PROBABILISTIC SERVICE LIFE PREDICTION MODEL FOR CONCRETE BRIDGE DECKS

by

Mariana X. Cruz

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Approved:

Thomas Schumacher, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Approved:

Harry W. Shenton III, Ph.D.
Chair of the Department of Civil and Environmental Engineering

Approved:

Babatunde Ogunnake, Ph.D.
Dean of the College of Engineering

Approved:

James G. Richards, Ph.D.
Vice Provost for Graduate and Professional Education
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ABSTRACT

Bridge deck deterioration is the leading cause of repair, rehabilitation or replacement of bridge superstructures (Li et al 2001). According to the National Bridge Inventory (NBI) in 2011, there are currently 605,102 bridges in the United States of which 361,986 have cast-in-place concrete decks and 53,286 have pre-stressed concrete decks. It is of great interest, therefore, to be able to reliably predict the durability of concrete bridge decks based on initial and time-dependent input parameters such as design, construction, environmental, site, and service parameters; and thus forecast and prevent failure.

In this study, a probabilistic model framework using Markov Models was developed that can be used to predict the service-life of concrete bridge decks based on the deck condition ratings recorded in the NBI database. This study also explores the correlations between several parameters and their effect in the bridge deterioration process. For instance, design loads, average daily traffic (ADT), environmental factors as established by location were all considered in the parameter analysis.

NBI data for fourteen different states was analyzed and used for the parameter analysis and the prediction model. It was concluded that, perhaps because of the qualitative nature and possible subjectivity of the deck condition ratings, no clear correlations were found between this rating and the selected parameters. Additionally, no significant environmental or geographical trends were observed. Therefore, the prediction model was developed by taking the condition ratings per state and creating a Markov chain based solely on this parameter. This model is capable of predicting the probability of future deck ratings given the current condition
of the deck. The Markov chain model is also capable of predicting steady state probabilities of the deck ratings for each of the fourteen states analyzed. These fourteen models provide some insight on how deck deterioration compares from one state to another. Moreover, these models and parameter analysis provide the basis from which a more complex prediction model based on observed data and NBI condition ratings can be developed as more information becomes available.

Additionally, other more refined probabilistic methods, Bayesian Networks (BN), were explored and are suggested for future work.
Chapter 1

INTRODUCTION

1.1 Motivation

According to the National Bridge Inventory (NBI) in 2011, about 69% of bridges accounted for in the United States have either cast-in place or pre-stressed concrete decks. The principal reason for bridge superstructure repair and rehabilitation is deck deterioration (Li and Zhang 2005). Therefore, it is crucial to understand and to accurately predict the durability of concrete decks, in order to properly plan for maintenance and repair of the aging infrastructure as well as to understand the reasons behind early deterioration. Bridge deck longevity is based on initial and time dependent influence parameters such as environmental factors, design, construction, and site parameters. The motivation behind this study was to evaluate the factors that affect the deterioration, in hopes to develop a prediction model for concrete bridge deck deterioration.

Service-life prediction software packages such as Life-365 (Ehlen, et al. 2009) or STADIUM (SIMCO 2011) are currently available to estimate the life expectancy of concrete structures. Life-365 v2.0 is available for free and assumes corrosion by chloride penetration to be the main deterioration mechanism where the prediction equation is based on laboratory and field data using different concrete mixes (Bentz 2003). The result is a mean prediction for the service-life but a probabilistic solution is also available in form of a sensitivity analysis and probability density functions. Life-365 v2.0 also offers the possibility to study life-cycle costs. The software utilizes
forward algorithms, thus not accounting for combined effects of the parameters considered. Additionally, the predictions are based on either laboratory or field observations but they do not provide a comprehensive analysis of the structure that takes into account actual inspection ratings. STADIUM is a commercial product that has similar capabilities but information on how the predictions are made was not available. As a result, these two software packages may be limited in accurately simulating complex real-world conditions.

1.2 Objective and Scope

The main objective of this research was to develop a concrete bridge deck prediction model based on observed inspection data as well as design, construction, and environmental parameters, if found relevant. Consequently, another objective of the study conducted was to determine which parameters affected deck deterioration the most.

In order to develop a prediction model, first it was desired to select a condition rating that is representative the deterioration of the concrete bridge decks. The National Bridge Inventory (NBI) deck condition rating, item fifty-eight, was selected for this purpose. This rating is a number ranging from nine to zero representing the deck condition from ‘excellent condition’ to ‘failed condition’, respectively, and is described in more detail in Section 3.3. After selecting the control parameter, different factors that contribute to concrete deck deterioration were investigated in order to look for correlations. Following this investigation, a database containing relevant workable data was created in order to be able to develop the model.

Several probabilistic methods were explored in order to create a prediction model. Initially, the thought was to develop a Dynamic Bayesian Network (DBN) to
account for all the different parameters that could affect deterioration in our model, in a manner in which they can be easily added and removed. However, as a preliminary proposition, a Markov Model was developed as prediction model based solely on the progression of the condition rating through time. This model is capable to predict the condition rating of a particular concrete deck, given its current condition rating, which can be related to the state of deterioration. As a result, this prediction model, accompanied with the parameter analysis conducted, provides the foundation from which a DBN can be developed.

1.3 Outline

This thesis will explain in detail how the data from the NBI was used and analyzed in order to develop a service-life prediction model of concrete bridge decks. Included in this study are a parameter relevance analysis, a comparison between deck deterioration, and the selected parameters in order to establish the relevance of design, service, and environmental factors. Also included is the development of the Markov model in order to predict future deck condition ratings based current ratings. Additionally, this study provides the basis from which a more complex prediction model, such as a DBN, can be developed and suggestions on what better sources of observed data may be.

Chapter 2 provides some background information on concrete bridge deck deterioration and an explanation of the methods used for this analysis. Chapter 3 outlines the process by which the NBI data was transformed into a workable dataset, and how the specific relevant parameters were selected. Chapter 4 shows the results of the condition rating and parameter analysis. The relationships that were encountered are presented, as well as a comparison regarding the relevance of
environmental factors. Chapter 5 shows the results obtained from the Markov Model and discusses how the deterioration process progresses by using this prediction model. Finally, Chapter 6 summarizes the findings of this study and provides recommendations for future work.
Chapter 2

METHODOLOGY

In this chapter, background information on concrete bridge deck deterioration is presented. Theories that explain the deterioration process are explored and were used as basis for the parameter selection. Also in this chapter, the theory behind Markov modeling is explained in detail. Finally this chapter provides information on how to develop Dynamic Bayesian Networks (DBN) and how this methodology was explored as part of this research.

2.1 Concrete Bridge Deck Deterioration

There are many causes of concrete deck deterioration. For instance, if a small crack is to form on the top of the concrete, water may penetrate to the rebar and cause corrosion. The presence of deicing salts in the winter can increase the corrosion rate of the rebar, which can lead to section loss. Ultimately, this can greatly decrease the strength of the deck. This strength decrease can cause spalling and create potholes; however, if proper maintenance is performed on the deck, many of these problems can be avoided.

Li and Zhang (2005) explained concrete deck deterioration as a five-step process by which the deck loses its strength and eventually fails. Initially, cracks are developed on the bottom the concrete deck in the transverse direction to traffic. These are mainly due to shrinkage and temperature changes, which can cause significant tensile stresses. When these loads are combined with traffic loads, the first network of
cracks is developed. The second stage of deterioration is reached once the deck loses load transfer in the longitudinal direction causing flexural cracks to form in the longitudinal direction on the bottom of the deck. These longitudinal cracks are developed while transverse cracks are developed on the top surface of the deck. These second set of cracks together with the first set of cracks form a network of cracks. In the third stage of deterioration, water penetrates into the already developed cracks migrating down through them, and through the deck and the rebar. This creates efflorescence on the bottom of the deck and initiates the corrosion process in the steel rebar. In the next stage, the through cracks developed in the previous stage are gradually worn under traffic loads. The loss of aggregate interlocking leads to the loss of load transfer in the longitudinal direction. For this reason, in this stage, the slab does not behave as a plate anymore, but acts as separate transverse beams. Additionally, water continues to penetrate through the cracks therefore accelerating the wearing of the cracks and the corrosion process. In the final stage, the transverse beams fail in shear fatigue due to insufficient amount of transverse steel reinforcement, which has now been corroded away. This failure leads to spalling, depression of the deck span, and eventual service termination.

From the Transportation Research Board (1979) study on the durability of concrete decks, there are several factors affect the deterioration process as outlined above. Material properties like water-to-cement ratio, adequate selection of cement type, and the use of appropriate admixtures have an effect on the durability of concrete decks and concrete structures in general. Additionally, aggregate reactions like the alkali-silica reaction (ASR) of concrete can also negatively influence the durability of a concrete deck. Some admixtures to be considered to increase the durability of concrete decks include ones that help resist freezing and thawing,
address workability and placement characteristics, and reduce susceptibility to plastic and drying shrinkage. Mineral admixtures such as fly ash, silica fume, slag cement, or metakaolin are also used in order to reduce the permeability of concrete and protects against sulfate attack and alkali-silica reaction and increase durability (ACI 2011).

Due to the presence of steel in reinforced concrete, steel material properties and protection are also important to the durability of concrete. Protective measures such as coatings like epoxy, galvanized, or metallic clad, and the use of different grades of steel can delay the deterioration of the deck (Transportation Research Board 1979). Moreover the use of more innovative alternatives to steel reinforcement such as stainless steel and fiber reinforced polymers (FRP) can also have an impact on durability as their use eliminates the possibility of reinforcement corrosion, which is one of the leading causes of severe deck deterioration (Li and Zhang 2005).

Deck deterioration is also affected, and perhaps delayed, if deck protection systems are installed during construction. In the United States, clear cover from the rebar is often the only form of deck protection other than rebar coating. However, this measure can lack effectiveness because this layer of concrete is the one most susceptible to severe conditions, and it can be compromised by finishing techniques. (ACI 2011). Other protective alternatives could also include waterproofing membranes on the concrete deck and passive-current or impressed –current cathodic protection systems for preventing corrosion (Transportation Research Board 1979).

Initial design parameters can also have an effect on the deterioration process of a concrete deck. For instance, higher depth of clear cover, c_c, as discussed above, can help protect the integrity of the rebar. Two inches is the minimum recommended clear cover, two and a half inches is recommended for areas subject to chain and strut wear, and a minimum of three inches is recommended for coastal areas.
Other design measures that can be taken to slow down the deterioration of a concrete deck include having less skews, providing adequate drainage, having a deck that is at least seven inches thick as thicker decks slow down the deterioration process, and reducing the number of joints as much as possible to prevent the filtering of water and chlorides (Transportation Research Board 1979).

Moreover, it is important to consider that certain environmental parameters are believed to have an effect on the deterioration of reinforced concrete. For instance, rain, in particular alternating wetting and drying cycles are particularly damaging to the integrity of reinforced concrete. Severe temperature gradients and frequent freeze and thaw cycles can also damage concrete decks as they increase shrinkage and expansion due to temperature, causing strain in the deck. Presence of salts in the environment, whether it is due to coastal environments or because of de-icing salts, also can accelerate the deterioration process as the increased presence of chlorides can lead to higher rates of steel corrosion (Transportation Research Board 1979).

Finally, service and maintenance factors can also influence the durability of concrete bridge decks. Average daily traffic (ADT) and average daily truck traffic (ADTT) are two important parameters that directly correlate with the traffic load a bridge is exposed to. High traffic loads are believed to advance the deterioration process of the bridge as explained by Li and Zhang (2005) above. Bridges that are exposed to lower traffic volumes that do not significantly increase with time arguably deteriorate slower than those exposed to higher volumes that increase rapidly through the years and that have been damaged by other hazards as previously explained. Additionally, frequency of maintenance and frequency and consistency of inspections can also play a role on the deterioration of a concrete deck.
2.2 Original Model Framework

After learning the different parameters that affect concrete deck deterioration, an initial model framework was developed. Figure 2.1 below shows the different parameters initially thought to be important in the progression of deck deterioration. The diagram also shows a simplified graphical summary of the model intended to be developed through this study. It was envisioned that all of the different parameters would feed into a prediction model that would take then be able to predict the service life of concrete decks. Sections 2.3 and 2.4 lay out the different probabilistic methods explored in order to achieve the prediction capabilities.

Figure 2.1: Original Model Framework
2.3 Markov Modeling

A Markov model is a probabilistic prediction model capable of predicting the future state of a discrete stochastic process given its current state. In order for this prediction model to hold true, the random variables analyzed must hold certain characteristics. The random variables must be mutually exclusive and collectively exhaustive, meaning that the occurrence of one event precludes the occurrence of another; the events thus do not intersect in the sample space, and the union of these events equals the entire underlying sample space (Davidson). In a Markov chain, the random variables identified in the process have to be discrete and defined a discrete time steps (Straub). A Markov model is said to be a “memory-less” process, meaning that the condition of a process in a particular state is only dependent on the condition at the immediately previous state (Davidson). This concept is explained as the Markov Property as expressed by the Equation 2.1 below (Straub):

\[ p(x_n|x_0, x_1, x_2, \ldots, x_{n-1}) = p(x_n|x_{n-1}) \]  

Where, \( x_n \) is a random variable at state \( n \), and \( p(x_n) \) is the probability of its occurrence. The formula above summarizes the Markov property that states that the probability of a random variable is only statistically dependent on its previous step, \( x_{n-1} \), but statistically independent from all other previous states. Thus, if all the random variables in a particular process follow the Markov property, then the sequence can be considered a Markov chain (Straub).

