GEORGIA DOT RESEARCH PROJECT 18-30

FINAL REPORT

Development of Depreciation Models Utilizing the NBI Condition Ratings Over 25 Years

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16. Abstract:
The Georgia Department of Transportation maintains an inventory of approximately 15,000 bridges and culverts across the state. These bridges and culverts have been inspected biennially since 1992, yielding over 25 years of bridge condition rating (CR) data from the National Bridge Inventory (NBI). Condition ratings are assigned on a discrete 0-9 scale during bridge inspection, and in this study, they are used to calculate deterioration rates for culverts and the three major components of bridges, namely deck, superstructure, and substructure. This study uses the Markov chain approach to generate long-term (100 years) depreciation models and considers key attributes (e.g., material types and geographic locations) influencing bridge performance. Therefore, CR data is divided into 39 analysis groups including 3 culvert and 36 bridge groups. The three culvert groups are formed by the three geographic locations of Georgia (Northern, Central, and Coastal regions). In these three regions, bridge groups are divided into 5 deck and 5 superstructure subgroups according to 5 material types, as well as 2 substructure subgroups based on the presence of waterways. A Chi-square test is conducted to confirm the alternative hypothesis that the depreciation models developed in this study are reasonably correlated with the deterioration models created in a long-term bridge performance study. The results indicate that the depreciation models presented in this report are reliable and thus are used to determine the expected service life and condition ratings of culverts and bridges in Georgia for the next 100 years. The depreciation models established in this report will be implemented in a long-term bridge asset management program (e.g., the AASHTO BrM software) in order to complete a life-cycle analysis of bridges/culverts.

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Development of Depreciation Models Utilizing the NBI Condition Ratings Over 25 Years

Final Report

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EXECUTIVE SUMMARY

This study develops depreciation models for bridges and culverts in Georgia utilizing the Federal Highway Administration (FHWA)'s National Bridge Inventory (NBI) condition rating (CR) data recorded between years 1992 and 2017. Specifically, this research study serves to establish a depreciation model for each culvert and each of three bridge components (deck, superstructure, and substructure) found in the latest (2017) NBI. The goal of this study is to assist the Georgia Department of Transportation (GDOT) with long-term transportation asset management plans (TAMPs). The depreciation models included in this report provide deterioration rates in terms of the NBI bridge CRs as the basis for engineering decisions on maintenance and replacement and are expected to better support estimates of long-term asset investment needs.

This study considers a total of 39 analysis groups including 3 culvert and 36 bridge groups. The three culvert groups are formed by the three geographic locations of Georgia (Northern, Central, and Coastal regions). In these same three regions, bridge groups are divided into 5 deck and 5 superstructure subgroups according to 5 material types, as well as 2 substructure subgroups based on the presence of waterways. The Markov chain method, an approach widely used for generating depreciation curves for transportation assets, is used by calculating CR transition probabilities from the NBI data sets (1992-2017). Results confirm that geographic locations and material types affect depreciation rates in bridge decks and superstructures and that the presence of waterways influences the performance of bridge substructures.

Since the reliability of a long-term life-cycle analysis of bridges vastly depends on the accuracy of depreciation models presented in this report, a Chi-square test is conducted to provide a high level of accuracy in forecasting bridge conditions. In other words, the depreciation models developed in this study are compared to the long-term bridge performance (LTBP) program's

deterioration curves provided by Dr. Moon's research team at Rutgers University. The depreciation models presented in this report, although constructed using a simpler approach, correlate well with the LTBP prediction models and thus are concluded reliable. Based on these findings, depreciation models are finalized for Georgia bridges and culverts present in the latest (2017) NBI.

Lastly, time increments required in each CR change are determined for culvert and 3 bridge components, which will be used as key input for the AASHTO Bridge Management (BrM) software. The software is expected to use this information in order to complete a life-cycle analysis. The following electronic files are submitted with this report to support the implementation of the findings:

- An excel spreadsheet file including the BrM input data (i.e., predicted time increments for each CR change organized by Bridge IDs).
- PDF files including a plot of CR history and depreciation models for each bridge (the files are named according to Bridge IDs) similar to shown in Appendices A and B.
- MATLAB codes and Excel output files used for the NBI data analysis.

ACKNOWLEDGEMENTS

The University of Georgia would like to acknowledge the financial support for this work provided by the Georgia Department of Transportation. The authors would like to thank many personnel at GDOT who assisted with this study and Dr. Moon's research team at Rutgers University for sharing the depreciation models for select Georgia bridges developed for the long-term bridge performance (LTBP) program. A special thanks to Mr. Clayton Bennett, P.E., Mr. Bob O'Daniels, and Mr. David Jared, P.E., for their research support and valuable input. Special thanks also to the project manager, Mrs. Supriya Kamatkar, who advised the research team in successfully performing the study and assisted in the coordination of project meetings with the GDOT bridge maintenance unit.

1. INTRODUCTION

1.1 Overview

The Georgia Department of Transportation (GDOT) maintains an inventory of over 15,000 bridges and culverts statewide. Transportation asset management planning and decisions must be based on a consistent understanding of the bridge asset life cycle and condition, as well as an understanding of differing levels of service, operational and maintenance costs, and alternative capital expenditure treatments. Therefore, bridge performance prediction models are generally based on its life cycle, condition, and factors driving the consumption of the asset (e.g., environment and traffic).

Increased deterioration rates induced by reduced bridge maintenance activities may not be apparent in the short term. Consequently, the prediction of asset depreciation, as part of a bridge management program, is crucial in preparing short-term and long-term capital programs for the construction and maintenance of bridges in Georgia. This study determines the historic bridge condition deterioration rates and is ultimately expected to promote decreasing depreciation rates by sustaining a desired State of Good Repair (SOGR) over the long term. In this report, the term 'deterioration' is used interchangeably with the word 'depreciation' because physical deterioration of structure is often accompanied by depreciation, a reduction in the value of an asset.

1.2 Literature Review

1.2.1 U.S. Transportation Agencies' Asset Depreciation Models

Bridge management programs (BMP) such as PONTIS and BRIDGIT traditionally had built-in capabilities for calculating bridge deterioration rates using the Markov chain approach in order to predict the probability of transition from one condition state to another condition state. The Markov chain approach has been used extensively to model the deterioration behavior of bridges in the United States (Bu et al. 2014; Agrawal et al. 2010; Cesare et al. 1992).

Generally, bridge deterioration rates are calculated by using the National Bridge Inventory (NBI) inspection data to assist decision makers in predicting the future condition of bridges and to optimize the allocation of scarce resources for maintenance, repair, and rehabilitation needs (Agrawal et al. 2010). However, the natural deterioration process is normally affected by traffic volume, environment, and maintenance efforts (Bu et al. 2012; Bu et al. 2014), and thus is challenging to predict.

One of the most common practices when the Markov chain approach is adopted is to develop a condition-rating-based depreciation model utilizing the NBI database. In this approach, it is assumed that without repair or rehabilitation, bridge condition ratings (CRs) should decrease over time. Therefore, only transition probabilities reflecting no CR change or a decrease in CRs are considered in the analysis (DeStefano et al. 1998). Depreciation models developed by the Markov chain process utilizing such transition probabilities are expected to follow the dominant deteriorating behavior observed in past inventories. As a general rule for reporting bridge condition states, three depreciation models (Hawk 2003) in total are generated for three bridge components (deck, superstructure, and substructure) and a single prediction model is determined for culverts.

1.2.2 GDOT Long-term Bridge Asset Management Software

Currently, depreciation models are not available in the bridge management program (AgileAssets or Georgia Asset Management System) software tool for its bridge asset management. According to the GDOT Transportation Asset Management Plan (TAM 2014-2018), GDOT uses the service life-based depreciation. Useful life of a transportation asset is considered to be 75 years. Therefore, depreciation models for Georgia bridges need to be developed over a span of more than 75 years for its long-term Transportation Asset Management Plans (TAMPs). Finally, it should also be recognized that bridges in Georgia are expected to last up to 100 years or beyond due to the state's favorable environmental conditions and climate (e.g., minimum freeze-thaw cycle) for retaining bridge CRs.

1.3 Research Need

1.3.1 Develop Bridge Depreciation Models

There is a need to develop depreciation models for the next 100 years in order for GDOT to conduct a life-cycle cost analysis of bridges and to assist GDOT with long-term TAMPs.

1.3.2 Enhance Long-term Bridge Asset Management Plans

It is necessary to establish long-range bridge performance prediction models that are reliable yet easily applicable in order to conduct a life-cycle cost analysis of bridges in Georgia.

1.3.3 Recent Adoption of the AASHTO Bridge Management (BrM) Software

Recently, a decision has been made by the GDOT Bridge Maintenance Unit (BMU) to adopt the American Association of State Highway and Transportation Officials (AASHTO) Bridge Management (BrM) software in order to have long-term TAMPs in place. This software requires depreciation models for each bridge as input to complete a life-cycle cost analysis and long-term TAMP. Specifically, this input consists of estimated time increments required for changes in CR. Section 3.6 addresses input information in greater detail.

1.4 Project Significance and Scope

As highlighted in the previous sections, depreciation models must be determined in order for GDOT to conduct a life-cycle cost analysis of bridges and to assist GDOT with long-term TAMPs. In order to capture the full effect of bridge deterioration, it is necessary to consider a long-term plan, which is consistent with the Moving Ahead for Progress in the 21st Century Act (MAP-21) requirements. This is because increased depreciation caused by reduced bridge maintenance activities is not apparent in the short term. For example, if the annual maintenance budget were to remain unchanged despite an increased number of bridges constructed and deteriorated, the average service life (75-100 years) expectancy would decrease in the long term. Therefore, it is essential to develop depreciation models for Georgia bridges over a 100-year time span, review scenarios for varying cash flows to sustain a desired State of Good Repair for all bridges and culverts, and study alternative capital expenditure treatments.

This study provides GDOT with three depreciation models for bridges and a single depreciation model for culverts over the next 100 years based on the NBI CRs to enhance long-term TAMPs, which will reflect the desired level of bridge conditions maintained.

1.5 Objectives

This study is aimed to develop depreciation models for all bridges and culverts in Georgia's bridge inventory, which will assist in enhancing GDOT's long-term TAMPs. This overall goal is consistent with the objectives of the MAP-21 (FHWA 2012). More specifically, this project is designed to

1) Develop bridge condition degradation curves for the complete bridge inventory.
2) Generate a plot showing CR history and a long-term prediction of CR for each bridge including the performance of its deck, superstructure, and substructure.
3) Provide an input file for use in the BrM software, an asset management tool, for conducting a life-cycle analysis.

1.6 Organization of the Report

The report consists of five sections. The first section presents the scope and purpose. The second section provides the definition of major terminologies used in this study. Moreover, it provides a brief description of analysis methods. The third section presents an analysis of CR transitions over the past 25 years and resulting depreciation models. Furthermore, a Chi-square test is performed to validate the models. Appendix D presents detailed information regarding the necessary steps used to analyze CR transitions in the NBI and develop depreciation models. The fourth section discusses the findings and limitations. The last section concludes the study with a summary of major findings and recommendations.

2. METHODOLOGY

2.1 Overview

The MATLAB software program (academic license version R17) is primarily used to determine CR transition probabilities and build depreciation models by means of the Markov chain approach (Agrawal et al., 2017).

Section 2.4 briefly presents the process, and Appendix D describes the NBI data analysis procedures in greater detail. The bridge CR data sets between years 1992 and 2017 are downloaded from the NBI database (FHWA NBI, 2018) and read into the MATLAB numerical computing environment to build the depreciation models presented in this report.

2.2 Definition of Terms

Project-specific terms used during the NBI data analysis are listed below:

- *Culvert* – A structure designed hydraulically to take advantage of submergence to increase hydraulic capacity. Culverts, as distinguished from bridges, are usually covered with embankment and are composed of structural material around the entire perimeter (FHWA 1995).

- *Bridge* - A structure including supports erected over a depression or an obstruction, such as water, highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 feet (6.1 m) between undercopings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes; it may also include multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening (FHWA 1995).

- *Bridge major components* – A bridge's major components include the deck, superstructure, and substructure.

- *Deck* – The portion (or surface) of a bridge that directly carries traffic.

- *Superstructure* – The portion of a bridge structure (e.g., girder, truss, arch) that directly supports the deck and receives the live load.

- *Substructure* – The portion of a bridge that supports the superstructure. On a bridge, piers, abutments, piles, fenders, footings, or other supporting components are defined as the substructure.

- *Waterway* – A river, lake, canal, or other route for travel by water.

- *Condition Rating* (CR) – Condition codes provide an "overall characterization of the general condition of the entire component" under evaluation (FHWA 1995). The following 9 general CR codes are used. The code 'N' (not applicable) or '0' (out of service) are not used in this analysis:
    - 9 - EXCELLENT CONDITION
    - 8 - VERY GOOD CONDITION - no problems noted.

- 7 - GOOD CONDITION - some minor problems.
- 6 - SATISFACTORY CONDITION - structural elements show some minor deterioration.
- 5 - FAIR CONDITION - all primary structural elements are sound but may have minor section loss, cracking, spalling, or scour.
- 4 - POOR CONDITION - advanced section loss, deterioration, spalling, or scour.
- 3 - SERIOUS CONDITION - loss of section, deterioration, spalling, or scour have seriously affected primary structural components.
- 2 - CRITICAL CONDITION - advanced deterioration of primary structural elements.
- 1 - IMMINENT FAILURE CONDITION - major deterioration or section loss present in critical structural components or obvious vertical or horizontal movement affecting structural stability.

2.3 NBI Data and Attributes Used for Analysis

The NBI data sets represent "bridge data submitted annually to FHWA by the States, Federal agencies, and Tribal governments in accordance with the National Bridge Inspection Standards and the Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges. Each data set is submitted in the spring, and may be corrected or updated throughout the year. The data [set] is considered final and is published on this website at the end of each calendar year" (FHWA NBI 2018). In this study, the 2017 data set is used as it is the latest data available as of November 2018. The following subsections list and describe major NBI items used for this study. Figure 1 presents an organization chart featuring the NBI items selected for building depreciation models. Culverts and bridges are divided into total 13 subgroups, and each subgroup is further divided into 3 regions based on the county codes shown in Figure 1.

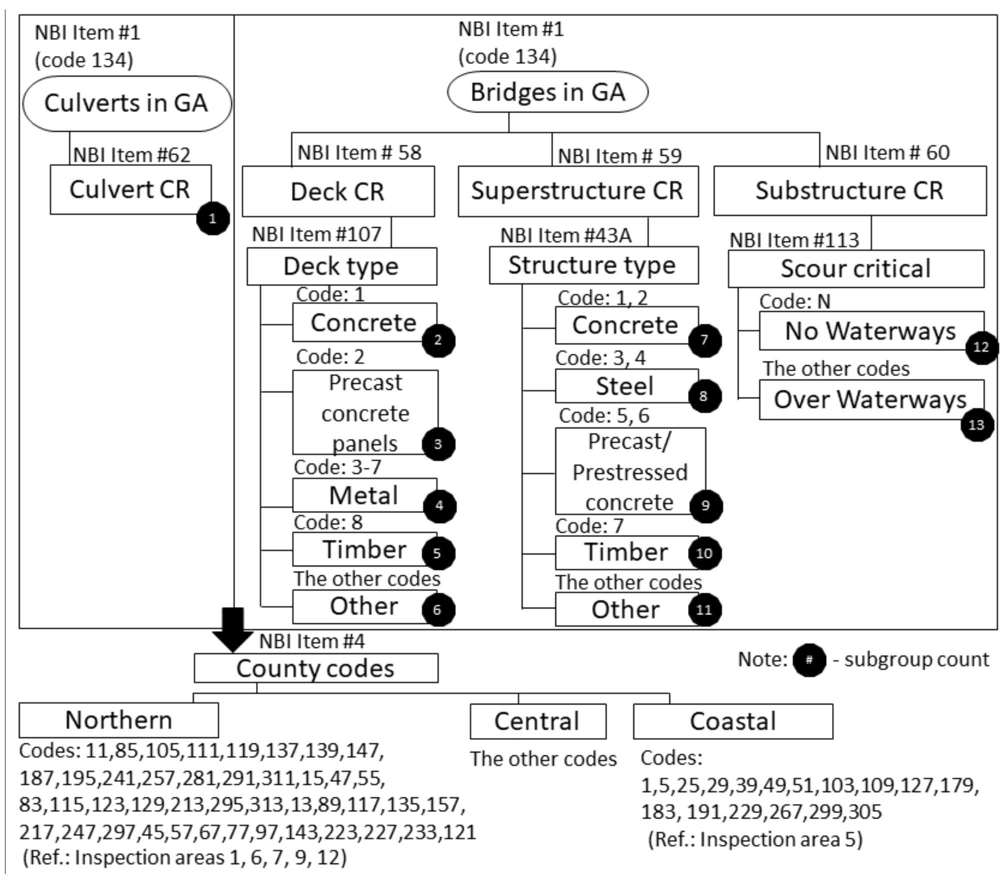


Figure 1 – An Organization Chart for Developing Depreciation Models.

2.3.1 State Code (Item No. 1)

A total of 26 NBI data sets (1992-2017) containing the three-digit state code '134' for Georgia are downloaded from the NBI website (FHWA NBI 2018). A total of 25 years of CR transitions exist.

2.3.2 County Code (Item No. 4)

The county codes are used to assign analysis groups (e.g., inspection areas and climate regions) for developing depreciation models. Section 2.5.6 provides the background and details on how this NBI item is used for creating analysis groups shown in Figure 1.

2.3.3 Structure Number (Item No. 8)

GDOT bridge identification numbers are saved to develop depreciation models for each Georgia bridge in the downloaded NBI data sets. The structural number is a unique identifier for each bridge within the state.

2.3.4 Year Built (Item No. 27)

The construction year is saved to graphically review historic CRs. See Appendices A and B.

2.3.5 Structure Type (Item No. 43)

This NBI item indicates the type of structure for the main span(s). The kind of material (43A) is primarily used to recognize more distinct bridge characteristics in differentiating depreciation models in bridge superstructures. They are divided into five categories: Concrete (Codes 1 and 2), Steel (Codes 3 and 4), Prestressed/Precast concrete (Codes 5 and 6), Timber (Code 7), and Other (the other remaining Codes). For the remainder of this report, the 'Prestressed/Precast' concrete superstructure category is referred to as 'Precast' concrete for brevity. Culverts are identified by Item No. 43B (Code 19) and are analyzed independently of bridges.

2.3.6 Deck Structure Type (Item No. 107)

Item 107 provides the (material) type of bridge deck system whereas Item 43A is associated with the bridge superstructure type. They are similarly divided into five categories: Concrete (Code 1), Precast concrete (Code 2), Metal (Codes 3 through 7), Timber (Code 8), and Other (the other remaining Codes). The "Metal" category includes "Open Grating", "Closed Grating", "Steel Plate", "Corrugated Steel", and "Aluminum" decks. For deck structures, the 'Precast concrete' category refers to 'precast concrete panels' for the remainder of this report.

2.3.7 Condition Ratings – Deck, Superstructure, and Substructure (Item Nos. 58 through 60)

Overall deck, superstructure, and substructure CRs are used, such that CR 9 indicates excellent condition, CR 7 indicates good condition, and CR 0 indicates an out-of-service condition.

2.3.8 Condition Rating - Culverts (Item No. 62)

For culverts, Items 58 through 60 are coded as 'N.' Therefore, Item 62 is used to evaluate the overall CR of culverts.

2.3.9 Scour Critical Bridges (Item No. 113)

This item is used to identify bridges that are over waterways for substructure CRs.

2.4 Analysis Methods

This section provides a brief description of analysis methods. Appendix D describes a detailed procedure for developing a bridge depreciation model.

2.4.1 Condition Rating Transition History

The frequency of CR transition occurrences is computed for three bridge components (deck, superstructure, and substructure) and culverts. For example, Figure 2 illustrates GDOT's historic trend in bridge deck CR distribution, and Figure 3 shows year-by-year CR transition probabilities for the past 25 years. In Figure 3, the first number indicates 'CR from' and the second number specifies 'CR to'.

