Deterioration Prediction Modeling for the Condition Assessment of Concrete Bridge Decks

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Deterioration Prediction Modeling for the Condition Assessment of Concrete Bridge Decks

by

Aqeed Mohsin Chyad

A dissertation submitted to the Graduate College in partial fulfillment of requirements for the degree of Doctor of Philosophy Interdisciplinary Ph.D. in Civil Engineering Western Michigan University June 2018

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Deterioration Prediction Modeling for the Condition Assessment of Concrete Bridge Decks

Aqeed Mohsin Chyad, Ph.D.

Western Michigan University, 2018

Bridges are key elements in the US transportation system. There are more than six hundred thousand bridges on the highway system in the United States. Approximately one third of these bridges are in need of maintenance and will cost more than $120 billion to rehabilitate or repair. Several factors affect the performance of bridges over their life spans. Identifying these factors and accurately assessing the condition of bridges are critical in the development of an effective maintenance program. While there are several methods available for condition assessment, selecting the best technique remains a challenge. Therefore, developing an accurate and reliable model for concrete bridge deck deterioration is a key step towards improving the overall bridge condition assessment process. Consequently, the main goal of this dissertation is to develop an improved bridge deck deterioration prediction model that is based on the National Bridge Inventory (NBI) database.

To achieve the goal, deterministic and stochastic approaches have been investigated to model the condition of bridge decks. While the literatures have typically proposed the Markov chain method as the best technique for the condition assessment of bridges, this dissertation reveals that some probability distribution functions, such as Lognormal and Weibull, could be better prediction models for concrete bridge decks under certain condition ratings. A new universal framework for optimizing the performance of prediction of concrete bridge deck
condition was developed for this study. The framework is based on a nonlinear regression model that combines the Markov chain method with a state-specific probability distribution function.

In this dissertation, it was observed that on average, bridge decks could stay much longer in their condition ratings than the typical 2-year inspection interval, suggesting that inspection schedules might be extended beyond 2 years for bridges in certain condition rating ranges. The results also showed that the best statistical model varied from one state to another and there was no universal statistical prediction model that can be developed for all states. The new framework was implemented on Michigan data and demonstrated that the prediction error in the combined model was less than each of the two models (i.e. Markov and Lognormal). The results also showed that average daily traffic, age, deck area, structure type, skew angle, and environmental factors have significant impact on the deterioration of concrete bridge decks.

The contributions of the work presented in this dissertation include: 1) the identification of the significant factors that impact concrete bridge deck deterioration; 2) the development of a universal deterioration prediction framework that can be uniquely tailored for each state’s data; and 3) supporting the possibility of extending inspection schedules beyond the typical 2-year cycles. Future work may involve: 1) evaluating each of the factors that impact the deterioration rates in more depth by refining the investigation ranges; 2) investigating the possibility of revising the regular bridge deck inspection intervals beyond the 2-year cycles; and 3) developing deterioration prediction models for other bridge elements (i.e. superstructure and substructure) using the framework developed in this dissertation.
ACKNOWLEDGMENTS

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Aqeed Mohsin Chyad
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INTRODUCTION

Bridge management systems have become a focus point in recent years as a result of deterioration, failures, and collapses of bridges (Agrawal et al., 2010; Yehia et al., 2007). Most bridge structures undergo numerous problems over the duration of their service life. This can range from environmental factors to increased traffic impact. Checking the condition of these structures is paramount in prioritizing maintenance, rehabilitation, and repair actions, and protects them from breakdown or accelerated damage (Sun and Gu, 2011). One of the important issues facing departments of transportation is the economic factor associated with maintaining bridges in good condition. The challenges of maintenance work increase as bridges get closer to the end of their design life or because of increased traffic loading. An accurate assessment of the condition of the structure and its elements is crucial to reductions in maintenance costs (Scott et al., 2003).

To manage the scarcity of available resources and bridge repair needs, the Federal Highway Administration (FHWA) is constantly supporting research projects to reach both short- and long-term solutions to required improvements. The FHWA has worked side-by-side with various agencies such as the American Association of State Highway Transportation Officials (AASHTO), the Transportation Research Board (TRB), and the National Cooperative Highway Research Program (NCHRP) to develop effective programs for bridge management programs (Deza, 2011). Therefore, any study that can improve the process of bridge management by using historical condition data as a source for predicting future performance will be valuable in optimizing the safety, serviceability, and functionality of transportation networks. Such studies must focus on developing the best bridge condition prediction models to support decision-makers in allocating the limited resources among maintenance, rehabilitation, and replacement (MR&R) actions (Morcous et al., 2009).
History of Bridges

Prior to the 1960s, maintenance, rehabilitation, or replacement actions were made when they were needed, without any regular schedules, and to the best remedy to reform the problems that were discovered (Thompson et al., 1998). After the collapse of the Ohio River Bridge (also known as the “Silver Bridge”) in 1967, however, the 1968 Federal-Aid Highway Act as well as the Surface Transportation Assistance Act (STAA) of 1978 prompted the development of the National Bridge Inspection Standards (NBISs) (Agrawal et al., 2010). These guidelines require regular inspection intervals on public highways once every 2 years. The fundamental objective of the inspection is to decide whether there is a need for repair or further examination (Yehia et al., 2007).

In the early 1970s, the FHWA employed the National Bridge Inventory (NBI) database as the main source of data for transportation network agencies concerned with the repair and replacement of highway bridges and other special programs through bridge management systems. In the early 1980s, there was a great concern regarding the increasing differences between the funding allocated and requirements needed to ensure the safety of the highway bridges. Specifically, there was a recognized need to optimize the procedures to establish new approaches for bridge management decision-making supports. Consequently, the FHWA and transportation network agencies began studying new tools for bridge decision support in the mid of 1980s by intensive research and development of a bridge management system (Huang, 2003).

The NBISs have been revised few times, including those following the disappointments of the Mianus River Bridge and the Schoharie Creek Bridge, which prompted fracture-critical and underwater bridge inspections within certain intervals (Freeby, 2013). The most recent revision of the NBIS was completed in 2004 and became effective in January 2005 (Agrawal et al., 2010).
The NBISs now include inspection procedures, inspection intervals, and qualifications of inspection personnel, inspection reports, and maintenance and replacement actions. Based on the NBIS, all types of bridges with length more than 6.1 m (20 ft.) should be inspected at 2-year intervals (Taddesse, 2007).

**Problem Statement and Significance**

Concrete bridge decks are typically the first component of a bridge that need repair after construction, more so than other parts. Since they are exposed to severe conditions during their service life, such as deicing salts and heavy traffic, the deterioration of concrete bridge decks and corrosion of the steel reinforcement can occur. This is especially significant given the huge numbers of bridges on US highways and roads that must be monitored and maintained (Goodwin, 2014). According to the NBI, there are more than 600,000 bridges in service around the United States. Half of these bridges were constructed before the year 1970, and 25% of the total bridges require rehabilitation, repair, and/or reconstruction. The available resources compared to the enormous quantity of work required for accomplishing the repair, rehabilitation, and reconstruction are often very limited (Agrawal et al., 2010; NBIS, 2004). Based on the reports available from the FHWA, more than 100 million $m^2$ of the entire 360 million $m^2$ U.S concrete bridges are either structurally deteriorated (SD) or functionally obsolete (FO). The costs required to address the nation’s backlog of damaged bridges are very high (Dinh, 2014). The largest portion of the estimated expenditure is assigned to concrete bridge decks as they are commonly the first components of bridge structures to require major rehabilitation or replacement. (Goodwin, 2014). Knowing the current condition ratings of bridge decks is necessary for engineers because it facilitates the prediction of future performance levels and enhances the efficiency in the distribution of inspection and maintenance resources (Dubey, 2007). Therefore, it is important to
develop effective methods for accurately predicting the deterioration of bridge decks to ensure resources are being spent where they are most needed.

Almost, all bridges in the United States are inspected every 2 years according to the FWHA regulations. Some states try to explore new inspection intervals that exceed the required 2 years. However, since there is no sufficient evidence to support the proposition for extending inspection intervals, the U.S Department of Transportation has indicated that U.S bridges should still be inspected every 2 years (Ariaratnam, 1994). States allocate large sums of funds for bridge maintenance, rehabilitation, or repair actions. Most of these bridges were built in the 1950s and 1960s, and are exposed to deterioration in their service lives due to many reasons such as traffic loads, old age, environment, and chemical materials (Ramcharitar, 2002). As Scott (2003) stated:

“Maintenance challenges increase as bridges approach the end of their design life and traffic loads increase. One means of reducing the cost of bridge deck maintenance is to accurately evaluate the condition of the structure.”

Hema (2005) noted that:

“Ultimately, development of a decision-making protocol that utilizes bridge deck condition assessment information in combination with life-cycle costs are especially important, since the costs associated with replacing every bridge deck are high and the funds are typically limited.”

Williams (2006) also mentioned that:

“If funds were unlimited, then bridges would be maintained or replaced as soon as a problem arises and the need to understand long-term bridge performance would not be so important. The reality is that bridge owners have restricted funds and have to make knowledgeable choices pertaining to managing and maintaining their
bridges based on the funding available. If the bridge behavior was better understood, bridge owners could make improved decisions regarding bridge management and maintenance.”

Taddesse (2007) has concluded that:

“Since highway management is limited by available resources such as personnel, equipment, and funds, it is difficult and economically impossible to maintain and replace all bridges at the same time. Therefore, any method which can extend the life of these bridges and use resources in an efficient manner will be useful in assuring public safety and saving resources.”

Consequently, it is not surprising that some bridges will become structurally deficient annually, particularly when resources are not always available to manage the large number of bridges around the United States (Cook 2014).

According to ASCE (2017), in 2016 there were approximately 614,387 bridges in the United States. Forty percent of these bridges were 50 years or older (Figure 1). Nine percent of these bridges were considered structurally deficient (Figure 2). The average life age of U.S. bridges continues to rise as poor condition bridges that are structurally deficient start decreasing. The estimated allocated expenditures for the nation’s backlog of bridge rehabilitation or repair actions were about $123 billion. As the lifespan of most bridges were designed to be 50 years, major rehabilitation or repair would be required as more bridges approach their design life. The figures below show the number of bridges and their ages as of 2016, as well as the deterioration rates of bridges within that time.
Figure 1. The Number of the Bridges in the U.S.A According to Their Ages (reproduced with permission from ASCE)

Figure 2. The Deterioration Rates of Bridges According to Their Numbers and Areas (reproduced with permission from ASCE)

Issues and Needs

Keeping bridges in good condition during their service lives continues to be a challenge. The limited resources, restricted funds, and inadequate condition evaluations are the main difficulties in the life cycle of bridges (Ramcharitar, 2002). These issues will cause poor planning for bridge maintenance, rehabilitation, and reconstruction actions. Consequently, durability problems and poor performance levels of concrete bridge decks can result. Additionally, the
Condition assessment of concrete bridge decks is complicated as it is influenced by several factors including environmental, average daily traffic (ADT), age, deck area, main structure type, material type, and design loads. Most of these factors are expected to have significant effects on deck deterioration. Therefore, transportation agencies have been dealing with deterioration challenges by attempting to establish optimal guidelines to maintain bridges in good condition (Tolliver and Lu, 2011; FHWA, 2011). The NBI database was developed by the FHWA to be a dependable reference for engineers to analyze and predict the condition of a bridge (NBIS, 2004).

Although there are few studies in the literature that have focused on the deterioration rates of overall bridge structures, evaluating and predicting the condition of individual bridge elements is still lacking. There are no studies that have focused on a comprehensive evaluation of the condition of bridge decks (one key element of a bridge) using the entire 25-year period of the NBI database. The NBI database provides the condition ratings for each major element in a bridge and the condition of these bridge elements may be rated at different levels within a specific period. For example, the condition rating of a bridge substructure may in a given year be rated as 8 and the deck as 6, while the entire bridge structure is rated at 7 (FHWA, 2016). The difference in element ratings is a result of the fact that they are exposed to several factors that may accelerate the deterioration of one bridge element such as the deck, while having less of an impact on the other elements. Only focusing on the entire bridge rating (i.e. 7 in the example above) can be misleading since it masks the deck condition (i.e. 6 in the example). Furthermore, exploring the reasons behind the deterioration of key bridge elements such as the deck is critical and needed, but is also still lacking in the literature. Consequently, understanding the process of concrete bridge deck deterioration and evaluating the condition in an accurate and reliable manner will help in better planning for the allocation of funds for bridge maintenance, rehabilitation, and reconstruction.
actions. Additionally, studying the various factors that have an impact on concrete bridge deck deterioration will enhance the accuracy of the evaluation of the current and future condition, resulting in improvements in the condition assessment of bridge decks and in optimizing the allocation of the limited resources and constrained funds. Moreover, in recent years, several methods have been developed to predict the condition of overall bridge structures in addition to some limited attempts at studying bridge decks. The Markov chain technique has emerged as one of the main methods that is being used to predict the deterioration rates of a bridge structure. However, it has some challenges that must be overcome before we can use it for predicting the deterioration rates of bridge elements, especially decks. Therefore, there is a need for developing optimized mathematical and statistical methods that can accurately predict the deterioration rates of bridge decks. Such methods must be based on the NBI database and may include such techniques as Markov chain and probability distribution functions.
LITERATURE REVIEW

This section discusses the condition assessment methods that have been used for evaluating the major components of the bridges as well as the factors that are expected to have an impact on the condition of bridges.

Bridge Inspection Methods

Inspections are very useful in guaranteeing the serviceability and safety of bridges (Yehia et al., 2007). A bridge inspection, therefore, is one of the most important tasks in the life cycle of a bridge. Once the inspection performed, the amount of maintenance required for each component of the bridge is calculated based on the inspection’s achieved results. Meeting these maintenance needs require expecting and allocating funds to cover expenses.

As a consequence of the disasters and collapses that happened in the latter part of the 20th century, bridge inspections have started to be based on a periodical system for inspecting and maintaining bridges widely. This system enables inspectors to learn about the breakdown of materials or elements in the bridges so that at each inspection, they might discover new facts about the types of failure happening in the bridges. There are some particular events that have affected the inspection and maintenance of bridges. When the construction of bridges started prospering between the 1950s and 1960s, there were few regulations concerning the safety of inspection and maintenance. This quickly changed as soon as the Silver Bridge in Point Pleasant, West Virginia collapsed in the Ohio River on December 15, 1967. The collapse caused the deaths of 46 drivers and travelers (NYSDT, 2008).

The FHWA developed an inspection process for all bridges around the United States. Specifically, the FHWA has established guidelines to inspect the bridges at periodical intervals
(every 2 years) to determine the condition rating for each major component in a bridge (NBIS, 2004). Based on inspector qualifications and experience, inspection cycles may take up to 5 or 6 years in the Europe, but in France, inspection intervals are usually up to 9 years (Everett et al., 2008).

According to the AASHTO, there are five types of bridge inspections (Freeby, 2013):

- **Initial Inspections**: This type of inspection starts immediately after constructing a new bridge. Achieving this inspection can help in collecting bridge inventory data. Additionally, performing this inspection can also determine the condition assessment of a bridge, and identify existing or possible problems.

- **Routine Inspections**: This inspection is performed on a fixed schedule of time. Specifically, a 2-year period needed for inspecting a bridge based on the requirements of the NBIS. This type of inspection can also be done to determine the condition assessment of a bridge (physically and functionally), and to monitor changes since the previous inspection.

- **Damage Inspections**: This type of inspection is conducted when the bridges are exposed to damage due to environmental and human activities. The main objective of this inspection is required to determine actions for repair or rehabilitation.

- **In-depth Inspections**: This type of inspection is performed when concentrating on specific components of the bridge to explore deterioration that cannot be detected by routine inspection.

- **Special Inspections**: This inspection is performed to investigate an identified flaw or a specific state.

