “Inspection needs of deteriorating bridge components.” Bridge Maintenance, Safety, Management and Life-Cycle Optimization Bridge Maintenance, Safety and Management, 147–147.

Adsit, D. (2008). “Cutting Edge Methods Target Real Call Center Waste.” isixsigma. com. Archived from the original on, 04-14. Retrieved on July 13, 2017.

Bailes F.B., Hilton M.H. (1985). “Application of Close-range Terrestrial Photogrammetry to Bridge Structures.” Virginia Highway and Transportation Research Council, USA.

Ballard, G., Harper, N., & Zabelle, T. (2002). “An application of Lean concepts and techniques to precast concrete fabrication.” In Proc. 10th Ann. Conf. Int’l. Group for Lean Construction (pp. 6-8).

Bureau of Transportation Statistics. (2014). “Table 1-11: Number of U.S. Aircraft, Vehicles, Vessels, and Other Conveyances: 1960–2014.” Retrieved on April 3, 2017, http://www.bts.gov.

Dennis A. (2008). “Cutting Edge Methods Target Real Call Center Waste.” isixsigma.com. Retrieved on July 7, 2017.

Dubose, B. (2016). “Drones Seen as Safer, Cheaper Choice for Bridge Inspections.” Materials Performance. 55 (11): 28-31.

Erol, H., Dikmen, I., & Birgonul, M. T. (2016). “Measuring the impact of Lean construction practices on project duration and variability: a simulation-based study on residential buildings.” Journal of Civil Engineering and Management, 1-11.

Estes, A. C., & Frangopol, D. M. (2003). “Updating bridge reliability based on bridge management systems visual inspection results.” Journal of Bridge Engineering, 8(6), 374-382.

FAA. (2014). “Fact Sheet – Small Unmanned Aircraft Regulations (Part 107).” Retrieved May 27, 2017, from https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=20516

Federal Highway Administration. FHWA. (2012). “Bridge Inspector's Reference Manual.” U.S. Department of Transportation, Publication No. FHWA NHI 12-049.

FHWA. (1995). “Recording and coding guide for the structure inventory and appraisal of the nation's bridges.” United States Department of Transportation (Ed.), Federal Highway Administration, USA.

Forbes, L. H., & Ahmed, S. M. (2011). “Modern construction.” CRC Press

Garrett, D. F., & Lee, J. (2010). “Lean construction submittal process—A case study.” Quality Engineering, 23(1), 84-93.

Garza-Reyes, J. A., Al-Balushi, M., Antony, J., & Kumar, V. (2016). “A Lean Six Sigma framework for the reduction of ship loading commercial time in the iron ore pelletizing industry.” Production Planning & Control, 27(13), 1092-1111.

Gillins, M. N., Gillins, D. T., & Parrish, C. (2016). “Cost-Effective Bridge Safety Inspections Using Unmanned Aircraft Systems (UAS).” In Geotechnical and Structural Engineering Congress 2016 (pp. 1931-1940).

Hoyland, A., and Rausand, M. (1994). “System reliability theory: Models and statistical methods.” Wiley, New York, 518.

Jauregui, D. V., & White, K. R. (2005). “Bridge inspection using virtual reality and photogrammetry.” Inspection and Monitoring Techniques for Bridges and Civil Structures, Woodhead Publishing Limited, Abington Hall, Abington, Cambridge CB, 1, 216-246.

Jáuregui, D., Tian, Y., & Jiang, R. (2006). “Photogrammetry applications in routine bridge inspection and historic bridge documentation.” Transportation Research Record: Journal of the Transportation Research Board, (1958), 24-32.

Jáuregui, David V., Kenneth R. White, James W. Pate, and Clinton B. Woodward. (2005). "Documentation of bridge inspection projects using virtual reality approach." Journal of infrastructure systems 11, no. 3:172-179.

Jáuregui, David, and Kenneth White. (2003). "Implementation of virtual reality in routine bridge inspection." Transportation Research Record: Journal of the Transportation Research Board 1827 29-35.

Kim, C. S., Spahlinger, D. A., Kin, J. M., & Billi, J. E. (2006). "Lean health care: what can hospitals learn from a world- class automaker?." Journal of Hospital Medicine, 1(3), 191-199.