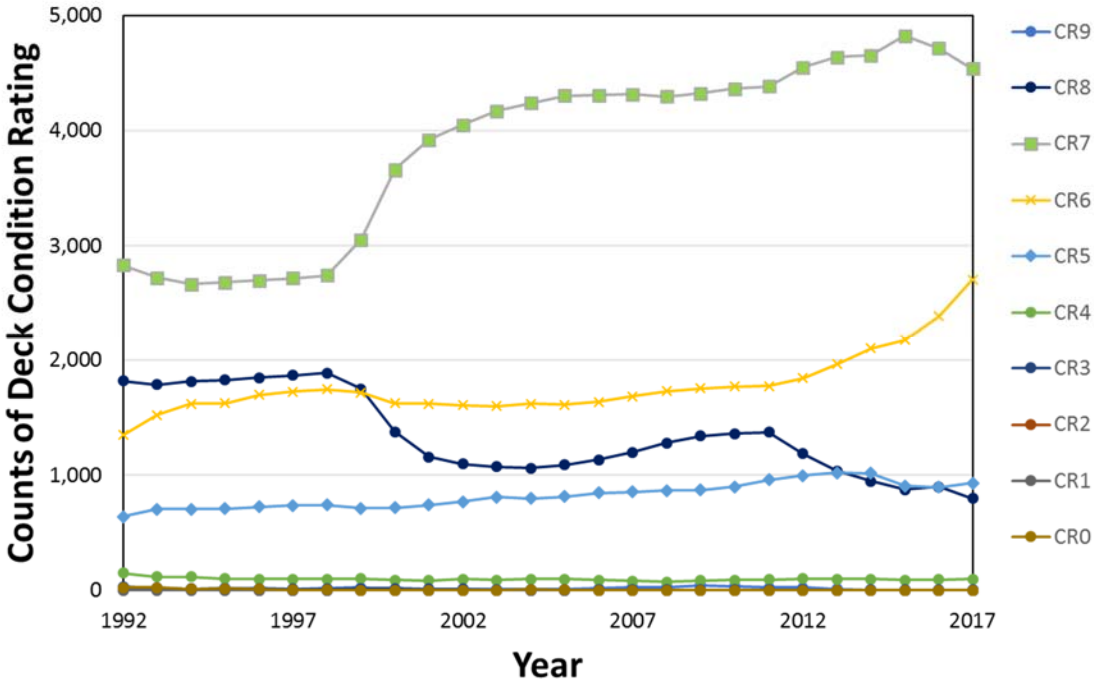


Figure 2 – Condition Rating over the Past 25 Years.

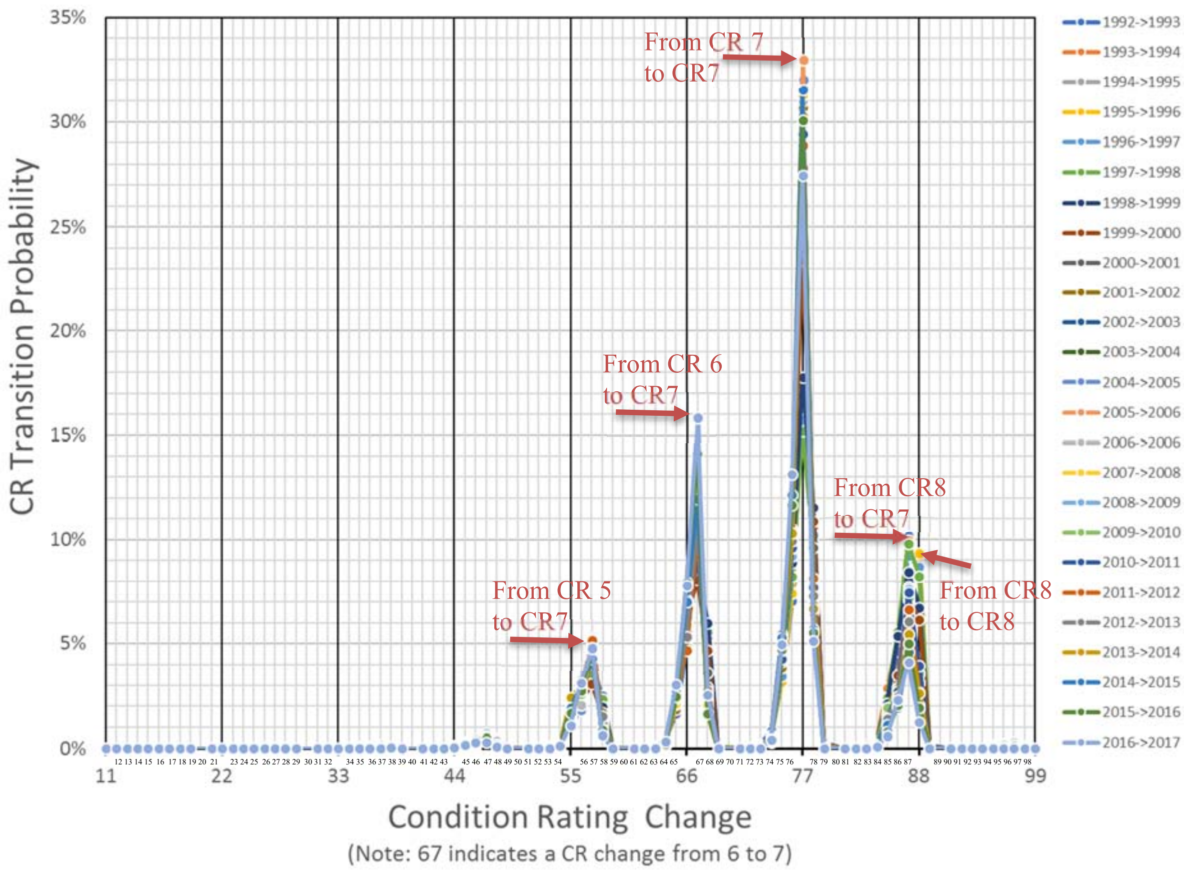


Figure 3 – Condition Rating Transition Probabilities.

2.4.2 The Markov Chain Approach

The Markov chain approach (Agrawal et al. 2010) is used to determine bridge deterioration models, or for this study, bridge depreciation. The Markov chain data generated by a transition probability matrix is expected to follow the dominant deteriorating behavior observed in Georgia bridges over the past 25 years. In this process, the most important task for Markov chain models is to determine reliable CR transition probabilities. For example, Figure 3 presents the two most frequent CR transition occurrences (e.g., depreciation) found in the Georgia inventory: CR 7 −> CR7 and CR 6−>CR7. It also indicates that CR transition trends have remained fairly unchanged over the past 25 years.

CR transition probabilities are determined by counting CR transition occurrences between 1992 and 2017 in the bridge inventory and are subsequently used to develop a depreciation curve as illustrated in Figure 4. During this analysis, the NBI data is divided into 39 groups by the selected attributes described in Section 2.5 in order to determine a transition matrix for each analysis group. Finally, depreciation curves are generated by the Markov chain process projecting CRs from the latest (2017) NBI.

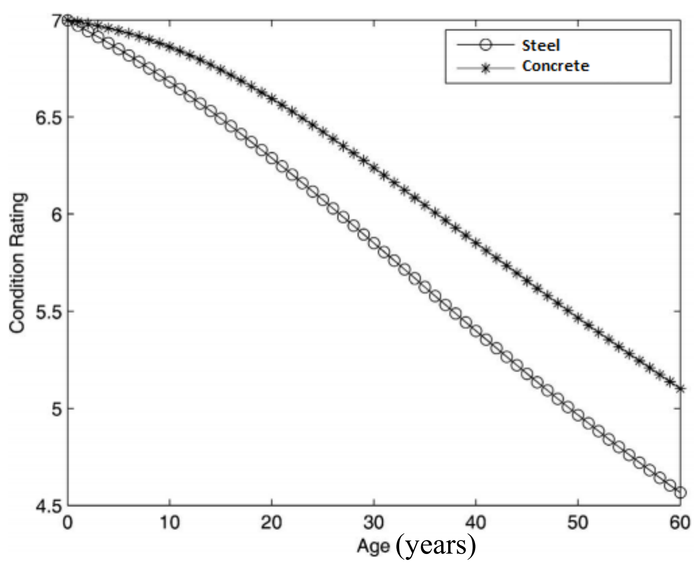


Figure 4 – Sample Depreciation Curve for Superstructure (Agrawal et al. 2010).

2.4.3 Development of Depreciation Models

The entire Georgia bridge inventory is used to derive a transition probability matrix for each group. As described in Section 2.4.1, CR transition counts are used to compute the transition probability matrix P which is raised to the power t (time) as shown in Eq. (1), where p9 indicates the probability of CR 9 remaining CR 9, and q8 indicates the probability of CR 9 transitioning to CR 8; the other components in the matrix are zero. Finally, Eq. (1) is multiplied by a CR matrix to determine a depreciation model (Agrawal et al. 2010) for each bridge or culvert group.

$$P^t = \begin{bmatrix} \boldsymbol{p1} & & & & & & & & \\ q1 & \boldsymbol{p2} & & & & & & & \\ & q2 & \boldsymbol{p3} & & & & & & \\ & & q3 & \boldsymbol{p4} & & & & & \\ & & & q4 & \boldsymbol{p5} & & & & \\ & & & & q5 & \boldsymbol{p6} & & & \\ & & & & & q6 & \boldsymbol{p7} & & \\ & & & & & & q7 & \boldsymbol{p8} & \\ & & & & & & & q8 & \boldsymbol{p9} \end{bmatrix}^t \qquad Eq.\ (1)$$

Once a depreciation model is constructed according to the above procedure, a plot illustrating the life cycle of each bridge is generated. Appendices A and B illustrate a sample plot for culverts and bridges, respectively. For culverts and bridges constructed before 1992, an initial CR 8 is assigned for the ‘year built’ (see Section 2.3.4) and is linearly decreased to CRs reported in 1992. Since their construction year predates the oldest NBI database, recorded CRs are not available.

2.4.4 Hypothesis Test for Validation of Depreciation Models

The depreciation models generated in this study are compared to the depreciation models developed by the LTBP’s research team. For example, the LTBP’s model includes a natural degradation model for approximately 3,300 concrete bridge decks in Georgia and about 8,300 bridges in total. This is approximately 55% of the GA bridge inventory (FHWA LTBP Report 2017). The LTBP's prediction models provide a fairly consistent depreciation trend resulting in depreciation rates of approximately 8% in 15 years and 20% in 35 years and are calculated to consider "natural depreciation" phenomenon as well as to reflect a wide range of variables influencing bridge performance, such as traffic and load rating.

The Chi-square goodness of fit test is used in this study to determine if there is a significant relationship between the two predicted depreciation models. In this test, the claim that must be substantiated (or the alternative hypothesis needed for a statistical analysis) is the two prediction models are correlated. Therefore, the Chi-square test evaluates the null hypothesis, H_0 (that there is no association between the depreciation models, or the LTBP data are not governed by the predicted depreciation models in this study) against the alternative hypothesis (that there is a correlation between the depreciation models). The null hypothesis, H_0, will be rejected if the χ^2 value evaluated by Eq. (2) exceeds the upper α critical value of the χ^2 for a selected degree of freedom, where α is the desired level of significance. The formula for the Chi-square distribution is given in Eq. (2) (Bu et al. 2013; Bu et al. 2014):

$$\chi^2 = \sum_{i=1}^{k} \frac{(E(t)_i - A(t)_i)^2}{E(t)_i} \qquad Eq.\ (2)$$

where χ^2 = Chi-square distribution with k − 1 degrees of freedom (DOF); $E(t)_i$ = expected value of CR in year i predicted by the Markov chain method; $A(t)_i$ = value of CR in year i, predicted by the LTBP study; and k = the number of prediction years.

The critical value depends on the degree of freedom (DOF) and the significance level. A one-way Chi-square test is conducted, and the DOF is equal to the number of predictions (in years) minus one. In this study, bridges with 34 years of predicted CRs at a 5% significance level have a DOF of 33 and a Chi-square critical value of 47.4. The DOF is limited by 34 years of forecasting data generated by the LTBP's research team.

Such a Chi-square test for comparing prediction models is usually carried out as a quality control measure. In this case, bridge depreciation models developed in the study are affected by the selected variables described in Section 2.5, which are different from the variables selected in the LTBP study. By means of a Chi-square goodness of fit test, the reliability of the depreciation models developed in this study are assured by comparing them against the depreciation models determined by the LTBP study (FHWA LTBP Draft Report 2017). The results are presented in Section 3.5.

2.5 Key Attributes Selected for Building Depreciation Models

2.5.1 Culverts

Culverts are separated from bridges and independently analyzed as they differ by physical characteristics and function.

2.5.2 Bridge Deck Types

Five deck material types are considered in addition to structure types. Material types are expected to have a notable effect on deterioration rates due to exposure caused by natural climate.

2.5.3 Bridge Superstructure Types

Similar to bridge deck types, five superstructure material types are considered in the NBI data analysis.

2.5.4 Bridge Substructure over Waterway

The NBI does not specify substructure types. The study team has reviewed substructure types available in GDOT's element-based inspection database and has determined not to include substructure material types for the following reasons:

(1) The element-based inspection data does not provide complete information for some of the bridges recorded in the NBI 1992-2017 inventory. Some bridges have been decommissioned.

(2) There are several combinations of substructure types including abutment, pier, pile, and foundation types. A permutation of these types results in numerous grouping of bridges.

The study team recognizes that substructure material type is an important attribute that should be considered for depreciation models. However, due to the above described limitations, another parameter has been selected: the presence of waterways. Accordingly, two substructure groups are created to recognize the difference in performance of bridges over waterways and non-waterways.

2.5.5 Geographic Regions

Three major geographic regions of Georgia are identified with reference to twelve bridge inspection areas as shown in Figure 5. The solid red lines show the geographic boundaries separating the Northern, Central, and Coastal Georgia regions. The ridge and valley regions are included in the Northern region. The Coastal region includes a large portion of Georgia's coastal plain region (Georgia Info 2018). Bridges are divided into these three regions consistent with their respective inspection areas to reduce potential human error in the bridge CR data. Moreover, the three regions are reasonably in line with climate regions (Department of Energy 2012).

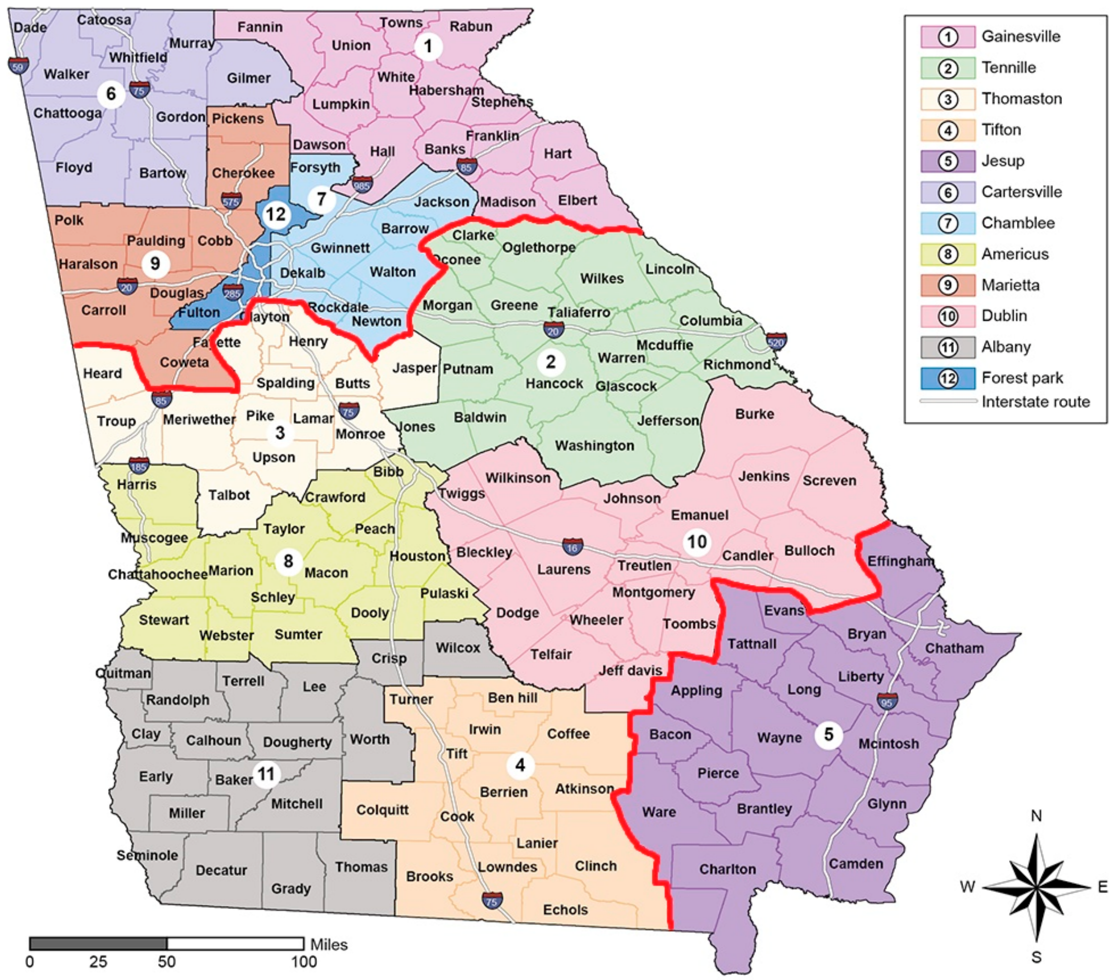


Figure 5 – Three Geographical Regions.

2.5.6 Thirty-Nine Groups Selected for Developing Depreciation Models

A total of 39 analysis groups are created according to the following elements: 1 culvert (vs. bridge), 5 bridge deck types, 5 superstructure types, and 2 substructure sites (waterways/non-waterways) in 3 geographical regions (i.e., 13 attributes × 3 regions). Table 1 presents the grouping designations developed in this study.

Table 1 – Designations Used for 39 Depreciation Models.

Designation #	Component	Material	Region
101	Culvert	n/a	Northern
102	Culvert	n/a	Central
103	Culvert	n/a	Coastal
211	Deck	Concrete	Northern
212	Deck	Concrete	Central
213	Deck	Concrete	Coastal
221	Deck	Metal	Northern
222	Deck	Metal	Central
223	Deck	Metal	Coastal
231	Deck	Precast concrete	Northern
232	Deck	Precast concrete	Central
233	Deck	Precast concrete	Coastal
241	Deck	Timber	Northern
242	Deck	Timber	Central
243	Deck	Timber	Coastal
251	Deck	Other	Northern
252	Deck	Other	Central
253	Deck	Other	Coastal
311	Superstructure	Concrete	Northern
312	Superstructure	Concrete	Central
313	Superstructure	Concrete	Coastal
321	Superstructure	Steel	Northern
322	Superstructure	Steel	Central
323	Superstructure	Steel	Coastal
331	Superstructure	Precast concrete	Northern
332	Superstructure	Precast concrete	Central
333	Superstructure	Precast concrete	Coastal
341	Superstructure	Timber	Northern
342	Superstructure	Timber	Central
343	Superstructure	Timber	Coastal
351	Superstructure	Other	Northern
352	Superstructure	Other	Central
353	Superstructure	Other	Coastal
401	Substructure (No Waterway)	n/a	Northern
402	Substructure (No Waterway)	n/a	Central
403	Substructure (No Waterway)	n/a	Coastal
501	Substructure (Waterway)	n/a	Northern
502	Substructure (Waterway)	n/a	Central
503	Substructure (Waterway)	n/a	Coastal

Note: (1) n/a = not applicable.

3. RESULTS

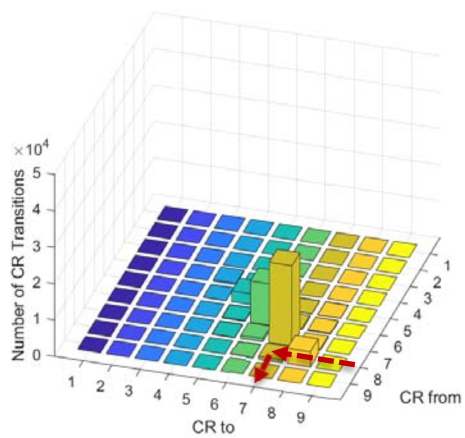
3.1 Overview

This section presents the number of transition counts in CRs and depreciation models for the aforementioned 39 groups of culverts and bridges in the Georgia inventory. A total of 20,710 data entries (i.e., bridges in service between year 1992 and 2017) are analyzed. This data set includes 26 years of the NBI's CRs and thus 25 years of CR transitions. The transition counts are shown by means of a three-dimensional bar chart. This allows a visual identification of the most frequent CR changes within each group. Based on the CR changes and associated transition probabilities for each analysis group, depreciation models are determined by the method described in Section 2.4. The following subsections present the results of the CR data analysis and depreciation models for each of the 39 groups defined in Section 2.5.6. The models are generated for the next 100 years in the figures presented in Sections 3.2 and 3.3. Predictions beyond 100 years are not expected to be used for a life-cycle analysis.