The inspection and maintenance of bridges have become a priority for the U.S. department of transportation. Currently, visual inspection is the main method to inspect bridges and can detect cracks, spalls, and other types of defects. However, visual inspections are considered unclear and ambiguous because they depend on the experience of the inspector, definition of the deteriorations, the condition level of the defects, and many other factors. Non-destructive testing methods are beginning to gain acceptance, but are still under research. Many studies have been conducted to
determine if non-destructive techniques are adequate for bridge inspection. Although several non-destructive techniques have been tested for this purpose, they still have some limitations. A list of several types of non-destructive techniques along with their uses, advantages, and limitations are described in Table 1 (Agdas et al., 2015; Yehia et al., 2007). Recently, unmanned aerial vehicles (UAV), also known as drones, have been investigated as a possible non-destructive technique for bridge inspection. The technique is expected to provide both quick and accurate detection of deterioration that occurs in bridges during their service life. This tool can access all parts of a bridge and can detect the defects that sometimes are difficult to identify by standard visual inspections. However, more studies are needed to evaluate the benefits and limitations this technique (Zink and Lovelace, 2015).
Table 1. Summary of Nondestructive Methods for Concrete Bridge Decks (reproduced with permission from ASCE)

<table>
<thead>
<tr>
<th>Method</th>
<th>Uses</th>
<th>Advantages</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Visual inspection</td>
<td>• Cracks</td>
<td>• Accessibility</td>
<td>• Subjective</td>
</tr>
<tr>
<td></td>
<td>• Geometry</td>
<td>• Oldest known technique</td>
<td>• Time consuming</td>
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<td></td>
<td>• Surface roughness</td>
<td>• Well established</td>
<td>• Qualitative results</td>
</tr>
<tr>
<td></td>
<td>• Surface flaws</td>
<td>• Portable</td>
<td>• Surface preparation</td>
</tr>
<tr>
<td></td>
<td>• Detection of irregularities</td>
<td>• Easy interpretation</td>
<td>• Exhaustring for the inspector</td>
</tr>
<tr>
<td>Liquid penetrant dye</td>
<td>• Flaw detection inside decks</td>
<td>• Simple</td>
<td>• Time consuming</td>
</tr>
<tr>
<td></td>
<td>• Delamination</td>
<td>• Portable</td>
<td>• Time consuming</td>
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<td></td>
<td></td>
<td>• Good for delamination</td>
<td>• Tedious</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>• Subjective</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Not good with overlays</td>
</tr>
<tr>
<td>Chain drag</td>
<td>• Detect corrosion state in concrete reinforcement</td>
<td>• Simple</td>
<td>• Deck needs preparation</td>
</tr>
<tr>
<td></td>
<td>• Corrosion rate</td>
<td>• Portable</td>
<td>• Time consuming</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Good for corrosion</td>
<td>• Not good for delamination</td>
</tr>
<tr>
<td>Half-cell potential</td>
<td>• Cracks</td>
<td></td>
<td>• Lane closure</td>
</tr>
<tr>
<td></td>
<td>• Delamination</td>
<td></td>
<td>• Not very accurate</td>
</tr>
<tr>
<td></td>
<td>• Corrosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acoustic emission</td>
<td>• Homogeneity of concrete cracks, voids</td>
<td>• Real-time response</td>
<td>• Qualitative results only</td>
</tr>
<tr>
<td></td>
<td>• Strength determination</td>
<td>• No lane closures</td>
<td>• Not good with overlays</td>
</tr>
<tr>
<td>Ultrasonic pulse velocity</td>
<td></td>
<td></td>
<td>• Interpretation</td>
</tr>
<tr>
<td>Ground penetrating radar</td>
<td>• Concrete mapping, mining, Geotechnical, road, and bridge</td>
<td>• Versatility</td>
<td>• Costly</td>
</tr>
<tr>
<td></td>
<td>• Forensics</td>
<td>• Portability</td>
<td>• Not reliable</td>
</tr>
<tr>
<td></td>
<td>• Detection of voids, honeycombing, Delamination</td>
<td>• Effectiveness</td>
<td>• Not very reliable for concrete</td>
</tr>
<tr>
<td></td>
<td>• Moisture content</td>
<td>• Low cost</td>
<td>• Attenuation negatively affects results</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Good with overlays</td>
<td>• Size of detected flaws is highly dependent on</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Minimum traffic control</td>
<td>• Less reliable in the presence of asphalt</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Prediction of repair quantities</td>
<td>• Interpretation of the results is difficult</td>
</tr>
<tr>
<td></td>
<td></td>
<td>in roads</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Interpretation of results sometimes requires</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>destructive testing</td>
</tr>
<tr>
<td>Impact echo</td>
<td>• Detection of voids, cracks, delamination, unconsolidated concrete,</td>
<td>• Requires one surface of the</td>
<td>• Size of detected flaws is highly dependent on</td>
</tr>
<tr>
<td></td>
<td>and debonding</td>
<td>tested material to be exposed,</td>
<td>• Less reliable in the presence of asphalt</td>
</tr>
<tr>
<td></td>
<td>• Determining thickness</td>
<td>independent of the geometry of the</td>
<td>overlays</td>
</tr>
<tr>
<td></td>
<td></td>
<td>structure</td>
<td>• Interpretation of the results is difficult</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Less susceptible to steel</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• High accuracy</td>
<td>• No information about the depth of defects</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>• Depending on environmental conditions</td>
</tr>
<tr>
<td>Thermography</td>
<td>• Detection of thermal differences, delamination, cracks, voids</td>
<td>• Portable</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Simple, easy interpretation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Minimum traffic interference</td>
<td></td>
</tr>
</tbody>
</table>
Maintaining the safety and serviceability of concrete bridge decks is very important because bridges are a critical part of the transportation networks. For this reason, the condition of a bridge must be tested and evaluated periodically (Deng et al., 2014; Wang et al., 2008). It is often difficult, however, to completely reconstruct or rehabilitate a bridge that is either structurally deficient or functionally obsolete because of limited funds. Condition assessment of concrete bridge decks, therefore, is more often used to measure the need of maintenance, rehabilitation, and repair actions, and to predict the safety and serviceability of bridges (Nabulsi et al., 2005).

The decision to rehabilitate or replace a bridge is influenced by technical and economic factors. A comprehensive inspection is needed for all types of bridges to provide appropriate information about the general condition of the bridges. This information includes measurements and the accompanying defects that are discovered in bridges under examination. Once the inspection phase is completed, analysis of collected data commences. These data are used to determine the best maintenance or rehabilitation method to maintain the service life of the bridge (Hema and Guthrie, 2005). Table 2 presents the types of defects and corresponding inspection methods, while Table 3 shows the specifications used for each type of inspection method for concrete bridge decks.

The FHWA developed the Pontis system for assessing the condition of bridges at U.S. departments of transportations. The goal of this system is to preserve a bridge in good condition for the duration of its service life, effectively reducing the life-cycle costs. In this type of assessment, the condition of the bridge is checked visually within certain time periods, with special number ratings given for varying conditions of a bridge. The assessment is classified into three
categories: severe deterioration that must be addressed immediately, minor issues that require repair, and good condition that requires no actions (Dinh, 2014).

Currently, there are several methods that have been developed for bridge condition assessments, including the fuzzy based analytic hierarchy approach (Sun and Gu, 2011; Sasmal and Ramanjaneyulu, 2008; Wang et al., 2008), deterministic methods (Caner et al., 2008; Bolukbasi et al., 2004), probability distribution methods (Nasrollahi and Washer 2015; Tabatabai et al., 2011), and Markov chain models (Mašović and Hajdin, 2013; Huang, 2003). These methods can be used to measure the deterioration rates of bridges. Consequently, an enhancement in the condition assessment of bridges has resulted due to using these methods.

Table 2. Condition Assessment Methods for Specific Deck Distresses (reproduced with permission from Utah DOT Research and Innovation)

<table>
<thead>
<tr>
<th>Item</th>
<th>Defects</th>
<th>Inspection Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aerobic blanks and honeycomb</td>
<td>Visual Inspection, Ultrasonic, Radar, Impact-Echo</td>
</tr>
<tr>
<td>2</td>
<td>Silica</td>
<td>Petrographic Analysis, Visual Inspection</td>
</tr>
<tr>
<td>3</td>
<td>Carbonation</td>
<td>Penetration Dyes, Petrographic Analysis</td>
</tr>
<tr>
<td>4</td>
<td>Chloride-Induced Corrosion</td>
<td>Chloride Concentration Testing, Half-Cell Potential, Rapid Chloride Permeability, Resistivity</td>
</tr>
<tr>
<td>5</td>
<td>Cracking</td>
<td>Impact-Echo, Penetration Dyes, Ultrasonic, Visual Inspection</td>
</tr>
<tr>
<td>6</td>
<td>Delamination</td>
<td>Chain Drag, Ground Penetrating Radar, Impact-Echo, Infrared Thermography, Ultrasonic</td>
</tr>
<tr>
<td>7</td>
<td>Scaling</td>
<td>Visual Inspection</td>
</tr>
<tr>
<td>8</td>
<td>Spalling</td>
<td>Visual Inspection</td>
</tr>
<tr>
<td>9</td>
<td>Sulfate Attack</td>
<td>Petrographic Analysis</td>
</tr>
</tbody>
</table>
Table 3. ASTM, AASHTO, and SHRP Standards for Deck Inspection (reproduced with permission from Utah DOT Research and Innovation)

<table>
<thead>
<tr>
<th>Item</th>
<th>Inspection Methods</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Chloride Concentration Testing</td>
<td>ASTM C 1218-99, AASHTO T 260-97 SHRP Product 2030</td>
</tr>
<tr>
<td>2</td>
<td>Ground Penetrating Radar</td>
<td>ASTM D 6087-97, ASTM D 6432-99</td>
</tr>
<tr>
<td>3</td>
<td>Half-Cell Potential</td>
<td>ASTM C 876-91</td>
</tr>
<tr>
<td>5</td>
<td>Impact-Echo</td>
<td>ASTM C 1383-98a</td>
</tr>
<tr>
<td>6</td>
<td>Infrared Thermography</td>
<td>ASTM D 4788-88</td>
</tr>
<tr>
<td>7</td>
<td>Penetration Dyes</td>
<td>None Identified</td>
</tr>
<tr>
<td>8</td>
<td>Petrographic Analysis</td>
<td>ASTM C 856-95</td>
</tr>
<tr>
<td>9</td>
<td>Rapid Chloride Permeability</td>
<td>ASTM C 1202-97, AASHTO T 277-96</td>
</tr>
<tr>
<td>10</td>
<td>Resistivity Testing</td>
<td>ASTM D 3633-98, ASTM D 6431-99</td>
</tr>
<tr>
<td>11</td>
<td>Ultrasonic Testing</td>
<td>ASTM E 494-95</td>
</tr>
<tr>
<td>12</td>
<td>Visual Inspection</td>
<td>None Identified</td>
</tr>
</tbody>
</table>

Condition Ratings of Concrete Bridge Decks

Immediately after the collapse of the Ohio River Bridge (also known as the Silver Bridge) in 1967, the Federal-Aid Highway Act of 1968, as well as the Surface Transportation Assistance Act (STAA) of 1978, established guidelines for bridge inspections known as the NBISs. The requirements for regular inspection intervals of bridges were outlined in these standards. The standards also identified the professional qualifications required to work as an inspector (Agrawal et al., 2010).

The data used to assess the condition of U.S. bridges are taken from the NBI, and represent information collected by the states during regular periodic inspection of their bridges (FHWA, 1995). The main considerations in determining bridge deficiencies are the bridge element condition ratings. These condition ratings present an overall description of the general condition of the bridge element being rated.
The NBI database includes condition ratings for each major element in U.S. bridges. Condition ratings vary from 0 to 9, as shown in Table 4. Typically, a bridge deck is considered structurally and functionally deficient if the bridge deck is rated as 3 or less, while it is considered structurally and functionally efficient if it receives a condition rating of 7 or more (MDOT, 2015). Condition ratings of bridges can be used as an indicator for needed actions such as maintenance, replacement, and rehabilitation. Essentially, condition ratings can be used to determine the performance level and reliability of concrete bridge decks (White and Minor, 1992).

Due to deteriorations that take place in the main components of the bridges, the condition ratings of the bridge components typically decrease over time. In other words, the main components are at 9 when bridges are newly built. They remain in the same condition rating for a period of time and then begin to deteriorate and drop to the next lower condition rating. This approach is repeated over time and the condition ratings decrease further (Bolukbasi et al., 2004). The American Association of State Highway and Transportation Officials recently changed the 0 to 9 condition ratings to the new 1 to 4 condition states (AASHTO, 2013). However, the FHWA still uses the 0 to 9 condition ratings for the NBI database. The new AASHTO condition states are shown in Table 5. Typically, a condition state of 1 indicates a good condition of bridge decks, whereas a condition state of 4 represents a poor condition.
<table>
<thead>
<tr>
<th>Rating</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td><strong>Excellent Condition</strong></td>
</tr>
<tr>
<td>8</td>
<td><strong>Very Good Condition</strong> - no problems noted</td>
</tr>
<tr>
<td>7</td>
<td><strong>Good Condition</strong> - some minor problems.</td>
</tr>
<tr>
<td>6</td>
<td><strong>Satisfactory Condition</strong> - structural elements show minor deterioration</td>
</tr>
<tr>
<td>5</td>
<td><strong>Fair Condition</strong> - all primary structural elements are sound but may have minor corrosion, cracking or chipping. May include minor erosion on bridge piers.</td>
</tr>
<tr>
<td>4</td>
<td><strong>Poor Condition</strong> - advanced corrosion, deterioration, cracking or chipping. Also, significant erosion of concrete bridge piers.</td>
</tr>
<tr>
<td>3</td>
<td><strong>Serious Condition</strong> - corrosion, deterioration, cracking and chipping, or erosion of concrete bridge piers have seriously affected deck, superstructure, or substructure. Local failures are possible</td>
</tr>
<tr>
<td>2</td>
<td><strong>Critical Condition</strong> - advanced deterioration of deck, superstructure, or substructure. May have cracks in steel or concrete, or erosion may have removed substructure support. It may be necessary to close the bridge until corrective action is taken.</td>
</tr>
<tr>
<td>1</td>
<td><strong>Failure Condition</strong> - major deterioration or corrosion in deck, superstructure, or substructure, or obvious vertical or horizontal movement affecting structure stability. Bridge is closed to traffic but corrective action may put back in light service.</td>
</tr>
<tr>
<td>0</td>
<td><strong>Failed Condition</strong> - out of service - beyond corrective action</td>
</tr>
</tbody>
</table>
### Table 5. Condition Ratings of Concrete Bridge Decks for specific deck defects (1-4) (reproduced with permission from AASHTO)

<table>
<thead>
<tr>
<th>Defects</th>
<th>Condition Ratings</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Good</td>
<td>Fair</td>
<td>Poor</td>
<td>Severe</td>
</tr>
<tr>
<td>Delamination</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spall</td>
<td>None</td>
<td>Delaminated. Spall ≤ 1 in. Spall ≤ 0.05 in. Diameter ≤ 6 in. Diameter ≤ 3 in. Patched area that is intact Patched area that is intact.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Patched Area</td>
<td>None</td>
<td>Spall ≥ 1 in. deep Spall ≥ 0.05 in. deep Diameter ≥ 6 in. Diameter ≥ 3 in. Patched area that is not safe or showing poverty. Patched area that is not safe or showing poverty.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Exposed Reinforcement</td>
<td>None</td>
<td>None</td>
<td>There is no loss in the exposed reinforcement</td>
<td>There is loss in the exposed reinforcement</td>
<td>It is required to evaluate the strength of the element and utilize its serviceability in the bridge.</td>
</tr>
<tr>
<td>Efflorescence/ Rust Staining</td>
<td>None</td>
<td>None</td>
<td>Just white layer on the surface without leaching or rust staining</td>
<td>Heavy build-up with rust staining</td>
<td></td>
</tr>
<tr>
<td>Cracking (RC and Other)</td>
<td>Width &lt; 0.012 in. or Spacing &gt; 3.0 ft.</td>
<td>0.012 ≤ Width ≤ 0.05 in. or 1.0 ≤ Spacing ≤ 3.0 ft.</td>
<td>Width ≥ 0.05 in. or Spacing ≤ 1 ft.</td>
<td>Coarse aggregate is unfastened or visible in the concrete matrix due to abrasion or wear</td>
<td></td>
</tr>
<tr>
<td>Abrasion/Wear</td>
<td>None</td>
<td></td>
<td></td>
<td>The deck has impact damage. The impact causes specific damage that has been located in condition state 2 under the appropriate element deterioration entry.</td>
<td>The deck has impact damage. The impact causes specific damage that has been located in condition state 3 under the appropriate element deterioration entry.</td>
</tr>
<tr>
<td>Damage</td>
<td>Not applicable.</td>
<td></td>
<td></td>
<td></td>
<td>The deck has impact damage. The impact causes specific damage that has been located in condition state 4 under the appropriate element deterioration entry.</td>
</tr>
</tbody>
</table>

### Reliability and Failure Rate Models

Understanding the deterioration process of infrastructure is an important task within transportation network agencies that requires the development of reliable and accurate deterioration models. Researchers can test the impact of various design alternatives with sophisticated deterioration models (Mauch and Madanat, 2001). To improve the safety,
serviceability, and functionality of transportation networks with limited resource availability for maintenance, rehabilitation, and replacement (MR&R) actions, optimized deterioration prediction models must be developed to facilitate resource allocation (Morcous et al., 2009). In the paragraphs below, deterioration models using the condition rating data will be reviewed. The main purpose of this review is to determine the most common methods that can be used to analyze condition ratings for determining the deterioration curves of bridge decks.