Krafcik, J. F. (1988). "Comparative analysis of performance indicators at world auto assembly plants." (Doctoral dissertation, Massachusetts Institute of Technology).

Laird, J. H., J. A. Paul, and J. K. Shaffer. (2010). "Integrated bridge inspection and management software for new jersey turnpike authority." Paper presented at 5th International Conference on Bridge Maintenance, Safety and Management, IABMAS 2010, July 11, 2010 - July 15.

Leite, H. D. R., & Vieira, G. E. (2015). "Lean philosophy and its applications in the service industry: a review of the current knowledge." Production, 25(3), 529-541.

Lichtenstein, A. G. (1993). "The silver bridge collapse recounted." Journal of performance of constructed facilities, 7(4), 249-261.

Liu, M., Ballard, G., & Ibbs, W. (2010). "Work flow variation and labor productivity: Case study." Journal of management in engineering, 27(4), 236-242.

Madanat, S., & Lin, D. J. (2000). "Bridge inspection decision making based on sequential hypothesis testing methods." Transportation Research Record: Journal of the Transportation Research Board, (1697), 14-18.

Moore, M., Phares, B. M., Graybeal, B., Rolander, D., & Washer, G. (2001). "Reliability of visual inspection for highway bridges," volume I (No. FHWA-RD-01-020).

NBIS. (1996). "National Bridge Inspection Standards." Code of federal regulations, No. 23CFR650, U.S. Government Printing Office, Washington, D.C., 238–240.

Ohno, T. (1988). "Toyota production system: beyond large-scale production." CRC Press.

Orcesi, A. D., & Frangopol, D. M. (2010). "Use of lifetime functions in the optimization of nondestructive inspection strategies for bridges." Journal of Structural Engineering, 137(4), 531-539.

Parr, M. J., Connor, R. J., & Bowman, M. (2009). “Proposed method for determining the interval for hands-on inspection of steel bridges with fracture critical members.” Journal of Bridge Engineering, 15(4), 352-363.

Phares, B. M., Washer, G. A., Rolander, D. D., Graybeal, B. A., & Moore, M. (2004). “Routine highway bridge inspection condition documentation accuracy and reliability.” Journal of Bridge Engineering, 9(4), 403-413.

Piercy, N., & Rich, N. (2009). “Lean transformation in the pure service environment: the case of the call service center.” International journal of operations & production management, 29(1), 54-76.

Salem, O., Solomon, J., Genaidy, A., & Minkarah, I. (2006). “Lean construction: From theory to implementation.” Journal of management in engineering, 22(4), 168-175.

Shahada, T. M., & Alsyouf, I. (2012). “Design and implementation of a Lean Six Sigma framework for process improvement: A case study.” In Industrial Engineering and Engineering Management (IEEM), 2012 IEEE International Conference on (pp. 80-84). IEEE.

Washer, G., Connor, R., Nasrollahi, M., & Provines, J. (2016). “New framework for risk-based inspection of highway bridges.” Journal of Bridge Engineering, 21(4), 04015077.

Womack, J. P., & Jones, D. T. (2005). “Lean consumption.” Harvard business review, 83(3), 58-68.

Womack, J. P., Jones, D. T., & Roos, D. (1990).” Machine that changed the world.” Simon and Schuster.

Yen, C.-I. (2010). "A heuristic approach for optimizing bridge inspection route" in Bridge Maintenance, Safety, Management and Life-Cycle Optimization - Proceedings of the 5th International Conference on Bridge Maintenance, Safety and Management (0-415-87786-5, 978-0-415-87786-2), (p. 3634)