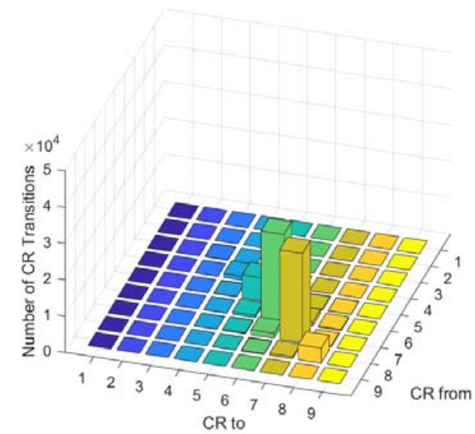
There are two parts to completing depreciation curves. Sections 3.2 and 3.3 present the first part in which nine depreciation models are developed for each of the 39 bridge groups representing deteriorating curves of Georgia bridges in CR 1 through CR 9. Then, in the second part, each bridge is assigned with one of 39 depreciation models according to its latest condition.

3.2 Condition Rating Transitions and Depreciation Models for Culverts

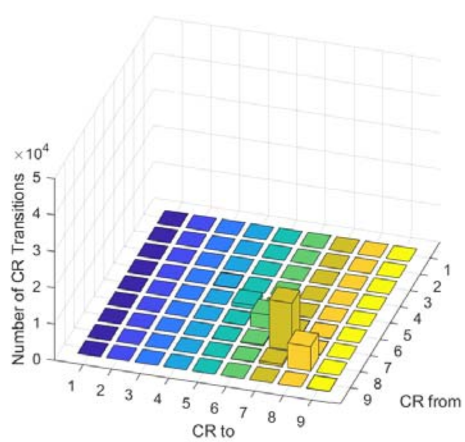
For culverts, three groups of depreciation models are developed. Figure 6 shows the CR transition counts, which are used to determine a transition matrix for each group. For example, Figure 6(a) illustrates that the number of transitions from CR 8 to CR 7 is approximately 1,000. Figure 7 illustrates the deterioration models which are used to assign a depreciation model for each culvert, corresponding to each of the three culvert groups in the bridge inventory. Based on a 1-9 CR scale, nine depreciation curves are developed for each culvert group. In addition to the culvert depreciation models constructed for the three geographic regions shown in Figures 7(a) through (c), the depreciation models determined for all regions (three regions combined) are presented in Figure 7(d) for reference but are not used in this study.



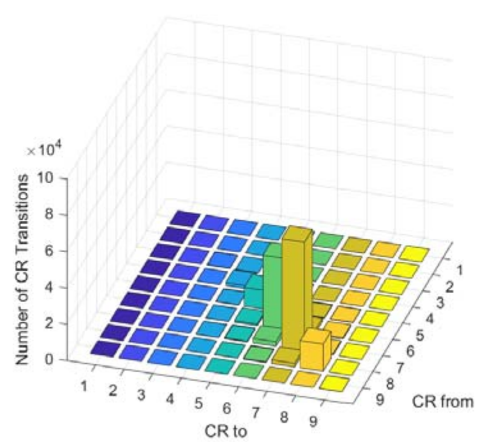
(a) Culverts in the Northern Region



(b) Culverts in the Central Region

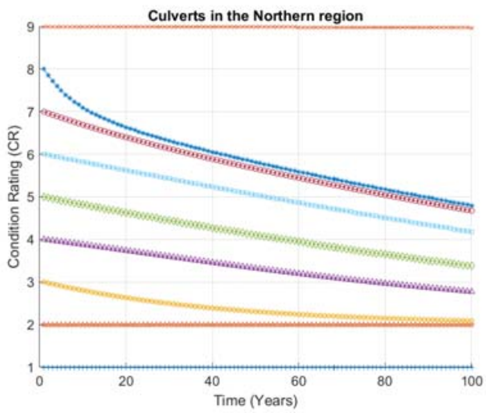


(c) Culverts in the Coastal Region

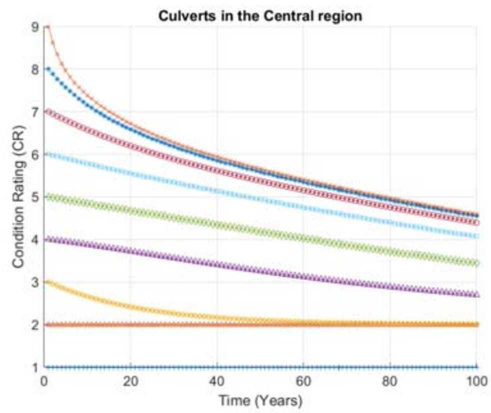


(d) Culverts in All Regions

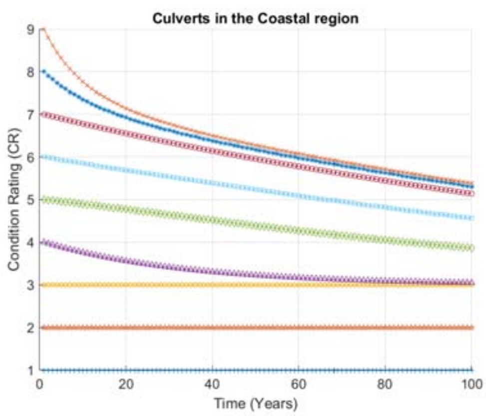
Figure 6 – Condition Rating Transition Counts in Culverts.



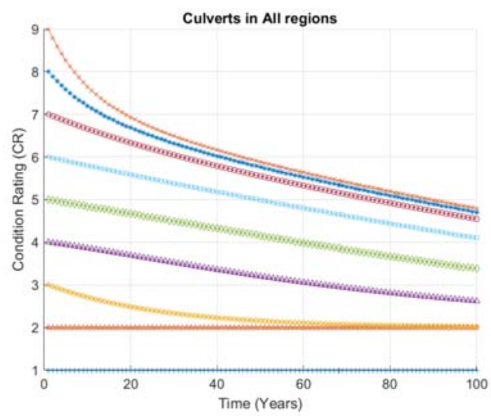
(a) Culverts in the Northern Region (Model No. 101)



(b) Culverts in the Central Region (Model No. 102)



(c) Culverts in the Coastal Region (Model No. 103)



(d) Culverts in All Regions (For reference)

Figure 7 – Depreciation Models for Culverts.

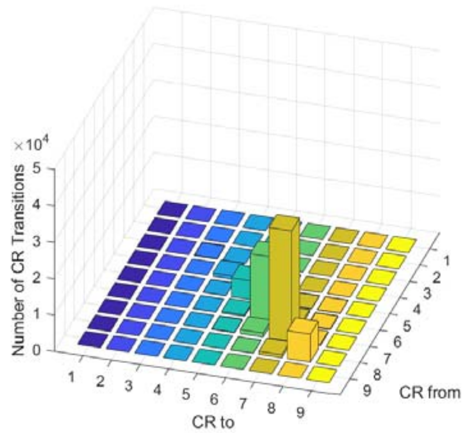
In Figure 7, the straight depreciation lines (in CR9, CR 2, and CR 3) indicate that there is no data (i.e., no culverts in such condition) observed and thus do not suggest the CR is expected to remain unchanged. These lines are not used to assign depreciation models in Section 3.4.

3.3 Condition Rating Transitions and Depreciation Models for Bridges

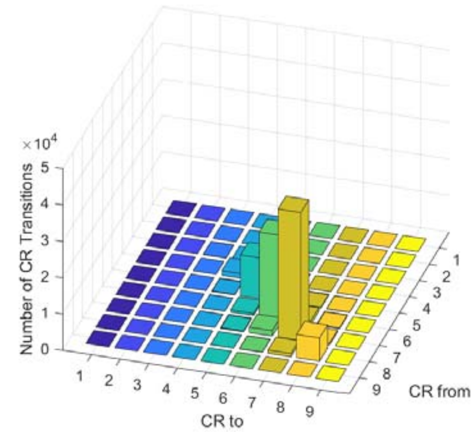
Similar to the results presented for culverts, this subsection presents CR transition counts followed by depreciation models developed for major bridge components (namely, decks, superstructures, and substructures) with reference to the 36 bridge analysis groups described in Section 2.5.6. The depreciation models developed for the 12 bridge attributes are presented for all regions (i.e., the entire state of Georgia) as a point of reference and are not used to assign depreciation models based on the latest bridge condition in Section 3.4.

3.3.1 Deck

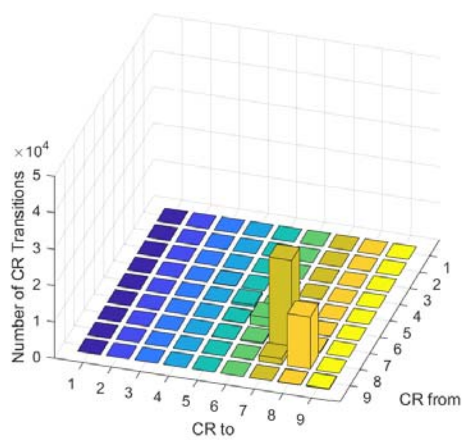
Figures 8 through 17 present the bridge deck CR transition counts over the past 25 years and corresponding depreciation models determined by analyzing the transitions. The depreciation models are grouped by five deck material types (concrete, precast concrete, metal, timber, and other) and subsequently into three geographical regions.



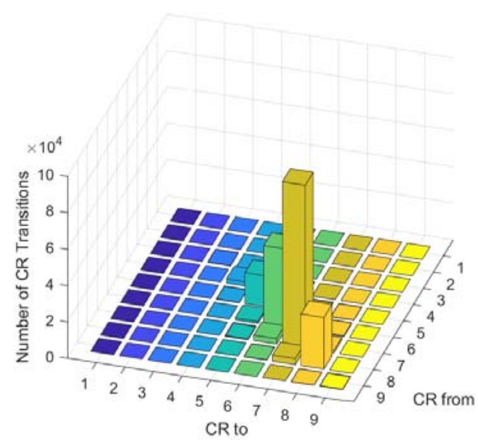
(a) Decks in the Northern Region



(b) Decks in the Central Region

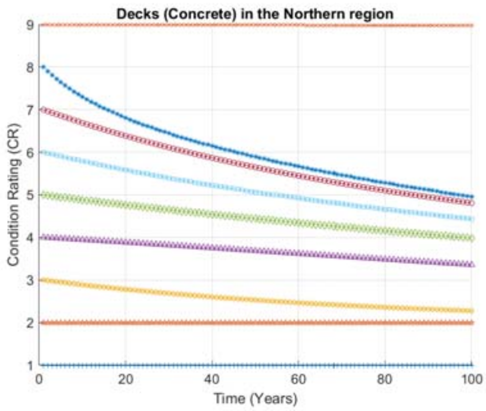


(c) Decks in the Coastal Region

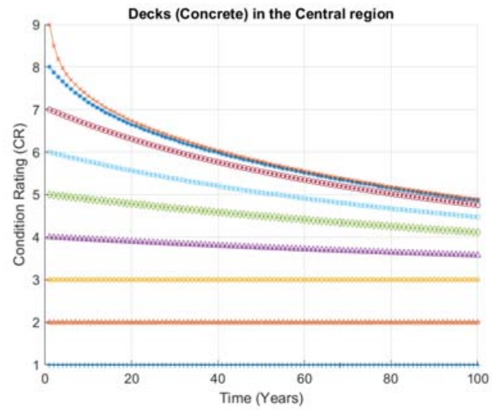


(d) Decks in All Regions

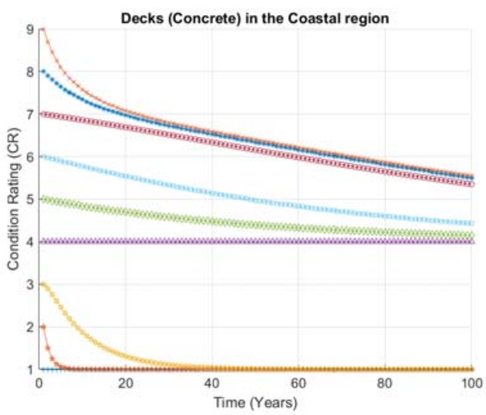
Figure 8 – Condition Rating Transition Counts in Bridge Decks (Concrete).



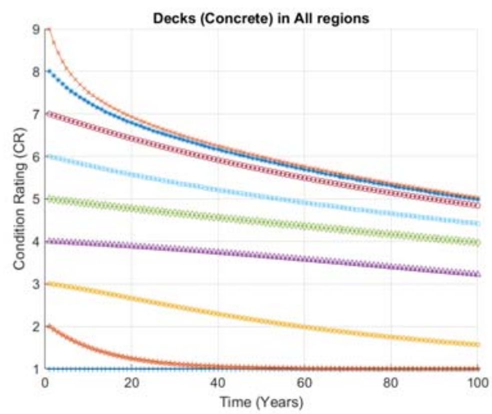
(a) Decks in the Northern Region
(Model No. 211)



(b) Decks in the Central Region
(Model No. 212)

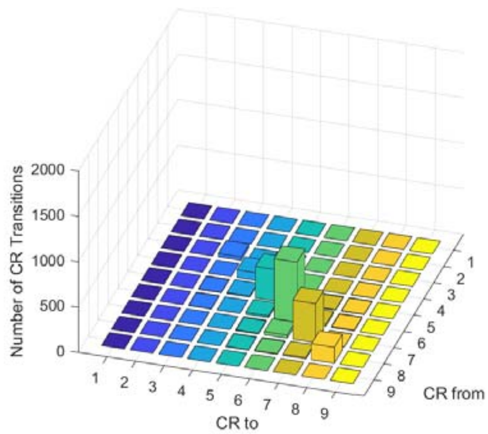


(c) Decks in the Coastal Region
(Model No. 213)

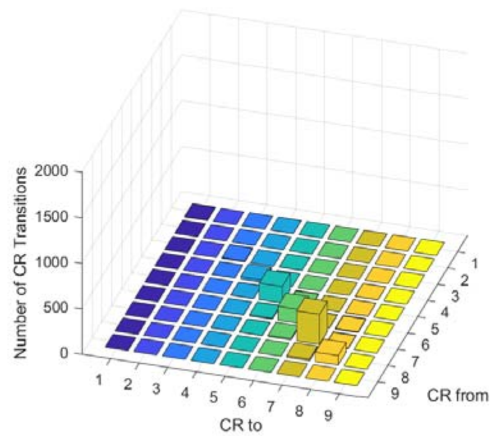


(d) Decks in All Regions
(For reference)

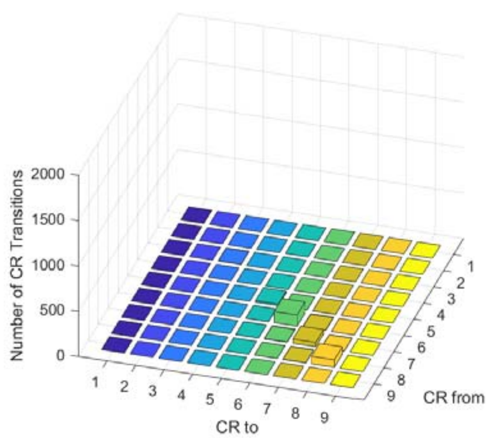
Figure 9 – Depreciation Models for Bridge Decks (Concrete).



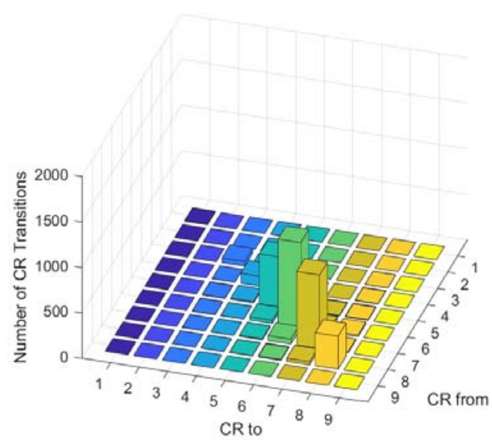
(a) Decks in the Northern Region



(b) Decks in the Central Region

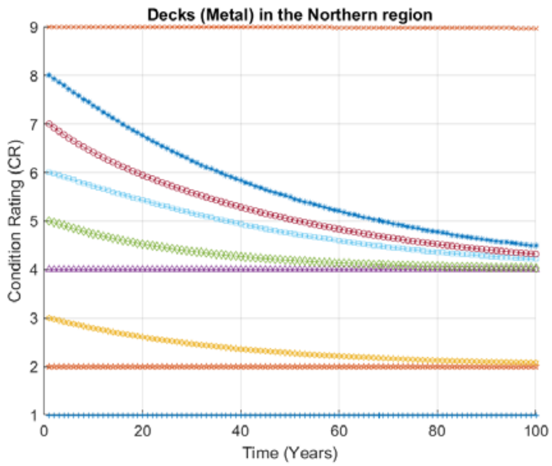


(c) Decks in the Coastal Region

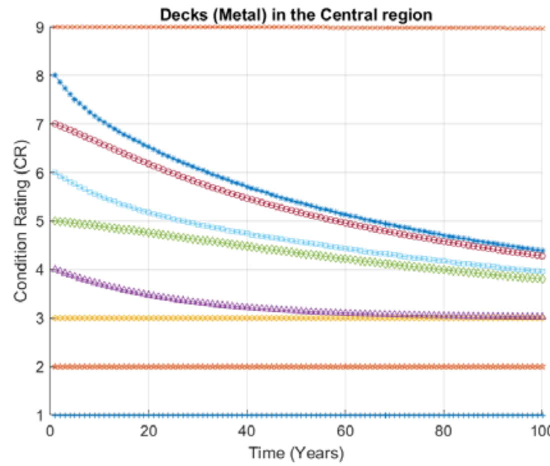


(d) Decks in All Regions

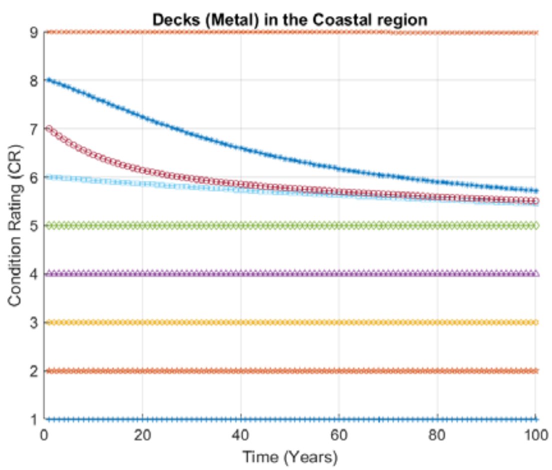
Figure 10 – Condition Rating Transition Counts in Bridge Decks (Metal).