In practice, a Markov model has two key components, initial state probabilities and transition probabilities (Straub), which are usually expressed in matrix form. The initial state probability matrix is a matrix that has one row, and \( m \) number of columns, where \( m \) represents the different potential states of a particular process. The transition
probability matrix is an $m$ by $m$ matrix where each column contains the probabilities of staying in a particular state if currently in the $m$th row state. For instance if there are nine different states for a random variable, and it was initially observed to be in the first state or ninth if counting the states backwards, the initial state probability matrix would be of this form:

$$[1 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0]$$

A sample transition probability matrix for this example, looking at a random variable with no recurrent states, would look like:

$$\begin{bmatrix}
0.7 & 0.2 & 0.1 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.8 & 0.1 & 0.1 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.6 & 0.3 & 0.1 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.5 & 0.3 & 0.1 & 0.1 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.6 & 0.2 & 0.1 & 0.1 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.7 & 0.2 & 0.1 & 0.1 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.8 & 0.2 & 0.1 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 1.0 & 0.0
\end{bmatrix}$$

As it can be observed in the matrix above, a transition matrix with no recurrent states has every probability left of the diagonal to be zero, as once the random variable has reached the next state, it cannot go back to the previous one. This would be true for a deterioration model without maintenance. If maintenance is considered, and all the states can be recurrent, then the probabilities left of the diagonal can be values other than zero. In any instance, however, the added probabilities of each row must be one (Davidson).

Once the initial conditions and transitional probabilities are defined, the Markov model can be used to predict the future state of a particular random variable.
The following Equation 2.2 for Markov chains can be used for this purpose (Davidson):

\[ P(n) = P(0) \times P^n \]  

(2.2)

where \( P(0) \) is the initial condition matrix, \( P \) is the average transition matrix, \( P(n) \) is the probability matrix at \( n \), and \( n \) the number of years. \( P(n) \) will then be a single row matrix, and each column will contain the probability of being in each different state as defined in the initial conditions matrix.

Additionally, Markov chains or models can be used to calculate the steady state probabilities of a particular process. Markov chains are said to be ergodic, meaning that the probabilities of being in each of the states converge over time. Because of this property, these steady state probabilities can be calculated using Equation 2.3 (Davidson):

\[ P^* = P^* P \]  

(2.3)

Where \( P^* \) is a matrix containing the steady state probabilities, and \( P \) is the transition probability matrix. Therefore the equation above must be solved as a system of simultaneous equations.

A Markov chain is said to be stationary when the transition matrix, as described above, remains constant over time. If the transition matrix changes, then the process is no longer stationary, and it will be further explored in the next section on Bayesian Networks.
2.4 Bayesian Networks

Bayesian Networks (BNs) are probabilistic graphical models that represent a set of random variables and their probabilistic dependencies in a directed non-recurring diagram (Bensi et al. 2011). In a BN, joint probability distributions are available for each variable or parameter and are dependent upon the conditional probability of a particular variable given its precedent state. This concept can be simplified by thinking of the following simple example. If we consider a simple BN containing three variables as shown in Figure 2.2 below:

![Simple Bayesian Network](image)

**Figure 2.2: Simple Bayesian Network**

If we consider $x_1$, $x_2$, and $x_3$ to be random variables in a BN, we can observe that $x_1$ is the parent variable of $x_2$ and $x_3$. This means that the probability of $x_2$ and $x_3$ are conditionally dependent on the occurrence of $x_1$. Therefore, the probability of the entire system has to account for these interdependencies. This makes the probability of the system to be as expressed in Equation 2.4 below (Straub 2009):

$$p(x_1, x_2, x_3) = p(x_1) p(x_2 | x_1) p(x_3 | x_1)$$  \hspace{1cm} (2.4)
Where \( p(x_2|x_1) \) is defined by the Bayes’ Theorem in Equation 2.5 below:

\[
p(x_2|x_1) = \frac{p(x_1|x_2) p(x_2)}{p(x_1)}
\]  

(2.5)

An advantage of BNs is that once new or additional data becomes available, for instance after an inspection, this newly gained knowledge can directly be used to update the current prediction model. BNs allow for new probabilities to be introduced and propagate through the network to update the posterior probabilities of probabilistic dependent variables. This process is called Bayesian updating, and it is achieved by applying Bayes’ Theorem as expressed in Equation 5 above (Straub 2009). This concept can be simply represented by Figure 2.3 below:

![Figure 2.3: Bayesian Updating](image)

It can be observed that in Figure 2.3, an observed state \( a \) has now replaced the random variable \( x_2 \) from the example in Figure 2.1. This observed condition is propagated through the entire network making the network probability be updated as shown in Equation 2.6 below:
\[ p(x_1, x_3 | a) = \frac{p(x_1, a, x_3)}{p(a)} = \frac{p(x_1) p(a | x_1) p(x_3 | x_1)}{p(x_1) p(a | x_1)} \]  

(2.6)

Dynamic Bayesian Networks (DBN) are a class of BN that can represent discrete-time stochastic processes. They are formed by a series of slices or stages, with each of them having multiple BN random variables (Straub 2009). DBNs incorporate time-variant parameters and invariant parameters into the model. The dependence among the different stages in a DBN is conditionally Markovian, such that the current time step, \( t \), is conditionally dependent solely on the previous stage, \( t-1 \) (Straub 2009). This means that the behavior of a DBN is similar to the behavior of a Markov chain described above, only that the transition probabilities between states is non-stationary and it can be updated as new observations are recorded. Like a Markov model, a DBN can be used for a deterioration model, but because of its unique capabilities of updating and considering multiple parameters at a time, it is arguably a more powerful prediction model.
Chapter 3

NATIONAL BRIDGE INVENTORY DATA SELECTION

The National Bridge Inventory (NBI) database provides the public with a vast amount of information regarding the condition of bridges throughout the United States. Yearly, a database is published by the Federal Highway Administration (FHWA) containing condition information, traffic, and certain design parameters relevant to the overall condition of bridges determined by federally mandated bi-annual in-service inspections. For the purpose of this research, a selection of parameters was considered from the database to be statistically analyzed to determine their impact on bridge deck deterioration. The deck condition rating from the NBI database was used to determine the deck deterioration rate, as this is the parameter that was hoped to be predicted using the proposed model.

3.1 Parameter Selection

Initially, it was desired to obtain design and construction parameters directly from the States’ Departments of Transportations (DOTs) via a survey. However, because of liability reasons, it became apparent that this information was not going to be made available for use in this research. Therefore, parameters relevant to bridge deck deterioration were directly selected from the publically available data in the NBI database.

The NBI database includes condition, design, service, and maintenance data for bridges from all fifty states, the District of Columbia, and Puerto Rico dating back
to 1992, divided both by state and year. This means that for the purposes of this research there were twenty years of data available to develop a probabilistic prediction model. A total of 116 items, or parameters, are accounted for in the NBI database for each bridge. For the purpose of this study, thirty-one relevant time-invariant and time-variant parameters were selected. These were considered to be the most influential to bridge deck deterioration. Some of these parameters were chosen to serve as filters, in order to select only appropriate bridges with concrete decks, and to ensure consistency in the data set.

The thirty-one parameters considered to be relevant for are listed below along with a brief description:

- State code: a three-digit reference identify the state or territory in which the bridge is located
- Structure Number: a unique number that is used to identify a bridge and track it through time. It serves as the bridge’s ID number.
- Inventory Route: an item containing three relevant parameters:
  1) Record Type- discrete variable indicating whether the traffic is carried on the structure
  2) Route Signing Prefix- a discrete variable describing the use of the road on the bridge
  3) Designated Level of Service- a discrete variable describing the service on the road
- Latitude: used for location purposes and to eventually tie in weather data
- Longitude: used for location purposes and to eventually tie in weather data
- Maintenance Responsibility: a discrete variable that provides information regarding the authority in charge of maintaining the bridge.
- Functional Classification of Inventory Route: a discrete item that provides information about the function of the road carried by the bridge and whether this is in a rural or urban area.
- Year Built
- Lanes on the Structure
- ADT (average daily traffic)
- Year of ADT, when the ADT was recorded
- Design Load: a discrete variable that shows what load combination was used for the design of the bridge
- Structure Open, Posted, or Closed: a discrete variable for the current state of the road
- Type of Service on the Bridge: a discrete parameter that reflects the use of the bridge
- Number of Spans in the Main Unit
- Length of Maximum Span
- Structure Length
- Deck Rating: a discrete rating that describes the condition of the deck. This is the parameter the DBN model will predict.
- Superstructure: a discrete parameter that provides a rating for the superstructure condition.
- Substructure: a discrete parameter that provides a rating for the substructure condition.
- Structural Evaluation: a parameter that contain the lowest rating between the superstructure and substructure value.
- **Bridge Posting:** a discrete parameter that provides with information about the percentage of legal loads the bridge is capable of carrying in ranges.

- **Type of Work:** an item containing two parameters:
  1) **Type of Work Proposed** - a discrete variable that describes the work needed
  2) **Work Done By** - a discrete variable that identifies what entity was responsible for the work

- **Inspection Date:** shows the exact month and year the bridge was inspected for that particular record.

- **Designated Inspection Frequency:** shows the period that the bridge must be inspected by in months.

- **Bridge Improvement Cost:** provides information about how much the cost of repairs proposed is.

- **Year of Improvement Cost Estimate**

- **Year Reconstructed**

- **Deck Structure Type:** a discrete variable that describes the material of the deck (only interested in cast-in-place and pre-stressed concrete decks)

- **Wearing Surface/ Protective System:** this item contains three variables of interest:
  1) **Type of Wearing Surface** - a discrete variable describing the wearing surface on the deck, if any
  2) **Type of Membrane** - a discrete variable that shows the type of protective membrane on the deck, if any
  3) **Deck Protection** - a discrete variable with information regarding the deck protection system on the deck, i.e. rebar coatings
-ADTT: average daily truck traffic as a percentage of the ADT

The data from the NBI records is available in text files, one for each state or territory for each year. Up until 2010, the records in this file were not character delimited but a coding guide has been available in order to sort through the data. For this reason, a MATLAB script was developed in order to extract the information from these data files, arrange them properly per state, and then establish basic statistical relationships between these parameters and the deck ratings. A sample of this script is attached in Appendix A.

3.2 Pre-Processing of NBI Data

Due to the large amount of data available in the NBI database, the goal was to load and sort through only the selected parameters for each state in order to compile it into a workable file. This process was achieved by creating a MATLAB script (Appendix A) that is capable of importing the data files per state into a dataset, assigning variable names to only the parameters of interest and deleting all unnecessary items.

Delaware was chosen as the first state to be loaded in this manner. Once the state data was fully loaded, filters were added to the script in order to sort through only the bridges that had the characteristics sought after, and to rid the data of any inconsistencies. This guaranteed that the progression of each bridge could be tracked through the twenty years of data. This being said, the number of bridges does change from year to year as some are added and others are unaccounted for in a particular record year, which is expected.

Like Delaware, thirteen other states were selected to be analyzed in the same manner in order to draw more robust conclusions. It was determined that due to the
large amount of data and the limitations in computing time and power, it would be useful to select meaningful geographical clusters of states. This would limit the need to process every single one of the fifty states, and allow us to draw some preliminary conclusions regarding deterioration rates and environmental parameters. The states selected represent seven distinct climatic regions in the continental United States. Maine and Rhode Island represent the Northeast, Virginia and Delaware the mid-Atlantic region, Alabama and Florida the Southeast, New Mexico and Arizona the Southwest, Oregon and Washington the Pacific Northwest, Minnesota and Nebraska the northern Midwest, and Arkansas and Indiana the Midwest.

3.3 Quantifying Deterioration

As previously stated, the Deck Rating, item fifty-eight in the NBI records, was selected to represent deck deterioration over time. This rating is a discrete parameter that describes the condition of the bridge by using a scale of zero to nine. Each of the ratings is explained in detail in Table 3.1 below taken from the NBI Reference Guide (Federal Highway Administration 1995). As it can be observed in the Table 3.1, the rating descriptions are rather qualitative which can introduce subjectivity of the inspector. It can be argued that this is perhaps not the best measure for deterioration. However, it is important to note that through this rating it was possible to analyze twenty years of condition data for each bridge of interest for this study. Additionally, this rating provides a number that can be used for statistical comparison against the other parameters of interest. Finally, we were advised that bridge deck condition data may be the most consistent of all NBI ratings, compared to superstructure or substructure condition ratings (Personal conversation with Brian M. Kozy, PhD, PE,
Senior Bridge Engineer, FHWA Office of Bridges and Structures, April 24, 2013, Newark, DE).

**Table 3.1: Description of NBI Condition Ratings, Deck**

<table>
<thead>
<tr>
<th>Code</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Use for all Culverts</td>
</tr>
<tr>
<td>9</td>
<td>Excellent Condition- No noticeable or noteworthy deficiencies, which affect the condition of the deck item. Usually new decks</td>
</tr>
<tr>
<td>8</td>
<td>Very Good Condition- No noticeable or noteworthy deficiencies, i.e. delamination, spalling, scaling or water saturation</td>
</tr>
<tr>
<td>7</td>
<td>Good Condition- Scalable deck cracks, light scaling (less than ¼ “ depth). No spalling or delamination of deck surface but visible tire wear. Substantial deterioration of curbs, sidewalks, parapets, railing or deck joints (need repair). Drains or scuppers need cleaning</td>
</tr>
<tr>
<td>6</td>
<td>Satisfactory Condition- Medium scaling (¼ “ to ½ “ in depth). Excessive number of open crack (5ft. intervals or less). Extensive deterioration of curbs, sidewalks, parapets, railing or deck joints (requires replacement of deteriorated elements)</td>
</tr>
<tr>
<td>5</td>
<td>Fair condition- Heavy scaling (½” to 1” in depth). Excessive cracking and up to 5% of the deck area is spalled; 20-40% is water saturated and/or deteriorated. Disintegrating of edges or around scuppers. Considerable leaching through deck. Some partial depth fractures, i.e. rebar exposed (repairs needed).</td>
</tr>
<tr>
<td>4</td>
<td>Poor condition- More than 50% of the deck area is water saturated and/or deteriorated. Leaching throughout deck. Substantial partial depth fractures (replace deck soon).</td>
</tr>
<tr>
<td>3</td>
<td>Serious condition- More than 60% of the deck area is water saturated and/or deteriorated. Use this rating if severe or critical signs of structural distress are visible and the deck is integral with the superstructure. A full depth failure or extensive partial depth failures (repair or load post immediately)</td>
</tr>
<tr>
<td>2</td>
<td>Critical condition- Some full depth failures in the deck (close the bridge until the deck is repaired or holes are covered)</td>
</tr>
<tr>
<td>1</td>
<td>“Imminent” failure condition- Substantial full depth failures in the deck (close the bridge until deck is repaired or replaced)</td>
</tr>
<tr>
<td>0</td>
<td>Failed condition- Extensive full depth failures in the deck (close the deck until the deck is replaced)</td>
</tr>
</tbody>
</table>
For the purposes of this research, and after a preliminary analysis of the data, it was determined that ratings nine (most optimal) through one (worst condition) would be used as the potential states a deck could be in as described above. It was discovered that the condition rating of zero did not apply to the states analyzed as far, and thus it was taken out of the analysis for simplicity.
Chapter 4

ANALYZING NATIONAL BRIDGE INVENTORY DATA

Once the NBI data was loaded into the appropriate datasets on MATLAB, it was of interest to establish whether correlations exist between the selected parameters and the deck condition ratings. The purpose of this process was to determine which parameters, if any, had a significant effect on the progression of the deck condition ratings. Additionally, it was of interest to calculate the deterioration rate of the bridges in each state in terms of the deck condition ratings. These were used as comparison with certain parameters as well as to establish any patterns between the different climatic regions investigated.