Appendix A

RECORDED INSPECTION ACTIVITIES OF BRIDGES

Table A1: Routine bridge inspection activities

Activity	Details of Activity	Stage	Classification Based on Waste & Work	Classification Based on Value	Total Time (min)	Daily Time (min)	Percent (%)	Total (%)
1	Driving to bridge	Mobilization	Transportation	RNV	696.0	49.7	11.5	11.5
2	Visual inspection of bridge elements	Inspection	Work	VA	675.0	48.2	11.1	22.6
3	Entering inspection report data of a bridge that inspected on the same day	Documentation	Work	VA	526.3	37.6	8.7	31.3
4	Driving back to office	Demobilization	Transportation	RNV	467.0	33.4	7.7	39.0
5	Checking clearance a bridge or scouring detail of a channel	Inspection	Work	VA	345.0	24.6	5.7	44.6
6	Communicating, non-work related	Documentation	Waiting/Motion	NV	312.3	22.3	5.1	49.8
7	Entering inspection report data of a bridge that was inspected on a previous day	Documentation	Inventory	RNV	211.0	15.1	3.5	53.3
8	Browsing internet, non-work related	Documentation	Waiting/Motion	NV	208.0	14.9	3.4	56.7
9	Taking a boat from inventory and handling it during mobilization and demobilization	Mob/Dem	Transporation	RNV	164.0	11.7	2.7	59.4
10	Taking photos of bridges	Inspection	Work	VA	163.3	11.7	2.7	62.1
11	Writing down sequential order of photographs in notebook	Documentation	Overprocessing	RNV	162.2	11.6	2.7	64.8
12	Discussion about inspected bridges among inspection team and manager	Inspection	Work	VA	147.7	10.6	2.4	67.2
13	Taking field notes	Documenation	Work	VA	145.2	10.4	2.4	69.6
14	Determining percentage of bridge deterioration measuring its location	Inspection	Work	VA	142.9	10.2	2.4	71.9
15	Examining drawings and reviewing previous report of a bridge	Review of doc	Work	VA	136.2	9.7	2.2	74.2
16	Adding comments to condition rating of bridge elements	Documentation	Work	VA	126.2	9.0	2.1	76.3
17	Walking around bridge site for inspection purposes	Inspection	Transportation	RNV	123.3	8.8	2.0	78.3
18	Getting ready, including collecting documents and camera as well as checking bridge inspection schedule and weather	Mob/Dem	Motion	RNV	114.1	8.2	1.9	80.2
19	Waiting in truck at parking lot before driving to a bridge	Mobilization	Waiting	NV	107.5	7.7	1.8	81.9
20	Putting on and taking off boots and chest waders for inspections in water	Mob/Dem	Motion	RNV	103.0	7.4	1.7	83.6
21	Walking between parking lot and office	Mob/Dem	Transportation	RNV	97.0	6.9	1.6	85.2

22	Creating bridge elements' inventory list on a paper and making a digital copy later for initial inspection of a bridge	Documentation	Overprocessing	RNV	82.5	5.9	1.4	86.6
23	Review of previous inspection report	Documentation	Work	VA	69.2	4.9	1.1	87.7
24	Locating and filling out traffic form needed for obtaining permission to block/redirect traffic	Mobiliztion	Overprocessing	NV	67.0	4.8	1.1	88.8
25	Taking and returning of necessary inspection tools from truck such as ladder, ruler, and measuring tape	Mob/Dem	Motion	RNV	60.0	4.3	1.0	89.8
26	Driving boat to bridge	Mob/Dem	Transporation	RNV	57.0	4.1	0.9	90.8
27	Missing a direction or a turn to bridge site and checking the paper map to find location	Mobilization	Defects	NV	48.8	3.5	0.8	91.6
28	Waiting for the completion of another agency's inspection for traffic control reasons	Inspection	Defects	NV	45.0	3.2	0.7	92.3
29	Making copies of element condition ratings page and scouring sketch detail of previous inspection	Review of Doc	Motion	RNV	44.0	3.1	0.7	93.0
30	Modifying scour measuring stick	Inspection	Overprocessing	NV	40.5	2.9	0.7	93.7
31	Adding comments to pictures and specifying location of deterioration while typing inspection report	Documentation	Work	VA	36.0	2.6	0.6	94.3
32	Being misdirected to site because of using outdated maps	Mobilization	Defects	NV	35.0	2.5	0.6	94.9
33	Positioning and movement of bucket truck	Mob/Dem	Motion	RNV	30.5	2.2	0.5	95.4
34	Searching for bridge drawings to check bridge elements detail, someone misplaced	Review of Doc	Defects	NV	26.5	1.9	0.4	95.8
35	Shifting positions of traffic signs to different locations to redirect traffic as needed	Inspection	Waiting	RNV	25.0	1.8	0.4	96.2
36	Refueling of vehicle	Mob/Dem	Waiting	RNV	25.0	1.8	0.4	96.6
37	Returning to previously inspected bridge site to inspect and collect missed images of elements	Inspection	Defects	NV	24.3	1.7	0.4	97.0
38	After reviewing previous report at the bridge site calling manager on phone to find immediate answer to queries about the bridge	Inspection	Defects	NV	23.0	1.6	0.4	97.4