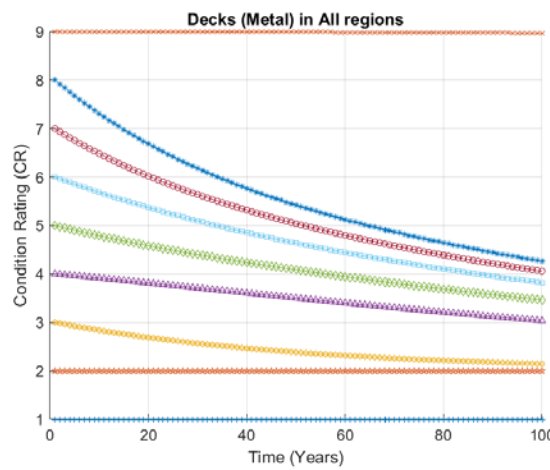
(a) Decks in the Northern Region
(Model No. 221)



(b) Decks in the Central Region
(Model No. 222)

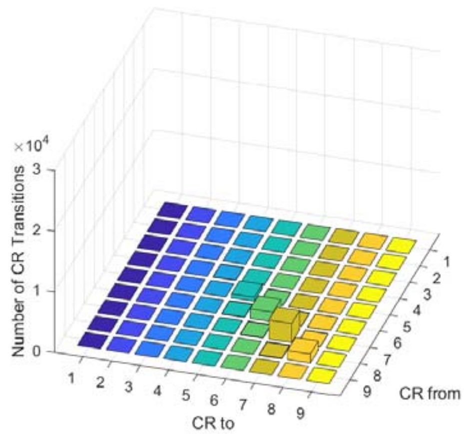


(c) Decks in the Coastal Region
(Model No. 223)

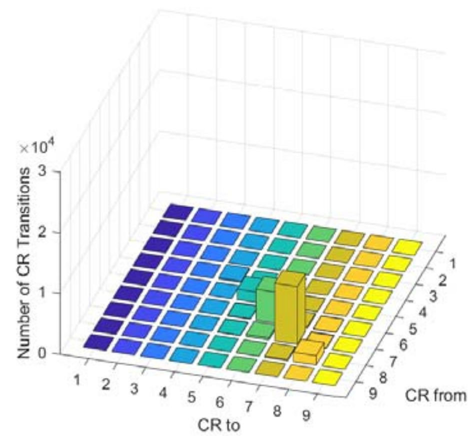


(d) Decks in All Regions
(For reference)

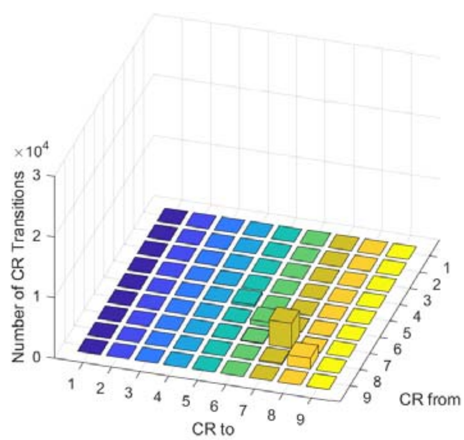
Figure 11 – Depreciation Models for Bridge Decks (Metal).



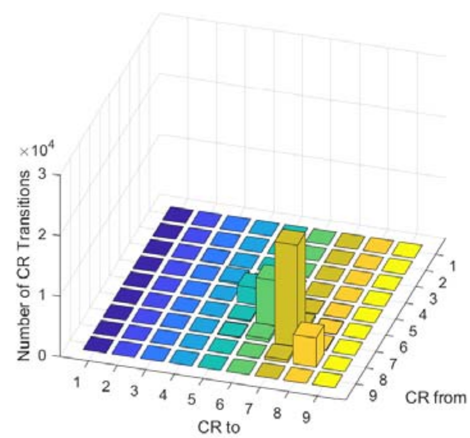
(a) Decks in the Northern Region



(b) Decks in the Central Region

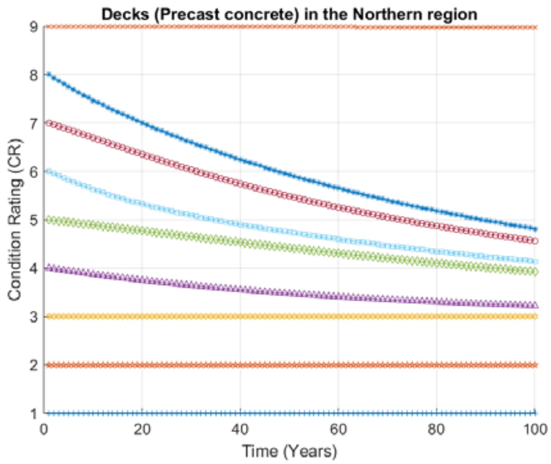


(c) Decks in the Coastal Region

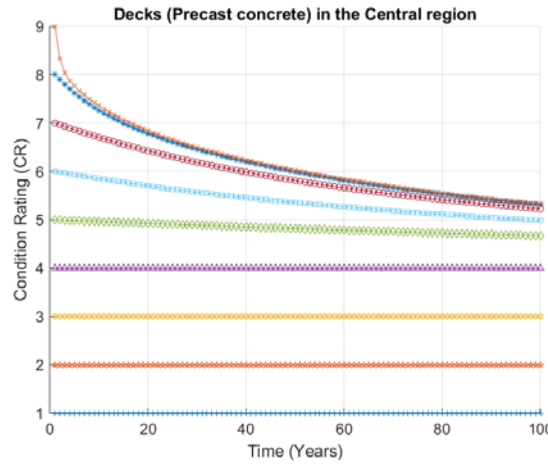


(d) Decks in All Regions

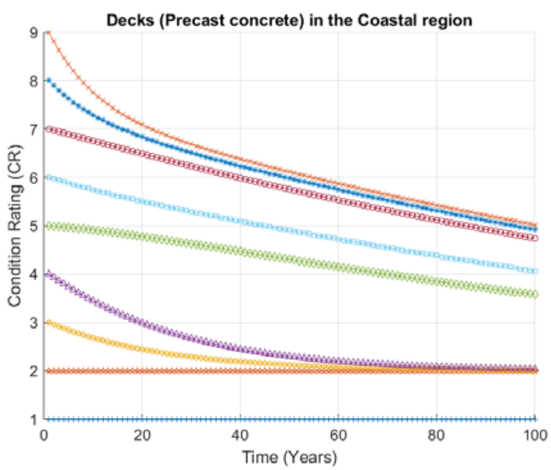
Figure 12 – Condition Rating Transition Counts in Bridge Decks (Precast concrete).



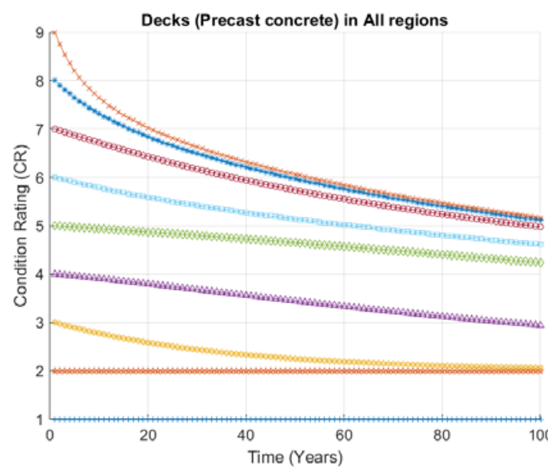
(a) Decks in the Northern Region
(Model No. 231)



(b) Decks in the Central Region
(Model No. 232)

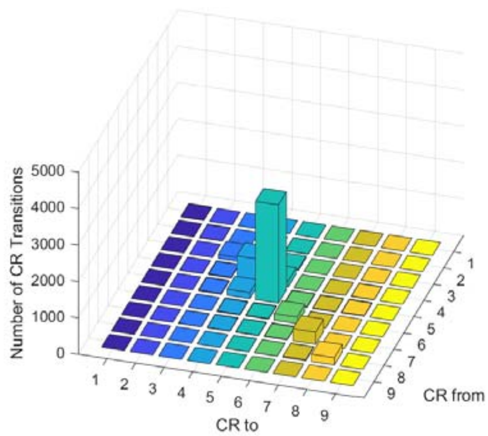


(c) Decks in the Coastal Region
(Model No. 233)

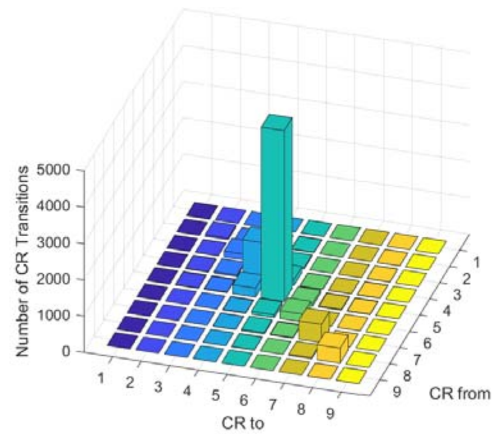


(d) Decks in All Regions
(For reference)

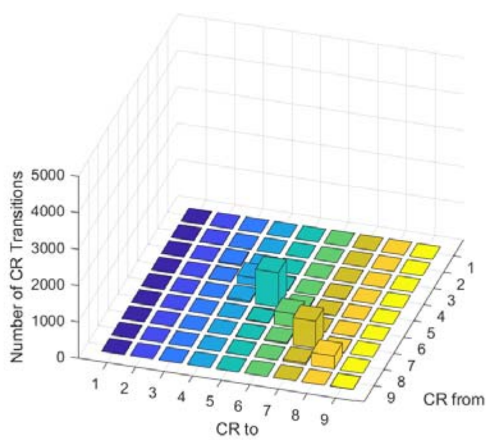
Figure 13 – Depreciation Models for Bridge Decks (Precast concrete).



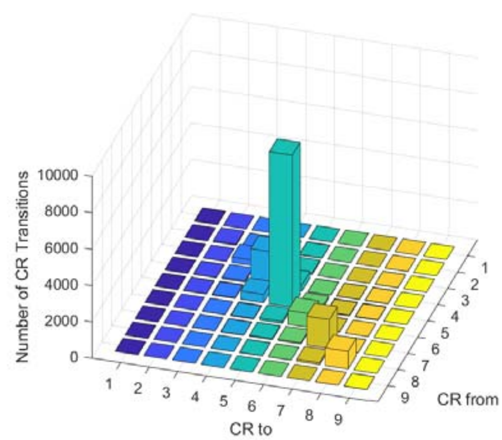
(a) Decks in the Northern Region



(b) Decks in the Central Region

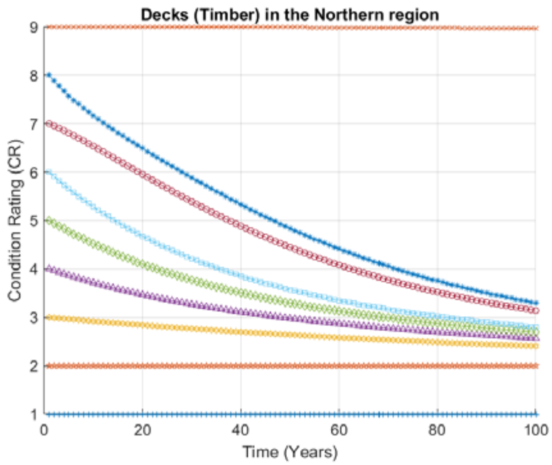


(c) Decks in the Coastal Region

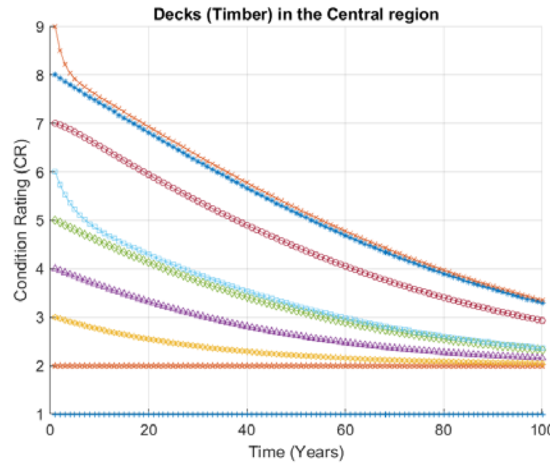


(d) Decks in All Regions

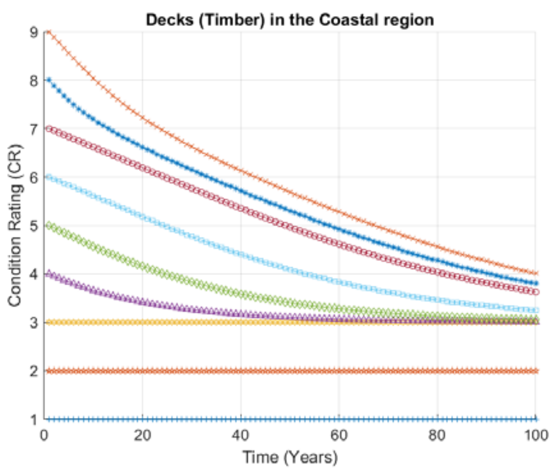
Figure 14 – Condition Rating Transition Counts in Bridge Decks (Timber).



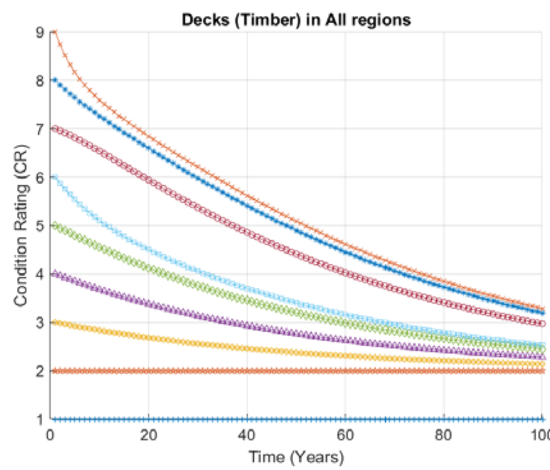
(a) Decks in the Northern Region
(Model No. 241)



(b) Decks in the Central Region
(Model No. 242)

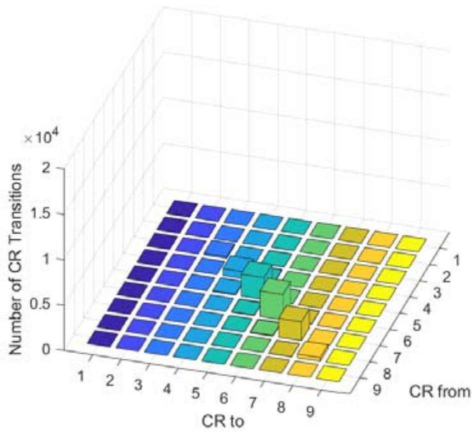


(c) Decks in the Coastal Region
(Model No. 243)

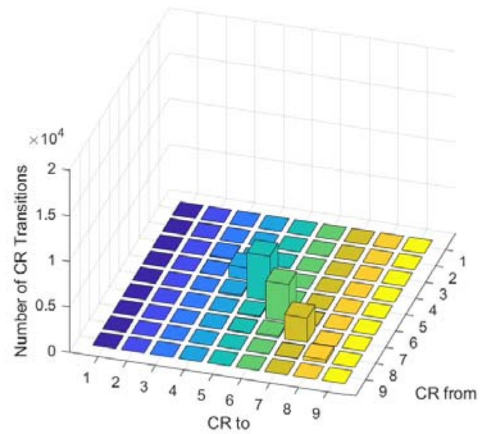


(d) Decks in All Regions
(For reference)

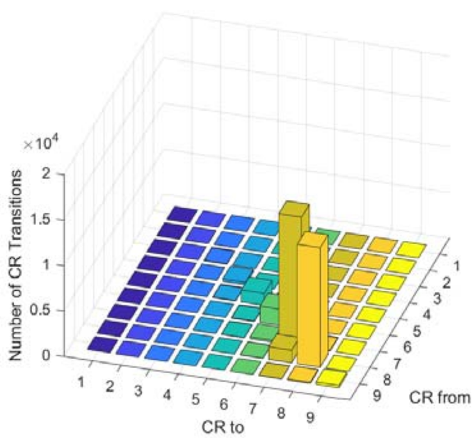
Figure 15 – Depreciation Models for Bridge Decks (Timber).



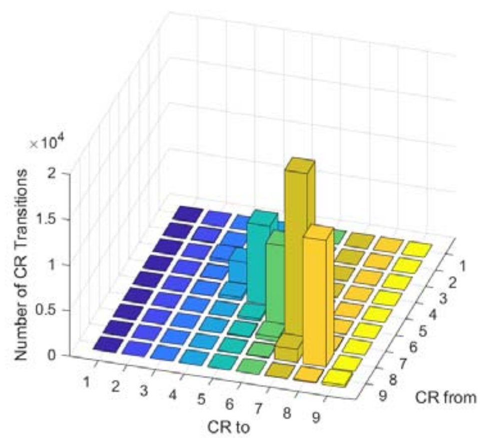
(a) Decks in the Northern Region



(b) Decks in the Central Region

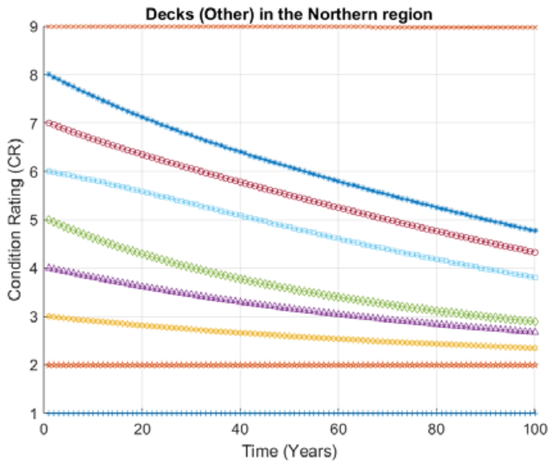


(c) Decks in the Coastal Region

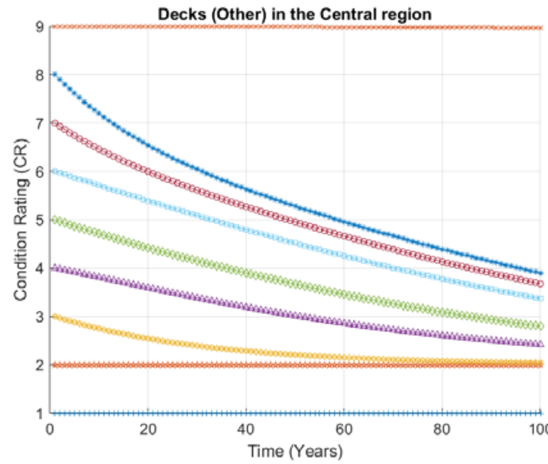


(d) Decks in All Regions

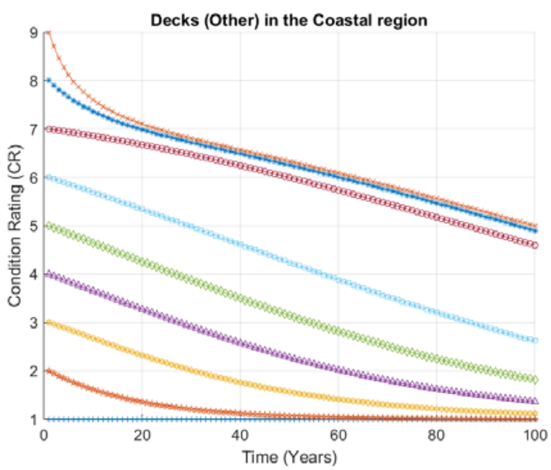
Figure 16 – Condition Rating Transition Counts in Bridge Decks (Other).



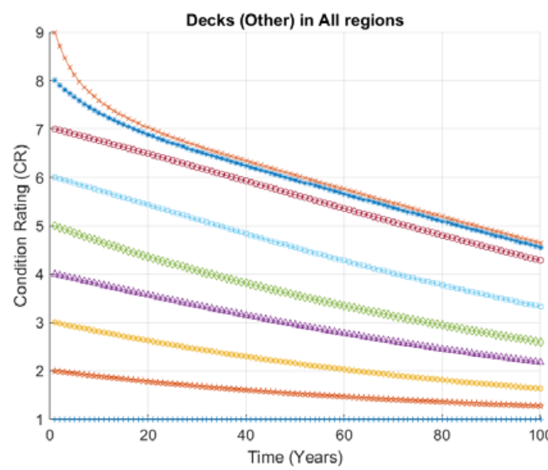
(a) Decks in the Northern Region
(Model No. 251)



(b) Decks in the Central Region
(Model No. 252)



(c) Decks in the Coastal Region
(Model No. 253)

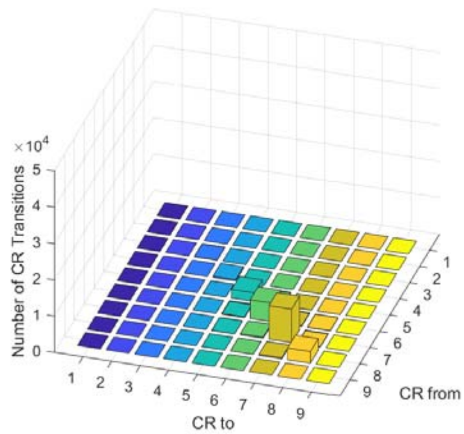


(d) Decks in All Regions
(For reference)

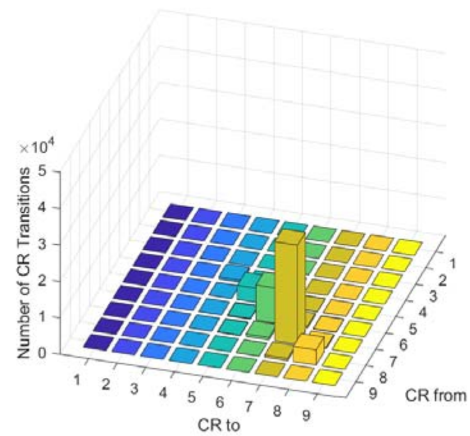
Figure 17 – Depreciation Models for Bridge Decks (Other).