4.1 Calculating Deck Deterioration Rates

Once the filters were established to reject bridges that did not qualify, the data was reorganized per parameter instead of per year. The first dataset created was one that organized the deck ratings per bridge, with each column corresponding to one year. In this manner, the progression of the deck condition ratings could be easily observed through time.

It was desired to obtain an average deterioration rate per bridge throughout the years in order to correlate this value with the time-invariant parameters in the database and to check for any correlations. The deterioration rate, for the purposes of this study, is defined as the change of the deck condition rating over the period of one year. For instance, a rate of 0.09 means that the deck condition rating would decrease
by 0.09 for that particular bridge in one year. Therefore, if a new bridge with a deck rating of nine (= excellent condition) experiences a constant deterioration rate of 0.09, it would take between eleven to twelve years for the deck rating of this bridge to decrease to a rating of eight (= very good condition), and eighty-eight years for the rating to decrease to a rating of two (= critical condition).

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<td>6</td>
<td>6</td>
<td>6</td>
<td>6</td>
<td>7</td>
</tr>
</tbody>
</table>

Figure 4.1: Sample Screen Shot of Deck Ratings in Delaware

Looking at the data, it became clear that the deck condition ratings did not always decrease as one would expect, but instead they could go up, meaning that the state of the bridge deck improved, from one previous year to the next. Figure 4.1 above provides a sample output screen shot of deck condition ratings, showing the inconsistencies in the dataset. These inconsistencies could be due to maintenance or inspection uncertainty. For this reason, two deterioration rates were calculated. The first one included all the ratings, whether they increased or decreased and calculated one single deterioration rate, titled “with maintenance,” for each bridge. Therefore, positive deterioration rates reflect that the bridge deteriorated through the years and negative ones would signify that the deck rating actually had an overall improvement through time. The second one calculated an average deterioration rate per bridge, labeled “without maintenance,” excluding all the instances where the bridge deck
rating went up. This second rate is assumed to be representative of an actual ‘true’ deterioration rate.

Additionally, statistical values such as mean and standard deviation were computed for the deterioration rates “with maintenance” and “without maintenance” for each of the states. Two graphical examples of the statistical distribution curves calculated for the deterioration rates per state are shown in Figures 4.2 and 4.3 for the State of Delaware. The continuous curves represent inferred probability density functions (PDF) selected based on the highest log-likelihood. The PDF were Exponential and Normal for the cases of “without maintenance” and “with maintenance”, respectively. Graphs for the remainder states can be found in Appendix B. A summary of the mean deterioration rates found in all the fourteen states analyzed is illustrated in Figure 4.4 below. As it can be observed, no clear trends in the deterioration rates can be established in states with similar climatic regions. Figure 4.5 displays the statistical spread of the deterioration rates per state by using box and whisker plots. This plot further corroborates the lack of trends within the selected climatic regions as all states seem to have similar statistical spreads. Additionally, states that have no climatic similarities, like New Mexico and Washington, have almost identical statistical spreads for the deterioration rates, again making it difficult to argue a trend based on geographic location.
Figure 4.2: Deterioration Rate (Without Maintenance) Density Curve for Delaware

Figure 4.3: Deterioration Rate (With Maintenance) Density Curve for Delaware
Figure 4.4: Deterioration Rates Per State (Without Maintenance)
Figure 4.5: Box and Whisker Plots of State Deterioration Rates (Without Maintenance)
4.2 Correlations Between Deterioration Rate and Time-Invariant Parameters

Once the deterioration rates per bridge were calculated, it was of interest to explore whether some statistical relationships could be revealed between these rates and the time-invariant parameters of the bridge. These parameters included: design load, functional classification of the road, year built, type of service, structure material, structure type, route prefix, service level, lanes on structure, number of spans, maximum span length, structure length, type of wearing surface, type of membrane, and deck protection. In this section only the parameters above were observed because, as explained in Chapter 3, some of the thirty-one parameters selected were used as filters, and the rest were either time-invariant or time-variant ones. Section 4.3 will explain the correlation process for the time-variant parameters.

In order to establish the correlations between these parameters and deck deterioration, all the values for these parameters were extracted from the data set for each bridge. Then a linear correlation between the non-discrete time-invariant and each of the two deck deterioration rates were calculated. For the discrete parameters, box and whisker plots were created for comparison with the average deterioration rates. Additionally, scatter plots were created of the deterioration rate and each non-discrete time-invariant parameter to observe if there were any correlations present that were non-linear. Sample summary plots for the State of Delaware can be observed in Figure 4.6. Also, Table 4.1 contains selected linear correlation values calculated for the non-discrete parameters.
Figure 4.6: Sample Plots for Time-Invariant Parameters for Delaware

Table 4.1: Linear Correlation for Non-Discrete Time Invariant Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Linear Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year Built</td>
<td>0.0285</td>
</tr>
<tr>
<td>Maximum Span Length</td>
<td>-0.0446</td>
</tr>
<tr>
<td>Length</td>
<td>0.0076</td>
</tr>
</tbody>
</table>
Figure 4.6 shows two box and whisker plots for Delaware. The first plot represents the spread of the deterioration rates for design load, and the second one for functional classification of the road. Both of these variables are considered discrete parameters, which means that the x-axis represents different values for these two variables that are not arranged in any particular ascending or descending other, but instead each represents a different category the particular variable. For this reason, a linear correlation would not have been a suitable way to understand the statistical dependencies between these parameters and the deterioration rates. Instead, the box and whisker plots in the figure above represent the spread of the deterioration rates, per bridge, of each value within each discrete parameter. The line crossing through the box and whisker diagrams on each plot is the average deterioration rate without maintenance. The goal was to determine whether or not one of the variables in each graph was driving the deterioration either up or down significantly, that is if one or more of the box and whisker diagrams in either plot had consistently higher or lower values than the other diagrams in the plot and the average deterioration line. As can be observed in the upper two plots, the spread of the different box and whisker diagrams within a plot are very similar to one another, and no particular value can be identified as one that is driving the deterioration rate significantly. For this reason, it cannot be argued that there is any significant correlation between these discrete parameters and the deterioration rate. Similar results were obtained for the remaining discrete time-invariant parameters identified at the beginning of this section for Delaware.

Moreover, the bottom plot in Figure 4.6 is an example of a time-invariant non-discrete parameter, year built. For this parameter, it was useful to plot the year a particular bridge was built vs. the deterioration rate of the bridge to identify any
particular correlation between age of the structure and how fast it deteriorated. The purpose was to identify a statistical trend between the two and identify whether it would be linear or not. A similar procedure was used for the other two non-discrete time-invariant parameters analyzed: length and maximum span length. Additionally, Table 4.1 shows the linear correlation values of these three parameters and the deterioration rates. As it can be observed in the scatter plot for year built, there is no significant statistical dependency between this particular variable and the deterioration rates per bridge. Similar results were obtained when analyzing the scatter plots for the other two variables. Table 4.1 reassures the fact that there is no significant linear dependency beyond what is observed in the scatter plots. Thus, it could not be argued that the deterioration rate of the bridges was dependent on this set of parameters for the Delaware data.

As it can be shown and discussed in the sample plots and the table above, the time-invariant parameters did not have a significant correlation with the deterioration rates for Delaware. Similar results were observed with all the other thirteen states with the exception of Nebraska, for which this particular analysis was not carried out due to the extensive computational time it required. Appendices D through N contain sample plots and tables for the time-invariant parameters as described in this section and the time-variant plots as described in Section 4.3 for the remainder twelve states that were subject to parameter analysis.

4.3 Correlations Between Deterioration Rate and Time-Variant Parameters

In order to find the correlation between the deck rating and the time-variant parameters such as: ADT, ADTT, inspection frequency, bridge posting, superstructure rating, and substructure rating, a different approach was taken. For these parameters, a
direct linear correlation between the deck rating and each parameter for each bridge per year was calculated.

The time variant parameters were rearranged into several datasets, one for each parameter as it was done for the deck rating previously. The cells that contained no information, i.e. if a parameter was not recorded for a specific bridge for a given year, were taken out of the correlation calculation in order to prevent these zeros from skewing the analysis. A linear correlation analysis was then run comparing the deck ratings versus each of the parameters. Additionally, scatter plots comparing each parameter to its corresponding rating for all bridges and all years were created to determine any other relevant statistical trend. Table 4.2 below shows the summary of the linear correlations between each of these parameters and the deterioration rate for the State of Delaware. Figures 4.7 and 4.8 show sample scatter plots with added histograms for average daily traffic (ADT) and superstructure ratings for the State of Delaware, used to determine any if there were any other statistical dependencies. The histograms were added to determine the weight of each variable that could be otherwise potentially missed due to point overlapping in the scatter plot.

**Table 4.2: Linear Correlation for Time-Variant Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Linear Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADT</td>
<td>-0.0112</td>
</tr>
<tr>
<td>ADTT</td>
<td>0.0184</td>
</tr>
<tr>
<td>Inspection Frequency</td>
<td>0.3465</td>
</tr>
<tr>
<td>Bridge Posting</td>
<td>0.1149</td>
</tr>
<tr>
<td>Superstructure Condition Rating</td>
<td>0.5759</td>
</tr>
<tr>
<td>Substructure Condition Rating</td>
<td>0.4622</td>
</tr>
</tbody>
</table>
Figure 4.7: Scatter Plot of ADT vs. Deck Rating for Delaware

Figure 4.8: Scatter Plot of Superstructure Rating vs. Deck Rating for Delaware
As previously described, Table 4.2 summarizes the results obtained from the linear correlation calculation between the time-variant parameters and the deck condition ratings carried out. From the table, it can be observed that no particular parameter has a significant linear correlation, i.e. above 90%, with the deck condition ratings. It is important to note, however, that superstructure ratings had a higher correlation than the other parameters, which was to be expected as the deck condition is a factor in the formulation of this particular parameter.

Figure 4.7 corroborates the low linear correlations obtained between ADT and deck rating as shown in Table 4.2 by simply noting how different the two variable distributions are from one another and the lack of a clear trend in the scatter plot. As it can be observed in this figure, the distribution of the deck ratings do not seem to be dependent on higher or lower ADT values, that is the density of the scatter plot does not follow the density of the ADT histogram. Because the distributions of the two variables in Figure 4.7 are so different, in order to establish some sort of correlation, the density of the scatter plot would have to follow the distribution of the ADT, especially since this variable is not discrete. However, since it does not, it cannot be argued that there is a significant statistical dependency between the two variables.

Figure 4.8 corroborates the presence of a slight linear correlation between the superstructure condition ratings and the deck condition ratings. As it can be observed, the distributions for these two variables are quite similar to one another; therefore the general trend of the scatter plot is a good indicator of the correlation between the two variables. From the scatter plot, we can observe that there is a slight linear trend between the two variables, which is consistent with a linear correlation of 57.6%. Even though it is clear that there is a certain relationship between the superstructure and deck rating, as it would be expected, it is again difficult to argue that there is a
significant relationship between the two given the correlation coefficient. Therefore, it cannot be concluded that the superstructure rating is a parameter that drives the bridge deck deterioration rates.

For all the other time-variant parameters for Delaware, the correlations between these and the deck ratings were even weaker, as shown in Table 4.2. Moreover, the scatter plots for these did not provide any additional signs of strong statistical correlations. Similar results were obtained for the other twelve states analyzed. A summary of tables and plots that include this portion of the analysis for each of the states, similar to the information presented for Delaware in this section, can be found in Appendices D through N.
Chapter 5
MARKOVIAN DETERIORATION MODEL

After determining the lack of strong correlations between the selected parameters from the NBI records and deck deterioration as defined in this study, it was desired to evaluate a way to forecast deterioration ratings relying solely on the condition ratings themselves. In order to accomplish this, a Markovian deterioration model was created that would predict the probability of deck condition rating through time. For the purpose of this model a transition matrix was calculated per state using a frequency analysis. Finally, a prediction model was created for each of the fourteen states selected for this study.

5.1 Markov Model Overview

As discussed previously in Chapter 2, a Markov model has two key elements that must be defined in order to create a prediction: the transition probability matrix, and the initial condition matrix. Once these two matrices are defined, equations 2.2 and 2.3 can be then utilized to formulate the prediction. Figure 5.1 below shows a graphical representation of the Markov model for this deterioration model application.