39	Searching for inspection files in office and arranging inspection files	Review Doc	Overprocessing	NV	23.0	1.6	0.4	97.8
40	Excessively removing vegetation around the bridge	Inspection	Overprocessing	NV	21.0	1.5	0.3	98.2
41	Filling out form for requesting maintenance of a bridge	Documentation	Work	VA	20.6	1.5	0.3	98.5
42	While writing inspection report on the computer, matching photographs to deterioration detail	Documentation	Overprocessing	RNV	17.5	1.3	0.3	98.8
43	Refilling water cooler and emptying garbage bin from vehicle	demobilization	Motion	RNV	13.0	0.9	0.2	99.0
44	Copying pictures from camera to computer	Documentation	Overprocessing	RNV	11.0	0.8	0.2	99.2
45	Returning to truck to retrieve forgotten documents or equipment	Demobilization	Defects	NV	11.0	0.8	0.2	99.4
46	Placing equipment in a new truck because the original one required maintenance	Mobilization	Motion	RNV	10.0	0.7	0.2	99.5
47	Checking high tide level under bridges to decide whether inspection operations can be carried out	Mob/Dem	Motion	NV	8.0	0.6	0.1	99.7
48	Returning to office to obtain forgotten documents or equipment	Mobilization	Defects	NV	7.0	0.5	0.1	99.8
49	Washing boat at fresh water lake to clean salt water from its engine	Demobilization	Transportation	RNV	5.0	0.4	0.1	99.9
50	Waiting due to malfunction of digital scour measuring device	Inspection	Defects	NV	4.0	0.3	0.1	99.9
51	Rectifying mistake, such as correcting bridge ID while communicating with traffic agency through email	Review of doc	Defects	NV	3.0	0.2	0.0	100.0
52	Obtaining directions to bridge locations from office computer	Review of doc	Transportation	RNV	2.0	0.1	0.0	100.0
	Total duration				6068.6	433.5	100.0	