3.3.2 Superstructure

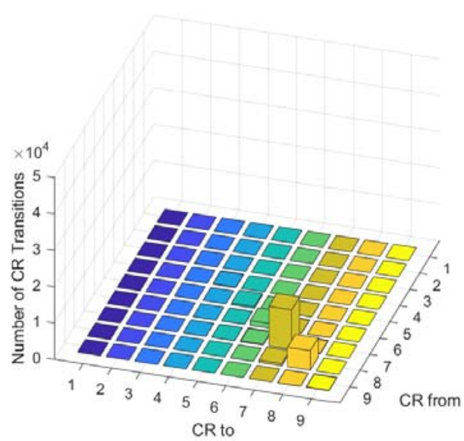
Figures 18 through 27 present the bridge superstructure CR transition counts over the past 25 years and corresponding depreciation models determined by analyzing the NBI data sets (1992-2017). Just as in the previous section, the depreciation models are grouped by five superstructure material types (concrete, precast concrete, steel, timber, and other) and then three geographical regions.



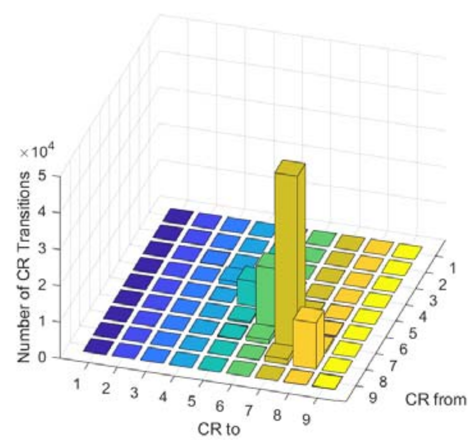
(a) Superstructures in the Northern Region



(b) Superstructures in the Central Region

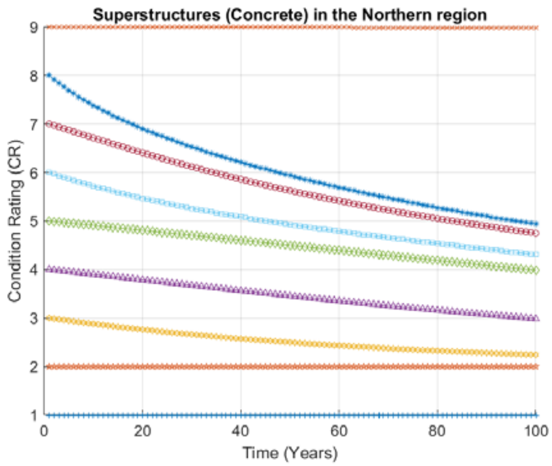


(c) Superstructures in the Coastal Region

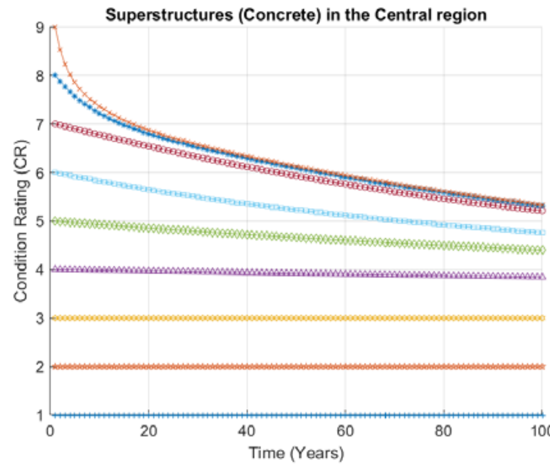


(d) Superstructures in All Regions

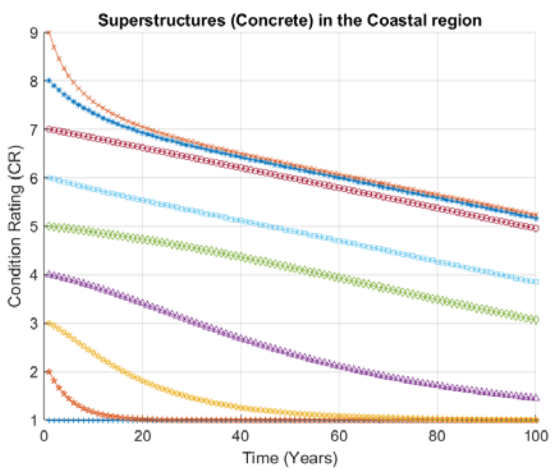
Figure 18 – Condition Rating Transition Counts in Superstructures (Concrete).



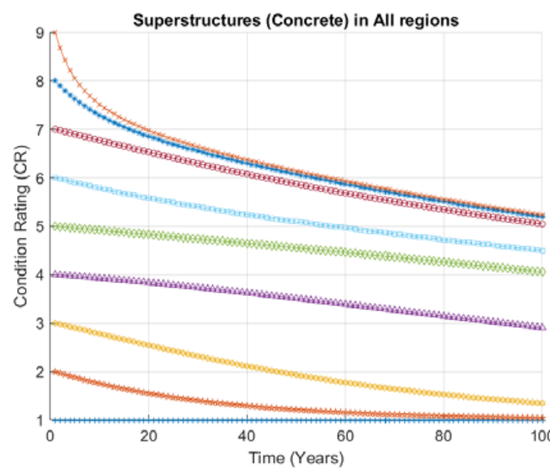
(a) Superstructures in the Northern Region (Model No. 311)



(b) Superstructures in the Central Region (Model No. 312)

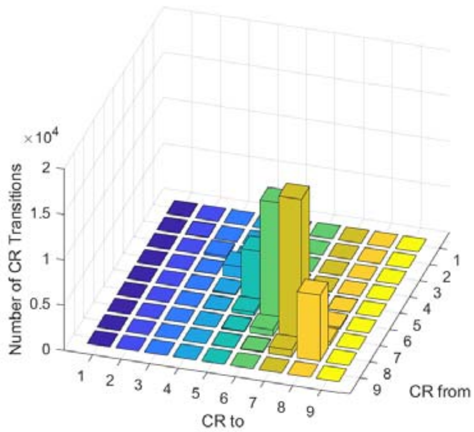


(c) Superstructures in the Coastal Region (Model No. 313)

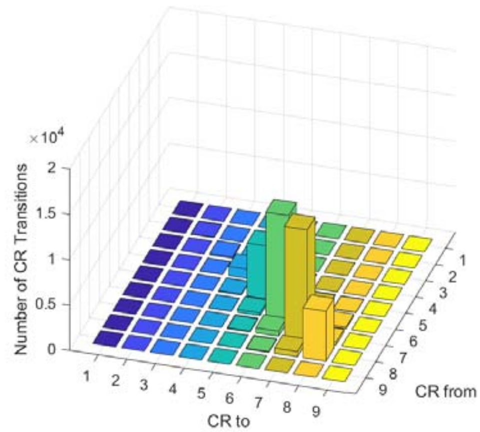


(d) Superstructures in All Regions (For reference)

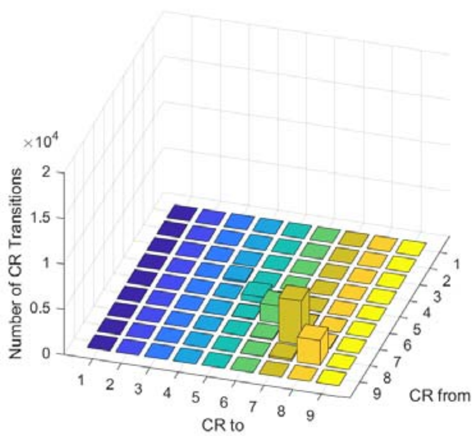
Figure 19 – Depreciation Models for Superstructures (Concrete).



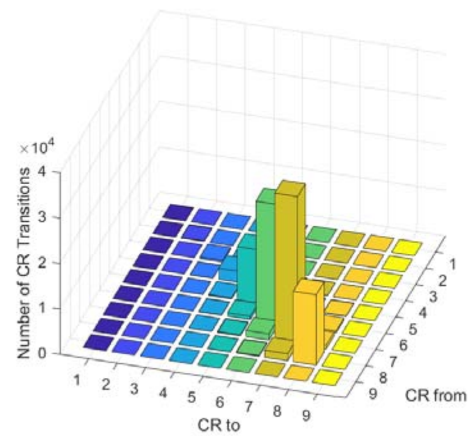
(a) Superstructures in the Northern Region



(b) Superstructures in the Central Region

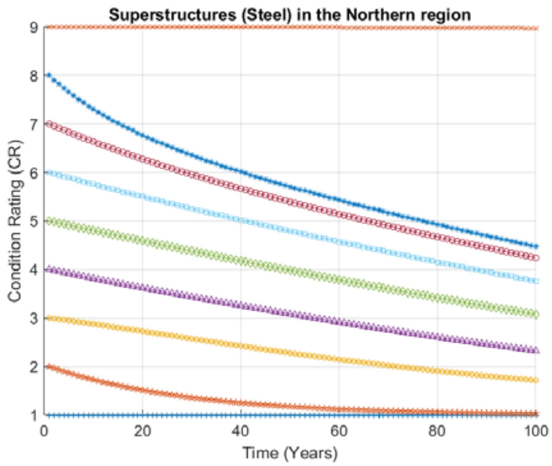


(c) Superstructures in the Coastal Region

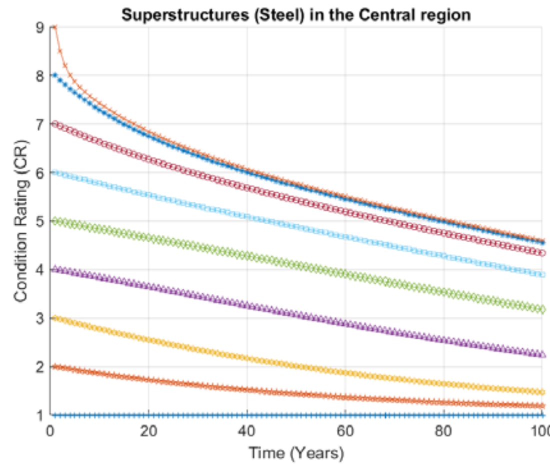


(d) Superstructures in All Regions

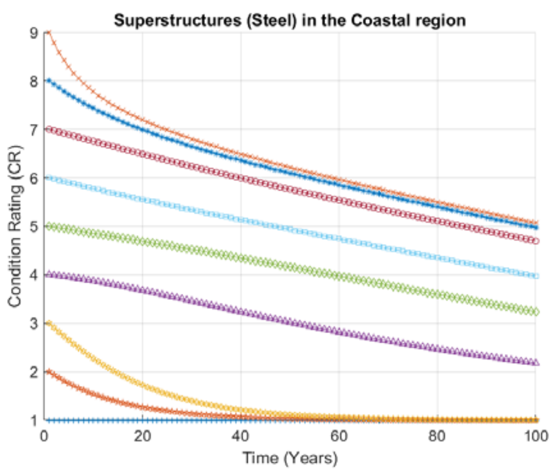
Figure 20 – Condition Rating Transition Counts in Superstructures (Steel).



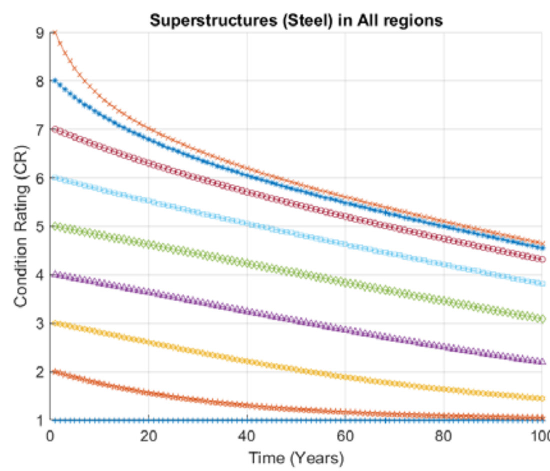
(a) Superstructures in the Northern Region (Model No. 321)



(b) Superstructures in the Central Region (Model No. 322)

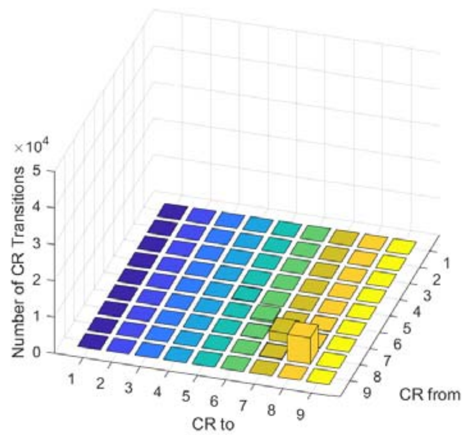


(c) Superstructures in the Coastal Region (Model No. 323)

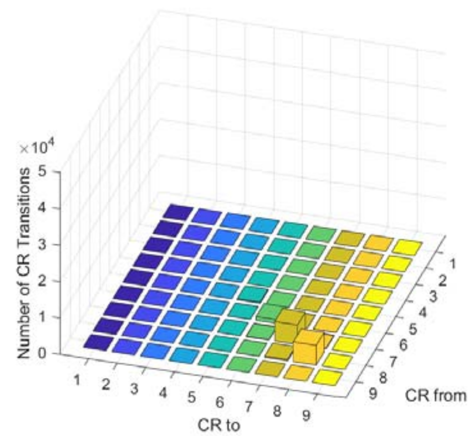


(d) Superstructures in All Regions (For reference)

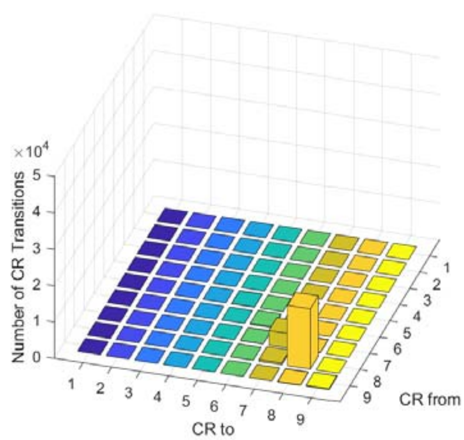
Figure 21 – Depreciation Models for Superstructures (Steel).



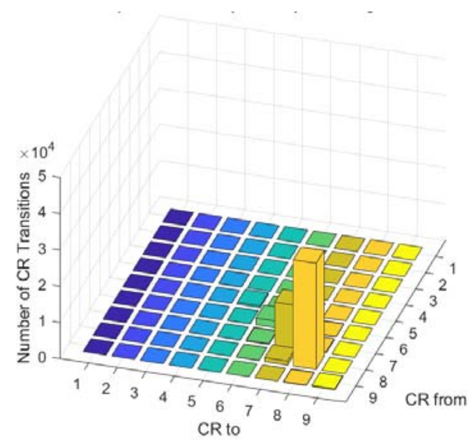
(a) Superstructures in the Northern Region



(b) Superstructures in the Central Region

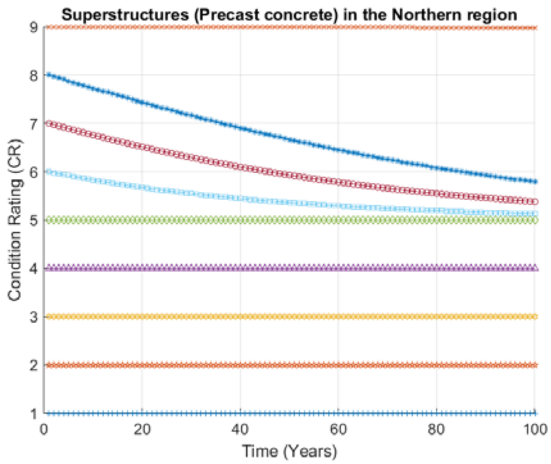


(c) Superstructures in the Coastal Region

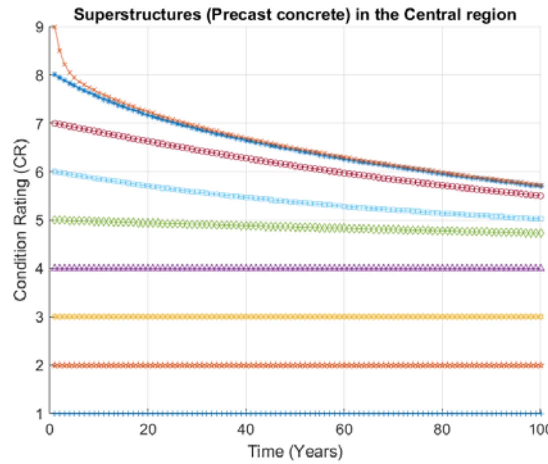


(d) Superstructures in All Regions

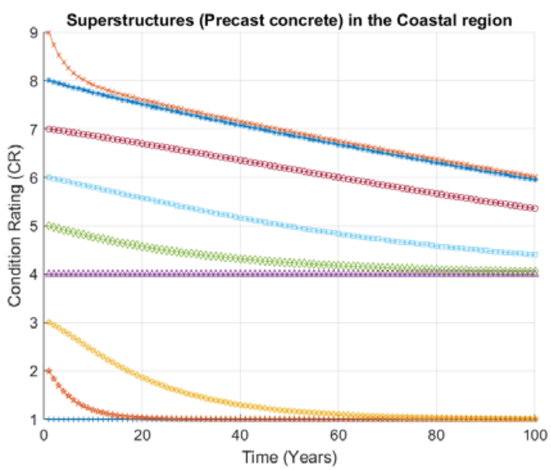
Figure 22 – Condition Rating Transition Counts in Superstructures (Precast concrete).



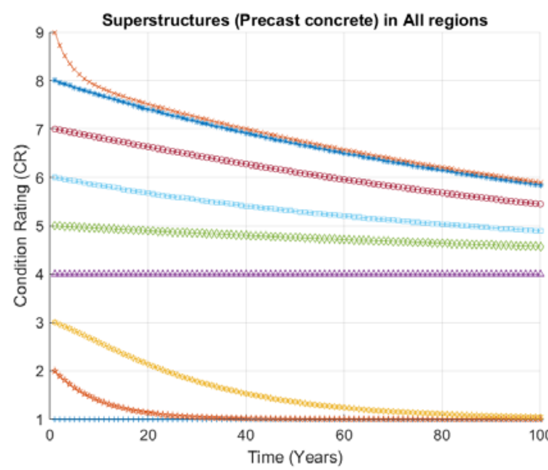
(a) Superstructures in the Northern Region (Model No. 331)



(b) Superstructures in the Central Region (Model No. 332)

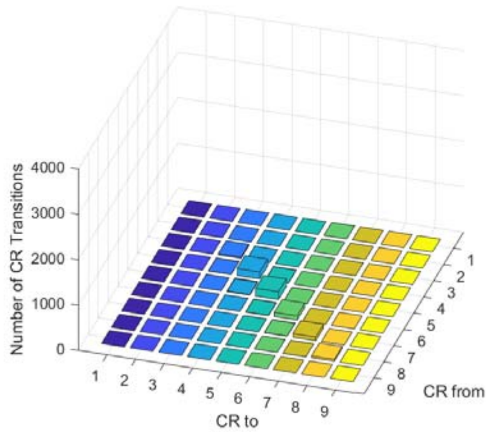


(c) Superstructures in the Coastal Region (Model No. 333)

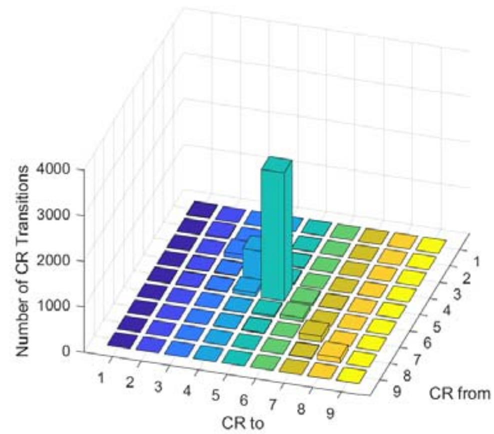


(d) Superstructures in All Regions (For reference)

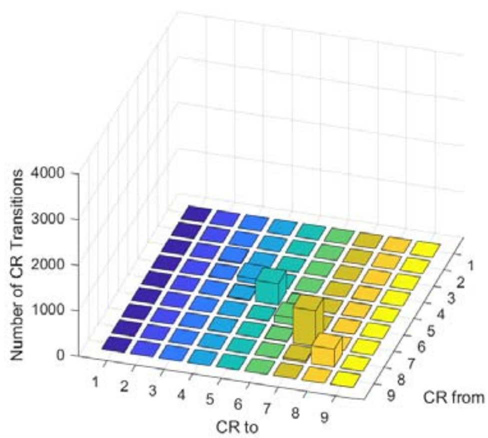
Figure 23 – Depreciation Models for Superstructures (Precast concrete).