![Markov Chain Model for Deck Condition Ratings]

Figure 5.1: Markov Chain Model for Deck Condition Ratings
In the particular chain above, the random variable, \( d \), represents the deck condition ratings over time. Therefore, \( d_1 \) represents the deck rating at the first time step. The arrows between each time step represent the probabilistic dependencies between the each time step. For the purpose of this model, the time step is one year. The chain structure depicts how the Markov model works, which as explained before, is a model in which a random variable in a particular time step is only conditionally dependent of the value of this variable at the immediate previous time step. Thus, in order to make a prediction using this particular model, it is necessary to know the initial condition of a particular process or random variable, and the probability of transition of this process through time.

5.2 Development of Transitional Probability Matrix

In order to develop the transitional probability matrices required to create a Markov chain prediction model per state, a frequency analysis was carried out to determine how often the deck condition ratings changed every year. A looping algorithm in MATLAB, also included in Appendix A, was developed to go through each bridge and each deck rating and count the frequency in which a particular rating changed from one number to another, regardless of whether it increased or decreased. Counters were utilized to store the number of times a deck rating changed from a particular number to another. Since none of the data sets for the deck condition ratings in any of the states contained a rating of zero, counters were only established for ratings from nine to one. This meant there were a total of 100 counters established in order to account for every possible transition between all ten ratings. For instance, if a rating went from eight to seven a total of 150 times in a particular dataset, then 150 would be the frequency stored for this particular transition or counter. Once the
frequencies for each of the 100 different transitions were computed for a particular state, each frequency was then divided by the total number of transitions in the dataset in order to obtain the different transition probabilities. These were then summarized in the form of transition matrices per state in order to be used for the Markov prediction model.

The method used to calculate these probabilities, as explained above, was purely based on the inspection data collected over the past twenty years. This allows for a purely probabilistic model based solely on observed bridge deck conditions. Because maintenance was not taken out of these calculations, that is the instances in which the ratings went up were also counted, this transition matrix does not have only zeros below its diagonal, meaning that all states had the possibility to be recurrent. This particular model thus accounts for maintenance and/or inspection error in its prediction, as those factors do contribute to the actual deck rating progression over time. Figure 5.2 shows the transition matrix for the State of Delaware. Appendix O contains the transition matrices for all the other thirteen states analyzed in this study. Although all the matrices were pretty similar for each state, no two states had the same transition matrix. For the most part, however, the ratings of seven and six were the most recurring ones among the different states. That was concluded from the fact that the transition probabilities into these two ratings were higher in comparison to the others consistently.
\[
\begin{array}{cccccccc}
9 & 8 & 7 & 6 & 5 & 4 & 3 & 2 & 1 \\
9 & 0.13 & 0.24 & 0.40 & 0.10 & 0.11 & 0.03 & 0 & 0 & 0 \\
8 & 0.03 & 0.27 & 0.55 & 0.08 & 0.03 & 0.03 & 0 & 0 & 0 \\
7 & 0.01 & 0.15 & 0.58 & 0.18 & 0.06 & 0.02 & 0 & 0 & 0 \\
6 & 0.01 & 0.14 & 0.49 & 0.25 & 0.09 & 0.02 & 0 & 0 & 0 \\
5 & 0.02 & 0.06 & 0.57 & 0.19 & 0.11 & 0.04 & 0.01 & 0 & 0 \\
4 & 0 & 0.10 & 0.46 & 0.28 & 0.08 & 0.03 & 0.01 & 0 & 0 \\
3 & 0 & 0.14 & 0.25 & 0.25 & 0.29 & 0.07 & 0 & 0 & 0 \\
2 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\end{array}
\]

Figure 5.2: Transition Probability Matrix for Deck Condition Ratings in Delaware

5.3 Deck Rating Prediction

Using equations 2.2 and 2.3, prediction histograms were produced using different initial condition matrices for all fourteen states. For the initial condition matrix, it was assumed that the current (latest) deck condition rating for a particular bridge was known. Therefore, the initial condition matrix for each scenario shown below is made up of all zeros and a one, meaning that the initial condition rating is known. Figures 5.3, 5.4, and 5.5 show the one, five, ten, twenty five, fifty year, and steady state predictions for bridges in Delaware with initial deck ratings of nine, seven and two respectively.
Figure 5.3: Prediction Histogram Starting at Deck Rating of 9

Figure 5.4: Prediction Histogram Starting at Deck Rating of 7
As it can be observed in Figures 5.3, 5.4, and 5.5, the Markov model for deterioration rates in Delaware stabilizes quite quickly. The probabilities of deterioration after five years are quite similar to the steady state ones in each of the four cases above. Also, it can be observed that in the one instance where a deck rating of two was recorded (Figure 5.5), the bridge was presumably maintained, as the rating jumped to a rating of seven within a year. This is proof that using this particular model, maintenance and potential inspection error were taken into account to formulate the predictions. With this model, it is possible to make a prediction in the deck rating progression of a particular bridge given its current stage. For instance, when looking at Figure 5.4, it can be said that if a bridge in Delaware is currently at stage seven, after one year there is an 89% change that it will be in either stage six, seven, or eight. Additionally, when looking at the steady state probabilities, it can be
argued that a deck rating of seven is the most likely recurrent stage in the model in comparison to the other ratings.

Appendix P has sample bar graphs for each of the thirteen remaining states analyzed in this study. Similar results to the ones shown for Delaware above were obtained for all other states analyzed. The most likely recurring deck ratings were seven and eight across the board. All the states stabilized pretty quickly as well. It is important to note that the transition matrices can and should be updated as new yearly ratings come in per state. This will not only increase the level of accuracy of the model, but it can provide new matrices that can be compared to the ones developed in this study.
Chapter 6

CONCLUSIONS

6.1 Summary

The objective of this thesis was to develop a concrete bridge deck deterioration prediction model based on inspection information, actual design and construction parameters, and environmental factors. The goal was to create a model based on probabilistic methods relying on statistical data and develop a database of information that could be learned by the model and used to formulate a prediction. It was desired to stay away from using methods based on experimental data and instead rely on observed and known conditions of actual in-service bridges.

As data was analyzed, the focus of this study quickly became the National Bridge Inventory (NBI) database, which provided a wide range of information pertaining to the design, deterioration, and service life conditions of bridges in all fifty states of the United States, plus the District of Columbia and Puerto Rico. Chapter 3 of this thesis explains the method by which key parameters from this database were selected because of the potential influence these had to deck deterioration. Additionally, other parameters were selected as filters in order to organize the data into useful databases effectively. It is important to note that for the purpose of this study, only fourteen states were analyzed chosen strategically to represent seven different climatic regions in the continental United States. By doing this, it was hoped that environmental effects on concrete deck deterioration could be observed indirectly through regional patterns.
Chapter 4 of this thesis described the process by which the selected parameters were processed, statistically analyzed, and compared to deck deterioration rates and ratings. The goal was to further identify which of these actually had a significant effect on the deck condition ratings. After no significant relationships were found, a prediction model was developed with the information gathered in Chapter 4. This prediction model was developed using the Markov chain model described in Chapter 2. Then, in Chapter 5 of this thesis, the model for this particular study is explained in detail, and sample predictions were presented and discussed.

6.2 Results

As a result of this study, a Markov chain model was developed for each state that could predict deck condition ratings as defined in the NBI database guide, given that the current state of the bridge is known. The predictions were summarized in bar graphs and were carried out to one year, five years, ten years, twenty-five years, and fifty years. Additionally, the steady state probabilities were also calculated for each of the fourteen states.

In addition to this prediction model, important conclusions were drawn from this study. Most notably, through this study it was found that there is very little correlation between any parameter as recorded in the NBI database and concrete bridge deck deterioration. It also became apparent that based on deck condition ratings solely, no conclusions can be drawn on how bridges in similar climatic regions experience comparable deck deterioration rates. Perhaps this can be attributed to the fact that different states have different particular design requirements based on the environmental and service needs of their bridges, and some of these might offset the effects of climatic factors on the decks.
Through the data analysis it was also found that there is a certain level of subjectivity and error that could be present in the NBI condition ratings. As discussed in Chapter 4 of this thesis, condition ratings for the bridge decks sometimes went up and down by one or two ratings in a manner that seemed to be inconsistent to maintenance. It can be argued that because these ratings come directly from inspections, there might be some subjectivity in these as inspectors change. This can lead to some inconsistencies when trying to observe true deterioration. However, if the goal is to predict the condition ratings, these inconsistencies cannot be ignored but instead must be taken in as a variable in the model. Hence the reason why both maintenance and presumed inspection error were taken into account when developing the Markov model in Chapter 5.

After conducting this analysis, it was also concluded that in order to create a better prediction model, quantitative inspection data could be a more powerful data source. For instance, having actual measurement such as Ground Penetrating Radar (GPR) readings in order to establish an actual depth of cover could help rid of one level of subjectivity in the model. Using actual measurements and establishing correlations between these and deck condition ratings could potentially lead to more conclusive results. This idea will further be discussed in Section 6.3.

6.3 Future Work

There are several probabilistic methods and different data sources that can be further explored in order to create a prediction model with more enhanced capabilities. One of the first things that could be studied is the development of a Dynamic Bayesian Network (DBN) as described in Chapter 2 that is only based in a single parameter as a baseline. Instead of looking at the multi-parameter model, a
simpler DBN could be created similarly to the way the Markov chain in Chapter 5 of the thesis was developed. Initial probabilities for this model could be obtained using the same looping algorithm used to create the transition probability matrix in this thesis. Then the model could be updated by adding the observed deck values so that the transition probabilities became updated every time a new rating comes in. This would add a new level of complexity to the model developed in this thesis and could become the basis for a more complex multi-parameter model.

As discussed in the previous section, using measured data of actual deck conditions could enhance the prediction model. Measured quantitative data could lead to more conclusive correlations between measured parameters and the deterioration rates. These parameters can then be easily added into a DBN and updated as new observations come in, thus enhancing the learning capabilities of the model. In addition, adding environmental data such as rain cycle and atmospheric deposition information can also refine the predictions. Another area that can be further be explored is the addition of design parameters as defined by each state in their respective design manuals. These could then be added into the model as additional parameters or initial conditions.

Finally, it could be interesting to investigate parameters that are not based on engineering knowledge but instead relate to the decision-making when it comes to bridge maintenance in each state. Looking at factors such as federal and state funding for bridge maintenance and repair, as well as the importance of bridge maintenance to constituents could provide a different set of factors that could contribute indirectly to concrete bridge deck deterioration.
REFERENCES


Appendix A

SAMPLE MATLAB ALGORITHM

%% Sorting NBI Database Files
clear
clc
clf

%% Loading Data Script
fPath = uigetdir('.','
'./Users/marianacruz/Documents/MATLAB/Research/Reading NBI Records');

if fPath==0
    error('no folder selected');
end

fNames = dir( fullfile(fPath,'*.txt') );
fNames = strcat(fPath, filesep, {fNames.name});

for i=1:length(fNames);
    out{i}=importfiled(fNames{i});
end

%% Deleting Unnecessary Columns
for i=1:21;
    out{1,i}(:, 'VarName6')=[];
    out{1,i}(:, 'VarName9')=[];
    out{1,i}(:, 'VarName11')=[];
    out{1,i}(:, 'VarName15')=[];
    out{1,i}(:, 'VarName19')=[];
    out{1,i}(:, 'VarName22')=[];
    out{1,i}(:, 'VarName25')=[];
    out{1,i}(:, 'VarName27')=[];
    out{1,i}(:, 'VarName30')=[];
    out{1,i}(:, 'VarName34')=[];
    out{1,i}(:, 'VarName36')=[];
    out{1,i}(:, 'VarName38')=[];
    out{1,i}(:, 'VarName41')=[];
    out{1,i}(:, 'VarName44')=[];
    out{1,i}(:, 'VarName46')=[];
    out{1,i}(:, 'VarName48')=[];
    out{1,i}(:, 'VarName55')=[];
end
%% Keeping only Concrete Deck Bridges
for i=1:21;
    out{1,i}.DeckStructureType(isnan(out{1,i}.DeckStructureType))=0;
    out{1,i}(out{1,i}.DeckStructureType == 3,:)=[];
    out{1,i}(out{1,i}.DeckStructureType == 4,:)=[];
    out{1,i}(out{1,i}.DeckStructureType == 5,:)=[];
    out{1,i}(out{1,i}.DeckStructureType == 6,:)=[];
    out{1,i}(out{1,i}.DeckStructureType == 7,:)=[];
    out{1,i}(out{1,i}.DeckStructureType == 8,:)=[];
    out{1,i}(out{1,i}.DeckStructureType == 9,:)=[];
    out{1,i}(out{1,i}.DeckStructureType == 0,:)=[];
end

%% Taking out Culverts
for i=1:21;
    out{1,i}.Deck(isnan(out{1,i}.Deck))=0;
    out{1,i}.Superstructure(isnan(out{1,i}.Superstructure))=0;
    out{1,i}.Substructure(isnan(out{1,i}.Substructure))=0;
    out{1,i}(out{1,i}.Deck == 0,:)=[];
    out{1,i}(out{1,i}.Superstructure == 0,:)=[];
    out{1,i}(out{1,i}.Substructure == 0,:)=[];
end

%% Filter Out Only Route on Structure Cases
for i=1:21;
    out{1,i}(out{1,i}.RecordType5A == 2,:)=[];
end

%% Filter out Arch with Approach Roadway Section Carried
for i=1:21;
    out{1,i}.DeckProtection108C(isnan(out{1,i}.DeckProtection108C))=10;
    out{1,i}.TypeOfMembrane108B(isnan(out{1,i}.TypeOfMembrane108B))=10;
    out{1,i}.TypeOfWearingSurface108A(isnan(out{1,i}.TypeOfWearingSurface108A))=10;
    out{1,i}(out{1,i}.DeckProtection108C == 10,:)=[];
    out{1,i}(out{1,i}.TypeOfMembrane108B == 10,:)=[];
    out{1,i}(out{1,i}.TypeOfWearingSurface108A == 10,:)=[];
end