One of the methods used for the condition assessment of bridge decks is the regression model. Bolukbasi discussed two methods to study a reasonable evaluation of a concrete bridge condition assessment. In the first method, treatment for the condition ratings was made based on the premise that unless there is no proof of rehabilitation or repair actions, the condition rating cannot be greater than a previous rating. In the second method, the time in condition rating (TICR), which is time between two consecutive inspections, is employed to create deterioration curves. In Illinois, the condition ratings for 2,601 bridges during the period of 1976 to 1998 were collected to be analyzed using these methods. It was concluded that the filtration of the NBI data is necessary to eliminate the impact of unrecorded rehabilitation or repair actions to create reasonable deterioration curves. The results showed that the regression method can be used to develop deterioration models. Figure 3 shows the deterioration curves for the major components of bridges (Bolukbasi et al., 2004).
Another study used the regression model to measure expected service life from deterioration rates. This study was performed to find a simple model that predicts the fuzzy service life of a bridge using the direct relationship between the condition rating and age. The remaining service life of a bridge was predicted by either a deterioration curve or a consistent analysis of the data of regular inspection intervals. Twenty-eight bridges were tested to evaluate the average life anticipation for the first time. Eighty years were concluded to be the average life of a bridge. In these datasets, the main components were deteriorated more than other components in the bridges. Figure 4 shows the prediction of the average life of the main body components of the bridges (Caner et al., 2008).
Condition ratings data were collected for bridge components in order to develop a deterioration model by (Mašović and Hajdin, 2013). The reliable deterioration models were estimated based on the distribution of condition state data. The Markov chain model was selected for this study based on the literature review. The expected condition rating at a certain time and the probability of failure to drop from the good condition to poor condition can be calculated using the estimated transition matrix. It is concluded that the estimated transition probability model is a sound and robust method used to measure bridge deterioration according to transportation network agency rules (Mašović and Hajdin, 2013).

A different study estimated inspection intervals for bridges using statistical analysis. This study showed that the Weibull distribution is likely the best fit for Oregon data. The author showed that bridges with a good condition rating, according to the NBIS, tend to stay in that rating longer than 2 years. This study also showed that the TICRs for bridges in fair to poor condition is shorter
than for bridges in good condition (Nasrollahi and Washer, 2015). Figure 5 shows the probability of failure for concrete bridge decks for condition ratings from 4 to 8.

Figure 5. The Probability of Failure for Concrete Bridge Decks for Condition Ratings from 4 to 8 (reproduced with permission from ASCE)

Factors Impacting Bridge Deck Condition

Deterioration of concrete bridge decks occurs due to many reasons including such factors as average daily traffic (ADT), type of superstructure (i.e., concrete or steel), skew angle, deck age (i.e. the period between the construction of the bridge to inspection year), environmental factors, and the deck area (Tabatabai 2011; Caner 2008; Mauch, 2001). Old bridges may deteriorate faster than newer ones (Tolliver and Lu, 2011; Bolukbasi et al., 2004). Additionally, as the concrete bridge deck is the main component that provides the riding surface, it is exposed to deterioration more than the other parts of a bridge, making ADT an important factor for consideration (Hatami
and Morcous, 2011). Furthermore, while the deck area may not be considered a key factor in the deterioration of a concrete bridge deck, the length of a bridge (and hence the deck area) can have a significant impact on the bridge deck deterioration. Large areas of bridge decks can be exposed to random types of defects that may result in inaccurate condition rating (Tabatabai et al., 2011). For example, if a relatively small part of a large area of a bridge deck has a defect level matching to a rating of 5, an inspector may rate the entire deck as 5, possibly resulting in a non-optimal maintenance decision.

Discussion

According to the literature, the ratings that are currently used to assess the condition of bridges are available in the NBI database, and represent information collected by the states during regular periodic inspection of their bridges. These condition ratings of a bridge element represent the main source for determining the efficiencies or deficiencies of bridges. All U.S. bridges are rated for a period of 25 years (from 1992 to 2016). Several methods were developed to evaluate the deterioration rates of overall bridge structures that are based on the NBI database. It has been necessary to clean the data before using it in modeling to insure accurate and reliable results regarding the condition assessment of bridges. Also, deck deterioration can result from several factors, and there are no studies in the literature that focus on them. Therefore, studying the factors that are expected to have significant impact on the deterioration rates of concrete bridge decks can help transportation agencies better plan for the maintenance, rehabilitation, and reconstruction actions and allocating the funds. Additionally, improving the current methods for evaluating and predicting the condition of bridges can result in better understanding of bridge behavior.
GOALS AND OBJECTIVES

The main goals of this study are to understand the bridge behavior, improve the condition assessment process, and assess the safety and serviceability of concrete bridge decks by developing a deterioration prediction model that is based on the condition ratings in the past 25 years. This study will evaluate the changes in condition ratings over time to develop a measure for the deterioration rates of bridge decks. It will also investigate the possible factors that influence the condition of bridge deck over time.

To achieve the goals of this study, the following objectives will be pursued:

• Study the TICRs of Michigan and National concrete bridge decks over a 25-year period.
• Identify the common factors impacting the condition of bridge decks.
• Develop a predictive model for bridge deck deterioration rates using national data during the period of 1992 to 2016 (25 years) to support decisions regarding appropriate bridge inspection intervals and the future condition of bridge decks.
• Validate the model to guarantee the reliability and accuracy and ensure the results regarding the maintenance, rehabilitation, or repair actions required for bridge decks.
• Develop recommendations on inspection schedules as well as the need of bridge maintenance, rehabilitation, or reconstruction actions.
RESEARCH METHODOLOGY

In this study, three-step plans have been followed to develop an improved condition assessment of concrete bridge decks by developing an optimum deterioration prediction model that is based on the NBI condition rating data in the past 25 years (1992-2016). The investigation was first focused on the Michigan data as a pilot study. Then, national data form all U.S. states have been used to explore whether there is a universal national predictive model for the condition assessment of concrete bridge decks. Finally, a framework for optimizing the performance of prediction modeling of concrete bridge deck condition have been developed and used to study the impact of ADT, Age, deck area, structure type, skew angles, and environmental factors on the deterioration rates of concrete bridge decks. Figure 6 shows a flow diagram of this research methodology.
The following provides a brief description for each step in the research methodology:

- **Predictive Modeling for concrete bridge deck condition assessment (A Michigan Pilot Study):**
  This step is focused on identifying the best model that represents the data set of the condition ratings for concrete bridge decks to be used for the condition assessment. Therefore, the five popular probability distribution functions (i.e., normal, lognormal, Weibull, gamma, and
exponential) models which represent stochastic approaches were used to determine the best fit for the data set. Then, the best probability distribution function was used to investigate the impact of ADT, age, and deck area on the deterioration rates of concrete bridge decks. Michigan data was used as a pilot study. To achieve this part several tasks were performed:

❖ **Task 1: Data Sources and Pre-Processing:** The NBI database includes numerical ratings of bridge components given by FHWA for the whole national bridges. The ratings vary from 0 to 9, and the data records describe the condition ratings for each major component in a bridge. In this task, Michigan data for the period of 25 years were used. Then, the filtration of the NBI data was performed to clean inappropriate data. Additionally, few assumptions were made to simplify the analysis. These assumptions are related to the data provided by the NBI database. These assumptions will be discussed in this part later.

❖ **Task 2: Analysis of NBI Condition Data for Bridge Decks:** Probability distribution functions are commonly used to measure the failure rate estimations for several applications. There are several distribution methods that can be used to evaluate the condition of bridges. However, the most common models used for measuring the failure rates are Weibull, lognormal, normal, gamma, and exponential (Sobanjo, 2010). In this task, the best method to fit the NBI condition rating data for concrete bridge decks was determined using the Anderson Darling test.

❖ **Task 3: Probability Distribution Function Analysis:** Once the best probability distribution function has been selected, the cumulative distribution function was defined and the parameters of the function were used as indicators for the TICRs in this study.

❖ **Task 4: Evaluation of the Bridge Deck Condition Prediction:** Once a predictive model is developed, the deterioration rates of concrete bridge decks were measured using
condition rating data. Predictive modeling was used as a tool for the condition assessment of concrete bridge decks to improve the maintenance decision-making process and to optimally allocate scarce resources. Additionally, it was used to determine the inspection schedules (inspection intervals) needed for concrete bridge decks. This model can be used to determine whether inspection intervals may be extended beyond the 2-year cycle as recommended by NBIS.

❖ **Task 5: Analysis of Factors Impacting Bridge Deck Condition:** In this task, the impact of three factors (ADT, age, and deck area) on the deterioration of concrete bridge decks have been studied. Since these factors are not independent from each other, each factor was classified into groups to study the deterioration rates of decks under the effect of each group by keeping the others constant. Verifying that there is a significant statistical difference within the same factors was also performed.

- **Exploring A Universal National Predictive Model for the Condition Assessment of Concrete Bridge Decks:** In this step, condition rating data over a 25-year were analyzed for each state to determine whether there is a universal national predictive model that can be used to evaluate the deterioration rates of concrete bridge decks. The same five common probability distribution functions that have been selected previously were used to determine the best probability distribution function that fit the data. Additionally, the environmental factors were investigated to figure out the impact on the deterioration rates of bridge decks. To achieve this part several tasks were performed.

❖ **Task 6: Data Pre-Processing for All States:** In this task, it was needed to clean all national data to prepare them for the analysis. The same process that was used for Michigan data was applied to remove the inappropriate data for each state separately.
Task 7: Predictive Modeling for All States: In this task, condition ratings data over the 25-year period were analyzed to determine the best fit probability distribution function for each state based on the Anderson Darling test.

Task 8: Analysis of Environmental Factors Impacting Bridge Deck Condition: In this task, all U.S. states were classified into regions based on the National Climate Report. Then, the deterioration rates were developed to investigate the impact of environmental factors on the bridge deck condition.

- A Framework for Optimizing the Performance of Prediction Modeling of Concrete Bridge Deck Condition: In this step, a methodology to combine the Markov chain method with the best probability distribution function was developed as a new universal framework for optimizing the condition assessment of bridge decks. Then, it was used to investigate the impact of such factors as ADT, main structure type, and skew angles on the deterioration of concrete bridge decks. To achieve this step several tasks were performed.

Task 9: Markov Chain Method: In this task, the Markov chain method was used to develop a model for predicting the condition of concrete bridge decks.

Task 10: Probability Distribution Method: In this task, the best probability distribution function was selected and used to develop a model for predicting the condition of concrete bridge decks.

Task 11: Optimizing the Predictive Model: In this task, the best fit nonlinear regression curve was created for the data generated from the Markov chain and the best probability distribution function models. This was made by combining the the data generated from both models for all condition ratings from 9 to 4.
❖ **Task 12: Validating the Optimized Predictive Model:** In this task, the optimized predictive model was verified for accuracy and reliability. Error percentages were calculated for the three methods (probability distribution function, Markova chain, and nonlinear regression). This calculation was based on the deviation of the prediction results from the original data represented in the condition ratings of concrete bridge decks.

❖ **Task 13: Analysis of Environmental Factors Impacting Bridge Deck Condition:** In this task, the optimized predictive model was used to investigate the impact of ADT, main structure type, and bridge skew angle on the deterioration rates of concrete bridge decks.
Concrete decks are among the most susceptible parts of bridges and their service lives are typically shorter than those of other components because they are exposed to deterioration produced by direct contact with traffic and other environmental factors such as freeze/thaw cycles or icing materials in cold weather regions (Oh et al., 2013; Yehia et al., 2007). Basically, the resources needed for rehabilitation, replacement, and repair of concrete bridge decks are typically inadequate (Deza, 2011; Agrawal et al., 2010). The FHWA, therefore, is continuously working to support scientific and technological research to achieve both short and long-term results for required enhancements (Deza, 2011). One of the significant issues that face transportation agencies is how to reduce the cost of bridge deck maintenance (Scott et al., 2003). Researchers have suggested the use of accurate and reliable condition assessment techniques that can assist in reducing the costs and increasing the efficiency of concrete bridge deck maintenance and repair (Tabatabai et al., 2011; Scott et al., 2003).

Since routine inspection requirements were first established in the early 1970s, the regular two-year interval assigned by the NBIS has been effective in guaranteeing an acceptable level of protection and serviceability for highway bridges. Currently, regardless of condition rating, most bridges in the United States are scheduled for inspection at a uniform calendar interval of two years. However, because of the fixed two-year inspection schedule of both newly constructed bridges with little or no deterioration along with old bridges with more deteriorated components, inefficiencies in the allocation of inspection resources are observed (Reising et al., 2014).

The fixed inspection intervals (i.e., the time between two consecutive inspections) can be reduced or increased based on conditions established by the bridge owner for bridges in certain
condition rating ranges. Inspection intervals of up to six years can be acceptable for certain bridges that meet condition criteria. Commonly, bridges with low ADT and short spans that are in good condition can be qualified for the extension of inspection intervals (Reising et al., 2014; Cady and Weyers, 1984). An earlier study used statistical models to analyses Oregon bridge condition data extracted from the NBIS (Nasrollahi and Washer, 2015). The authors concluded that bridges with good condition ratings tend to stay in those ratings longer than two years and therefore suggested a possible extension of the inspection intervals.

Data Sources and Pre-Processing

Two main issues will be explored and discussed in this study: 1) The data needed to track bridge deterioration rates, and 2) Factors that affect bridge deterioration rates. NBI condition ratings are used to rank bridges and can be used to track concrete bridge deck deterioration rates (FHWA, 1995). Data from 1992 to 2015 was used in this study. Since inspections are performed yearly or biennially, NBI records of condition ratings are available for each of the structural parts of the bridge. These condition ratings are then transformed into consistent NBI condition codes, which are also identified by FHWA.

Data Pre-processing

For an accurate evaluation of deterioration rates, inspection data must be treated to eliminate the effects of issues other than uniform maintenance that may result in an increase or decrease in condition ratings. These issues include repair, miscoding (Bolukbasi et al., 2004). This study is based on the NBI database, which includes numerical ratings of Michigan bridge decks for the period of 1992 to 2015. The treatment of data was performed in several steps:
• Due to the fact that ratings of 0-3 are considered severe conditions that require immediate attention, such bridges typically undergo significant rehabilitation or replacement rather than staying in their current condition. Therefore, these condition ratings were not included in this study. It is also worth noting that there are few bridges with condition ratings of 0-3 as compared with other condition ratings. Additionally, data with condition ratings of 9 were removed from the analysis because they represent new bridge construction with no deterioration (Nasrollahi and Washer, 2015).

• Data with condition ratings of N (for not applicable data) and inspection data with unusual rating drop were removed from the data set. For example, if the bridge was in the condition rating of 8 for 3 years and then dropped to a condition rating of 6 or 5 for 2 years and then jumped to a condition rating of 7 or 8 for 2 or 3 years and this process was replicated every 2 or 3 years for the period from 1992 to 2015 without any records about rehabilitation or repair, then these data were eliminated (Agrawal et al., 2010).

• Bridges that did not have key parameter records such as deck rating, year built, ADT, deck width, and structure length were eliminated (Bolukbasi et al., 2004).

• All bridges that had recently undergone rehabilitation, repair, or reconstruction of the deck were removed (Tabatabai et al., 2011).