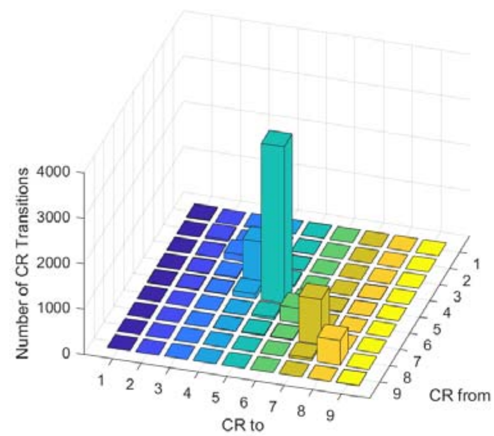
(a) Superstructures in the Northern Region



(b) Superstructures in the Central Region

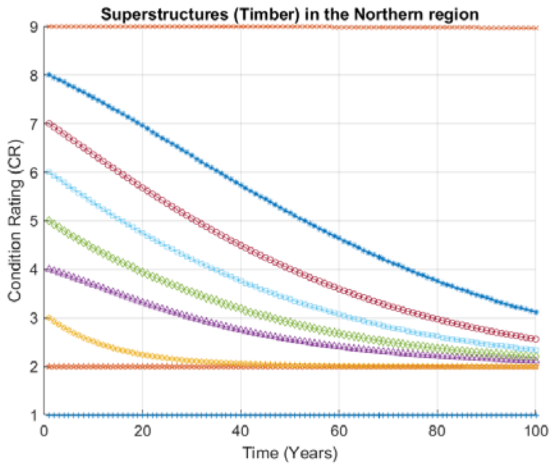


(c) Superstructures in the Coastal Region

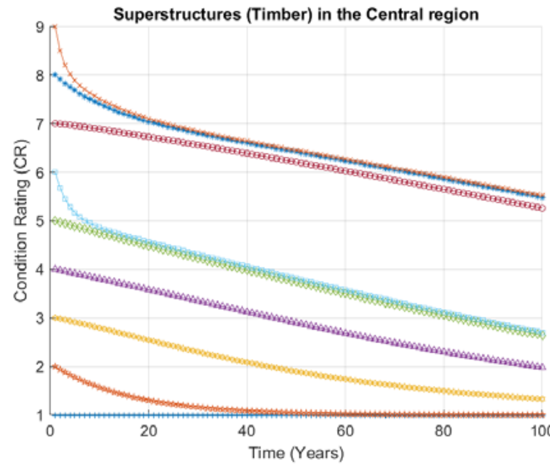


(d) Superstructures in All Regions

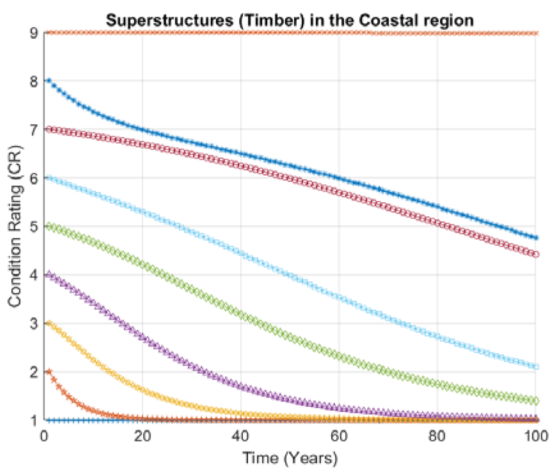
Figure 24 – Condition Rating Transition Counts in Superstructures (Timber).



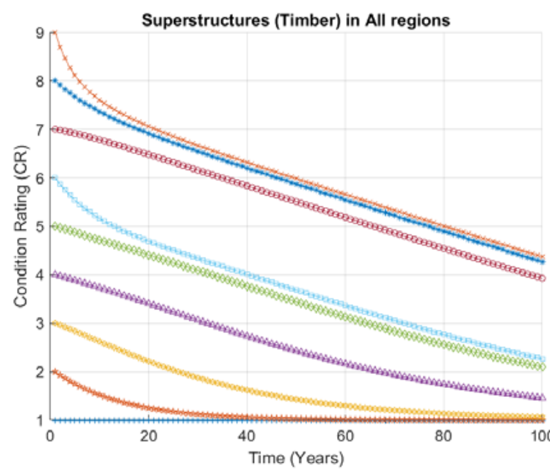
(a) Superstructures in the Northern Region (Model No. 341)



(b) Superstructures in the Central Region (Model No. 342)

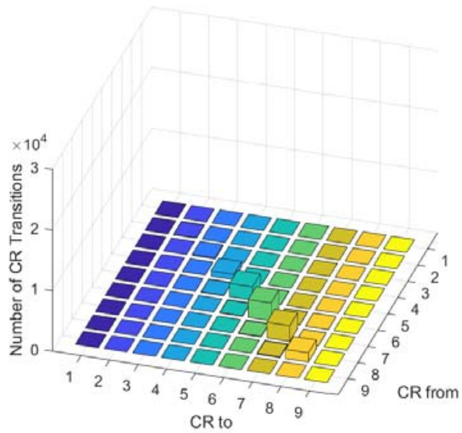


(c) Superstructures in the Coastal Region (Model No. 343)

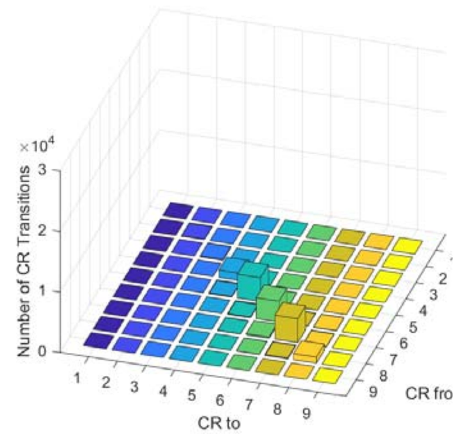


(d) Superstructures in All Regions (For reference)

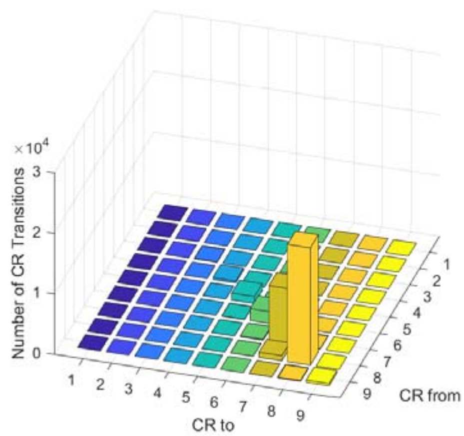
Figure 25 – Depreciation Models for Superstructures (Timber).



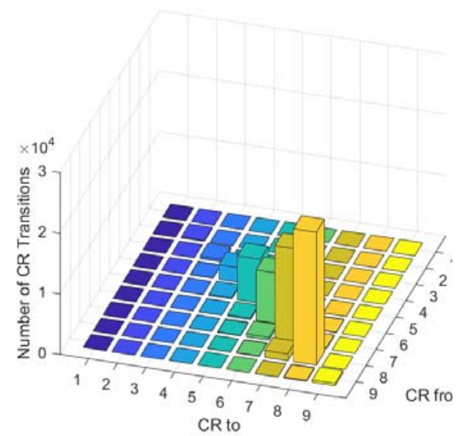
(a) Superstructures in the Northern Region



(b) Superstructures in the Central Region

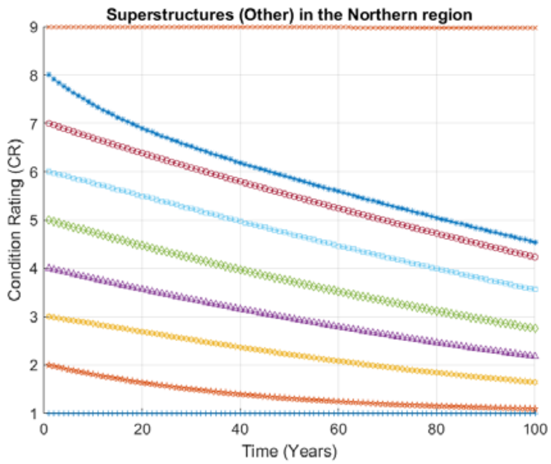


(c) Superstructures in the Coastal Region

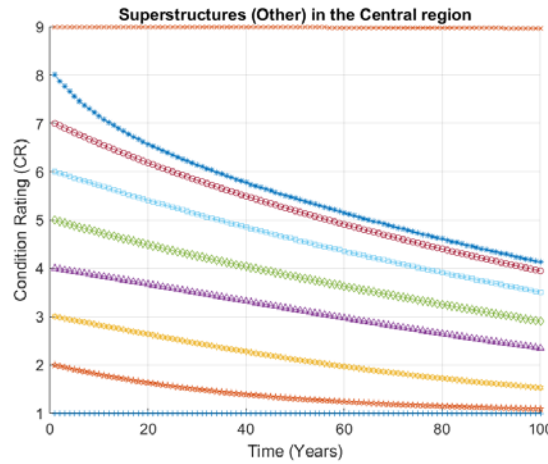


(d) Superstructures in All Regions

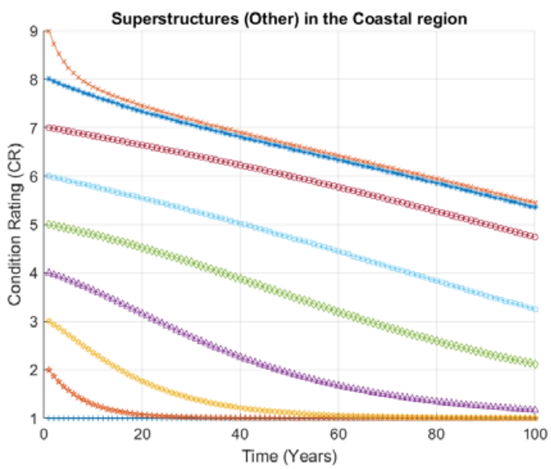
Figure 26 – Condition Rating Transition Counts in Superstructures (Other).



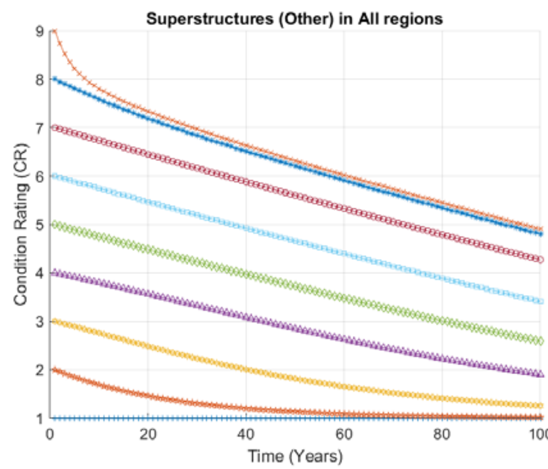
(a) Superstructures in the Northern Region (Model No. 351)



(b) Superstructures in the Central Region (Model No. 352)



(c) Superstructures in the Coastal Region (Model No. 353)

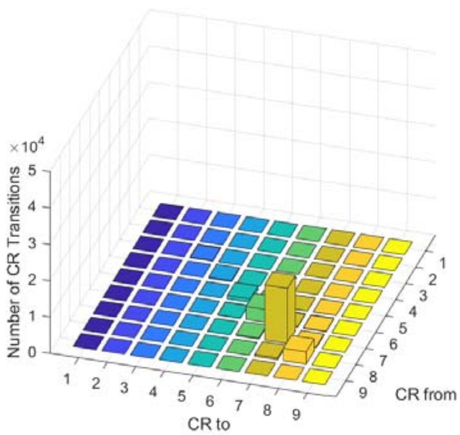


(d) Superstructures in All Regions (For reference)

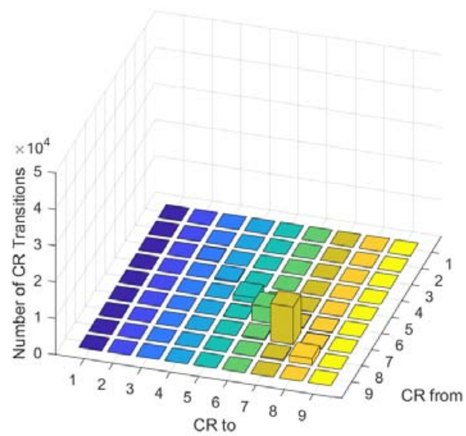
Figure 27 – Depreciation Models for Superstructures (Other).

3.3.3 Substructure

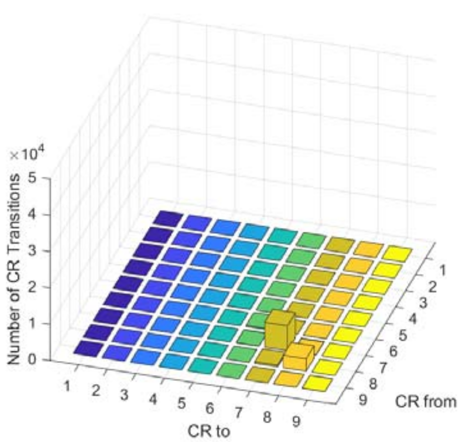
Figures 28 through 31 show the bridge substructure CR transition counts over the past 25 years and corresponding depreciation models determined by analyzing past transitions. In contrast to superstructures, bridge substructure models are not divided by material types. They are divided by the presence of waterways in the Northern, Central, and Coastal regions of Georgia.



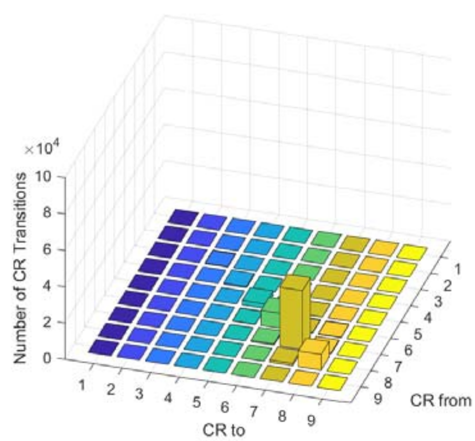
(a) Substructures in the Northern Region



(b) Substructures in the Central Region

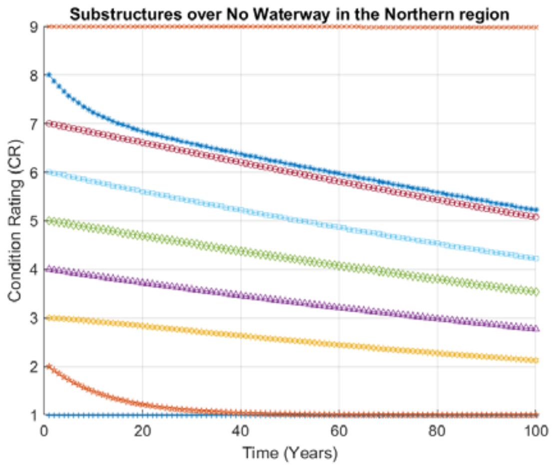


(c) Substructures in the Coastal Region

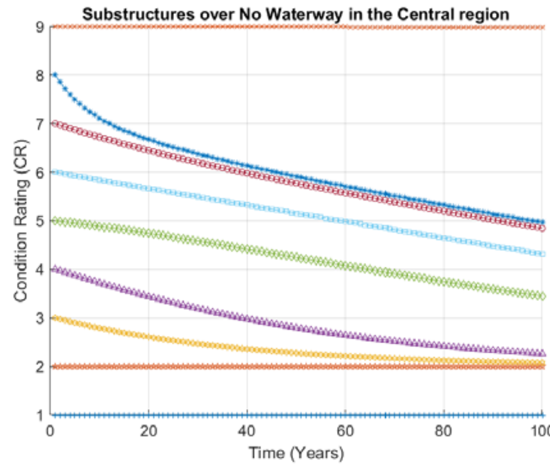


(d) Substructures in All Regions

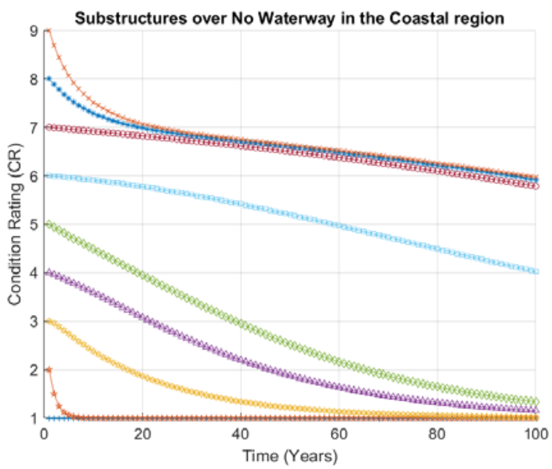
Figure 28 – Condition Rating Transition Counts in Substructures (No Waterway).



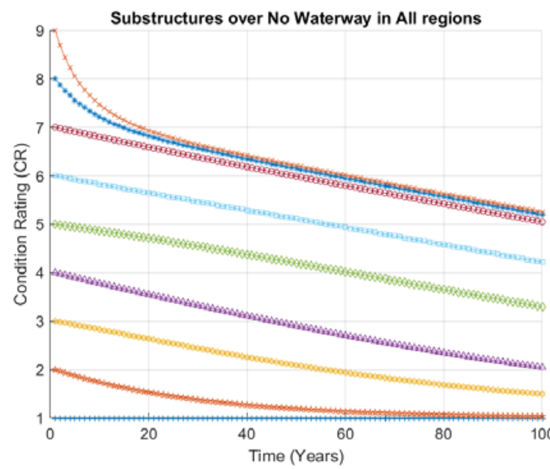
(a) Substructures in the Northern Region (Model No. 401)



(b) Substructures in the Central Region (Model No. 402)

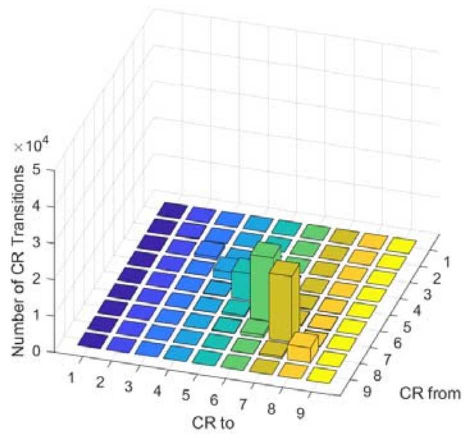


(c) Substructures in the Coastal Region (Model No. 403)

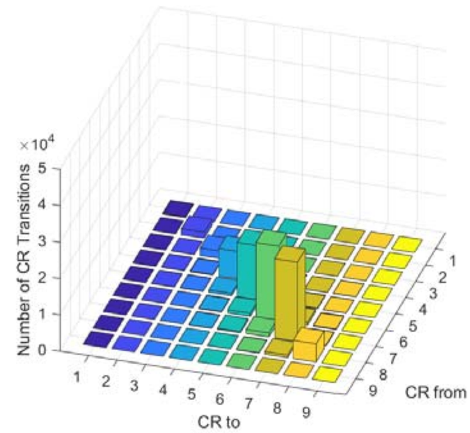


(d) Substructures in All Regions (For reference)

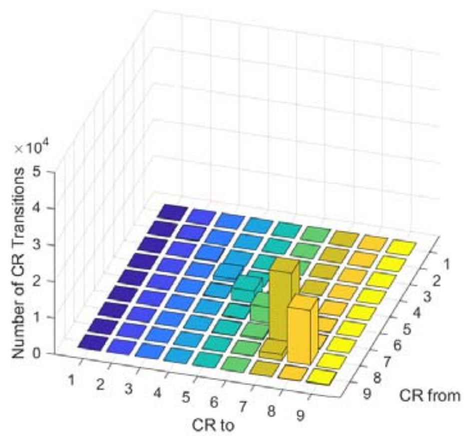
Figure 29 – Depreciation Models for Substructures (No Waterway).