%% Adding year
yr=1991;
for i=1:21;
    yr = yr + 1;
    out{1,i}.Var39(:,1)=yr;
end
Calculating Deck Deterioration Rate

for i=1:21; % Deleting inconsistent structure numbers
    out{1,i}(out{1,i}.StructureNumber > 30000,:)=[];
    out{1,i}(isnan(out{1,i}.StructureNumber),:)=[];
    out{1,i}(out{1,i}.StructureNumber < 1,:) =[];
end

ddeckdata=[1:3000]'; % Creating deck rating matrix organized by structure number

for i=1:21;
    [n, bin] = histc(out{1,i}.StructureNumber, unique(out{1,i}.StructureNumber));
    multiple = find(n > 1);
    index = find(ismember(bin, multiple));
    for j=index;
        out{1,i}(j,:)=[];
    end
end

d= deckdata';
for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = d;
        for n = s;
            if m == n;
                [r,c] = find(deckdata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                deckdata(r,i+1)=out{1,i}.Deck(r1,1);
                continue
            end
        end
    end
end

deckdata(deckdata(:,2)== 0 & deckdata(:,3) == 0 & deckdata(:,4) == 0 & deckdata(:,5) == 0 & deckdata(:,6) == 0 & deckdata(:,7) == 0 & deckdata(:,8) == 0 ... & deckdata(:,9) == 0 & deckdata(:,10) == 0 & deckdata(:,11) ==0 & deckdata(:,12) == 0 & deckdata(:,13) == 0 & deckdata(:,14) == 0 ... & deckdata(:,15) == 0 & deckdata(:,16) == 0 & deckdata(:,17) ==0 & deckdata(:,18) == 0 & deckdata(:,19) == 0 & deckdata(:,20) == 0 ... & deckdata(:,21) == 0 & deckdata(:,22) == 0, :)=[];

deckdata(deckdata(:,1)==0, :)=[];
deckdata(deckdata==0)=NaN;

yr=1991;  % Creating year matrix
for i=1:21;
    yr = yr + 1;
    year(1:length(deckdata),i)=yr;
end

% Deck Deterioration Transition Probability Matrix
deckdata(isnan(deckdata))=10;
n = length(deckdata)-1;
p = zeros(10,10);
for i=2:21;
    for t = 1:n
        p(deckdata(t,i), deckdata(t + 1,i)) = p(deckdata(t,i),
        deckdata(t + 1,i)) + 1;
    end
end
for j = 1:10
    p(j, :) = p(j, :) / sum(p(j, :));
end
for i=1:10
    p(i,:)=p(i,:)/(1-p(i,10));
end
p(:,10)=[];
p(10,:)=[];
p(isnan(p))=0;
deckdata(deckdata==10)=0;

% Deck Deterioration Rate (including maintenance)
for i=1:length(deckdata);
    x=find(deckdata(i,2:22),1,'first');
    y=find(deckdata(i,2:22),1,'last');
    a=deckdata(i,x+1);
    b=deckdata(i,y+1);
    deckdata(i,23)=(a-b)/(y-x);
end

deckdata(isnan(deckdata(:,23)),23)=0;

avgdetm =mean(deckdata(:,23));

disp('Average Deteriorarion Rate w/ Maintenance='), disp(avgdetm)

% Deck Deterioration Rate (without maintenance)

g=0;
k=0;
z=0;

for i=1:length(deckdata);
    x=find(deckdata(i,2:22));
    for j=1:(length(x)-1);
        if deckdata(i,x(j)+1) > deckdata(i,x(j+1)+1);
            k=(deckdata(i,x(j)+1)-deckdata(i,x(j+1)+1));
        else
            k=0;
            continue
        end
        z=g+k;
        g=z;
    end
    deckdata(i,24)=z/(x(length(x))-x(1));
    k=0;
    g=0;
    z=0;
end

deckdata(isnan(deckdata(:,24)),24)=0;

avgdetnm= mean(deckdata(:,24));

disp('Average Deteriorarion Rate w/o Maintenance='), disp(avgdetnm)

%%% Editing Parameters in Database

% Coverting ADTT Percentage to a Number

for i=1:21;
    x = find(strcmp('  ',out{1,i}.ADTT));
    for j=1:length(x);
        out{1,i}.ADTT{x(j,1)}='00';
    end
end
for i=1:21;
    for j=1:length(out{1,i}.ADTT);
        a=out{1,i}.ADTT(j,1);
        a1=cell2mat(a);
        b=str2num(a1);
        out{1, i}.Var40(j,1) = (b/100)*out{1,i}.ADT(j,1);
    end
end

% Getting Lengths in Right Units

for i=1:21;
    for j=1:length(out{1,i}.StructureLength);
        a=out{1,i}.StructureLength(j,1);
        out{1, i}.StructureLength(j,1) = a/10;
    end
end

for i=1:21;
    for j=1:length(out{1,i}.LengthOfMaximunSpan);
        a=out{1,i}.LengthOfMaximunSpan(j,1);
        out{1, i}.LengthOfMaximunSpan(j,1) = a/10;
    end
end

%%% Correlation Between Deterioration Rate and Time-Invariant Parameters

% Design Load

designloaddata=[1:3000]';
designload= designloaddata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = designload;
        for n = s;
            if m == n;
                [r,c] = find(designloaddata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                designloaddata(r,i+1)=out{1,i}.DesignLoad(r1,1);
                continue
            end
        end
    end
end

q = deckdata(:,1);
w = designloaddata(:,1);
v=ismember(w,q);
index=find(v == 0);
for i = index;
    designloaddata(i,:)=[];
end

for i=1:length(deckdata);
    x=find(designloaddata(i,2:22),1,'first');
    if isempty(x)
        a=NaN;
        continue
    end
    a=designloaddata(i,x+1);
    designloaddata(i,23)=a;
end

% Functional Classification of Road
funclassdata=[1:3000]';
funclass= funclassdata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = funclass;
        for n = s;
            if m == n;
                [r,c] = find(funclassdata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);

                funclassdata(r,i+1)=out{1,i}.FunctionalClassificationOfInventoryRoute(r1,1);
                continue
            end
        end
    end
end

g = deckdata(:,1);
ww = funclassdata(:,1);
v=ismember(ww,q);
index=find(v == 0);
for i = index;
    funclassdata(i,:)=[];
end

for i=1:length(deckdata);
    x=find(funclassdata(i,2:22),1,'first');
    if isempty(x)
        a=NaN;
        continue
    end
a=funclassdata(i,x+1);
funclassdata(i,23)=a;
end

% Year Built

yearbuiltdata=[1:3000]';

yearbuilt= yearbuiltdata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = yearbuilt;
        for n = s;
            if m == n;
                [r,c] = find(yearbuiltdata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                yearbuiltdata(r,i+1)=out{1,i}.YearBuilt(r1,1);
                continue
            end
        end
    end
end

q = deckdata(:,1);
w = yearbuiltdata(:,1);
v=ismember(w,q);
index=find(v == 0);
for i = index;
    yearbuiltdata(i,:)=[];
end

for i=1:length(deckdata);
    x=find(yearbuiltdata(i,2:22),1,'first');
    if isempty(x)
        a=NaN;
        continue
    end
    a=yearbuiltdata(i,x+1);
    yearbuiltdata(i,23)=a;
end

dekyearm=corr(yearbuiltdata(:,23),deckdata(:,23));
dekyearnm=corr(yearbuiltdata(:,23),deckdata(:,24));

disp('Linear Corr Year Built w/ Maintenace='), disp(dekyearm)
disp('Linear Corr Year Built w/o Maintenace='), disp(dekyearnm)

% Type of Service
typeserdata=[1:3000]';

typeser= typeserdata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = typeser;
        for n = s;
            if m == n;
                [r,c] = find(typeserdata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                typeserdata(r,i+1)=out{1,i}.TypeOfServiceOnBridge42A(r1,1);
                continue
            end
        end
    end
end

q = deckdata(:,1);
w = typeserdata(:,1);
v=ismember(w,q);
index=find(v == 0);
for i = index;
    typeserdata(i,:)=[];
end

for i=1:length(deckdata);
    x=find(typeserdata(i,2:22),1,'first');
    if isempty(x)
        a=NaN;
        continue
    end
    a=typeserdata(i,x+1);
    typeserdata(i,23)=a;
end

% Structure Material
strmatdata=[1:3000]';

strmat= strmatdata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = strmat;
        for n = s;
            if m == n;
                [r,c] = find(strmatdata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                strmatdata(r,i+1)=out{1,i}.StructureTypeMaterial43A(r1,1);
q = deckdata(:,1);
w = strmatdata(:,1);
v = ismember(w, q);
index = find(v == 0);
for i = index;
    strmatdata(i, :) = [];
end

for i = 1:length(deckdata);
    x = find(strmatdata(i, 2:22), 1, 'first');
    if isempty(x)
        a = NaN;
        continue
    end
    a = strmatdata(i, x + 1);
    strmatdata(i, 23) = a;
end

% Structure Type
strtypedata = [1:3000]';

strtype = strtypedata';

for i = 1:21;
    s = out{1, i}.StructureNumber';
    for m = strtype;
        for n = s;
            if m == n;
                [r, c] = find(strtypedata == m);
                [r1, c1] = find(out{1, i}.StructureNumber == n);
                strtypedata(r, i + 1) = out{1, i}.StructureType43B(r1, 1);
                continue
            end
        end
    end
end

q = deckdata(:, 1);
w = strtypedata(:, 1);
v = ismember(w, q);
index = find(v == 0);
for i = index;
    strtypedata(i, :) = [];
end
for i=1:length(deckdata);
    x=find(strtypedata(i,2:22),1,'first');
    if isempty(x)
        a=NaN;
        continue
    end
    a=strtypedata(i,x+1);
    strtypedata(i,23)=a;
end

% Route Prefix

rtprefixdata=[1:3000]';

rtprefix = rtprefixdata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = rtprefix;
        for n = s;
            if m == n;
                [r,c] = find(rtprefixdata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                rtprefixdata(r,i+1)=out{1,i}.RoutePrefix5B(r1,1);
                continue
            end
        end
    end
end

q = deckdata(:,1);
w = rtprefixdata(:,1);
v=ismember(w,q);
index=find(v == 0);
for i = index;
    rtprefixdata(i,:)=[];
end

for i=1:length(deckdata);
    x=find(rtprefixdata(i,2:22),1,'first');
    if isempty(x)
        a=NaN;
        continue
    end
    a=rtprefixdata(i,x+1);
    rtprefixdata(i,23)=a;
end

% Service Level
serleveldata = [1:3000]';
serlevel = serleveldata';

for i = 1:21;
    s = out{1,i}.StructureNumber';
    for m = serlevel;
        for n = s;
            if m == n;
                [r,c] = find(serleveldata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                serleveldata(r,i+1) = out{1,i}.ServiceLevel5C(r1,1);
                continue
            end
        end
    end
end

q = deckdata(:,1);
w = serleveldata(:,1);
v = ismember(w,q);
index = find(v == 0);
for i = index;
    serleveldata(i,:) = [];
end

for i = 1:length(deckdata);
    x = find(serleveldata(i,2:22), 1, 'first');
    if isempty(x)
        a = NaN;
        continue
    end
    a = serleveldata(i,x+1);
    serleveldata(i,23) = a;
end

% Lanes on Structure
lanesdata = [1:3000]';
lanes = lanesdata';

for i = 1:21;
    s = out{1,i}.StructureNumber';
    for m = lanes;
        for n = s;
            if m == n;
                [r,c] = find(lanesdata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                lanesdata(r,i+1) = out{1,i}.LanesOnStructure(r1,1);
                continue
            end
        end
    end
end
end
end

q = deckdata(:,1);
w = lanesdata(:,1);
v=ismember(w,q);
index=find(v == 0);
for i = index;
    lanesdata(i,:)=[];
end

for i=1:length(deckdata);
    x=find(lanesdata(i,2:22),1,'first');
    if isempty(x)
        a=NaN;
        continue
    end
    a=lanesdata(i,x+1);
    lanesdata(i,23)=a;
end

decklanesm=corr(lanesdata(:,23),deckdata(:,23));
decklanesnm=corr(lanesdata(:,23),deckdata(:,24));

disp('Linear Corr Lanes w/ Maintenance='), disp(decklanesm)
disp('Linear Corr Lanes w/o Maintenance='), disp(decklanesnm)

% Number of Spans

spansdata=[1:3000]';

spans= spansdata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = spans;
        for n = s;
            if m == n;
                [r,c] = find(spansdata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                spansdata(r,i+1)=out{1,i}.NumberOfSpansInMainUnit(r1,1);
                continue
            end
        end
    end
end

g = deckdata(:,1);
w = spansdata(:,1);
v=ismember(w,g);

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index=find(v == 0);
for i = index;
    spansdata(i,:)=[ ];
end

for i=1:length(deckdata);
    x=find(spansdata(i,2:22),1,'first');
    if isempty(x)
        a=NaN;
        continue
    end
    a=spansdata(i,x+1);
    spansdata(i,23)=a;
end

dekspansm=corr(spansdata(:,23),deckdata(:,23));
dekspansnm=corr(spansdata(:,23),deckdata(:,24));

disp('Linear Corr Spans w/ Maintenance='), disp(dekspansm)
disp('Linear Corr Spans w/o Maintenance='), disp(dekspansnm)

% Max Span Length
maxspandata=[1:3000]';
maxspan= maxspandata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = maxspan;
        for n = s;
            if m == n;
                [r,c] = find(maxspandata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                maxspandata(r,i+1)=out{1,i}.LengthOfMaximunSpan(r1,1);
                continue
            end
        end
    end
end

q = deckdata(:,1);
w = maxspandata(:,1);
v=ismember(w,q);
index=find(v == 0);
for i = index;
    maxspandata(i,:)=[ ];
end

for i=1:length(deckdata);
    x=find(maxspandata(i,2:22),1,'last');
    if isempty(x)
a=NaN;
continue
a=maxspandata(i,x+1);
maxspandata(i,23)=a;
end

dekmaxspanm=corr(maxspandata(:,23),deckdata(:,23));
dekmaxspannm=corr(maxspandata(:,23),deckdata(:,24));

disp('Linear Corr Max Span w/ Maintenance='), disp(dekmaxspanm)
disp('Linear Corr Max Span w/o Maintenance='), disp(dekmaxspannm)