• Rehabilitation or repair is determined by noticing an improvement in condition rating from poor (i.e. 4 or 5) to good (i.e. 8 or 9) of concrete bridge decks that continues in the following years (not a one-time error). Consequently, the ages of bridge decks that we have used are the ones that correspond to the years of the recorded improvements.

• If the TICR was 3 years or less for sequential inspection cycles at the beginning or the end of the study period interval (1992-2015), data were clipped from the original record. For
example, if the bridge was in the condition rating of 6 from 1992 to 1994 (which is 3 years (TICR)) and then dropped to a condition rating of 5 or jumped to a condition rating of 7 due to rehabilitation or repair in the next inspection cycle in 1996, then the data from 1992 to 1994 were removed. Similarly, if the condition rating of the bridge changed to 6 in 2013 and stayed at 6 through 2015, this data was also clipped. The 3-year threshold for clipping was based on a sensitivity analysis of different probable trimming values ranging from 3 to 7 years. The results showed that TICR of more than 3 years at the beginning or end of the available Michigan data set had the largest impact on the final analysis results. Consequently, 3 years was selected as a suitable value. A similar analysis was performed on the Oregon data set that resulted in a 5-year clipping threshold, suggesting that this criterion would depend on the data set and the time interval under investigation (Nasrollahi and Washer, 2015).

- Some of the NBI records for the concrete bridge deck showed an increase or decrease in the condition rating for 1 or 2 years, and then a return to the same condition rating without any recognized rehabilitation. These increases and decreases are considered inspector errors and the condition rating is manually revised to be identical to the previous value. For example, if the concrete bridge deck was at condition rating of 7 for 5 years, then dropped to a condition rating of 6 for 2 years, and then returned to the initial value of 7 for 4 years, we would consider this as an error and would correct the results to display the concrete bridge deck at condition 7 for 11 years (Nasrollahi and Washer, 2015; Tolliver and Lu, 2011).
Assumptions

A few assumptions were made to simplify the analysis as follows:

- Only bridges with concrete decks were included in the analysis (item 107 in NBI data).
- The original construction date of the bridge is determined from the year built (item 27 in NBI data). This is used as the base when determining if the overlay and the deck are part of the original construction.
- The value of ADT is determined from the total ADT (item 29 in NBI data). Bridges with ADT of 0 were eliminated from the data set and the data of this factor was divided into three categories: less than 4,000, 4,000 to 10,000, and more than 10,000 (vehicles/day).
- The age of the deck is determined by comparing the current year to the year built (item 27 in NBI data). Then, the year built data for bridge decks have been updated with the new dates of reconstruction as listed in the NBI (item 106) when bridges have been reconstructed.
- The deck areas were calculated from the structure length (item 49 in NBI data) and the deck width (item 51 in NBI data).
- The age values in years were classified into two ranges: less than or equal to 25 and more than 25 years. (The lifespan of the most bridges was designed to be 50 years (ASCE, 2017). Therefore, bridges within this range were analyzed in this study.
- The deck area values in square meters (m²) were divided into two groups: less than 500 m² and more than 500 m².

To verify whether the bins for the above factors are appropriate for the study, Kruskal-Wallis test was performed. This test was chosen because condition rating data are not normally distributed. Therefore, the bins for each factor were analyzed under this test to evaluate if there
was significant statistical difference between the factor groups. Table 6 shows the parameters of the Kruskal-Wallis test. Statistical significance between bins exists when the p-value is less than the 0.05 (Bhattacharyya, 2014). As shown in the table, all p-values were less than 0.05, suggesting that all bins were classified appropriately. Additionally, the chi square values further demonstrate that the TICR data vary between bins for each factor and support the appropriateness of the bin selections.

**Table 6. Kruskal-Wallis Test for Factor Groups**

<table>
<thead>
<tr>
<th>CR</th>
<th>Factors</th>
<th># of Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ADT (vehicles/day)</td>
<td>Age (years)</td>
</tr>
<tr>
<td>8</td>
<td>ADT&lt;4,000, 4,000-10,000, and &gt;10,000</td>
<td>Age ≤ 25 &amp; &gt; 25</td>
</tr>
<tr>
<td></td>
<td>P-Value</td>
<td>Chi Square</td>
</tr>
<tr>
<td>8</td>
<td>0</td>
<td>74.3</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>33.3</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>19.0</td>
</tr>
<tr>
<td>5</td>
<td>0.004</td>
<td>11.1</td>
</tr>
<tr>
<td>4</td>
<td>0.21</td>
<td>7.8</td>
</tr>
</tbody>
</table>

**Analysis of NBI Condition Data for Bridge Decks**

The study described in this chapter is based on the NBI bridge inspection data for the period from 1992 to 2015. Table 7 shows the description of condition ratings for concrete bridge decks in addition to their ages in 2015.

In this chapter, statistical analyses were performed to determine the distribution model that best fits the TICR values for Michigan bridge deck condition rating data. There are three most commonly used goodness-of-fit tests available for evaluating and ranking the most commonly used statistical models: Anderson-Darling (AD), Chi-Square, and Kolmogorov-Smirnov (K-S) (Mehrannia and Pakgohar, 2014). The Anderson-Darling is the most appropriate goodness-of-fit test for the bridge condition data at hand. It is performed to examine data derived from a population...
with a particular distribution and produces more weight to the tails than does the K-S test. The AD test is also more precise at the tails data than the Chi-Square and K-S tests. Since AD uses the maximum difference between the cumulative distribution function curves, it gives more weight to outliers than KS. Thus, the test considers all the differences at the tail end that may be neglected or removed by the other test methods (Engmann and Cousineau, 2011). The most frequently used statistical models under the Anderson-Darling test are the exponential, Weibull, lognormal, normal, and gamma distributions. In this study, these models were investigated.

### Table 7. Condition Ratings for Michigan Concrete Bridge Decks, 2015

<table>
<thead>
<tr>
<th>Condition Rating</th>
<th>Description</th>
<th>No. of Bridges</th>
<th>Average Age (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>Excellent Condition</td>
<td>229</td>
<td>5.67</td>
</tr>
<tr>
<td>8</td>
<td>Very Good Condition</td>
<td>1606</td>
<td>18.31</td>
</tr>
<tr>
<td>7</td>
<td>Good Condition</td>
<td>3272</td>
<td>32.25</td>
</tr>
<tr>
<td>6</td>
<td>Satisfactory Condition</td>
<td>2598</td>
<td>43.16</td>
</tr>
<tr>
<td>5</td>
<td>Fair Condition</td>
<td>1029</td>
<td>53.97</td>
</tr>
<tr>
<td>4</td>
<td>Poor Condition</td>
<td>375</td>
<td>58.98</td>
</tr>
<tr>
<td>3</td>
<td>Serious Condition</td>
<td>121</td>
<td>65.89</td>
</tr>
<tr>
<td>2</td>
<td>Critical Condition</td>
<td>18</td>
<td>72.39</td>
</tr>
<tr>
<td>1</td>
<td>Imminent Failure Condition</td>
<td>1</td>
<td>70</td>
</tr>
<tr>
<td>0</td>
<td>Failed Condition</td>
<td>6</td>
<td>102.5</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>9225</td>
<td></td>
</tr>
</tbody>
</table>

The Michigan concrete bridge deck condition ratings that were used in this investigation ranged from 4 to 8 over the past 24 years (1992-2015). Table 8 summarizes the Anderson-Darling test values of the five commonly used statistical models. In the table, the statistical analyses are grouped by condition rating values. The lognormal probability distribution function had the smallest Anderson-Darling test value for most of the CR values, making it the best statistical model for the TICR data set. The Gamma distribution function was a better fit than (but fairly close to) the lognormal distribution method for CR values of 6 and 8, but was fairly behind for the other three CR values, resulting in the choice of lognormal as the best fit. It is also clear from Table 8
that the exponential distribution method is the least desirable model with the highest Anderson-
Darling test values. Moreover, goodness-of-fit tests were done for each group of factors and the
lognormal distribution function was the best distribution for each factor in the Michigan dataset.

**Table 8.** Anderson-Darling Test Values for TICR Statistical Models for Michigan Concrete
Bridge Decks

<table>
<thead>
<tr>
<th>Condition Rating</th>
<th>Normal</th>
<th>Lognormal</th>
<th>Gamma</th>
<th>Weibull</th>
<th>Exponential</th>
<th># of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>21.70</td>
<td>17.86</td>
<td>17.62</td>
<td>16.16</td>
<td>159.11</td>
<td>1360</td>
</tr>
<tr>
<td>7</td>
<td>74.46</td>
<td>28.90</td>
<td>32.45</td>
<td>60.34</td>
<td>238.43</td>
<td>2321</td>
</tr>
<tr>
<td>6</td>
<td>39.67</td>
<td>15.25</td>
<td>15.82</td>
<td>33.16</td>
<td>222.36</td>
<td>1845</td>
</tr>
<tr>
<td>5</td>
<td>30.58</td>
<td>11.04</td>
<td>12.40</td>
<td>25.29</td>
<td>86.19</td>
<td>760</td>
</tr>
<tr>
<td>4</td>
<td>13.08</td>
<td>5.46</td>
<td>8.22</td>
<td>11.11</td>
<td>29.41</td>
<td>176</td>
</tr>
</tbody>
</table>

**Lognormal Distribution Function**

The lognormal distribution function is considered one of the most appropriate and flexible
models commonly used to determine failures produced by deterioration processes because of
certain features of the lognormal random variable such as the non-negative values and the
skewness (Martin and Perez, 2009). The lognormal cumulative distribution function is expressed
as (Ginos et al., 2009):

\[
F(t) = \Phi \left( \frac{\ln(t) - \mu}{\sigma} \right) \quad 0 < t < +\infty
\]  

(1)

Where \( \Phi \): is the cumulative distribution function of the lognormal distribution.

\( t \): is independent positive random variable  ............................................(1a)

\( \sigma \): is the shape parameter and can be calculated as \( \sigma = \sqrt{\frac{\sum_{i=1}^{N} (\ln(t_i) - \mu)^2}{N}} \)  ......(1b)

\( \exp^\mu \): is the scale parameter where \( \mu \) can be calculated as \( \mu = \frac{\sum_{i=1}^{N} \ln(t_i)}{N} \)  ......(1c)
m: is the mean and can be calculated as \[ m = e^{\mu + \sigma^2/2} \] ........................(2)

V: is the variance and can be calculated as: \[ V = (e^{\sigma^2} - 1) e^{2\mu + \sigma^2} \]  ......(3)

S: is the standard deviation and can be calculated from the \[ V = S^2 \] equation... (4)

In this chapter, t (1a) is a variable that represents the time interval in which concrete bridge decks can remain in a condition rating before dropping to a lower one (i.e. TICR). For example, if the concrete bridge deck is changed from a condition rating of 8 to 7 and stays at the new rating for 9 years before dropping to 6, then the time interval is 9 years in this equation. The shape parameter \( \sigma \) (1b) is always more than 0. The relationship between the value of \( \sigma \) and the skewness of the lognormal distribution is positive. An increase (or decrease) in the value of \( \sigma \) increases (or decreases) the skewness of the distribution. Skewness is the scale of the symmetry of the distribution. Additionally, when the value of \( \sigma \) is less than 1, the lognormal distribution becomes very close to the normal distribution model. The scale parameter \( e^{\mu} \) (1c) represents the average of TICRs of concrete bridge decks (Aristizabal, 2012).

**Evaluation of the Bridge Deck Condition Prediction**

The lognormal distribution method was used to model the deterioration rates of Michigan concrete bridge decks using historic data for the period from 1992 to 2015. The data records of concrete bridge decks are distributed on condition ratings (CRs) from 4 to 8. The results obtained from this study can be used to predict the time needed for periodical inspection of concrete bridge decks.

The values of the shape parameter for all CRs were less than 1, suggesting that the behavior of the lognormal distribution model was close to that of a normal distribution. Table 9 shows the values of this parameter in the lognormal distribution model for the different CRs of Michigan.
concrete bridge decks. As shown in Table 9, all of the values of the scale parameter (i.e., TICRs) are greater than 2 years (the fixed inspection schedule for bridges according to NBI). The TICR decreases when the condition rating decreases. For example, when a concrete bridge deck condition is rated at 8, it can take 11.29 years to drop to the lower CR by 7. However, when the concrete bridge deck condition is rated at 4, it may take 6.64 years to drop to the lower condition rating of 3. Essentially, concrete bridge decks that are in the same condition (i.e., CRs of 7 and 8) tend to stay longer in good condition as compared to those that are in poor condition (i.e., CRs of 5 or less). Figure 7 shows an example of the lognormal probability density function for the Michigan concrete bridge deck condition rating of 5.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Condition Ratings</th>
<th>CR = 4</th>
<th>CR = 5</th>
<th>CR = 6</th>
<th>CR = 7</th>
<th>CR = 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shape Parameter ($\sigma$)</td>
<td></td>
<td>0.43</td>
<td>0.52</td>
<td>0.5</td>
<td>0.54</td>
<td>0.53</td>
</tr>
<tr>
<td>Scale Parameter ($\exp^\mu$)</td>
<td></td>
<td>6.64</td>
<td>8.25</td>
<td>9.63</td>
<td>9.97</td>
<td>11.29</td>
</tr>
<tr>
<td>Mean ($m$)</td>
<td></td>
<td>7.28</td>
<td>9.43</td>
<td>10.39</td>
<td>11.57</td>
<td>12.98</td>
</tr>
<tr>
<td>Standard Deviation ($S$)</td>
<td></td>
<td>3.26</td>
<td>5.21</td>
<td>5.86</td>
<td>6.8</td>
<td>7.35</td>
</tr>
<tr>
<td># of Samples</td>
<td></td>
<td>176</td>
<td>760</td>
<td>1845</td>
<td>2321</td>
<td>1360</td>
</tr>
</tbody>
</table>
Figure 7. The Lognormal Probability Density Function for a Condition Rating of 5

Figure 8 shows the probability of deterioration rates of different concrete bridge deck condition ratings based on the cumulative distribution functions for CRs ranging from 4 to 8. Specifically, the Figure shows the probability of a concrete bridge deck remaining in its condition rating before dropping to a lower CR. For example, at the 0.1 probability (or 10% chance), a deck at CR of 4 will stay in its condition rating for about 3.84 years before dropping to a CR of 3, which is longer than the 2-year inspection schedule. For the same probability (i.e. 0.1), a CR of 8 will take 5.74 years before dropping to a CR of 7. As another example, consider that there is an interest in estimating how long it will take for a concrete bridge deck to deteriorate from a CR of 8 to a CR of 4. Looking at the 0.05 probability (the probability of failure 5%; drop from a certain level to the next low level) in Figure 8, dropping from a CR 8 to CR 4 will take around 16.55 years (4.74 + 4.07 + 4.21 + 3.53). This chapter, therefore, can support decision-makers as they examine the
possibility of changing inspection intervals for concrete bridge decks in Michigan, especially for those that are in good condition.

![Cumulative Distribution Function of Concrete Bridge Decks with Different Condition Ratings](image)

**Figure 8.** Cumulative Distribution Function of Concrete Bridge Decks with Different Condition Ratings

**Analysis of Factors Impacting Bridge Deck Condition**

The impact of each factor (ADT, age, and deck area) on the TICR was investigated. Since these factors are not independent from each other, the investigation was performed by keeping two factors constant and evaluating the effect of the third factor. Figure 9 is a flow diagram showing the sequence followed in evaluating the impact of each factor. The following sections will discuss the impact of each factor on the deterioration rates.
(a)

(b)
**Figure 9.** A Diagram of the Classification of (a) ADT, (b) Age, and (c) Deck Area Factors
The Impact of ADT

The ADT factor has a major effect on the deterioration rates of concrete bridge decks, as shown in Tables 10 and 11. Specifically, it was found that ADT can significantly impact a concrete bridge deck when it is still in good condition, and has a slight effect on bridge decks that are in poor condition. For example, the concrete bridge decks in CR of 8 (see Table 10) can stay in this condition for 13.09 years before dropping to a condition rate of 7 when the ADT is less than 4,000 vehicles/day with age ≤ 25 years and deck area < 500 m²; but the concrete bridge decks for the same condition rating may just stay 9.40 years before dropping when the ADT is more than 10,000 vehicles/day. On the other hand, and for the same conditions of Table 10, concrete bridge decks in CR of 4 can remain for 7.26 years when the ADT is less than 4,000 vehicles/day and 6.39 years when the ADT is more than 10,000 vehicles/day. Similarly, the concrete bridge decks in CR of 8 and under the conditions of Table 11 (Age > 25 years and deck area > 500 m²) can stay in this condition for 8.00 years before dropping to a condition rating of 7, when the ADT is less than 4,000 vehicles/day, but when the ADT is more than 10,000 vehicles/day, the concrete bridge decks for the same condition rating may stay 7.42 years before dropping. Also, concrete bridge decks in CR of 4 can remain for 7.24 years when the ADT is less than 4,000 vehicles/day and 5.38 years when the ADT is more than 10,000 vehicles/day (Table 11). Tables 12 and 13 show the impact of ADT on the deck condition with different ranges of age and deck area.