Appendix B

INSPECTION TIME VARIABILITY

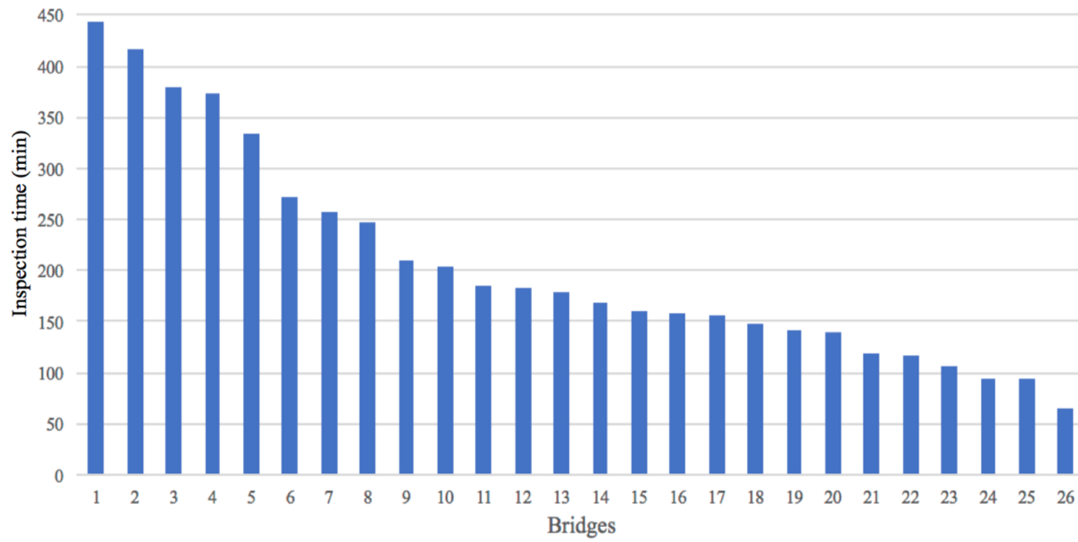

Figure B1: Recorded inspection duration of bridges

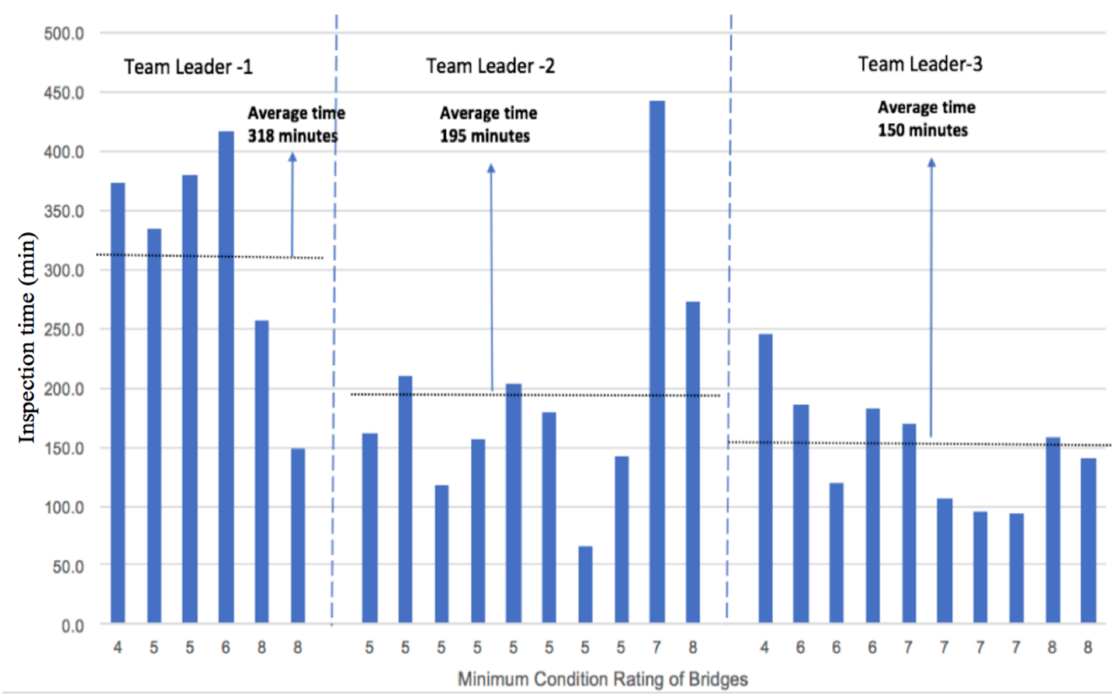

Figure B2: Time variability based on team leaders

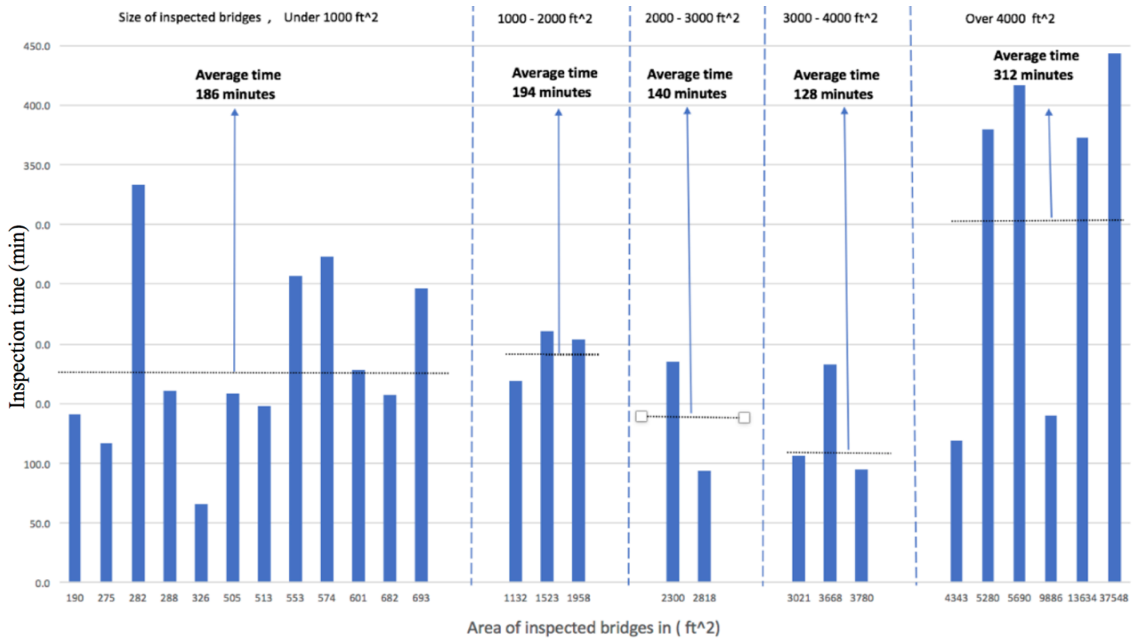

Figure B3: Time variability based on size of bridges

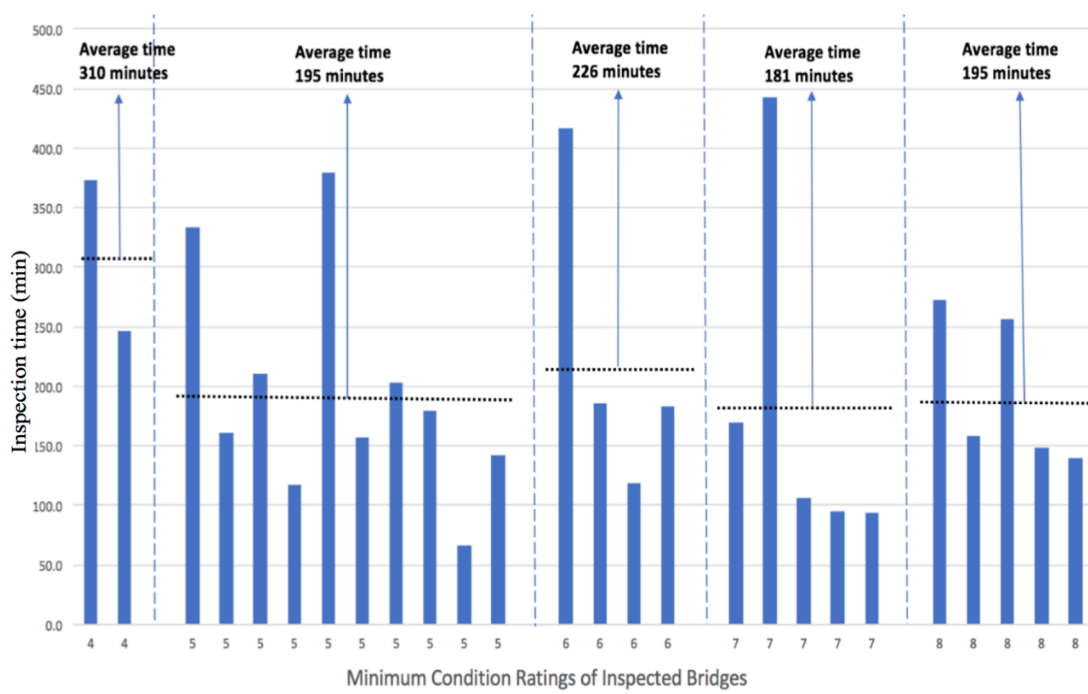

Figure B4: Time variability based on bridges' condition ratings