% Structure Length
lengthdata=[1:3000]';

lengthd = lengthdata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = lengthd;
        for n = s;
            if m == n;
                [r,c] = find(lengthdata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                lengthdata(r,i+1)=out{1,i}.StructureLength(r1,1);
                continue
            end
        end
    end
end

q = deckdata(:,1);
w = lengthdata(:,1);
v=ismember(w,q);
index=find(v == 0);
for i = index;
    lengthdata(i,:)=[];
end

for i=1:length(deckdata);
    x=find(lengthdata(i,2:22),1,'last');
    if isempty(x)
        a=NaN;
        continue
    end
    a=lengthdata(i,x+1);
    lengthdata(i,23)=a;
end

deklengthm=corr(lengthdata(:,23),deckdata(:,23));
deklengthnm=corr(lengthdata(:,23),deckdata(:,24));
disp('Linear Corr Length w/ Maintenance='), disp(decklengthm)
disp('Linear Corr Length w/o Maintenance='), disp(decklengthnm)

% Type of Wearing Surface

wearsurfdata=[1:3000]';

wearsurf= wearsurfdata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = wearsurf;
        for n = s;
            if m == n;
                [r,c] = find(wearsurfdata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                wearsurfdata(r,i+1)=out{1,i}.TypeOfWearingSurface108A(r1,1);
                continue
            end
        end
    end
end

q = deckdata(:,1);
w = wearsurfdata(:,1);
v=ismember(w,q);
index=find(v == 0);
for i = index;
    wearsurfdata(i,:)=[];
end

for i=1:length(deckdata);
    x=find(wearsurfdata(i,2:22),1,'first');
    if isempty(x)
        a=NaN;
        continue
    end
    a=wearsurfdata(i,x+1);
    wearsurfdata(i,23)=a;
end

% Type of Membrane

membranedata=[1:3000]';

membrane= membranedata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = membrane;
for n = s;
    if m == n;
        [r,c] = find(membranedata == m);
        [r1,c1] = find(out{1,i}.StructureNumber == n);
        membranedata(r,i+1)=out{1,i}.TypeOfMembrane108B(r1,1);
        continue
    end
end
end

g = deckdata(:,1);
w = membranedata(:,1);
v=ismember(w,q);
index=find(v == 0);
for i = index;
    membranedata(i,:)=[];
end
for i=1:length(deckdata);
    x=find(membranedata(i,2:22),1,'first');
    if isempty(x)
        a=NaN;
        continue
    end
    a=membranedata(i,x+1);
    membranedata(i,23)=a;
end

% Deck Protection

deckprodata=[1:3000]';
deckpro= deckprodata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = deckpro;
        for n = s;
            if m == n;
                [r,c] = find(deckprodata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                deckprodata(r,i+1)=out{1,i}.DeckProtection108C(r1,1);
                continue
            end
        end
    end
end

g = deckdata(:,1);
w = deckprodata(:,1);
v=ismember(w,q);
index=find(v == 0);
for i = index;
    deckprodata(i,:)=[];
end

for i=1:length(deckdata);
    x=find(deckprodata(i,2:22),1,'first');
    if isempty(x)
        a=NaN;
        continue
    end
    a=deckprodata(i,x+1);
    deckprodata(i,23)=a;
end

deckdeckprom=corr(deckprodata(:,23),deckdata(:,23));
deckdeckpronm=corr(deckprodata(:,23),deckdata(:,24));

disp('Linear Corr Protection w/ Maintenance='), disp(deckdeckprom)
disp('Linear Corr Protection w/o Maintenance='), disp(deckdeckpronm)

%% Correlation between the Deck Deterioration Rating and Time-Variant Parameters

deqdata(deckdata==0)=NaN;

% ADT

adtdata=[1:3000]';

adt= adtdata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = adt;
        for n = s;
            if m == n;
                [r,c] = find(adtdata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                adtdata(r,i+1)=out{1,i}.ADT(r1,1);
                continue
            end
        end
    end
end

q = deckdata(:,1);
w = adtdata(:,1);
v=ismember(w,q);

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index=find(v == 0);
for i = index;
    adtdata(i,:)=[];
end

adtdata(adtdata==0)=NaN;

deckadt=corr(adtdata(:,2:22),deckdata(:,2:22),'rows','pairwise');
deckadtcoef=corrcoef(adtdata(:,2:22),deckdata(:,2:22),'rows','pairwise');

disp('Linear Corr ADT and Deck Rating='), disp(deckadtcoef(1,2))

% ADTT

adttdata=[1:30000]';
adtt= adttdata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = adtt;
        for n = s;
            if m == n;
                [r,c] = find(adtdata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                adtdata(r,i+1)=out{1,i}.Var40(r1,1);
                continue
            end
        end
    end
end

q = deckdata(:,1);
w = adttdata(:,1);
v=ismember(w,q);
index=find(v == 0);
for i = index;
    adtdata(i,:)=[];
end

adtdata(adtdata==0)=NaN;

deckadtt=corr(adttdata(:,2:22),deckdata(:,2:22),'rows','pairwise');
deckadttcoef=corrcoef(adttdata(:,2:22),deckdata(:,2:22),'rows','pairwise');

disp('Linear Corr ADTT and Deck Rating='), disp(deckadttcoef(1,2))

% Inspection Period
freqdata=[1:3000]';

freq= freqdata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = freq;
        for n = s;
            if m == n;
                [r,c] = find(freqdata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                freqdata(r,i+1)=out{1,i}.InspectionFrequency(r1,1);
                continue
            end
        end
    end
end

q = deckdata(:,1);
w = freqdata(:,1);
v=ismember(w,q);
index=find(v == 0);
for i = index;
    freqdata(i,:)=[];
end

freqdata(freqdata==0)=NaN;

deckfreq=corr(freqdata(:,2:22),deckdata(:,2:22),'rows','pairwise');
deckfreqcoef=corrcoef(freqdata(:,2:22),deckdata(:,2:22),'rows','pairwise');

disp('Linear Corr Inspection Period and Deck Rating='),
disp(deckfreqcoef(1,2))

% Bridge Posting

postdata=[1:3000]';

post= postdata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = post;
        for n = s;
            if m == n;
                [r,c] = find(postdata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                postdata(r,i+1)=out{1,i}.BridgePosting(r1,1);
                continue
            end
        end
    end
end
end

q = deckdata(:,1);
w = postdata(:,1);
v = ismember(w,q);
index = find(v == 0);
for i = index;
    postdata(i,:) = [];
end

postdata(postdata==0)=NaN;
depost = corr(postdata(:,2:22),deckdata(:,2:22),'rows','pairwise');
depostcoef = corrcoef(postdata(:,2:22),deckdata(:,2:22),'rows','pairwise');
disp('Linear Corr Bride Posting and Deck Rating='),
disp(deckpostcoef(1,2))

% Superstructure

superdata = [1:3000]';
super = superdata';
for i = 1:21;
    s = out{1,i}.StructureNumber';
    for m = super;
        for n = s;
            if m == n;
                [r,c] = find(superdata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                superdata(r,i+1)=out{1,i}.Superstructure(r1,1);
            continue
            end
        end
    end
end

q = deckdata(:,1);
w = superdata(:,1);
v = ismember(w,q);
index = find(v == 0);
for i = index;
    superdata(i,:) = [];
end

superdata(superdata==0)=NaN;
deksupercorr = corr(superdata(:,2:22),deckdata(:,2:22),'rows','pairwise');
deksupercorcoef = corrcoef(superdata(:,2:22),deckdata(:,2:22),'rows','pairw
rwise');

disp('Linear Corr Superstructure and Deck Rating='),
disp(decksupercoef(1,2))

% Substructure

subdata=1:3000';

sub= subdata';

for i=1:21;
    s = out{1,i}.StructureNumber';
    for m = sub;
        for n = s;
            if m == n;
                [r,c] = find(subdata == m);
                [r1,c1] = find(out{1,i}.StructureNumber == n);
                subdata(r,i+1)=out{1,i}.Substructure(r1,1);
                continue
            end
        end
    end
end

q = deckdata(:,1);
w = subdata(:,1);
v=ismember(w,q);
index=find(v == 0);
for i = index;
    subdata(i,:)=[];
end
subdata(subdata==0)=NaN;

deksub=corr(subdata(:,2:22),deckdata(:,2:22),'rows','pairwise');
deksubcoef=corrcoef(subdata(:,2:22),deckdata(:,2:22),'rows','pairwise');

disp('Linear Corr Substructure and Deck Rating='),
disp(deksubcoef(1,2))

%% Statistics on Deterioration Rate

dekdata(isnan(deckdata(:,24)),24)=0;
dekdata(isnan(deckdata(:,23)),23)=0;

figure(17)
hist(deckdata(:,24))
title('Deterioration without Maintenance')
avgdetnm = mean(deckdata(:, 24));
disp('Average Deterioration Rate w/o Maintenance'), disp(avgdetnm)

stdnm = std(deckdata(:, 24));
disp('STDV Deterioration Rate w/o Maintenance'), disp(stdnm)

figure(18)
hist(deckdata(:, 23))
title('Deterioration with Maintenance')

avgdetm = mean(deckdata(:, 23));
disp('Average Deterioration Rate w/ Maintenance'), disp(avgdetm)

stdm = std(deckdata(:, 23));
disp('STDV Deterioration Rate w/ Maintenance'), disp(stdm)

% Transition Matrix Calculations
par = [p(9, 9) p(9, 8) p(9, 7) p(9, 6) p(9, 5) p(9, 4) p(9, 3) p(9, 2)
p(9, 1); p(8, 9) ...
p(8, 8) p(8, 7) p(8, 6) p(8, 5) p(8, 4) p(8, 3) p(8, 2) p(8, 1); p(7, 9)
p(7, 8) ... 
p(7, 7) p(7, 6) p(7, 5) p(7, 4) p(7, 3) p(7, 2) p(7, 1); p(6, 9) p(6, 8)
p(6, 7) ... 
p(6, 6) p(6, 5) p(6, 4) p(6, 3) p(6, 2) p(6, 1); p(5, 9) p(5, 8) p(5, 7)
p(5, 6) ...
p(5, 5) p(5, 4) p(5, 3) p(5, 2) p(5, 1); p(4, 9) p(4, 8) p(4, 7) p(4, 6)
p(4, 5) ... 
p(4, 4) p(4, 3) p(4, 2) p(4, 1); p(3, 9) p(3, 8) p(3, 7) p(3, 6) p(3, 5)
p(3, 4) ...
p(3, 3) p(3, 2) p(3, 1); p(2, 9) p(2, 8) p(2, 7) p(2, 6) p(2, 5) p(2, 4)
p(2, 3) ...
p(2, 2) p(2, 1); p(1, 9) p(1, 8) p(1, 7) p(1, 6) p(1, 5) p(1, 4) p(1, 3)
p(1, 2) p(1, 1)];

% Steady State Probability
[V D] = eigs(par');
pss = V(:, 1)/sum(V(:, 1));

% Starting at rating 9
p91 = [1 0 0 0 0 0 0 0 0]*par;
p95 = [1 0 0 0 0 0 0 0 0]*par^5;
p910 = [1 0 0 0 0 0 0 0 0]*par^10;
p925 = [1 0 0 0 0 0 0 0 0]*par^25;
\begin{verbatim}

p950 = [1 0 0 0 0 0 0 0 0]*par^50;
p9s9 = [p91(1,1) p95(1,1) p910(1,1) p925(1,1) p950(1,1) pss(1,1)];
p9s8 = [p91(1,2) p95(1,2) p910(1,2) p925(1,2) p950(1,2) pss(2,1)];
p9s7 = [p91(1,3) p95(1,3) p910(1,3) p925(1,3) p950(1,3) pss(3,1)];
p9s6 = [p91(1,4) p95(1,4) p910(1,4) p925(1,4) p950(1,4) pss(4,1)];
p9s5 = [p91(1,5) p95(1,5) p910(1,5) p925(1,5) p950(1,5) pss(5,1)];
p9s4 = [p91(1,6) p95(1,6) p910(1,6) p925(1,6) p950(1,6) pss(6,1)];
p9s3 = [p91(1,7) p95(1,7) p910(1,7) p925(1,7) p950(1,7) pss(7,1)];
p9s2 = [p91(1,8) p95(1,8) p910(1,8) p925(1,8) p950(1,8) pss(8,1)];
p9s1 = [p91(1,9) p95(1,9) p910(1,9) p925(1,9) p950(1,9) 0];

% Starting at rating 8
p81= [0 1 0 0 0 0 0 0 0]*par;
p85= [0 1 0 0 0 0 0 0 0]*par^5;
p810= [0 1 0 0 0 0 0 0 0]*par^10;
p825= [0 1 0 0 0 0 0 0 0]*par^25;
p850= [0 1 0 0 0 0 0 0 0]*par^50;
p8s9 = [p81(1,1) p85(1,1) p810(1,1) p825(1,1) p850(1,1) pss(1,1)];
p8s8 = [p81(1,2) p85(1,2) p810(1,2) p825(1,2) p850(1,2) pss(2,1)];
p8s7 = [p81(1,3) p85(1,3) p810(1,3) p825(1,3) p850(1,3) pss(3,1)];
p8s6 = [p81(1,4) p85(1,4) p810(1,4) p825(1,4) p850(1,4) pss(4,1)];
p8s5 = [p81(1,5) p85(1,5) p810(1,5) p825(1,5) p850(1,5) pss(5,1)];
p8s4 = [p81(1,6) p85(1,6) p810(1,6) p825(1,6) p850(1,6) pss(6,1)];
p8s3 = [p81(1,7) p85(1,7) p810(1,7) p825(1,7) p850(1,7) pss(7,1)];
p8s2 = [p81(1,8) p85(1,8) p810(1,8) p825(1,8) p850(1,8) pss(8,1)];
p8s1 = [p81(1,9) p85(1,9) p810(1,9) p825(1,9) p850(1,9) 0];