Figure 10 is the 5% probability chart for TICR under the effect of ADT. This figure, for example, can show how many years it can take for concrete bridge decks to deteriorate from 8 to 4 under the effect of ADT. It may take around 18.57 years to deteriorate from 8 to 4 if the ADT is less than 4,000 vehicles/day with age ≤ 25 years and deck area < 500 m², while it may take just
14.96 years to deteriorate from 8 to 4 if the ADT is more than 10,000 vehicles/day for the same conditions.

**Table 10.** TICRs with Different Ranges of ADT, Age $\leq$ 25 year, and Deck Area $\leq$ 500 m$^2$

<table>
<thead>
<tr>
<th>Range of ADT</th>
<th>Time in Condition Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CR = 4</td>
</tr>
<tr>
<td>ADT &lt; 4,000</td>
<td>7.34</td>
</tr>
<tr>
<td>ADT 4,000-10,000</td>
<td>7.06</td>
</tr>
<tr>
<td>ADT &gt; 10,000</td>
<td>6.39</td>
</tr>
</tbody>
</table>

**Table 11.** TICRs with Different Ranges of ADT, Age $> 25$ year, and Deck Area $> 500$ m$^2$

<table>
<thead>
<tr>
<th>Range of ADT</th>
<th>Time in Condition Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CR = 4</td>
</tr>
<tr>
<td>ADT &lt; 4,000</td>
<td>7.24</td>
</tr>
<tr>
<td>ADT 4,000-10,000</td>
<td>6.46</td>
</tr>
<tr>
<td>ADT &gt; 10,000</td>
<td>5.38</td>
</tr>
</tbody>
</table>

**Table 12.** TICRs with Different Ranges of ADT. Age $\leq$ 25 year and Deck Area $> 500$ m$^2$

<table>
<thead>
<tr>
<th>Range of ADT</th>
<th>Time in Condition Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CR = 4</td>
</tr>
<tr>
<td>ADT &lt; 4,000</td>
<td>6.00</td>
</tr>
<tr>
<td>ADT 4,000-10,000</td>
<td>5.65</td>
</tr>
<tr>
<td>ADT &gt; 10,000</td>
<td>5.91</td>
</tr>
</tbody>
</table>

**Table 13.** TICRs with Different Ranges of ADT. Age $> 25$ year and Deck Area $\leq 500$ m$^2$

<table>
<thead>
<tr>
<th>Range of ADT</th>
<th>Time in Condition Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CR = 4</td>
</tr>
<tr>
<td>ADT &lt; 4,000</td>
<td>7.53</td>
</tr>
<tr>
<td>ADT 4,000-10,000</td>
<td>6.48</td>
</tr>
<tr>
<td>ADT &gt; 10,000</td>
<td>6.49</td>
</tr>
</tbody>
</table>
The Impact of Age

The effect of age on the deterioration rates of bridge decks is similar to the effect of ADT. The progress of age showed a significant effect on the deterioration of the bridge decks as shown in Tables 14 and 15. In fact, with the same ADT, age had an effect on the deterioration rate of concrete bridge decks that are in good conditions more than those in poor conditions. For example, bridge decks within 25 years of service life, ADT < 4,000 vehicles/day, and deck area < 500 m² can stay for 13.12 years in the condition rating of 8, while for those that are more than 25 years in service for under the same ADT and area may stay just 8.61 years in the condition rating of 8 (see Table 14). On the other hand, and for the same condition ratings of Table 14, concrete bridge decks
in CR of 4 can remain for 7.34 years when the bridges are less than or equal to 25 years of age and 7.26 years when the age is more than 25 years. Similarly, for the conditions of Table 15, bridge decks within 25 years, ADT > 10,000 vehicles/day, and deck area > 500 m² can remain for 7.66 years in the condition rating of 8, while those bridges with more than 25 years in service may stay just 7.59 years in the condition rating of 8. Also, concrete bridge decks in CR of 4 can remain for 6.66 years when the bridges are less than or equal to 25 years of age and 5.91 years when the age is more than 25 years (Table 15). Tables 16 to 19 show the impact of the age on the deck condition with different ranges of ADT and deck area.

Figure 11 shows that bridges within 25 years, ADT < 4,000 vehicles/day, and deck area < 500 m² will have a period of 17.68 years to deteriorate from a condition rating of 8 to 4, while it can just take 15.64 years for bridges more than 25 years of service with the same conditions under a chance of 5%.

<table>
<thead>
<tr>
<th>Table 14. TICRs with Different Ranges of Age, ADT &lt; 4,000 vehicles/day, and Deck Area ≤ 500 m²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range of Age</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Age ≤ 25</td>
</tr>
<tr>
<td>Age &gt; 25</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 15. TICRs with Different Ranges of Age, ADT &gt; 10,000 vehicles/day, and Deck Area &gt; 500 m²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range of Age</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Age ≤ 25</td>
</tr>
<tr>
<td>Age &gt; 25</td>
</tr>
</tbody>
</table>
### Table 16. TICRs with Different Ranges of Age, ADT < 4,000 vehicles/day, and Deck Area > 500 m²

<table>
<thead>
<tr>
<th>Range of Age</th>
<th>CR = 4</th>
<th>CR = 5</th>
<th>CR = 6</th>
<th>CR = 7</th>
<th>CR = 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age ≤ 25</td>
<td>6.00</td>
<td>8.08</td>
<td>8.75</td>
<td>10.24</td>
<td>9.63</td>
</tr>
<tr>
<td>Age &gt; 25</td>
<td>7.24</td>
<td>8.03</td>
<td>9.78</td>
<td>9.65</td>
<td>8.00</td>
</tr>
</tbody>
</table>

### Table 17. TICRs with Different Ranges of Age, ADT 4,000-10,000 vehicles/day, and Deck Area ≤ 500 m²

<table>
<thead>
<tr>
<th>Range of Age</th>
<th>CR = 4</th>
<th>CR = 5</th>
<th>CR = 6</th>
<th>CR = 7</th>
<th>CR = 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age ≤ 25</td>
<td>7.01</td>
<td>7.74</td>
<td>10.21</td>
<td>10.18</td>
<td>10.14</td>
</tr>
<tr>
<td>Age &gt; 25</td>
<td>6.48</td>
<td>8.70</td>
<td>9.50</td>
<td>9.83</td>
<td>8.21</td>
</tr>
</tbody>
</table>

### Table 18. TICRs with Different Ranges of Age, ADT 4,000-10,000 vehicles/day, and Deck Area > 500 m²

<table>
<thead>
<tr>
<th>Range of Age</th>
<th>CR = 4</th>
<th>CR = 5</th>
<th>CR = 6</th>
<th>CR = 7</th>
<th>CR = 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age ≤ 25</td>
<td>5.65</td>
<td>7.74</td>
<td>10.67</td>
<td>10.70</td>
<td>8.44</td>
</tr>
<tr>
<td>Age &gt; 25</td>
<td>6.46</td>
<td>8.03</td>
<td>9.64</td>
<td>8.33</td>
<td>8.00</td>
</tr>
</tbody>
</table>

### Table 19. TICRs with Different Ranges of Age, ADT > 10,000 vehicles/day, and Deck Area ≤ 500 m²

<table>
<thead>
<tr>
<th>Range of Age</th>
<th>CR = 4</th>
<th>CR = 5</th>
<th>CR = 6</th>
<th>CR = 7</th>
<th>CR = 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age &gt; 25</td>
<td>6.49</td>
<td>7.94</td>
<td>7.08</td>
<td>9.23</td>
<td>8.49</td>
</tr>
</tbody>
</table>
The Impact of Deck Area

Similar to ADT and age, the size of the bridge deck area can have a considerable effect on the deterioration rate for all condition ratings of concrete bridge deck (Tables 20 and 21). For example, bridges with deck area less than 500 m² with ADT < 4,000 vehicles/day and age ≤ 25 year can stay in the condition rating of 8 for 13.09 years, while bridges with deck areas more than 500 m² will stay just 9.63 years. Additionally, bridges with deck area less than 500 m² and a condition rating of 4 may stay 7.26 years, while staying for 6.00 years if the deck area is more than 500 m² (Table 20). Also, bridges with deck area less than 500 m² with ADT > 10,000 vehicles/day and age > 25 year can stay in the condition rating of 8 for 8.49 years, while the for the same CR with deck area more than 500 m² decks will stay 7.87 years (Table 21). Additionally, bridges with deck area less than 500 m² and a CR of 4 may stay 7.77 years, while staying for 7.43 years if the
deck area is more than 500 m² (Table 21). Tables 22 to 25 show the impact of the area on the deck condition with different ranges of ADT and age.

Figure 12 shows the time intervals wherein concrete bridge decks can move from good condition to poor condition (i.e., from a condition rating of 8 to 4) under the effect of deck area for a chance of 5%. It may take around 17.83 years for a concrete bridge deck to deteriorate from 8 to 4 if the area of the bridge decks is less than 500 with ADT < 4,000 and age ≤ 25 year, while it may take just 16.87 years to deteriorate from 8 to 4 if the area is more than 500 for the same conditions.

**Table 20.** TICRs with Different Ranges of Area, Age ≤ 25 year, and ADT < 4,000 vehicles/day

<table>
<thead>
<tr>
<th>Range of Deck Area</th>
<th>Time in Condition Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CR = 4</td>
</tr>
<tr>
<td>Area ≤ 500</td>
<td>7.34</td>
</tr>
<tr>
<td>Area &gt; 500</td>
<td>6.00</td>
</tr>
</tbody>
</table>

**Table 21.** TICRs with Different Ranges of Area, Age > 25 year, and ADT > 10,000 vehicles/day

<table>
<thead>
<tr>
<th>Range of Deck Area</th>
<th>Time in Condition Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CR = 4</td>
</tr>
<tr>
<td>Area ≤ 500</td>
<td>7.77</td>
</tr>
<tr>
<td>Area &gt; 500</td>
<td>7.43</td>
</tr>
</tbody>
</table>

**Table 22.** TICRs with Different Ranges of Area, Age ≤ 25 year, and ADT 4,000-10,000 vehicles/day

<table>
<thead>
<tr>
<th>Range of Deck Area</th>
<th>Time in Condition Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CR = 4</td>
</tr>
<tr>
<td>Area ≤ 500</td>
<td>7.01</td>
</tr>
<tr>
<td>Area &gt; 500</td>
<td>5.65</td>
</tr>
</tbody>
</table>
Table 23. TICRs with Different Ranges of Area, Age ≤ 25 year, and ADT > 10,000 vehicles/day

<table>
<thead>
<tr>
<th>Range of Deck Area</th>
<th>Time in Condition Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CR = 4</td>
</tr>
<tr>
<td>Area ≤ 500</td>
<td>6.39</td>
</tr>
<tr>
<td>Area &gt; 500</td>
<td>5.91</td>
</tr>
</tbody>
</table>

Table 24. TICRs with Different Ranges of Area, Age > 25 year, and ADT < 4,000 vehicles/day

<table>
<thead>
<tr>
<th>Range of Deck Area</th>
<th>Time in Condition Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CR = 4</td>
</tr>
<tr>
<td>Area ≤ 500</td>
<td>7.26</td>
</tr>
<tr>
<td>Area &gt; 500</td>
<td>7.24</td>
</tr>
</tbody>
</table>

Table 25. TICRs with Different Ranges of Area, Age > 25 year, and ADT 4,000-10,000 vehicles/day

<table>
<thead>
<tr>
<th>Range of Deck Area</th>
<th>Time in Condition Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CR = 4</td>
</tr>
<tr>
<td>Area ≤ 500</td>
<td>6.48</td>
</tr>
<tr>
<td>Area &gt; 500</td>
<td>6.46</td>
</tr>
</tbody>
</table>
This chapter illustrated that Michigan concrete bridge decks that are in good condition can stay in those conditions longer than the typical two-year inspection schedules as recommended by the NBISs. Additionally, this study revealed that concrete bridge decks in good conditions deteriorate at a slower rate than those decks in poor conditions. Consequently, inspection schedules for concrete bridge decks can be extended beyond the two years, especially for those decks that are in good condition (CRs of 7, and 8), or for those that are recently constructed. However, if such an action is to be adopted, it must initially be at a slow rate and be carefully monitored before fully extending inspection schedules to ensure bridge safety and to guarantee that proper and timely maintenance actions are not compromised. Essentially, while inspection intervals can be extended.
up to 6 years in Michigan, which parallels the conclusions of others, this study revealed that there is currently no universal statistical prediction model that can be developed in one state and used by others. Each state will need to develop its own model based on its specific data. For example, the Weibull distribution method was the best for Oregon state data, while the lognormal distribution method was the best model for Michigan data. However, using the probability of failure 5% has reduced the extension of inspection intervals up to 4 years. The results in this paper also demonstrated that the ADT, age, and deck area factors have significant impact on the deterioration rates of concrete bridge decks.
EXPLORING A UNIVERSAL NATIONAL PREDICTIVE MODEL FOR THE CONDITION ASSESSMENT OF CONCRETE BRIDGE DECKS

Bridges are an integral part of the highway network and the overall transportation system in the United States. The bridges users are seeking to make these structures to be safe and sufficient to support their transportation needs. The deterioration rates can be used to estimate the remaining life or predict the future conditions to help in determining the regular maintenance period, rehabilitation, or replacement. A better understanding of the bridge performance level and deterioration rates process is essential for bridge deck assessment and management to reduce costs (Morcous et al., 2009).

Since the condition prediction method is crucial in making bridge maintenance decisions, it is very important to choose an optimum model (Moomen, 2016). The NBI database includes condition ratings for the main bridge components for a period of 25 years. Some studies have used the Weibull method to develop predictive deterioration curves for bridges without evaluating whether it is the best model to use (Agrawal et al., 2010; Nasrollahi and Washer, 2015). Therefore, investigating whether or not there will be a universal national predictive model for the condition assessment of concrete bridge decks is a significant part for bridge management system. Moreover, it is very important to investigate the factors impacting the bridge condition. There are various factors that affect the performance of bridges over the span of their lives. Aging, environmental condition, increased traffic demand, and delayed maintenance lead to deterioration and affect the serviceability and safety of existing bridges. The environmental factors can be severe and cause corrosion of steel reinforcement, create cracks, and reduce the strength of concrete (Mauch and Madanat, 2001).
Data Pre-Processing for All States

Inspection data are available since the 1992 for all major bridge elements, creating a 25-year database for analysis and modeling. Some studies have suggested that inspection data must be treated to remove the effects of inappropriate records. Therefore, the filtration of NBI data is a significant and essential step to remove the impact of inappropriate data. In the pilot study described in this paper is based on the NBI database, which includes numerical ratings of concrete bridge decks for the period of 1992 to date. To simplify the filtration process, all national concrete bridge decks inspection data have been arranged in descending order from the highest to the lowest ratings starting from the year 1992 through 2016. Inappropriate or incomplete records are removed from the original data at the same process as described previously for Michigan data to achieve an accurate and reliable prediction of bridge deck deterioration rates according to the literatures (Agrawal et al., 2010; Bolukbasi et al., 2004).