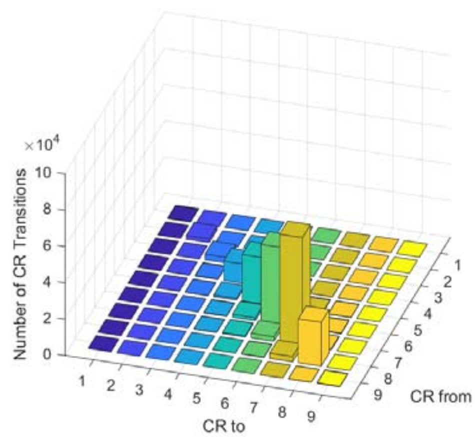
(a) Substructures in the Northern Region



(b) Substructures in the Central Region

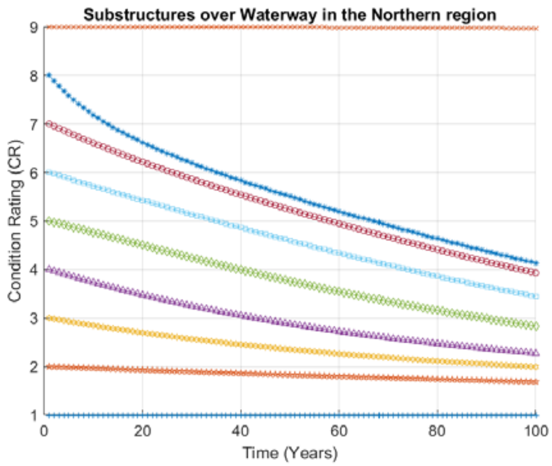


(c) Substructures in the Coastal Region

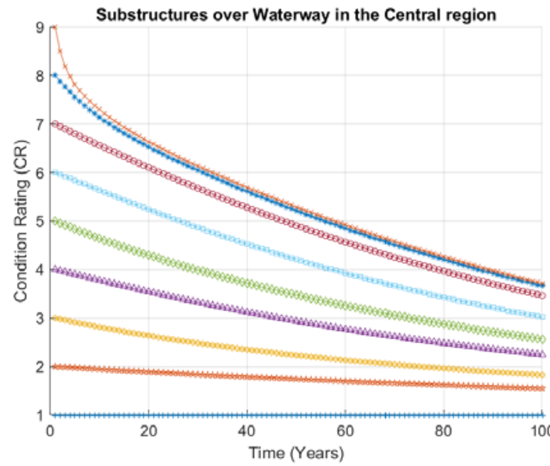


(d) Substructures in All Regions

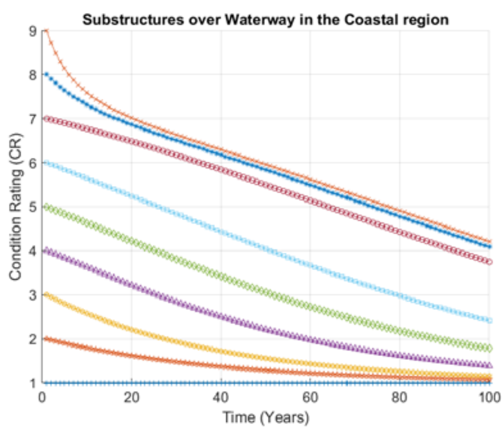
Figure 30 – Condition Rating Transition Counts in Substructures (over Waterway).



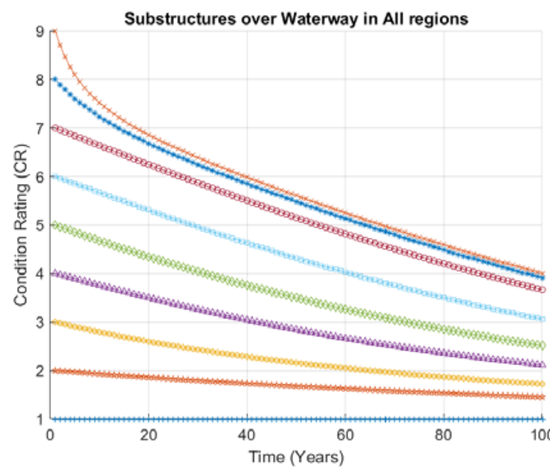
(a) Substructures in the Northern Region (Model No. 501)



(b) Substructures in the Central Region (Model No. 502)



(c) Substructures in the Coastal Region (Model No. 503)



(d) Substructures in All Regions (For reference)

Figure 31 – Depreciation Models for Substructures (over Waterway).

3.4 Assignment of 39 Depreciation Models

Each culvert in the NBI 2017 inventory is given one of the 3 depreciation models (101-103) presented in Section 3.2, and each bridge is assigned 3 depreciation models for its deck, superstructure, and substructure, respectively, from the remaining 36 models presented in Section 3.3. Appendices A and B illustrate the results.

3.5 Model Validation and Chi-square Test Results

The predicted depreciation models assigned in Section 3.4 are compared with the depreciation models determined by the LTBP's research team by performing the Chi-square ($\chi 2$) test described in Section 2.4.3 to determine if there is a significant relationship between the two models. The test data set from the LTBP includes bridge performance predictions of 8,355 Georgia bridges in total. Thus, depreciation models for the same 8,355 bridges from the current study are analyzed. It is concluded to reject the null hypothesis and thus accept the alternative hypothesis. That is, the predicted depreciation models are in reasonable agreement with the depreciation models generated by the LTBP study. The evidence for this conclusion is presented in greater detail below.

The outcomes of the Chi-square (χ^2) test are presented in Table 2, which summarizes the Chi-square values for the selected bridges as well as DOF, the Chi-square critical values at a significance level of $\alpha = 0.05$, and the Chi-square percentage. Table 3 provides a summary of all data analyzed. The Chi-square percentage measured with respect to the critical value (i.e., χ^2/χ^2critical) is computed and shown in the last column of Table 2. A breakdown of the discretized Chi-square percentages is shown in Table 3, and Figure 32 illustrates the Chi-square distribution.

Table 2 – χ^2 Values at a Significance Level of α = 0.05 for Selected Components.

Bridge component	Bridge ID	χ^2	DOF	χ^2 critical (α = 0.05)	χ^2 percentage $(\chi^2/\chi^2 \text{critical})$*100
Deck	100220	10.95	33	47.40	31.14
	100310	4.53	33	47.40	12.89
	150070	2.75	33	47.40	7.83
	150410	0.23	33	47.40	0.66
	150420	0.36	33	47.40	1.01
Superstructure	100220	11.47	33	47.40	32.60
	100310	4.87	33	47.40	13.84
	150070	2.56	33	47.40	7.27
	150410	0.23	33	47.40	0.64
	150420	0.38	33	47.40	1.08
Substructure	100220	8.24	33	47.40	23.42
	100310	0.54	33	47.40	1.54
	150070	0.54	33	47.40	1.54
	150410	0.387	33	47.40	1.10
	150420	0.52	33	47.40	1.48

Table 3 – χ^2 Distribution.

χ^2 discrete	Description	Bridge count		
		Deck	Superstructure	Substructure
10	$0 \leq \chi^2$ percentage ≤ 10	4024	3601	3817
20	$11 \leq \chi^2$ percentage ≤ 20	1635	1775	1519
30	$21 \leq \chi^2$ percentage ≤ 30	749	855	1103
40	$31 \leq \chi^2$ percentage ≤ 40	906	890	577
50	$41 \leq \chi^2$ percentage ≤ 50	170	224	331
60	$51 \leq \chi^2$ percentage ≤ 60	196	277	322
70	$61 \leq \chi^2$ percentage ≤ 70	251	272	219
80	$71 \leq \chi^2$ percentage ≤ 80	70	70	104
90	$81 \leq \chi^2$ percentage ≤ 90	64	95	63
100	$91 \leq \chi^2$ percentage ≤ 100	45	58	52

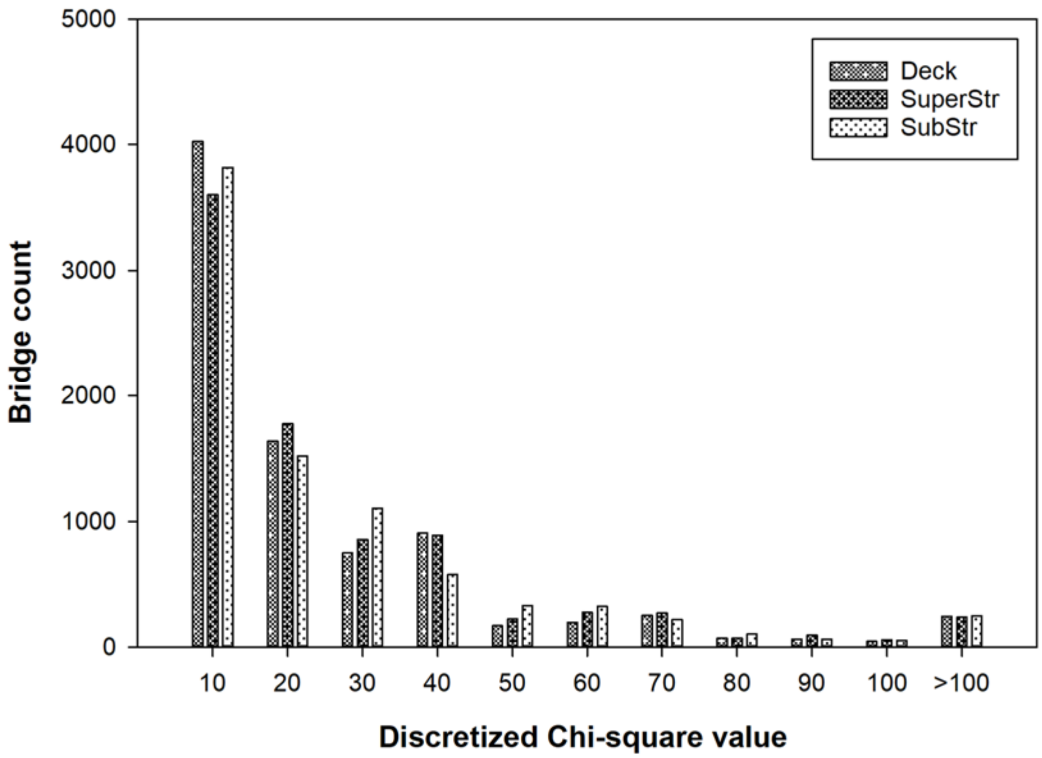


Figure 32 – Discretized Chi-square Distribution for Bridge Deck, Superstructure, and Substructure.

Notes: (1) SuperStr: Superstructure
(2) SubStr: Substructure

Below, Figures 33 through 35 illustrate the $\chi 2$ values computed for the 8,355 bridges analyzed. Most of the deterioration predictions have a Chi-square value well below 100, regardless of bridge components examined. The calculated Chi-square values of approximately 8,100 bridges are lower than the critical Chi-square value of 47.4 at a significance level of $\alpha = 0.05$. The 8,100 bridges represent 97% of the 8,355 bridges tested (see Figure 32). This suggests that the difference in long-term bridge performance predictions as a whole is considered insignificant although some discrepancy exists in the test data sets as illustrated in the figures below. The y-axis chi-square values in Figures 33 through 35 correspond to the x-axis chi-square values shown in Figure 32. In Figures 33 through 35, however, each data point (for bridge deck, superstructure, and substructure) with the chi-square value between 0 and 100, or greater than 100, is explicitly shown.

In summary, the Chi-square test evaluates the null hypothesis, H_0 (that the LTBP data are not governed by the predicted models). The null hypothesis, H_0, is rejected because the χ^2 value does not exceed the critical χ^2 value (computed with a 95% confidence interval) 97% of the time. The high probability (>95%) provides sufficient evidence to reject the null hypothesis and accept the alternative hypothesis (that the two prediction models are correlated).

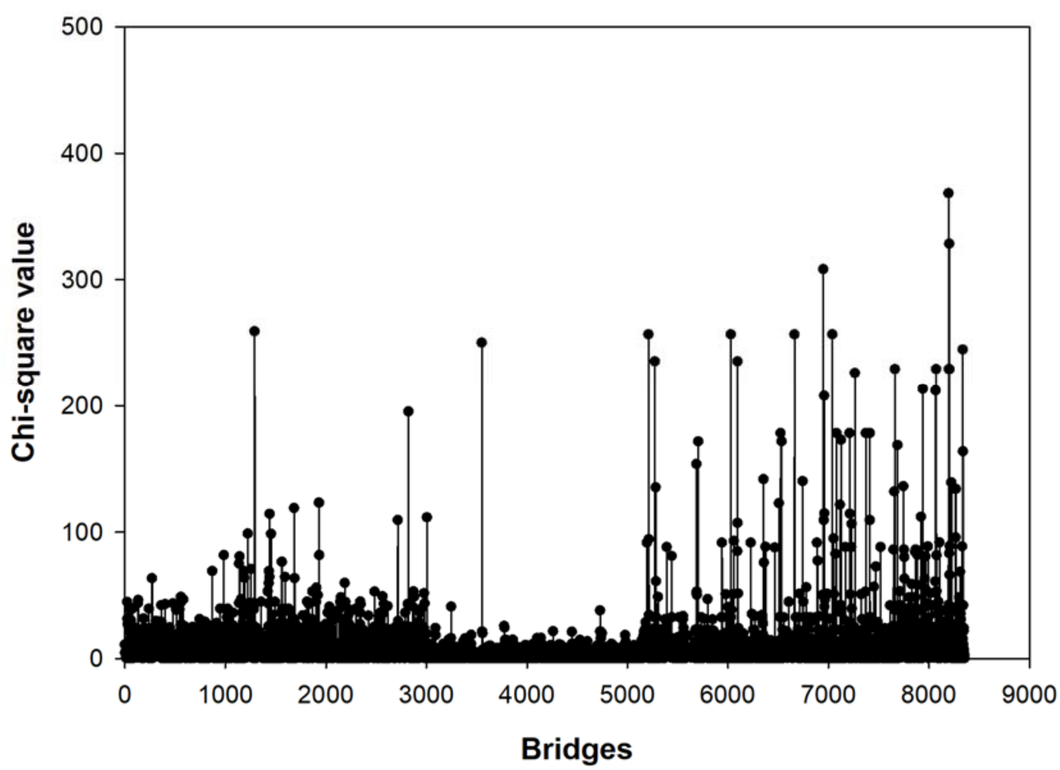


Figure 33 – Chi-square Scatter Plot for Bridge Decks.

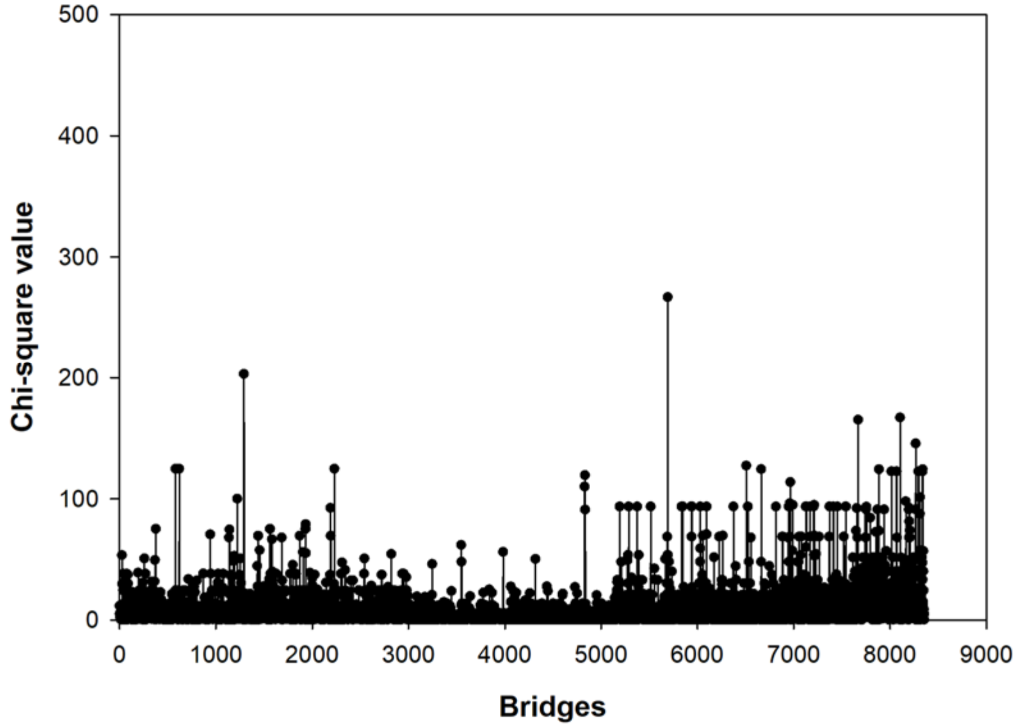


Figure 34 – Chi-square Scatter Plot for Bridge Superstructures.

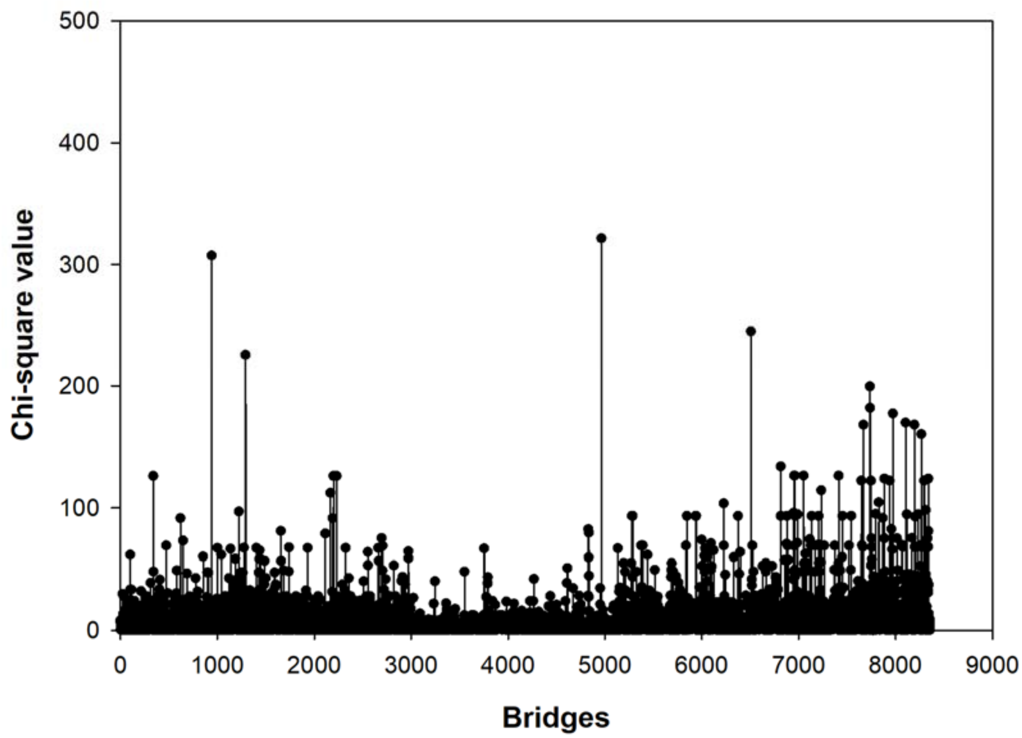


Figure 35 – Chi-square Scatter Plot for Bridge Substructures.

3.6 Estimated Time Increments for CR Transitions

In Sections 3.2 and 3.3, nonlinear depreciation curves are developed for each culvert and bridge in Georgia's NBI. However, the required input by the AASHTO BrM software includes the duration of estimated time for each CR change. For instance, it takes about 26 years for a CR change from 7 to 6 for a concrete bridge deck located in the Northern Georgia region, and then it takes another 44 years for a CR transition from 6 to 5. Therefore, this indicates that a concrete deck with a CR of 7 is estimated to realize a CR of 5 in the next 70 years.