% Starting at rating 7
p71= [0 0 1 0 0 0 0 0 0]*par;
p75= [0 0 1 0 0 0 0 0 0]*par^5;
p710= [0 0 1 0 0 0 0 0 0]*par^10;
p725= [0 0 1 0 0 0 0 0 0]*par^25;
p750= [0 0 1 0 0 0 0 0 0]*par^50;
p7s9 = [p71(1,1) p75(1,1) p710(1,1) p725(1,1) p750(1,1) pss(1,1)];
p7s8 = [p71(1,2) p75(1,2) p710(1,2) p725(1,2) p750(1,2) pss(2,1)];
p7s7 = [p71(1,3) p75(1,3) p710(1,3) p725(1,3) p750(1,3) pss(3,1)];
\end{verbatim}
\[ p_{7s6} = [p_{71(1,4)} p_{75(1,4)} p_{710(1,4)} p_{725(1,4)} p_{750(1,4)} p_{ss(4,1)}]; \]
\[ p_{7s5} = [p_{71(1,5)} p_{75(1,5)} p_{710(1,5)} p_{725(1,5)} p_{750(1,5)} p_{ss(5,1)}]; \]
\[ p_{7s4} = [p_{71(1,6)} p_{75(1,6)} p_{710(1,6)} p_{725(1,6)} p_{750(1,6)} p_{ss(6,1)}]; \]
\[ p_{7s3} = [p_{71(1,7)} p_{75(1,7)} p_{710(1,7)} p_{725(1,7)} p_{750(1,7)} p_{ss(7,1)}]; \]
\[ p_{7s2} = [p_{71(1,8)} p_{75(1,8)} p_{710(1,8)} p_{725(1,8)} p_{750(1,8)} p_{ss(8,1)}]; \]
\[ p_{7s1} = [p_{71(1,9)} p_{75(1,9)} p_{710(1,9)} p_{725(1,9)} p_{750(1,9)} 0]; \]

% Starting at rating 6
\[ p_{61} = [0 0 0 1 0 0 0 0 0] \times \text{par}; \]
\[ p_{65} = [0 0 0 1 0 0 0 0 0] \times \text{par}^5; \]
\[ p_{610} = [0 0 0 1 0 0 0 0 0] \times \text{par}^{10}; \]
\[ p_{625} = [0 0 0 1 0 0 0 0 0] \times \text{par}^{25}; \]
\[ p_{650} = [0 0 0 1 0 0 0 0 0] \times \text{par}^{50}; \]

\[ p_{6s9} = [p_{61(1,1)} p_{65(1,1)} p_{610(1,1)} p_{625(1,1)} p_{650(1,1)} p_{ss(1,1)}]; \]
\[ p_{6s8} = [p_{61(1,2)} p_{65(1,2)} p_{610(1,2)} p_{625(1,2)} p_{650(1,2)} p_{ss(2,1)}]; \]
\[ p_{6s7} = [p_{61(1,3)} p_{65(1,3)} p_{610(1,3)} p_{625(1,3)} p_{650(1,3)} p_{ss(3,1)}]; \]
\[ p_{6s6} = [p_{61(1,4)} p_{65(1,4)} p_{610(1,4)} p_{625(1,4)} p_{650(1,4)} p_{ss(4,1)}]; \]
\[ p_{6s5} = [p_{61(1,5)} p_{65(1,5)} p_{610(1,5)} p_{625(1,5)} p_{650(1,5)} p_{ss(5,1)}]; \]
\[ p_{6s4} = [p_{61(1,6)} p_{65(1,6)} p_{610(1,6)} p_{625(1,6)} p_{650(1,6)} p_{ss(6,1)}]; \]
\[ p_{6s3} = [p_{61(1,7)} p_{65(1,7)} p_{610(1,7)} p_{625(1,7)} p_{650(1,7)} p_{ss(7,1)}]; \]
\[ p_{6s2} = [p_{61(1,8)} p_{65(1,8)} p_{610(1,8)} p_{625(1,8)} p_{650(1,8)} p_{ss(8,1)}]; \]
\[ p_{6s1} = [p_{61(1,9)} p_{65(1,9)} p_{610(1,9)} p_{625(1,9)} p_{650(1,9)} 0]; \]

% Starting at rating 5
\[ p_{51} = [0 0 0 1 0 0 0 0 0] \times \text{par}; \]
\[ p_{55} = [0 0 0 1 0 0 0 0 0] \times \text{par}^5; \]
\[ p_{510} = [0 0 0 1 0 0 0 0 0] \times \text{par}^{10}; \]
\[ p_{525} = [0 0 0 1 0 0 0 0 0] \times \text{par}^{25}; \]
\[ p_{550} = [0 0 0 1 0 0 0 0 0] \times \text{par}^{50}; \]

\[ p_{5s9} = [p_{51(1,1)} p_{55(1,1)} p_{510(1,1)} p_{525(1,1)} p_{550(1,1)} p_{ss(1,1)}]; \]
\[ p_{5s8} = [p_{51(1,2)} p_{55(1,2)} p_{510(1,2)} p_{525(1,2)} p_{550(1,2)} p_{ss(2,1)}]; \]
\[ p_{5s7} = [p_{51(1,3)} p_{55(1,3)} p_{510(1,3)} p_{525(1,3)} p_{550(1,3)} p_{ss(3,1)}]; \]
\[ p_{5s6} = [p_{51(1,4)} p_{55(1,4)} p_{510(1,4)} p_{525(1,4)} p_{550(1,4)} p_{ss(4,1)}]; \]
\[ p_{5s5} = [p_{51(1,5)} p_{55(1,5)} p_{510(1,5)} p_{525(1,5)} p_{550(1,5)} p_{ss(5,1)}]; \]
\[ p_{5s4} = [p_{51(1,6)} p_{55(1,6)} p_{510(1,6)} p_{525(1,6)} p_{550(1,6)} p_{ss(6,1)}]; \]
\[ p_{5s3} = [p_{51(1,7)} p_{55(1,7)} p_{510(1,7)} p_{525(1,7)} p_{550(1,7)} p_{ss(7,1)}]; \]
\[ p_{5s2} = [p_{51(1,8)} p_{55(1,8)} p_{510(1,8)} p_{525(1,8)} p_{550(1,8)} p_{ss(8,1)}]; \]
\[ p_{5s1} = [p_{51(1,9)} p_{55(1,9)} p_{510(1,9)} p_{525(1,9)} p_{550(1,9)} 0]; \]

% Starting at rating 4
p41= [0 0 0 0 0 1 0 0 0]*par;
p45= [0 0 0 0 0 1 0 0 0]*par^5;
p410= [0 0 0 0 0 1 0 0 0]*par^10;
p425= [0 0 0 0 0 1 0 0 0]*par^25;
p450= [0 0 0 0 0 1 0 0 0]*par^50;
p4s9 = [p41(1,1) p45(1,1) p410(1,1) p425(1,1) p450(1,1) pss(1,1)];
p4s8 = [p41(1,2) p45(1,2) p410(1,2) p425(1,2) p450(1,2) pss(2,1)];
p4s7 = [p41(1,3) p45(1,3) p410(1,3) p425(1,3) p450(1,3) pss(3,1)];
p4s6 = [p41(1,4) p45(1,4) p410(1,4) p425(1,4) p450(1,4) pss(4,1)];
p4s5 = [p41(1,5) p45(1,5) p410(1,5) p425(1,5) p450(1,5) pss(5,1)];
p4s4 = [p41(1,6) p45(1,6) p410(1,6) p425(1,6) p450(1,6) pss(6,1)];
p4s3 = [p41(1,7) p45(1,7) p410(1,7) p425(1,7) p450(1,7) pss(7,1)];
p4s2 = [p41(1,8) p45(1,8) p410(1,8) p425(1,8) p450(1,8) pss(8,1)];
p4s1 = [p41(1,9) p45(1,9) p410(1,9) p425(1,9) p450(1,9) 0];
% Starting at rating 3
p31= [0 0 0 0 0 0 1 0 0]*par;
p35= [0 0 0 0 0 0 1 0 0]*par^5;
p310= [0 0 0 0 0 0 1 0 0]*par^10;
p325= [0 0 0 0 0 0 1 0 0]*par^25;
p350= [0 0 0 0 0 0 1 0 0]*par^50;
p3s9 = [p31(1,1) p35(1,1) p310(1,1) p325(1,1) p350(1,1) pss(1,1)];
p3s8 = [p31(1,2) p35(1,2) p310(1,2) p325(1,2) p350(1,2) pss(2,1)];
p3s7 = [p31(1,3) p35(1,3) p310(1,3) p325(1,3) p350(1,3) pss(3,1)];
p3s6 = [p31(1,4) p35(1,4) p310(1,4) p325(1,4) p350(1,4) pss(4,1)];
p3s5 = [p31(1,5) p35(1,5) p310(1,5) p325(1,5) p350(1,5) pss(5,1)];
p3s4 = [p31(1,6) p35(1,6) p310(1,6) p325(1,6) p350(1,6) pss(6,1)];
p3s3 = [p31(1,7) p35(1,7) p310(1,7) p325(1,7) p350(1,7) pss(7,1)];
p3s2 = [p31(1,8) p35(1,8) p310(1,8) p325(1,8) p350(1,8) pss(8,1)];
p3s1 = [p31(1,9) p35(1,9) p310(1,9) p325(1,9) p350(1,9) 0];
% Starting at rating 2
p21= [0 0 0 0 0 0 1 0 0]*par;
p25= [0 0 0 0 0 0 1 0 0]*par^5;
p210= [0 0 0 0 0 0 1 0 0]*par^10;
\[ p_{225} = [0 0 0 0 0 0 1 0] \cdot \text{par}^{25}; \]
\[ p_{250} = [0 0 0 0 0 0 1 0] \cdot \text{par}^{50}; \]
\[ p_{2s9} = [p_{21}(1,1) \ p_{25}(1,1) \ p_{210}(1,1) \ p_{225}(1,1) \ p_{250}(1,1) \ \text{pss}(1,1)]; \]
\[ p_{2s8} = [p_{21}(1,2) \ p_{25}(1,2) \ p_{210}(1,2) \ p_{225}(1,2) \ p_{250}(1,2) \ \text{pss}(2,1)]; \]
\[ p_{2s7} = [p_{21}(1,3) \ p_{25}(1,3) \ p_{210}(1,3) \ p_{225}(1,3) \ p_{250}(1,3) \ \text{pss}(3,1)]; \]
\[ p_{2s6} = [p_{21}(1,4) \ p_{25}(1,4) \ p_{210}(1,4) \ p_{225}(1,4) \ p_{250}(1,4) \ \text{pss}(4,1)]; \]
\[ p_{2s5} = [p_{21}(1,5) \ p_{25}(1,5) \ p_{210}(1,5) \ p_{225}(1,5) \ p_{250}(1,5) \ \text{pss}(5,1)]; \]
\[ p_{2s4} = [p_{21}(1,6) \ p_{25}(1,6) \ p_{210}(1,6) \ p_{225}(1,6) \ p_{250}(1,6) \ \text{pss}(6,1)]; \]
\[ p_{2s3} = [p_{21}(1,7) \ p_{25}(1,7) \ p_{210}(1,7) \ p_{225}(1,7) \ p_{250}(1,7) \ \text{pss}(7,1)]; \]
\[ p_{2s2} = [p_{21}(1,8) \ p_{25}(1,8) \ p_{210}(1,8) \ p_{225}(1,8) \ p_{250}(1,8) \ \text{pss}(8,1)]; \]
\[ p_{2s1} = [p_{21}(1,9) \ p_{25}(1,9) \ p_{210}(1,9) \ p_{225}(1,9) \ p_{250}(1,9) \ 0]; \]
Appendix B

DETERIORATION DISTRIBUTION CURVES
B.1 Alabama

Figure B.1: Deterioration Rate (Without Maintenance) Density Curve

Figure B.2: Deterioration Rate (With Maintenance) Density Curve
B.2 Arizona

Figure B.3: Deterioration Rate (Without Maintenance) Density Curve

Figure B.4: Deterioration Rate (With Maintenance) Density Curve
B.3 Arkansas

Figure B.5: Deterioration Rate (Without Maintenance) Density Curve

Figure B.6: Deterioration Rate (With Maintenance) Density Curve
B.4 Florida

Figure B.7: Deterioration Rate (Without Maintenance) Density Curve

Figure B.8: Deterioration Rate (With Maintenance) Density Curve
B.5 Indiana

Figure B.9: Deterioration Rate (Without Maintenance) Density Curve

Figure B.10: Deterioration Rate (With Maintenance) Density Curve
B.6 Maine

Figure B.11: Deterioration Rate (Without Maintenance) Density Curve

Figure B.12: Deterioration Rate (With Maintenance) Density Curve
B.7 Minnesota

Figure B.13: Deterioration Rate (Without Maintenance) Density Curve

Figure B.14: Deterioration Rate (With Maintenance) Density Curve
B.8 Nebraska

Figure B.15: Deterioration Rate (Without Maintenance) Density Curve

Figure B.16: Deterioration Rate (With Maintenance) Density Curve
B.9 New Mexico

Figure B.17: Deterioration Rate (Without Maintenance) Density Curve

Figure B.18: Deterioration Rate (With Maintenance) Density Curve
B.10 Oregon

Figure B.19: Deterioration Rate (Without Maintenance) Density Curve

Figure B.20: Deterioration Rate (With Maintenance) Density Curve
B.11 Rhode Island