Predictive Modeling for All States

Mathematical and statistical models have been developed to assess and predict the condition of bridge elements using the NBI database (Moomen, 2016; Mašović and Hajdin, 2013). Developing optimum prediction models is crucial for making maintenance, repair, or replacement decisions. The most frequently probability distributions used for predictive modeling are the Exponential, Weibull, and Lognormal distributions. The Normal and Gamma distributions are also occasionally useful (Meeker and Escobar, 1998). Additionally, condition ratings of 3 or less are typically not included in the development of deterioration models since at these ratings bridges have reached serious conditions that require immediate actions such as rehabilitation or reconstruction (Nasrallah and Washer 2015). Therefore, in this chapter, the Exponential, Weibull,
Lognormal, Gamma, and Normal statistical models have been used to model bridge deck condition ratings ranging from 9 to 4 over a period of 25 years (1992 to 2016) for most of US states. Based on these data, the best fitting probability distribution can be determined using the Anderson-Darling test.

**Weibull Distribution Function**

In terms of life testing and reliability, the Weibull and lognormal distributions are known as competitors. Typically, the Weibull distribution function is the most flexible method used for estimating failure rates for several applications. It is defined by the density function as follows (Nasrollahi and Washer, 2015):

\[
f(t) = \left( \frac{(t-\gamma)^{\beta-1}}{\eta^\beta} \right) \exp\left[\left(\frac{t-\gamma}{\eta}\right)^{\beta} \right] \quad \text{.......... (5)}
\]

Where,

- \( \beta \) is the shape parameter and it is always more than 0. When it’s value is less than 1, the failure rate decreases over time. If it’s value is 1, the failure rate is constant over time. When it`s value is more than 1, the failure rate increases with time. \( \eta \) is the scale parameter and represents the time to failure. It is sometimes called the characteristic life. In this study, it represents the TICRs of concrete bridge decks. The location parameter \( \gamma \) is sometimes called the guarantee time. It represents a time period in which no failures occur at the beginning of the service life of a structure.

**Analysis of Environmental Factors Impacting Bridge Deck Condition**

The second objective in this chapter is to critically evaluate the impact of environmental conditions on concrete bridge deck deterioration. Two significant parts have been pursued to
achieve this work. First, the condition ratings of existing concrete bridge decks have been used to develop the deterioration trends of bridges considering the environmental effects. Secondly, classify all states in the USA into regions based the National Climate Report (NCR) (NOAA, 2017). The condition rating data from 9 to 4 were considered excluding 3 or less during the period from 1992 to 2016. This is because a bridge deck in a condition rating of 3 or less has serious problems and requires immediate actions such as a replacement or extensive rehabilitation. Based on the NCR 2017, the regional climate summaries are provided by six climate centers. Table 26 is prepared based on the six regional climate centers, which represents climate data for the six regions while figure 13 illustrates the locations of the six climatic regions.

### Table 26. Climatic Regions of the National Centers for Environmental Information

<table>
<thead>
<tr>
<th>Region #</th>
<th>Climate Region Name</th>
<th>States Included</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Northeast</td>
<td>DE, MD, WV, NJ, PA, CT, RI, ME, MA, NH, NY, and VT.</td>
<td>The climate of this region has four distinct seasons with warm summer and cold winter including heavy snow and ice. This region has also witnessed powerful storms and several notable tornado events.</td>
</tr>
<tr>
<td>2</td>
<td>Midwest</td>
<td>IL, IN, IA, KY, MI, MN, MO, OH, and WI.</td>
<td>This region has a similar climate to the Northeast region with four distinct seasons, warm summer and cold winter, but there is the difference of having a drier climate overall.</td>
</tr>
<tr>
<td>3</td>
<td>Southeast</td>
<td>VA, NC, SC, GA, FL, and AL.</td>
<td>This region has a hot and dry climate in summers, and mild in winter seasons with some snow.</td>
</tr>
<tr>
<td>4</td>
<td>High Plains</td>
<td>CO, KS, NE, ND, SD, and WY.</td>
<td>This region consists of areas with both wet and dry conditions. The high plains region has a wet winter and dry summer.</td>
</tr>
<tr>
<td>5</td>
<td>Southern</td>
<td>TN, MS, AR, LA, OK, and TX.</td>
<td>This region consists of hot desert climate areas. This region has thunderstorms and heavy rainfall in summer seasons.</td>
</tr>
<tr>
<td>6</td>
<td>Western</td>
<td>MT, ID, WA, OR, UT, NM, AZ, CA, NV, AL, and HI.</td>
<td>This region has different types of weather. Some parts of the west get high amount of rain and some are deserts with less than 5 inches of rain per year. The low elevation parts have warm summers and little or no snow. The desert parts of the west have very hot summers and pleasant winters.</td>
</tr>
</tbody>
</table>
Results and Discussion

In this section, the predictive modeling approaches of all national data for concrete bridge decks as well the impact of environmental factors on deck condition will be presented and discussed.

Predictive Modeling of National Data

Condition ratings data over a 25-years was analyzed using the Anderson darling test for each state to determine the best probability distribution function that can meet the state data. Appendix A summarizes the Anderson-Darling test values of the five commonly used statistical models for US states. Basically, the smallest value of the Anderson-Darling test is the best method for the data set in that state (Nasrollahi et al., 2015). In this appendix, the statistical analyses are grouped by condition rating values for each state. The results revealed that the best statistical model varies from state to state. Figure 14 shows the Goodness of Fit Distributions for all US states.
was concluded that the Weibull model is the best fit in 25 states, the lognormal model is the best in 16 states, Gamma is the best in 6 states, and the Normal model represents 1 state. The US map was used to show the best distribution model for each state. While figure 15 shows the best probability distribution function that meets each climatic region data.

Figures 16-18 represent the probability density functions for a condition rating of 7 for Oakland, Oregon, and Michigan states respectively. In these figures, the best fit probability distribution function is based on the distribution of each state data and basically, several factors have a significant role in making the distribution of the data varying from state to others such as environmental factors, ADT, Structure Type.
Figure 15. Goodness of Fit Distributions for Six Climatic Regions

<table>
<thead>
<tr>
<th>Region</th>
<th>Probability Distribution Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northeast</td>
<td>Lognormal</td>
</tr>
<tr>
<td>Midwest</td>
<td>Lognormal</td>
</tr>
<tr>
<td>Southern</td>
<td>Weibull</td>
</tr>
<tr>
<td>High Plain</td>
<td>Lognormal</td>
</tr>
<tr>
<td>Southest</td>
<td>Weibull</td>
</tr>
<tr>
<td>Western</td>
<td>Weibull</td>
</tr>
</tbody>
</table>

Figure 16. The Weibull Probability Density Function for a Condition Rating of 7 of Oakland State
Figure 17. The Gamma Probability Density Function for a Condition Rating of 7 of Oregon State

Figure 18. The Lognormal Probability Density Function for a Condition Rating of 7 of Michigan State
The Impact of Environment on Bridge Deck Condition

Deterioration curves of concrete bridge decks have been developed for all six climatic regions based on the best function for each region to study the impact of environmental factors on the condition of bridge decks. The results revealed that the bridge decks in the Midwest and Northeast regions deteriorated much faster than others while for those in Southwest and Southern regions, they deteriorated at a slow rate compared with others. For example, concrete bridge decks in the Midwest and Northeast regions have taken 51 and 53 years to deteriorate from condition rating of 9 (excellent condition) to 4 (poor condition) respectively. While for those in Southwest and Southern regions have taken around 58 years to drop from condition rating of 9 to 4. Figure 19 shows the deterioration curves for concrete bridge decks for the six climatic regions.

On the other hand, concrete bridge decks in the High Plains and Western regions deteriorate at a moderate rate compared with the other regions. For example, bridges in these regions can take 55 years to deteriorate from condition rating of 9 to 4. Appendices from B to G represent the TICR values for each region and for each state within a certain climatic region while appendix H indicates the TICR values for six climatic regions. Basically, the deterioration rates for each state and climatic region can be developed from the TICR values in these appendices.
Discussion

The National bridge condition data from 1992 to 2016 were analyzed to determine the best probability distribution function that model the condition rates in each U.S. state and predict the impact of environmental factors on the condition of bridge decks after classifying the US into six different climatic regions. The Anderson-Darling statistical test was used to assess and rate the five most commonly used probability distribution methods to identify the best fit for each state. The results in this chapter showed that the best statistical model varies from state to state and there
is no universal statistical prediction model that can be developed for all states. The results also show that the environmental factors (particularly the amount of precipitation and temperature) play a significant role in concrete bridge deck deterioration. This study revealed that bridges in cold regions deteriorate at a faster rate than those bridges located in warm regions. It was also concluded that condition ratings of bridges in Northeast and High Plains climatic regions drop from a certain condition rating to the next lower level rapidly. This is mainly happening because those bridges are exposed to harsh weather condition.
A FRAMEWORK FOR OPTIMIZING THE PERFORMANCE OF PREDICTION MODELING OF CONCRETE BRIDGE DECK CONDITION

The primary goal of a bridge management system (BMS) is to allow transportation agencies to predict the future condition of bridge elements (Madanat and Ibrahim, 1995). Typically, BMS uses accurate and reliable prediction models to compute the deterioration rates of the various bridge elements, which are then used in making maintenance, rehabilitation, or replacement decisions to minimize expenditures (Mašović and Hajdin, 2013; Morcous et al., 2009). Several prediction methods have been developed since the early 1970s to measure deterioration rates of bridges using bridge inspection data. These methods can be used to optimize the distribution of scarce capital resources on maintenance, repair, and rehabilitation actions. The FHWA has developed the NBI database as a main source of data for transportation agencies to use in analyzing and predicting the condition of a bridge (Moomen, 2016; Mašović and Hajdin, 2013; NBIS, 2004).

Remaining service life, time of maintenance, and effect of external factors on the condition state of concrete bridge decks can be estimated from the deterioration rates, which can be calculated by mathematical methods (Agrawal et al., 2010; Hema and Guthrie, 2005). Several methods have been explored as models for predicting the condition of bridges, including the fuzzy based analytic hierarchy approach (Sun and Gu, 2011; Wang et al., 2008), deterministic methods (Caner et al., 2008; Bolukbasi et al., 2004), probability distribution methods (Nasrollahi and Washer 2015; Tabatabai et al., 2011), and Markov chain models (Stacey, 2015; Mašović and Hajdin, 2013). While deterioration rates and predictions of the future condition of bridges can be determined using these methods, each method has its advantages and limitations based on the data observed.
The following diagram shows the sequence followed in this part to optimize the prediction model of concrete bridge decks.

Figure 20. A Flow Diagram of the Optimized Prediction Model Framework

Markov Chain Modeling

The Markov chain method is also one of the most commonly used approach for modeling and predicting bridge performance levels (Li et al., 2014; Agrawal et al., 2010). This method is
based on the concept of component condition transitioning from one state to another during a given amount of time. The transition probability matrix is a key in using the Markov chain method because it is the basis for predicting the condition of the component (Agrawal et al., 2010). This transition probability matrix is commonly attained using statistical data of bridge conditions. The transition probability matrix of a future state depends only on the current state. In this process, both time and state are discrete parameters. In the current study, the condition ratings of Michigan concrete bridge decks were modeled using the Markov chain method for six condition ratings (i.e., 9 to 4). Each condition rating can be defined according to the Markov process as a state. For example, state 1 represents a condition rating of 9, state 2 indicates a rating of 8, and so on. The probability of a bridge component transforming from a certain condition rating to the next rating during one transition time is referred to as $P_{ij}$. The Markov chain transition probabilities for the 9 to 4 condition ratings of Michigan concrete bridge decks are represented by the matrix $P$ as follows:

$$
P = \begin{bmatrix}
P_{11} & P_{12} & P_{13} & P_{14} & P_{15} & P_{16} \\
P_{21} & P_{22} & P_{23} & P_{24} & P_{25} & P_{26} \\
P_{31} & P_{32} & P_{33} & P_{34} & P_{35} & P_{36} \\
P_{41} & P_{42} & P_{43} & P_{44} & P_{45} & P_{46} \\
P_{51} & P_{52} & P_{53} & P_{54} & P_{55} & P_{56} \\
P_{61} & P_{62} & P_{63} & P_{64} & P_{65} & P_{66}
\end{bmatrix}
$$

Since it is assumed that the deterioration of a bridge component can drop just one step, the probability of a bridge element staying at the same rating during a given period of time can be defined as $1 - P_{ij}$, and the probability to transform more than one rating is considered zero. Therefore, unless there are repair or rehabilitation records, the bridge component condition either remains at the same rating or transforms from a particular condition rating to the next lower rating.
during one transition time and the probability of transforming from a low to a high rating is considered zero. Table 27 shows the transition probabilities \( P_{ij} \), condition ratings (CR), and states (S) for the Michigan concrete bridge deck data. As shown in Table 27, if a bridge deck rating transforms from a rating of 9 to 8 after a period of time, then the probability of this case is \( P_{12} \), the probability of staying at that rating is \( P_{11} \), and so on.

Essentially, the condition rating of a bridge component decreases over time. However, some bridge decks may have the same condition rating while at different ages. Therefore, bridge deck ages were classified into groups so that at each group the Markov chain was assumed to be homogeneous (Agrawal et al., 2010). Each group consisted of 5 years and had its own transition probability matrix, which was different from the other groups. If the current or initial condition of the bridge deck is known, the future condition after a period of time \( t \) can be calculated by multiplication of the initial-condition vector and the transition probability matrix.

\[
C_R(t) = C_i(0) * P^t \quad \ldots \quad (7)
\]

Where: \( C_R(t) \) = condition rating at any time \( t \).

\( C_i(0) = \) initial condition of deck \( (t = 0) \).

\( P^t = \) the transition probability matrix \( P \) raised to the power \( t \).

The most common challenge in the Markov chain method is calculating the transition probability matrix (Li et al., 2014). Although the percentage method increases the difficulty of data treatment, it is considered appropriate for this type of analysis. In this study, the percentage method was used because it needs at least two consecutive condition ratings. The initial-condition vector for bridges that are newly built is \([1 \ 0 \ 0 \ 0 \ 0] \), while for bridges that are in a rating of 7, for example, the initial condition rating can be defined as \([0 \ 0 \ 1 \ 0 \ 0] \), and so on.
Table 27. Transition Probability Matrix of Michigan Concrete Bridge Decks

<table>
<thead>
<tr>
<th>Current Rating</th>
<th>CR = 9 (S=1)</th>
<th>CR = 8 (S=2)</th>
<th>CR = 7 (S=3)</th>
<th>CR = 6 (S=4)</th>
<th>CR = 5 (S=5)</th>
<th>CR = 4 (S=6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CR = 9 (S=1)</td>
<td>P_{11}</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CR = 8 (S=2)</td>
<td>0</td>
<td>P_{22}</td>
<td>P_{23}</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CR = 7 (S=3)</td>
<td>0</td>
<td>0</td>
<td>P_{33}</td>
<td>P_{34}</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CR = 6 (S=4)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>P_{44}</td>
<td>P_{45}</td>
<td>0</td>
</tr>
<tr>
<td>CR = 5 (S=5)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>P_{55}</td>
<td>P_{56}</td>
</tr>
<tr>
<td>CR = 4 (S=6)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Nonlinear Regression Predictive Modeling

While it has been observed from this study that the lognormal and Markov chain bridge deck condition prediction models are comparable, the authors attempted to develop an optimized approach by developing a nonlinear regression model that combines the lognormal and Markov chain models. In this approach, the best fit nonlinear regression curve is created for the data generated from the lognormal and the Markov chain models. A combination between the best prediction of each model and for each condition rating is developed. For example, if the lognormal method is the best prediction in condition rating of 9 and the Markov chain model is the best fit in condition rating of 8, then the combination can be created between the results of lognormal and Markov chain methods at condition rating of 9 and 8, respectively. Therefore, evaluating each model for predicting the condition rating of concrete bridge deck is necessary. this evaluation is accomplished by calculating the error rates for the results of each model.

The condition rating of concrete bridge decks can be expressed by the following nonlinear regression model (Jiang 1998):

$$CR(t) = \beta_1 + \beta_2 t + \beta_3 t^2 + \beta_4 t^3 + \beta_5 t^4 \quad \ldots \quad (8)$$

Where: $CR(t)$ = The condition rating of bridge deck at any time of service.
\[ t = \text{Bridge deck age or number of years since last major reconstruction}. \]

\[ \beta_1 \text{ to } \beta_5 = \text{Coefficients to be determined}. \]

The coefficients will be obtained and discussed later based on the results of both lognormal and Markov chain models.