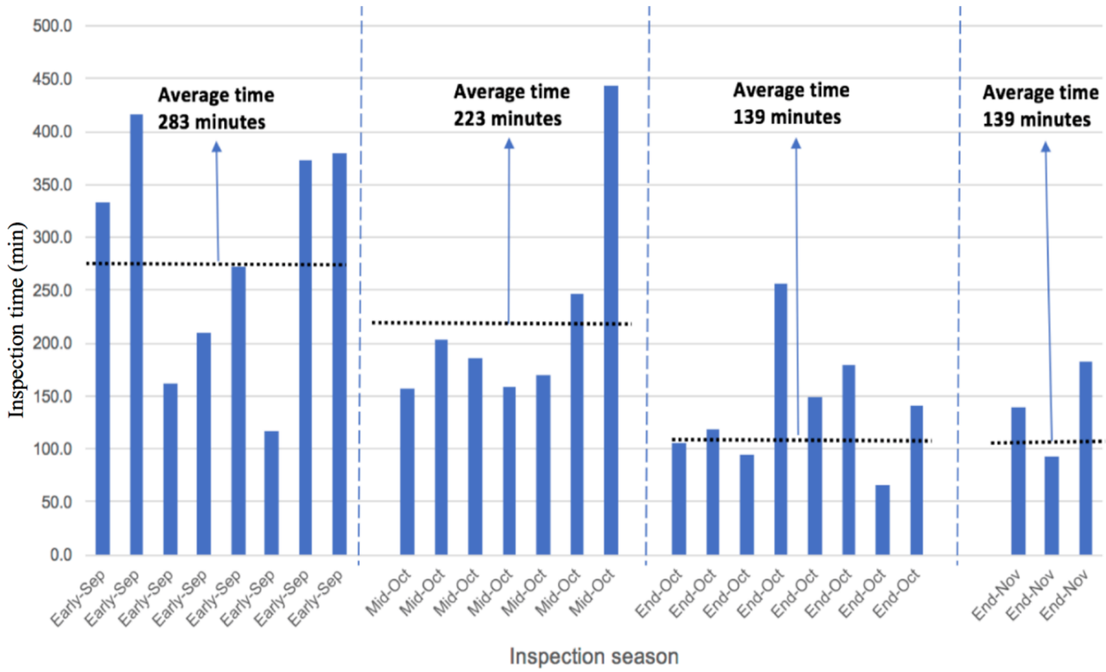

Figure B5: Time variability based on months of routine inspection

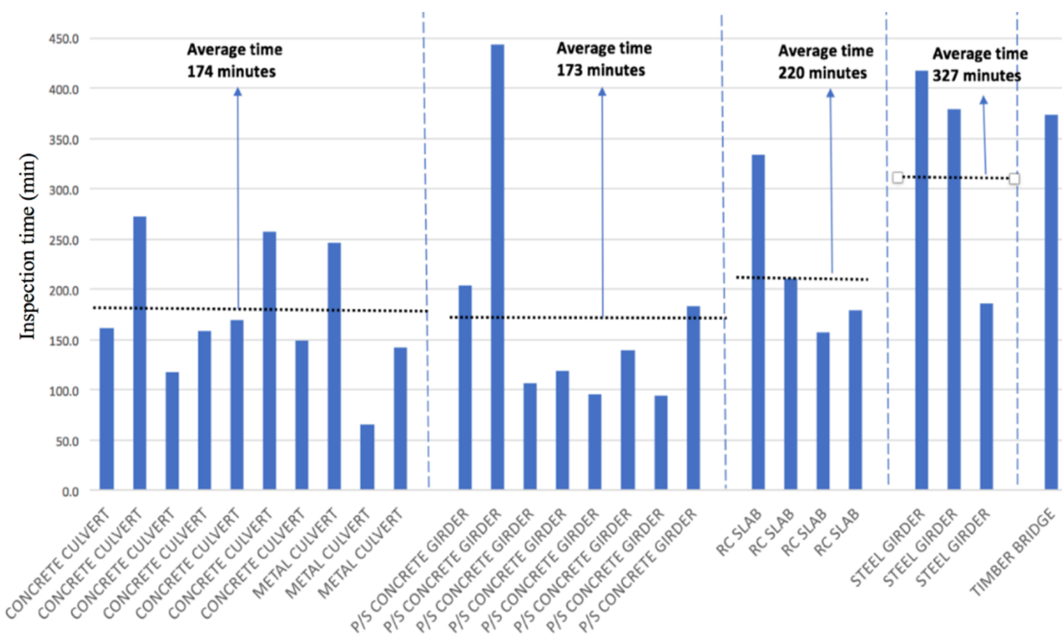

Figure B6: Time variability based on type of bridges

Appendix C

BRIDGE INSPECTION STAGES

Figure C1: Review of previous inspection documents

Figure C2: Mobilization to the bridge site

Figure C3: Inspection of bridge elements