Figure B.21: Deterioration Rate (Without Maintenance) Density Curve

Figure B.22: Deterioration Rate (With Maintenance) Density Curve
B.12 Virginia

Figure B.23: Deterioration Rate (Without Maintenance) Density Curve

Figure B.24: Deterioration Rate (With Maintenance) Density Curve
B.13 Washington

Figure B.25: Deterioration Rate (Without Maintenance) Density Curve

Figure B.26: Deterioration Rate (With Maintenance) Density Curve
Appendix C

PARAMETER ANALYSIS: ALABAMA

C.1 Time-Invariant Parameters

Figure C.1: Sample Plots for Time-Invariant Parameters

Table C.1: Linear Correlation for Non-Discrete Time Invariant Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Linear Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year Built</td>
<td>0.4364</td>
</tr>
<tr>
<td>Maximum Span Length</td>
<td>-0.0577</td>
</tr>
<tr>
<td>Length</td>
<td>-0.0204</td>
</tr>
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</table>
C.2 Time-Variant Parameters

Figure C.2: Scatter Plot of ADT vs. Deck Rating

Figure C.3: Scatter Plot of Superstructure Rating vs. Deck Rating
Table C.2: Linear Correlation for Time-Variant Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Linear Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADT</td>
<td>0.0366</td>
</tr>
<tr>
<td>ADTT</td>
<td>-0.018</td>
</tr>
<tr>
<td>Inspection Frequency</td>
<td>0.2753</td>
</tr>
<tr>
<td>Bridge Posting</td>
<td>0.1669</td>
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<tr>
<td>Superstructure Condition Rating</td>
<td>0.8191</td>
</tr>
<tr>
<td>Substructure Condition Rating</td>
<td>0.7746</td>
</tr>
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Appendix D

PARAMETER ANALYSIS: ARIZONA

D.1 Time-Invariant Parameters

Figure D.1: Sample Plots for Time-Invariant Parameters

Table D.1: Linear Correlation for Non-Discrete Time Invariant Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Linear Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year Built</td>
<td>0.1308</td>
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<tr>
<td>Maximum Span Length</td>
<td>-0.0440</td>
</tr>
<tr>
<td>Length</td>
<td>0.0034</td>
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</table>
D.2 Time-Variant Parameters

Figure D.2: Scatter Plot of ADT vs. Deck Rating

Figure D.3: Scatter Plot of Superstructure Rating vs. Deck Rating
Table D.2: Linear Correlation for Time-Variant Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Linear Correlation</th>
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<tbody>
<tr>
<td>ADT</td>
<td>0.0043</td>
</tr>
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<td>ADTT</td>
<td>-0.0144</td>
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<tr>
<td>Inspection Frequency</td>
<td>0.1521</td>
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<td>Bridge Posting</td>
<td>0.0896</td>
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<tr>
<td>Superstructure Condition Rating</td>
<td>0.5757</td>
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<tr>
<td>Substructure Condition Rating</td>
<td>0.4108</td>
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Appendix E

PARAMETER ANALYSIS: ARKANSAS

E.1 Time-Invariant Parameters

![Sample Plots for Time-Invariant Parameters]

Figure E.1: Sample Plots for Time-Invariant Parameters

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<thead>
<tr>
<th>Parameter</th>
<th>Linear Correlation</th>
</tr>
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<tbody>
<tr>
<td>Year Built</td>
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<tr>
<td>Maximum Span Length</td>
<td>0.1571</td>
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<td>Length</td>
<td>0.1602</td>
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E.2 Time-Variant Parameters

Figure E.2: Scatter Plot of ADT vs. Deck Rating

Figure E.3: Scatter Plot of Superstructure Rating vs. Deck Rating
Table E.2:  Linear Correlation for Time-Variant Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Linear Correlation</th>
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<tr>
<td>ADT</td>
<td>0.0027</td>
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<td>ADTT</td>
<td>-0.1511</td>
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<tr>
<td>Inspection Frequency</td>
<td>0.0077</td>
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<td>Bridge Posting</td>
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<td>Superstructure Condition Rating</td>
<td>0.6651</td>
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<td>Substructure Condition Rating</td>
<td>0.5295</td>
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Appendix F
PARAMETER ANALYSIS: FLORIDA

F.1 Time-Invariant Parameters

Figure F.1: Sample Plots for Time-Invariant Parameters

Table F.1: Linear Correlation for Non-Discrete Time Invariant Parameters

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<th>Parameter</th>
<th>Linear Correlation</th>
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<tbody>
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<td>Year Built</td>
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<tr>
<td>Maximum Span Length</td>
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<td>Length</td>
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F.2 Time-Variant Parameters

Figure F.2: Scatter Plot of ADT vs. Deck Rating

Figure F.3: Scatter Plot of Superstructure Rating vs. Deck Rating
Table F.2: Linear Correlation for Time-Variant Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Linear Correlation</th>
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<tr>
<td>ADT</td>
<td>0.0951</td>
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<td>ADTT</td>
<td>0.0294</td>
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<td>Inspection Frequency</td>
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<tr>
<td>Substructure Condition Rating</td>
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Appendix G

PARAMETER ANALYSIS: INDIANA

G.1 Time-Invariant Parameters

![Sample Plots for Time-Invariant Parameters]

Figure G.1: Sample Plots for Time-Invariant Parameters

Table G.1: Linear Correlation for Non-Discrete Time Invariant Parameters

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<th>Linear Correlation</th>
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<td>Length</td>
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G.2 Time-Variant Parameters

Figure G.2: Scatter Plot of ADT vs. Deck Rating

Figure G.3: Scatter Plot of Superstructure Rating vs. Deck Rating
Table G.2: Linear Correlation for Time-Variant Parameters

<table>
<thead>
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<th>Parameter</th>
<th>Linear Correlation</th>
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<td>ADTT</td>
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<td>Inspection Frequency</td>
<td>0.2936</td>
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<tr>
<td>Superstructure Condition Rating</td>
<td>0.5753</td>
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<td>Substructure Condition Rating</td>
<td>0.5585</td>
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Appendix H
PARAMETER ANALYSIS: MAINE

H.1 Time-Invariant Parameters

Figure H.1: Sample Plots for Time-Invariant Parameters

Table H.1: Linear Correlation for Non-Discrete Time Invariant Parameters

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<td>Maximum Span Length</td>
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<td>Length</td>
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</table>
H.2 Time-Variant Parameters

![Figure H.2: Scatter Plot of ADT vs. Deck Rating](image)

Figure H.2: Scatter Plot of ADT vs. Deck Rating

![Figure H.3: Scatter Plot of Superstructure Rating vs. Deck Rating](image)

Figure H.3: Scatter Plot of Superstructure Rating vs. Deck Rating
Table H.2: Linear Correlation for Time-Variant Parameters

<table>
<thead>
<tr>
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<tbody>
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<td>Bridge Posting</td>
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<td>Superstructure Condition Rating</td>
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<tr>
<td>Substructure Condition Rating</td>
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Appendix I

PARAMETER ANALYSIS: MINNESOTA

I.1 Time-Invariant Parameters

Figure I.1: Sample Plots for Time-Invariant Parameters,

Table I.1: Linear Correlation for Non-Discrete Time Invariant Parameters

<table>
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I.2 Time-Variant Parameters

Figure I.2: Scatter Plot of ADT vs. Deck Rating,

Figure I.3: Scatter Plot of Superstructure Rating vs. Deck Rating,
Table I.2: Linear Correlation for Time-Variant Parameters

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Appendix J

PARAMETER ANALYSIS: NEW MEXICO

J.1 Time-Invariant Parameters

Figure J.1: Sample Plots for Time-Invariant Parameters

Table J.1: Linear Correlation for Non-Discrete Time Invariant Parameters

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J.2 Time-Variant Parameters

Figure J.2: Scatter Plot of ADT vs. Deck Rating

Figure J.3: Scatter Plot of Superstructure Rating vs. Deck Rating,
Table J.2: Linear Correlation for Time-Variant Parameters

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Appendix K

PARAMETER ANALYSIS: OREGON

K.1 Time-Invariant Parameters

Table K.1: Linear Correlation for Non-Discrete Time Invariant Parameters

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Figure K.1: Sample Plots for Time-Invariant Parameters
K.2 Time-Variant Parameters

Figure K.2: Scatter Plot of ADT vs. Deck Rating

Figure K.3: Scatter Plot of Superstructure Rating vs. Deck Rating.
### Table K.2: Linear Correlation for Time-Variant Parameters

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Appendix L

PARAMETER ANALYSIS: RHODE ISLAND

L.1 Time-Invariant Parameters

![Sample Plots for Time-Invariant Parameters]

Figure L.1: Sample Plots for Time-Invariant Parameters

Table L.1: Linear Correlation for Non-Discrete Time Invariant Parameters

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L.2 Time-Variant Parameters

Figure L.2: Scatter Plot of ADT vs. Deck Rating

Figure L.3: Scatter Plot of Superstructure Rating vs. Deck Rating
Table L.2: Linear Correlation for Time-Variant Parameters

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Appendix M

PARAMETER ANALYSIS: VIRGINIA

M.1 Time-Invariant Parameters

Table M.1: Linear Correlation for Non-Discrete Time Invariant Parameters

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M.2 Time-Variant Parameters

Figure M.2: Scatter Plot of ADT vs. Deck Rating

Figure M.3: Scatter Plot of Superstructure Rating vs. Deck Rating
Table M.2: Linear Correlation for Time-Variant Parameters

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Appendix N

PARAMETER ANALYSIS: WASHINGTON

N.1 Time-Invariant Parameters

Figure N.1: Sample Plots for Time-Invariant Parameters

Table N.1: Linear Correlation for Non-Discrete Time Invariant Parameters

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N.2 Time-Variant Parameters

Figure N.2: Scatter Plot of ADT vs. Deck Rating

Figure N.3: Scatter Plot of Superstructure Rating vs. Deck Rating.
Table N.2: Linear Correlation for Time-Variant Parameters

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Appendix O

TRANSITION MATRICES

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Figure O.1: Transition Probability Matrix for Deck Condition Ratings
### O.2 ARIZONA

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*Figure O.2: Transition Probability Matrix for Deck Condition Ratings*
### O.3 ARKANSAS

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**Figure O.3:** Transition Probability Matrix for Deck Condition Ratings
## O.4 FLORIDA

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*Figure O.4: Transition Probability Matrix for Deck Condition Ratings*
O.5  INDIANA

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Figure O.5: Transition Probability Matrix for Deck Condition Ratings
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Figure O.6: Transition Probability Matrix for Deck Condition Ratings
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*Figure O.7: Transition Probability Matrix for Deck Condition Ratings*
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**Figure O.8:** Transition Probability Matrix for Deck Condition Ratings
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**Figure O.9**: Transition Probability Matrix for Deck Condition Ratings
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**Figure O.10:** Transition Probability Matrix for Deck Condition Ratings
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Figure O.11: Transition Probability Matrix for Deck Condition Ratings
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*Figure O.12: Transition Probability Matrix for Deck Condition Ratings*
Fig. O.13: Transition Probability Matrix for Deck Condition Ratings
Appendix P

MARKOV PREDICTION MODELS
Figure P.1: Prediction Histogram Starting at Deck Rating of 9

Figure P.2: Prediction Histogram Starting at Deck Rating of 7
Figure P.3: Prediction Histogram Starting at Deck Rating of 2

P.2 ARIZONA

Figure P.4: Prediction Histogram Starting at Deck Rating of 9
Figure P.5: Prediction Histogram Starting at Deck Rating of 7

Figure P.6: Prediction Histogram Starting at Deck Rating of 2
Figure P.7: Prediction Histogram Starting at Deck Rating of 9

Figure P.8: Prediction Histogram Starting at Deck Rating of 7
Figure P.9: Prediction Histogram Starting at Deck Rating of 2

P.4 FLORIDA

Figure P.10: Prediction Histogram Starting at Deck Rating of 9
Figure P.11: Prediction Histogram Starting at Deck Rating of 7

Figure P.12: Prediction Histogram Starting at Deck Rating of 2
Figure P.13: Prediction Histogram Starting at Deck Rating of 9

Figure P.14: Prediction Histogram Starting at Deck Rating of 7
Figure P.15: Prediction Histogram Starting at Deck Rating of 2

Figure P.16: Prediction Histogram Starting at Deck Rating of 9

P.6 MAINE
Figure P.17: Prediction Histogram Starting at Deck Rating of 7

Figure P.18: Prediction Histogram Starting at Deck Rating of 2
P.7 MINNESOTA

Figure P.19: Prediction Histogram Starting at Deck Rating of 9

Figure P.20: Prediction Histogram Starting at Deck Rating of 7
Figure P.21: Prediction Histogram Starting at Deck Rating of 2

P.8 NEBRASKA

Figure P.22: Prediction Histogram Starting at Deck Rating of 9
Figure P.23: Prediction Histogram Starting at Deck Rating of 7

Figure P.24: Prediction Histogram Starting at Deck Rating of 2
NEW MEXICO

Figure P.25: Prediction Histogram Starting at Deck Rating of 9

Figure P.26: Prediction Histogram Starting at Deck Rating of 7
Figure P.27: Prediction Histogram Starting at Deck Rating of 2

P.10 OREGON

Figure P.28: Prediction Histogram Starting at Deck Rating of 9
Figure P.29: Prediction Histogram Starting at Deck Rating of 7

Figure P.30: Prediction Histogram Starting at Deck Rating of 2
P.11 RHODE ISLAND

Figure P.31: Prediction Histogram Starting at Deck Rating of 9

Figure P.32: Prediction Histogram Starting at Deck Rating of 7
Figure P.33: Prediction Histogram Starting at Deck Rating of 2

Figure P.34: Prediction Histogram Starting at Deck Rating of 9
Figure P.33: Prediction Histogram Starting at Deck Rating of 7

Figure P.34: Prediction Histogram Starting at Deck Rating of 2
Figure P.35: Prediction Histogram Starting at Deck Rating of 9

Figure P.36: Prediction Histogram Starting at Deck Rating of 7
Figure P.37: Prediction Histogram Starting at Deck Rating of 3