**Analysis of Factors Impacting Bridge Deck Condition**

There are several factors that may have an effect on the deterioration rates of bridges such as ADT, skew angle, environmental factors, structure type, material type, number of spans, the number of traffic lanes, and deck width (Caner et al., 2008; Bolukbasi et al., 2004). In this pilot study, the ADT, structure type, and skew angle factors were selected to investigate their impact on the concrete bridge deck deterioration to demonstrate how the nonlinear regression model can be used for predicting bridge deck performance. To study the effect of these factors on the deck condition over time, each factor was considered independently from the impact of all others. This was accomplished by identifying the appropriate ranges for a given factor while keeping all others constant. Figure 21 is a flow diagram showing the sequence followed in evaluating the impact of each factor. The following section will discuss whether or not there is a significant statistical difference between these factor groups.
Figure 21. A Diagram of the Classification of (a) Structure Type, (b) ADT, and (c) Skew Angles Factors
The same process that have been done previously for verifying whether the bins for the group factors are appropriate for the study, Kruskal-Wallis test was performed. Table 28 shows the parameters of the Kruskal-Wallis test. As shown in the table, most p-values were less than 0.05, suggesting that all bins were classified appropriately. Additionally, the chi square values further demonstrate that the TICR data vary between bins for each factor and support the appropriateness of the bin selections.

Table 28. Kruskal-Wallis Test for Factor Groups

<table>
<thead>
<tr>
<th>CR</th>
<th></th>
<th>P-Value</th>
<th>Chi Square</th>
<th>P-Value</th>
<th>Chi Square</th>
<th>P-Value</th>
<th>Chi Square</th>
<th># of Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skew Angles (Degree)</td>
<td>ADT (vehicle/day)</td>
<td>Structure Type</td>
<td>Concrete, Steel, and Prestress</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skew ≤ 30° &amp; &gt; 30°</td>
<td>ADT ≤ 4,000 &amp; &gt; 4,000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>0.183</td>
<td>1.8</td>
<td>0.094</td>
<td>2.8</td>
<td>0.417</td>
<td>1.8</td>
<td>263</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>0</td>
<td>36.3</td>
<td>0</td>
<td>109.3</td>
<td>0</td>
<td>191.7</td>
<td>1970</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>0</td>
<td>7.6</td>
<td>0</td>
<td>28.8</td>
<td>0</td>
<td>21.2</td>
<td>3772</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>0.006</td>
<td>7.6</td>
<td>0</td>
<td>13.2</td>
<td>0</td>
<td>66.9</td>
<td>2141</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>0.0379</td>
<td>8.0</td>
<td>0.031</td>
<td>11.0</td>
<td>0</td>
<td>16.7</td>
<td>788</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>0.024</td>
<td>5.1</td>
<td>0.0434</td>
<td>6.2</td>
<td>0.0944</td>
<td>1.0</td>
<td>247</td>
</tr>
</tbody>
</table>

Results and Discussion

In this part Michigan data have been used as a case study to develop the optimized prediction model for concrete bridge decks, therefore, the flow diagram can be reformatted to be as follows as shown in figure 22. Additionally, the evaluation of the three predictive modeling approaches for concrete bridge decks will be presented and discussed.
Figure 22. The Flow Diagram of the Optimized Prediction Model for Michigan Data

Comparative Analysis of the Condition Assessment Models

The lognormal distribution function has been found to be the best probability distribution method to fit the condition ratings of Michigan concrete bridge decks. To assess whether the lognormal method is comparable to the Markov chain model in predicting the condition of bridge decks, the deterioration curves of Michigan bridge decks were developed using both approaches. It was concluded that lognormal results are close to those derived from the Markov chain method,
see Figure 23 Both curves are typically S-shaped, suggesting that the deterioration is fast at the beginning and end, and slow in the middle. The results illustrate that Michigan concrete bridge decks will take 16 years to drop from a condition rating of 9 to 7 (the good range) under the Markov chain method and 21 years under the lognormal model. Additionally, bridge decks will take 11 years to drop from 6 to 4 (fair range) under the lognormal model and 11 years under the Markov chain method. Moreover, the curves show that it will take 42 years for bridge decks to deteriorate from a condition rating of 9 to 4 with the lognormal model, and 40 years with the Markov chain method. These results demonstrate that the two methods are comparable. Therefore, the lognormal method is considered a new approach in predicting the condition ratings of bridge decks compared to the existing Markov chain method. In other words, the deterioration rates in both methods are around 0.2 CR/year at the beginning and end of the curves, while in the middle they are around 0.1 CR/year.

To further evaluate the results obtained from the lognormal and Markov chain models, error rates were computed based on the deviation of the prediction results from the original data represented in the condition ratings of concrete bridge decks. The error rates under the two methods are displayed in Table 29.
Figure 23. Deterioration Curves of Michigan Concrete Bridge Decks Using Lognormal and Markov Chain Methods

Table 29. Error Rates of Lognormal, Markov Chain, and Nonlinear Regression Models

<table>
<thead>
<tr>
<th>Condition</th>
<th>CR</th>
<th>Error Percentage (%)</th>
<th>Lognormal</th>
<th>Markov</th>
<th>Nonlinear Regression</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good</td>
<td>9</td>
<td>4.74</td>
<td>5.59</td>
<td>4.73</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>3.91</td>
<td>5.53</td>
<td>5.45</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>7.10</td>
<td>5.26</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>10.58</td>
<td>7.97</td>
<td>7.54</td>
<td></td>
</tr>
<tr>
<td>Fair</td>
<td>5</td>
<td>11.96</td>
<td>9.62</td>
<td>8.91</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>17.99</td>
<td>13.01</td>
<td>11.99</td>
<td></td>
</tr>
</tbody>
</table>

As demonstrated by Table 29, the lognormal model had the smallest error rates for the condition ratings of 9 and 8, while the Markov chain method showed the smallest error rates for condition ratings 7, 6, 5, and 4. The TICR for all Michigan concrete bridge decks and for each
condition rating from 9 to 4 have been taken into account in this calculation. Basically, the condition rating calculated by each method (lognormal and Markov chain) was compared with the original data to find the error rates. In this calculation, the minimum and maximum values of TICR for each condition rating have been taken into consideration. For example, if the minimum and maximum values of TICR for condition rating of 9 were 3 and 8 years respectively, then the original data can be arranged in the following manner {9, 9, 9, 9, 9, 9, 9, 9; 9, 9, 9, 9, 9, 9, 9, 9; 9, 9, 9, 9, 9, 9, 8, 8; 9, 9, 9, 9, 9, 9, 8, 8; 9, 9, 9, 9, 9, 9, 8, 8; 9, 9, 9, 9, 9, 9, 8, 8}. Now consider the TICR for condition rating of 9 was 6 years, then the original data would be {9, 9, 9, 9, 9, 9, 8, 8} and the lognormal CR values would be {8.999, 8.7744, 8.5783, 8.4073, 8.2584, 8.1288, 8.0156, 7.9166} based on the deterioration curve of the lognormal model. The error rate is then calculated as \[(9 - 8.999)/9 + (9 - 8.7744)/9 + (9 - 8.5783)/9 + (9 - 8.4073)/9 + (9 - 8.2584)/9 + (9 - 8.1288)/9\] \*100/6 = 5.28 \%. This approach is then repeated for all TICR values at CR of 9 to take the average error rate. Similarly, error values were calculated for the remaining CRs (i.e. 8, 7, 6, 5, and 4). It is worth noting that for CR of 8, the error rates are calculated starting from CR of 8 to CR of 7, and the same applies for all remaining CRs. Figure 24 shows an example about how the condition ratings calculated by the prediction methods deviate from the original data.
In this section, the best fit nonlinear regression curve was created for the data generated from the lognormal model in the good condition range (9 and 8) and from the Markov chain model for the condition range from 7 to 4. These range selections were based on the minimum error rates for the lognormal and Markov chain models as shown in Table 29. Therefore, the coefficients in equation (9) were obtained based on the final results of lognormal at condition ratings of 9 and 8 and Markov chain at condition ratings of 7 to 4. Consequently, the best fit nonlinear regression model for Michigan data can be expressed as:

$$\text{CR}(t) = 9.175 - 0.285t + 0.01485t^2 - 0.000395t^3 + 3*10^{-6}t^4 \quad \cdots \quad (9)$$
Figure 25 shows the deterioration rates of concrete bridge decks using the nonlinear regression model based on the equation (9). It is observed that the trend of the nonlinear regression curve follows the same behavior of both the lognormal and Markov chain models. To evaluate the results obtained from the nonlinear regression modeling approach, error rates were computed based on the deviation of the prediction results from the original data represented in the condition ratings of concrete bridge decks using the same error calculations approach. The error rates under the nonlinear regression modeling approach are displayed in Table 29.

As shown in Table 29, the nonlinear regression model had the smallest error rates for the condition ratings of 9, 6, 5, and 4. while for the condition rating of 8 and 7, the lognormal and Markov chain methods showed the smallest error rates respectively (Table 29). Additionally, the average error rates for all condition ratings from 9 to 4 are 7.37, 7.83, and 9.38 for nonlinear regression, Markov chain and lognormal models respectively. These results showed that the nonlinear regression model had the smallest average error rates.
The Impact of Factors on Bridge Deck Condition

Prediction equations under the nonlinear regression model have been created to evaluate the impact of these factors on the condition of concrete bridge decks, see Table 30 For example, equation \( CR = 8.9986 - 0.2205t + 0.00091t^2 - 0.00002t^3 + 1 \times 10^{-6}t^4 \) in Table 30 can be applied to determine the condition rating of concrete bridge decks at any time of service if the main structure type is concrete, ADT is less than or equal to 4,000 vehicle/day, and skew angles is less than or equal to 30°. Then, the estimated condition ratings will be 8, 7, and 6 after 5, 18, and 30 years in service, respectively. The following are discussions of the impact of each factor on the condition of concrete bridge decks based on the nonlinear regression model:
Table 30. Prediction Equations for Each Case of Michigan Concrete Bridge Decks Using Nonlinear Regression Model

<table>
<thead>
<tr>
<th>Item #</th>
<th>Case Type</th>
<th>Prediction Equation</th>
<th>Determination Coefficient ($R^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Michigan Concrete Bridge Decks</td>
<td>$9.175-0.285t+0.01485t^2-0.000395t^3+3*10^{-4}t^4$</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Concrete Structure</td>
<td>$8.9986-0.2205t+0.0091t^2-0.0002t^3+1*10^{-4}t^4$</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>Prestress-Concrete Structure</td>
<td>$8.9927-0.2218t+0.0094t^2-0.0002t^3+1*10^{-4}t^4$</td>
<td>0.9995</td>
</tr>
<tr>
<td>4</td>
<td>Steel Structure</td>
<td>$8.9806-0.2305t+0.0101t^2-0.0003t^3+3*10^{-4}t^4$</td>
<td>0.9995</td>
</tr>
<tr>
<td>5</td>
<td>ADT ≤ 4000 (Concrete)</td>
<td>$8.9986-0.2205t+0.0091t^2-0.0002t^3+1*10^{-4}t^4$</td>
<td>0.9992</td>
</tr>
<tr>
<td>6</td>
<td>ADT &gt; 4000 (Concrete)</td>
<td>$8.964-0.2803t+0.0104t^2-0.0002t^3+1*10^{-4}t^4$</td>
<td>0.9995</td>
</tr>
<tr>
<td>7</td>
<td>ADT ≤ 4000 (Prestress)</td>
<td>$8.9927-0.2218t+0.0094t^2-0.0002t^3+1*10^{-4}t^4$</td>
<td>0.9999</td>
</tr>
<tr>
<td>8</td>
<td>ADT &gt; 4000 (Prestress)</td>
<td>$9.0212-0.2716t+0.0128t^2-0.0004t^3+4*10^{-4}t^4$</td>
<td>0.9997</td>
</tr>
<tr>
<td>9</td>
<td>ADT ≤ 4000 (Steel)</td>
<td>$8.9806-0.2305t+0.01t^2-0.0003t^3+3*10^{-4}t^4$</td>
<td>0.9999</td>
</tr>
<tr>
<td>10</td>
<td>ADT &gt; 4000 (Steel)</td>
<td>$9.0053-0.2455t+0.0094t^2-0.0003t^3+3*10^{-4}t^4$</td>
<td>0.9999</td>
</tr>
<tr>
<td>11</td>
<td>Skew Angle ≤ 30 (Concrete)</td>
<td>$8.9986-0.213t+0.0091t^2-0.0002t^3+1*10^{-4}t^4$</td>
<td>1</td>
</tr>
<tr>
<td>12</td>
<td>Skew Angle &gt; 30 (Concrete)</td>
<td>$8.9716-0.2852t+0.0161t^2-0.0005t^3+5*10^{-4}t^4$</td>
<td>0.9995</td>
</tr>
<tr>
<td>13</td>
<td>Skew Angle ≤ 30 (Prestress)</td>
<td>$8.991-0.1684t+0.0048t^2-6<em>10^{-5}t^3-5</em>10^{-4}t^4$</td>
<td>0.9995</td>
</tr>
<tr>
<td>14</td>
<td>Skew Angle &gt; 30 (Prestress)</td>
<td>$8.9767-0.2266t+0.0095t^2-0.0002t^3+1*10^{-4}t^4$</td>
<td>0.9995</td>
</tr>
<tr>
<td>15</td>
<td>Skew Angle ≤ 30 (Steel)</td>
<td>$8.9755-0.2175t+0.0075t^2-0.0001t^3-5*10^{-4}t^4$</td>
<td>0.9995</td>
</tr>
<tr>
<td>16</td>
<td>Skew Angle &gt; 30 (Steel)</td>
<td>$8.9683-0.2603t+0.0097t^2-0.0002t^3+5*10^{-4}t^4$</td>
<td>0.9995</td>
</tr>
</tbody>
</table>

- **The Superstructure Type Factor:** Concrete, steel, and prestress are considered the main structure types for most U.S. bridges, and specifically those in Michigan that are currently in service. Therefore, knowing the bridge behavior under the effect of each type of structure may be useful in deciding how to distribute resources for bridge deck maintenance, rehabilitation, and replacement actions. Figure 26 shows the deterioration curves of Michigan concrete bridge decks under the nonlinear regression model with the different types of structures. It was concluded that all three deterioration curves have approximately the same behavior in the beginning of the service. In other words, the period to drop from a condition rating of 9 to 8 is almost the same. Conversely, a difference between the deterioration curves was noticed within condition ratings from 8 to 4. The steel structure type showed the highest deterioration rates within this range of condition ratings, while the prestress type was found to have the lowest deterioration rates for the same range of condition ratings (Figure 26). On the other hand, the deterioration curves of the concrete structure type are between the steel and prestress type, but
closer to the prestress than the steel type. For example, it took around 15, 18, and 20 years to deteriorate from condition rating 9 to 7 for steel, concrete, and prestress structure types, respectively. Furthermore, the periods to drop from a condition rating of 9 to 4 were 40 years for the steel type, while the period was 42 years for both concrete and prestress. All of the deterioration curves became close to each other when they arrived at the condition rating of 3. For example, steel and prestress structure types dropped to condition rating of 3 after 45 years in service, while for concrete structure type, it took 46 years to become a condition rating of 3.