Figure C4: Demobilization from the bridge site

Figure C5: Documentation of inspection report

Appendix D

IMAGES WHILE INSPECTION OF BRIDGE ELEMENTS

Figure D1: Inspection of substructure elements of the bridge

Figure D2: Collecting scouring detail of channel

Figure D3: Hands-on inspection of steel girders of the bridge

Figure D4: Taking photos of fixed bearings of the bridge

Figure D5: Checking clearance of the bridge

Figure D6: Hands-on inspection of steel girders and bracings of the bridge

Appendix E

INSPECTION TIME DISTRIBUTION IN PERCENTAGE

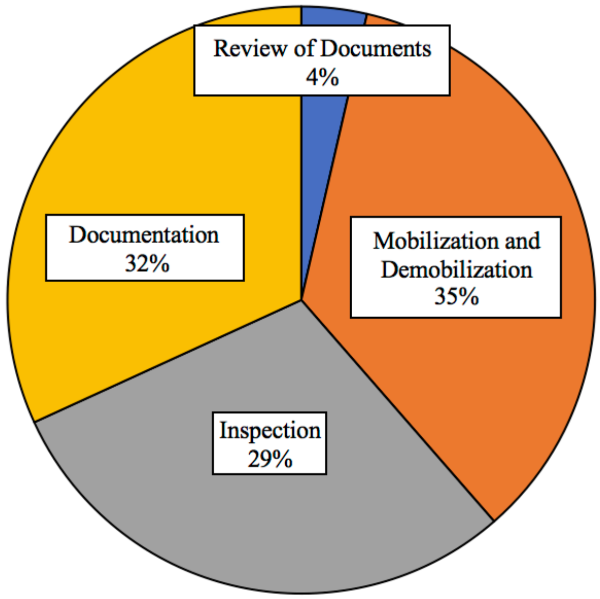

Figure E1: Time distribution based on stages of routine inspection of bridges

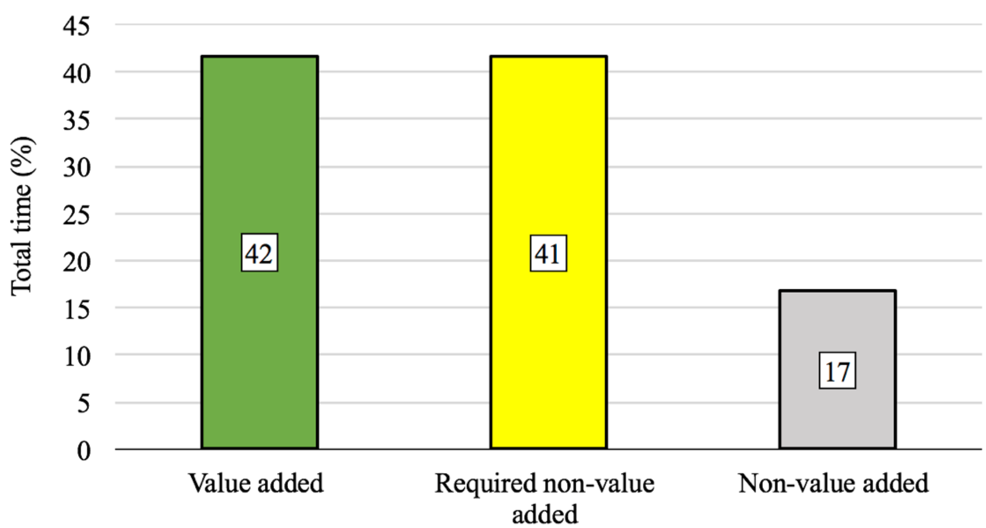

Figure E2: Value based classification of total routine inspection duration