**Figure 26.** Deterioration Curves of Concrete Bridge Decks with Different Types of Main Structures, ADT ≤ 4,000, and SA ≤ 30º

- **The ADT Factor:** The deck is typically the first bridge element that is exposed to deterioration, making ADT a significant factor for consideration (Hatami and Morcous, 2011). Studying the
effect of this factor on bridge deck deterioration improves understanding of the bridge behavior. The ADT factor had a significant effect on the condition of bridge decks as shown in Figure 27. All curves show that increasing the value of ADT leads to increasing the deterioration of the deck condition. Figure 27 shows the deterioration curves of Michigan concrete bridge with two ranges of ADT, different structure type, and skew less than 30º (i.e., ADT less and more than 4,000 vehicle/day). The bridge decks that have ADT of more than 4,000 (vehicles/day) deteriorated faster than of those decks with ADT less than 4,000 with the same type of structure and skew angle. For example, it took around 18 years to deteriorate from a condition rating of 9 to 7 for bridge decks with ADT less than 4,000 vehicles/day for a concrete structure and skew angle less than 30º, while it was just about 12 years to drop from a condition rating of 9 to 7 for bridge decks under ADT of more than 4,000 vehicles/day for the same other factors. On the other hand, the deterioration curves became close to each other at the poor conditions (i.e., 4 or 3), under the effect of different ranges of ADT. For example, the periods of time to deteriorate from a condition rating of 9 to 4 were about 40 and 42 years for ADT more and less than 4,000 vehicles/day, respectively. The same conclusion of bridge deck behavior can be seen in the other curves of the same figure.
The Skew Angle Factor: The effect of skew angles on the deterioration rates of bridge decks is similar to the effect of ADT. Increasing the values of skew angles resulted in a significant effect on the deterioration of the bridge decks for all condition ratings from 9 to 4 as shown in Figure 28. For example, bridge decks with skew angles less than 30° that have concrete structure type and ADT less than or equal to 4,000 vehicles/day can take about 30 years to deteriorate from a condition rating of 9 to 6, while those with skew angles more than 30°can take around 24 years to drop from condition ratings of 9 to 6. Additionally, the same process of deterioration can be noticed for the same factor with different types of main structure (i.e., steel and prestress) in the other curves of the same figure. Furthermore, it has been shown that most Michigan concrete bridge decks could take at least 40 years before arriving to the

Figure 27. Deterioration Curves of Concrete Bridge Decks with Different Ranges of ADT, Main Structure Type, and Skew < 30°
condition rating of 3, which was the critical rating of most types of bridges (i.e., time needed for major rehabilitation, and/or replacement).

![Deterioration Curves of Concrete Bridge Decks with Different Ranges of Skew, Main Structure Type, and ADT < 40,000](image)

**Figure 28.** Deterioration Curves of Concrete Bridge Decks with Different Ranges of Skew, Main Structure Type, and ADT < 40,000

**Discussion**

Michigan concrete bridge decks condition ratings during the period from 1992 to 2016 were analyzed and used to develop statistical, Markov chain, and nonlinear regression models to optimally evaluate the deterioration rates and to investigate the impact of ADT, main structure types, and skew angles on the deck condition. According to the literatures, the Markov chain model is considered the most commonly used method for evaluating the deterioration rates of bridges. This pilot study has also found that the lognormal statistical model is comparable to the Markov
chain approach and has sought to further optimize the analysis and prediction by developing a nonlinear regression model that is based on the lognormal and Markov chain approaches.

This study illustrated that the deterioration rates of Michigan concrete bridge decks are fast at the beginning and end of their service lives, and slow in the middle. Additionally, they can take at least 40 years before dropping to condition rating of 3, which was the indicator for serious repair, or reconstruction, regardless of the amount of ADT, main structure types, and skew angles of bridges. Consequently, inspection schedules and maintenance actions for Michigan concrete bridge decks can be planned based on their deterioration rates under the effect of the factors discussed in this paper.
CLOSURE

This chapter outlines the conclusion of the developed methodologies and results, highlights the contributions of the work presented in this dissertation, and proposes future work directions that may be some interesting topics.

Summary and Conclusions

This study has found that the probability distribution function model is comparable to the Markov chain approach and has sought to further optimize the analysis and prediction by developing a nonlinear regression model that is based on the best probability distribution function for each state and Markov chain approaches. Therefore, the analysis and modeling approaches presented in this study provide a framework for further investigations into the best prediction modeling and analysis of all the factors that impact bridge deck performance. Each state would need to develop its own models based on its specific data. Additionally, ADT, age, deck area, main structure type, and bridge skew angle have significant impact on the deterioration rates of concrete bridge decks. More ranges for ADT, age, deck area, and bridge skew angle can be established for each factor to provide a more detailed impact analysis for the deterioration rates of concrete bridge decks. The results also showed that the environmental factors (particularly the amount of precipitation and temperature) play a significant role in concrete bridge deck deterioration. This study revealed that bridge decks in cold regions deteriorate at a faster rate than those located in warm regions. It was also concluded that condition ratings of bridge decks in Northeast and High Plains climatic regions drop from a certain condition rating to the next lower level rapidly. This is mainly happening because those bridges are exposed to harsh weather condition.
This study also illustrated that Michigan concrete bridge decks that are in good condition can stay in those conditions longer than the typical two-year inspection schedules as recommended by the NBIS. Additionally, this study revealed that concrete bridge decks in good conditions deteriorate at a slower rate than those decks in poor condition. Consequently, inspection schedules for concrete bridge decks can be extended beyond the two years, especially for those decks that are in good condition (CRs of 7, and 8), or for those that are recently constructed. However, if such an action is to be adopted, it must initially be at a slow rate and be carefully monitored before fully extending inspection schedules to ensure bridge safety and to guarantee that proper and timely maintenance actions are not compromised. Essentially, while inspection intervals can be extended up to 6 years in Michigan, which parallels the conclusions of others, this study revealed that there is currently no universal statistical prediction model that can be developed in one state and used by others. Each state will need to develop its own model based on its specific data. For example, the Weibull distribution method was the best for Oregon state data, while the lognormal distribution method was the best model for Michigan data. However, using the 5% probability of failure has reduced the extension of inspection intervals up to 4 years. Thus, more studies are required to select the acceptable threshold for this purpose to support decision-makers as they study the possibility of extending inspection intervals.

**Contributions**

Knowing the condition rating of a concrete bridge deck at any time of its service life and the factors affecting the condition rating can help in making significant decisions that serve transportation network officials in this field. This study contributes to the improvement of the condition assessment process for concrete bridge decks which is an important step towards achieving an accurate and reliable performance prediction model. Although some research
attempts in the literature have considered the condition assessment of bridges, there is still lacking to explore the significant factors that can cause the deterioration either for the overall bridge condition or for specific element in the bridge itself. Additionally, improving the method used to evaluate the bridge element by overcoming on the limitations can result in producing an accurate and reliable model for predicting. Therefore, the contributions of this study can be summarized as follows:

- Identification and evaluation of the significant factors that impact concrete bridge deck deterioration.
- The development of a universal deterioration prediction framework for concrete bridge decks that can be uniquely tailored for each state’s TICR data and for other bridge elements.
- The development of an optimized deterioration prediction model for evaluating future condition of concrete bridge decks that is based on stochastic and nonlinear regression methods to assist decision-makers in prioritizing maintenance, rehabilitation, and reconstruction actions.
- Supporting the possibility of extending inspection schedules beyond the typical 2-year cycles.

**Recommendations for Future Research Directions**

The analysis and modeling approach in this dissertation can provide a framework for future investigations to further develop and optimize prediction models to improve the bridge deck performance level. Future work can include the following: (1) evaluating each of the factors that impact the deterioration rates in more depth by refining the investigation ranges; (2) investigating the possibility of revising the regular bridge deck inspection intervals beyond the 2-year cycles;
(3) developing deterioration prediction models for other bridge elements (i.e. superstructure and substructure) using the framework developed in this dissertation; (4) identifying other factors that may impact the deterioration rates of concrete bridge decks such as average daily truck traffic (ADTT), number of spans, direction of traffic, and regions (urban/rural); and, (5) investigating the onset of deterioration of concrete bridge decks early in their service lives.
REFERENCES


NYSDOT. (2008). Fundamentals of bridge maintenance and inspection, New York State Department of Transportation (NYSDOT), Albany, N.Y.


Appendix A
Anderson-Darling Test Values for TICR Statistical Models for Concrete Bridge Decks
### Table A1. Anderson-Darling Test Values for TICR Statistical Models for Alabama Concrete Bridge Decks

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Table A26. Anderson-Darling Test Values for TICR Statistical Models for Nebraska Concrete Bridge Decks

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Table A27. Anderson-Darling Test Values for TICR Statistical Models for Nevada Concrete Bridge Decks

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Table A28. Anderson-Darling Test Values for TICR Statistical Models for New Hampshire Concrete Bridge Decks

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Table A34. Anderson-Darling Test Values for TICR Statistical Models for Oklahoma Concrete Bridge Decks

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Table A36. Anderson-Darling Test Values for TICR Statistical Models for Pennsylvania Concrete Bridge Decks

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Table A39. Anderson-Darling Test Values for TICR Statistical Models for South Dakota Concrete Bridge Decks

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Table A40. Anderson-Darling Test Values for TICR Statistical Models for Tennessee Concrete Bridge Decks

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Table A41. Anderson-Darling Test Values for TICR Statistical Models for Texas Concrete Bridge Decks

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Table A43. Anderson-Darling Test Values for TICR Statistical Models for Vermont Concrete Bridge Decks

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Table A44. Anderson-Darling Test Values for TICR Statistical Models for Virginia Concrete Bridge Decks

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Appendix B
The Time in Condition Ratings for the States in the Northeast Region
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**Table B2.** The Time in Condition Ratings for Connecticut State

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**Table B9.** The Time in Condition Ratings for New York State

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**Table B10.** The Time in Condition Ratings for Pennsylvania State

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**Table B12.** The Time in Condition Ratings for Vermont State

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### Table B14. The Time in Condition Ratings for District of Columbia

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Appendix C
The Time in Condition Ratings for the States in the Midwest Region
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Table C6. The Time in Condition Ratings for Missouri State

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Appendix D
The Time in Condition Ratings for the States in the Southeast Region
### Table D1. The Time in Condition Ratings for Southeast Region

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### Table D2. The Time in Condition Ratings for Alabama State

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Table D6. The Time in Condition Ratings for Virginia State

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Appendix E
The Time in Condition Ratings for the States in the High Plains Region
Table E1. The Time in Condition Ratings for High Plains Region

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Table E2. The Time in Condition Ratings for Colorado State

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Table E3. The Time in Condition Ratings for Kansas State

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Table E4. The Time in Condition Ratings for Nebraska State

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</tr>
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</tr>
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123
### Table E5. The Time in Condition Ratings for South Dakota State

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<tbody>
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<td>5.77</td>
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### Table E6. The Time in Condition Ratings for Wyoming State

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<td>669</td>
</tr>
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</tr>
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<td>6</td>
<td>12.84</td>
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<tr>
<td>5</td>
<td>12.14</td>
<td>410</td>
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<tr>
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### Table E7. The Time in Condition Ratings for North Dakota State

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<td>8</td>
<td>16.42</td>
<td>304</td>
</tr>
<tr>
<td>7</td>
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<tr>
<td>6</td>
<td>12.83</td>
<td>296</td>
</tr>
<tr>
<td>5</td>
<td>7.94</td>
<td>119</td>
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<tr>
<td>4</td>
<td>7.27</td>
<td>26</td>
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Appendix F
The Time in Condition Ratings for the States in the Southern Region
### Table F1. The Time in Condition Ratings for Southern Region

<table>
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<th>Condition Rating</th>
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<th># of Samples</th>
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<tbody>
<tr>
<td>9</td>
<td>6.19</td>
<td>2334</td>
</tr>
<tr>
<td>8</td>
<td>12.04</td>
<td>17965</td>
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<td>15.61</td>
<td>24941</td>
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<td>14.02</td>
<td>14072</td>
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<td>10.35</td>
<td>4185</td>
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### Table F2. The Time in Condition Ratings for Arkansas State

<table>
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<th># of Samples</th>
</tr>
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<tr>
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<td>8.27</td>
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<td>8</td>
<td>15.51</td>
<td>2237</td>
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<td>16.13</td>
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<td>15.03</td>
<td>1795</td>
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<td>9.63</td>
<td>410</td>
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<tr>
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<td>40</td>
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### Table F3. The Time in Condition Ratings for Louisiana State

<table>
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</tr>
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<tbody>
<tr>
<td>9</td>
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<td>8</td>
<td>13.05</td>
<td>2192</td>
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<td>3871</td>
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<td>6</td>
<td>14.55</td>
<td>3283</td>
</tr>
<tr>
<td>5</td>
<td>9.06</td>
<td>813</td>
</tr>
<tr>
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<td>8.21</td>
<td>337</td>
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### Table F4. The Time in Condition Ratings for Mississippi State

<table>
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<th>Time in Condition Rating</th>
<th># of Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>8.17</td>
<td>1463</td>
</tr>
<tr>
<td>8</td>
<td>13.80</td>
<td>5582</td>
</tr>
<tr>
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Table F5. The Time in Condition Ratings for Oklahoma State

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<th># of Samples</th>
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<tbody>
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<td>8</td>
<td>4.24</td>
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Table F6. The Time in Condition Ratings for Tennessee State

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<th># of Samples</th>
</tr>
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<tbody>
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<td>8</td>
<td>13.96</td>
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Table F7. The Time in Condition Ratings for Texas State

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Appendix G
The Time in Condition Ratings for the States in the Western Region
Table G1. The Time in Condition Ratings for Western Region

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
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<td>4.93</td>
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<tr>
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<td>10.54</td>
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Table G2. The Time in Condition Ratings for Alaska State

<table>
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<th># of Samples</th>
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<td>16.64</td>
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<td>7</td>
<td>11.20</td>
<td>178</td>
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<tr>
<td>6</td>
<td>10.04</td>
<td>56</td>
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<td>5</td>
<td>15.77</td>
<td>86</td>
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Table G3. The Time in Condition Ratings for Arizona State

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</tr>
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<td>8</td>
<td>11.00</td>
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<tr>
<td>7</td>
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<td>6.31</td>
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Table G4. The Time in Condition Ratings for California State

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</tr>
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<td>8.90</td>
<td>1565</td>
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<td>567</td>
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### Table G5. The Time in Condition Ratings for Hawaii State

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<tbody>
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<td>9</td>
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<td>NA</td>
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<td>8</td>
<td>11.20</td>
<td>10</td>
</tr>
<tr>
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<td>20.28</td>
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<td>17.30</td>
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<td>10.08</td>
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### Table G6. The Time in Condition Ratings for Idaho State

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<th># of Samples</th>
</tr>
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<tbody>
<tr>
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<td>8</td>
<td>11.38</td>
<td>354</td>
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### Table G7. The Time in Condition Ratings for Nevada State

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<td>6.66</td>
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### Table G8. The Time in Condition Ratings for New Mexico State

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<th># of Samples</th>
</tr>
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<tbody>
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<tr>
<td>8</td>
<td>7.16</td>
<td>19</td>
</tr>
<tr>
<td>7</td>
<td>17.82</td>
<td>591</td>
</tr>
<tr>
<td>6</td>
<td>16.71</td>
<td>510</td>
</tr>
<tr>
<td>5</td>
<td>12.61</td>
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Table G9. The Time in Condition Ratings for Oregon State

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</tr>
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<tbody>
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<tr>
<td>8</td>
<td>12.77</td>
<td>1969</td>
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<tr>
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<td>13.33</td>
<td>2682</td>
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<td>6</td>
<td>10.64</td>
<td>1153</td>
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<tr>
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<td>9.59</td>
<td>317</td>
</tr>
<tr>
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Table G10. The Time in Condition Ratings for Utah State

<table>
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</tr>
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<tbody>
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<tr>
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<td>9.93</td>
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<tr>
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<td>12.13</td>
<td>409</td>
</tr>
<tr>
<td>5</td>
<td>10.82</td>
<td>116</td>
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<tr>
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<td>10.64</td>
<td>11</td>
</tr>
</tbody>
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Table G11. The Time in Condition Ratings for Washington State

<table>
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</tr>
</thead>
<tbody>
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<td>NA</td>
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<tr>
<td>8</td>
<td>13.65</td>
<td>599</td>
</tr>
<tr>
<td>7</td>
<td>19.29</td>
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</table>
Appendix H
The Average of Time in Condition Ratings for Six Climatic Regions within U.S.
<table>
<thead>
<tr>
<th>CR</th>
<th>Northeast</th>
<th>Midwest</th>
<th>Southeast</th>
<th>High Plains</th>
<th>Southern</th>
<th>Western</th>
<th>Total No. of Samples</th>
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</thead>
<tbody>
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David Stevens, P.E.
Project Manager
Utah DOT Research & Innovation

ph. 801-589-8340
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<table>
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<th>Title of Paper</th>
<th>Name of main author</th>
<th>Year</th>
<th>No. of Fig.</th>
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March 15, 2018

Aqeel M. Chyad
Western Michigan University
4556 Dover Hills Road #105
Kalamazoo, MI 49009

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Information Resource Manager