In summary, discrete-time increments are required for each CR transition for use in the AASHTO BrM software. They are determined for each culvert and bridge component in the Georgia inventory for the next 100+ years in order to capture as many CR changes as possible. For illustration, Table 4 shows the time increments estimated for a concrete bridge deck in the Northern region (ID 1150320 with a deck CR of 7). The input file is created by completing the table for each of the culverts and bridge components (14,863 in total) present in the latest (2017) inventory.

Table 4 – Discrete-time Increments (in Years) Estimated for CR Transitions.

Bridge ID	Time increment CR9−>8	8−>7	7−>6	6−>5	5−>4	4−>3	3−>2	2−>1
1150320	0*	0*	26	44	90	140	0**	0**

Notes:
(1) '0*' indicates not applicable as the bridge's current CR is 7 (the red line in Figure 36).
(2) '0**' indicates no significant change in CR to substantiate a depreciation model as the CR 7 curve eventually plateaus. This information will not be used for a life-cycle analysis.

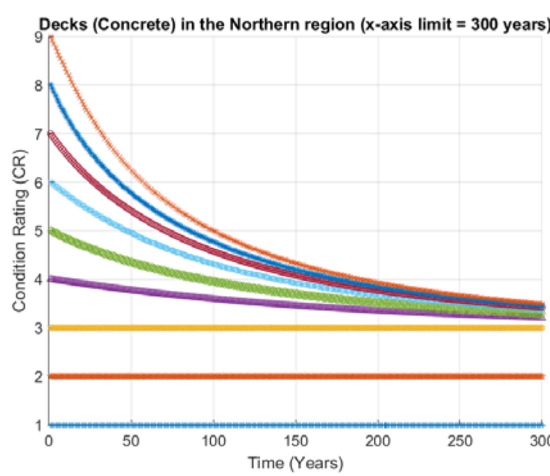


Figure 36 – Nonlinear Depreciation Curves for Concrete Decks.

3.7 Summary of Findings

The results of depreciation models with 13 variables and 3 geographic locations influencing bridge performance are presented in this section. The effect of each variable is listed below:

- Geographic locations affect depreciation rates to a varying degree when culverts and bridges are analyzed with different attributes. However, there is an overall trend in the results: bridges/culverts in the Northern and Coastal regions have the fastest and slowest depreciation rates, respectively, with rates in the Central region falling in between.
- Culverts as a whole depreciate slightly faster than concrete decks. They depreciate slightly faster when located in the Northern region although the difference is small (**see Figures 7 and 9**).
- Concrete bridge decks, particularly those in good condition (i.e., CR 7), in the Northern region depreciate twice as fast as those located in the Coastal region (**see Figures 9a and 9c**).
- Metal decks in Northern Georgia, including corrugated steel decks, particularly those in satisfactory condition (i.e., CR 6), depreciate much faster than those located in the Coastal region (**see Figures 11a and 11c**). Metal decks overall depreciate faster than concrete decks (**see Figures 9d and 11d**).
- Depreciation rates between precast and cast-in-place concrete decks are not appreciably different (**see Figures 9d and 13d**).
- Depreciation rates in timber decks are the fastest of all bridge deck models (**see Figure 15**). Timber decks in good condition (i.e., CR 7→CR6) depreciate twice as fast as concrete decks (**see Figures 15d and 9d**).

- For other deck material types, deterioration rates are overall significantly faster for bridges in the Northern region than for those in the Coastal region (**see Figures 17a and 17c**). This may be due to the number of bridges in the Coastal region (**see Figure 16c**).
- For both concrete and steel superstructures, depreciation rates are generally faster in the Northern region, although the CR7 rates for steel structures are almost twice as fast as the rates for concrete structures (**see Figures 19 and 21**).
- Depreciation rates for precast concrete superstructures are slightly slower than the rates for concrete structures (**see Figures 19d and 23d**). Overall, precast concrete superstructures rarely fall below CR 6 (**see Figures 22d and 23d**).
- Similar to the timber bridge deck depreciation rates, the depreciation rates for timber superstructures are drastically faster than the rates for superstructures made of other materials, particularly in the Northern region (**see Figure 25**).
- Superstructures that fall into the remaining types yield similar results to the deck depreciation models. That is, depreciation rates are mostly slower in the Coastal region compared to rates in the other regions (**see Figure 27**). This may be attributed to the fact that more structures exist in the Coastal region than in the other regions (**see Figure 26**).
- Substructures in good condition (e.g., CR7) depreciate twice as fast in Northern Georgia compared to those in Coastal Georgia when they do not cross waterways (**see Figures 29a and 29c**). This trend exists in substructures over waterways although the geographic variation is not as influential on deterioration rates (**see Figures 31a and 31c**).
- In contrast, the presence of waterways significantly affects deterioration rates. Substructures over waterways depreciate almost twice as fast as those over non-waterways, particularly those in satisfactory condition or CR 6 (**see Figures 29d and 31d**).

- Among the three major bridge components, substructures, particularly those over waterways, have the fastest depreciation rates (**see Figure 31**). Bridge decks depreciate faster than superstructures when bridges with concrete (or precast concrete) superstructures and concrete decks are considered (**see Figures 9, 19, and 23**).

4. DISCUSSION AND LIMITATIONS

As discussed in the objectives in Section 1.5, this study is designed to develop depreciation models for all bridges and culverts in Georgia. This section contains a discussion of the findings and limitations that can be drawn from the results.

4.1 Discussion

A total of 39 depreciation models have been established with key attributes, including material types and geographical locations. These variables affect depreciation rates although some had an insignificant influence on the rates. The Chi-square test confirms that the relatively simple depreciation models developed herein do not significantly differ from those determined by the LTBP study, which was a complex parameter analysis on a national scale. This outcome may indicate that the variables considered for a national study do not meaningfully affect the depreciation models of bridges in Georgia. For example, the freeze-thaw cycle was identified as one of the most important variables for a national study, yet this parameter should have little influence on the majority of Georgia bridges. Furthermore, traffic counts (e.g., average annual daily truck traffic) and load ratings as documented in the NBI may not have a significant influence on bridge performance.

Age is another significant variable considered in the LTBP study; however, with the Markov approach, the number of CR transitions in the inventory significantly reduces when the bridge data are further broken down into age groups. Moreover, by creating age groups in the current study, deck replacements or rehabilitation efforts associated with aged bridges could yield misleading transition probabilities. With the Markov approach, the age effect is indirectly reflected by considering the history of CR transitions. Therefore, despite not considering age, the depreciation models appear to be well correlated with the prediction models recommended by the LTBP's research team.

4.2 Acknowledgement of Limitations

The limitations of this study include the selection of the key attributes presented in Section 2.5. As discussed in Section 4.1, it should be acknowledged that there are factors such as age and annual average daily truck traffic which are not included in this study and may affect the prediction of bridge performance. This study indicates that there may be considerable disparity in the effect of attributes on the depreciation models. That is, selected attributes affect the depreciation models to a varying degree. In addition, the attributes influencing bridge performance are selected without explicit selection criteria, and thus the results may be prone to a selection bias. Therefore, a parameter correlation study is necessary for identifying critical attributes. For example, annual average daily truck traffic should be used to instruct how asset utilization affects the depreciation rates.

It should also be recognized that the Markov approach used herein heavily relies on the number of bridge CR transitions in each group. Groups are divided by key attributes that could affect bridge deterioration. Thus as the number of variables increases, bridges are broken into smaller analysis groups. This, in turn, results in an analysis of a CR transition probability based on a reduced number of CR changes. That is, the sampling size is reduced to a degree where no data is observed in a group. In order to substantiate a bridge depreciation prediction model, the sampling size (i.e., the number of CR transitions) has to be reasonable. Based on the experience of analyzing the NBI data sets, a sample size of 15 or greater yields a reasonable depreciation curve. When additional attributes are considered, the accuracy in a depreciation model may improve at the cost of reduced reliability in another model. In analyzing the NBI data with limited sample sizes, a reasonable balance between accuracy and reliability must be considered.

One of the limitations of this research study was the constitution of the sample. First, CRs were not randomly selected from a larger population in the study. Due to limited sample sizes, the entire inventory is used. This might have biased the sample. The sample was also relatively homogeneous with mostly concrete or precast concrete bridges although they are analyzed independently from other types. Finally, the results may not be generalized to other bridge types, particularly those in other states with greater seasonal climate variations and traffic intensities.

The LTBP study provides a point of validation by means of a Chi-square test. However, since the NBI data in this study are also used for the LTBP study, the comparative data set used for the Chi-square test might have been biased. This conclusion is unlikely because the prediction models from the LTBP study are constructed based on the natural depreciation observed in selected bridges and considering a wide range of variables not used in the current study. A blind prediction of bridge deterioration and a comparison of the two (this study and LTBP) models might have been more desirable. This is because there is always a possibility that an outcome bias can occur in evaluating depreciation prediction models if the outcome of the LTBP study were known.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

In this study, a total of 39 depreciation models are developed for culverts and bridges in the latest (2017) NBI, featuring 3 for culverts and 36 for bridges. The effects of bridge deck and superstructure material types and geographic locations are considered in constructing the deterioration prediction models for bridges with 9 Condition Ratings (CRs) on a discrete 1-9 scale. In addition, the presence of waterways is considered for substructures. Based on the findings of this study, the following conclusions are made:

1. Material types affect the performance of bridge decks and superstructures.
2. There is a distinct difference in the performance of bridge decks, superstructures, and sub-structures between the Northern and Coastal regions. Overall, bridges and culverts depreciate faster in the Northern region. The depreciation rates for bridges in the Central region generally fall in between rates for the Northern and Coastal regions.
3. The presence of a waterway significantly affects the performance of substructures.
4. The depreciation models established in this study are well correlated with the depreciation models developed for selected bridges in the LTBP study. A Chi-square test confirms the results, and thus it is concluded to accept the alternative hypothesis that the two bridge condition prediction models are correlated.
5. A total of 39 depreciation models are developed in this study:
   - There are a total of three models available for culverts with reference to three geographical locations (Northern, Central, and Coastal Georgia).
   - There are 15 bridge deck and 15 superstructure models consisting of 5 material types in each of the 3 geographic regions.

- Finally, 6 depreciation models are available for bridge substructures crossing waterways and non-waterways in the three regions.

6. The 39 depreciation models have been assigned to approximately 15,000 culverts and bridges' major components (deck, superstructure, and substructure) present in the latest (2017) NBI.

5.2 Recommendations and Future Studies

The following recommendations are made for future studies:

1. The NBI (1992-2017) dataset was instrumental in building the depreciation models presented in this report and understanding major attributes influencing the performance of bridges in Georgia. Therefore, such information should be well maintained and further analyzed until more recent element-based inspection data are fully able to provide the basis for establishing more accurate prediction models. Accordingly, continuous management of bridge performance data (both traditional NBI CRs and element-based inspection states) is highly recommended to better understand major changes in bridge asset performance in Georgia.
2. Traditional NBI CR data and depreciation models should be used to further improve bridge performance prediction models using bridge element-based inspection data. Changes in CR from the NBI CR records should be a powerful comparative tool for building element-based inspection depreciation models, showing what it means to attain a CR drop of 1 or greater on a 0-9 scale when selected elements are significantly deteriorated. Research on learning the difference between the NBI CR-based and element-based depreciation models is highly recommended.

3. Up-to-date traffic information is necessary to address asset utilization and increase the accuracy of depreciation prediction models.
4. A life-cycle cost analysis is better performed when digital collections of rehabilitation and maintenance cost information become available and are effectively delivered to a bridge asset manager. Therefore, continuous effort in bridge asset valuation/management is highly recommended.
5. GDOT's risk assessment framework consists of economic impact and condition based priorities (TAMP 2018). In addition to a life-cycle analysis, establishing a relationship between the priorities is strongly recommended.
6. Finally, it is recommended to periodically analyze growing data sets in the bridge inventory, digitally document the findings, and allow time to reflect on major findings.

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APPENDICES

Appendix A – Sample Culvert CR History and Depreciation Model

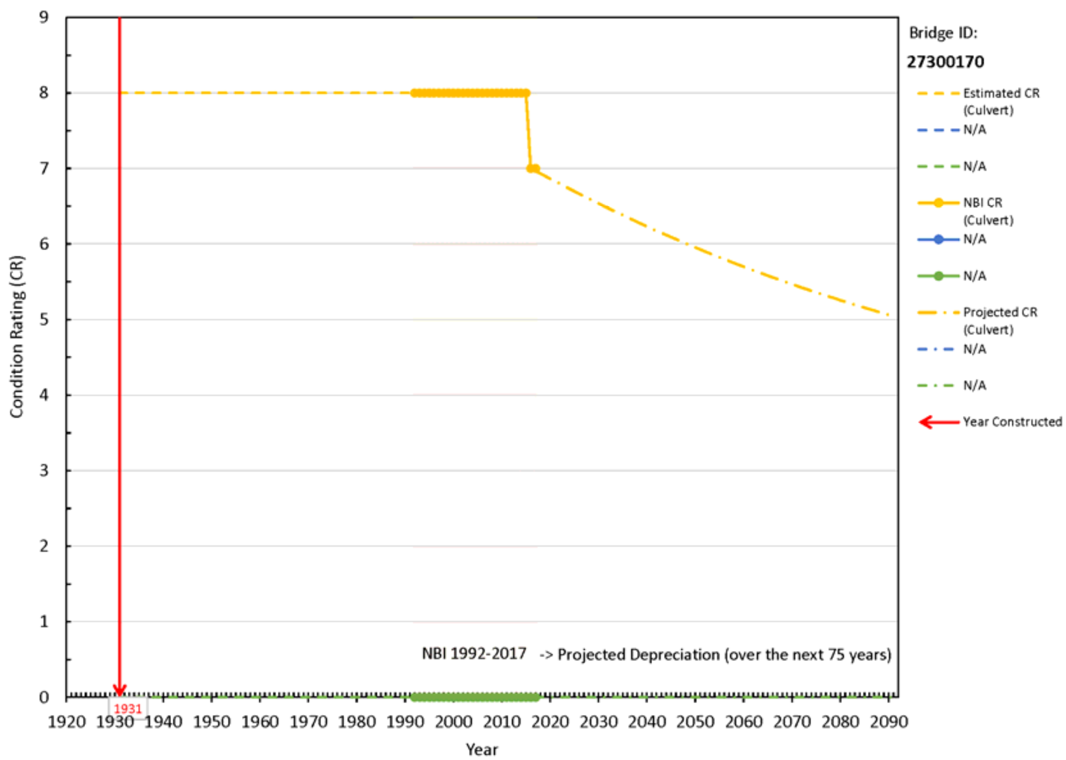

Figure A1 – CR History and Depreciation Model for a Culvert.

Appendix B – Sample Bridge CR History and Depreciation Models

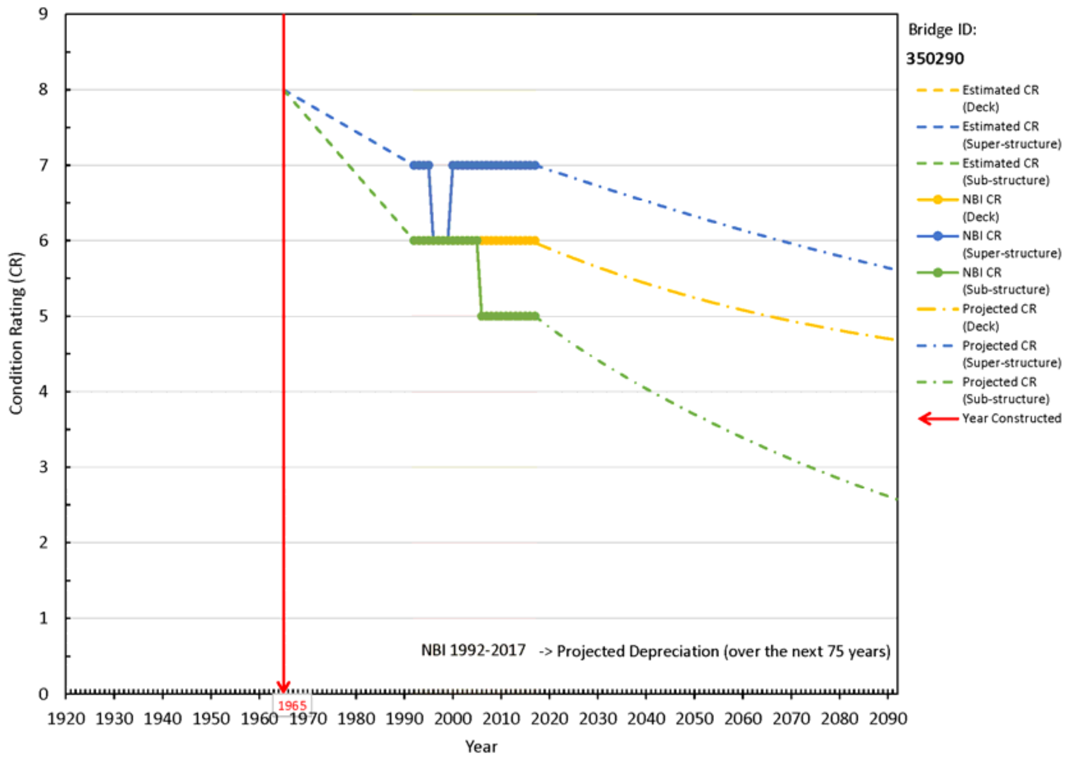

Figure B1 – CR History and Depreciation Models for a Bridge.

Appendix C – List of Electronic Submittals

C.1 Microsoft Excel spreadsheet file including the BrM input data (i.e., predicted time increments for each CR change organized by Bridge IDs).

C.2 MATLAB codes and Microsoft Excel output files used for the NBI data analysis.

C.3 PDF files including a plot of CR history and depreciation models for each bridge (the files are named according to Bridge IDs) similar to Appendices A and B.

Appendix D – Bridge Depreciation Model Development Guide

BRIDGE DEPRECIATION MODEL DEVELOPMENT GUIDE

June 2019

GDOT RP No. 18-30

BRIDGE DEPRECIATION MODEL DEVELOPMENT GUIDE

by

Mi G. Chorzepa

University of Georgia

June 2019

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SUMMARY

This guide describes how one develops a bridge depreciation model using National Bridge Inventory (NBI) data. It demonstrates the process by analyzing selected condition ratings (CRs) between years 1992 and 2017. The goal of this report is to describe a step-by-step procedure for forecasting bridge performance and for identifying anomalous results, if any. Transition probabilities affect the shape of depreciation models. When the probability of bridges transitioning to a lower CR is less than 3%, the depreciation model remains linear. Overall, the transition probability has to be less than 1% to yield a more desirable depreciation model. For example, when 10% of bridges with a CR 8 transition to a CR 7, the depreciation model should contain a sharp declining nonlinear curve within the first 15 years. Lastly, this guide reviews historical data in order to validate a 'CR8' depreciation model.

1. INTRODUCTION

1.1 Background and Scope

State Departments of Transportation maintain an inventory of over 15,000 bridges. Each state agency is responsible for making transportation asset management decisions based on past and present bridge performance. This report describes how one evaluates bridge depreciation using condition ratings (CRs). The CR data is available in the National Bridge Inventory (FHWA, 2019).

Depreciation represents the consumption of a bridge asset. Bridge inspectors quantify the level of consumption on a discrete 0-9 scale. CR 9 indicates an excellent condition (no depreciation), CR 7 indicates a good condition, CR 3 indicates a poor condition, and CR 0 indicates an out-of-service condition. A depreciation model evaluates how a bridge should perform in the future. Thus, for the purposes of this guide, the terms ‘bridge performance’ and ‘depreciation’ are interchangeable.

1.2 Objectives

This guide describes a procedure for developing a bridge depreciation model. More specifically, this document:

1) Provides a step-by-step process for predicting bridge performance;
2) Shows an ideal model and describes how to identify anomalous results, if any; and
3) Presents a validation process.

2. DEVELOPING A BRIDGE DEPRECIATION MODEL

The Markov-chain approach (Agrawal et al., 2010) is the most widespread method for forecasting bridge performance. It uses the probability of transitioning from one condition state to another and mathematically determines a decrease in CR over time. Figure 1 illustrates the progressive order for determining a depreciation model

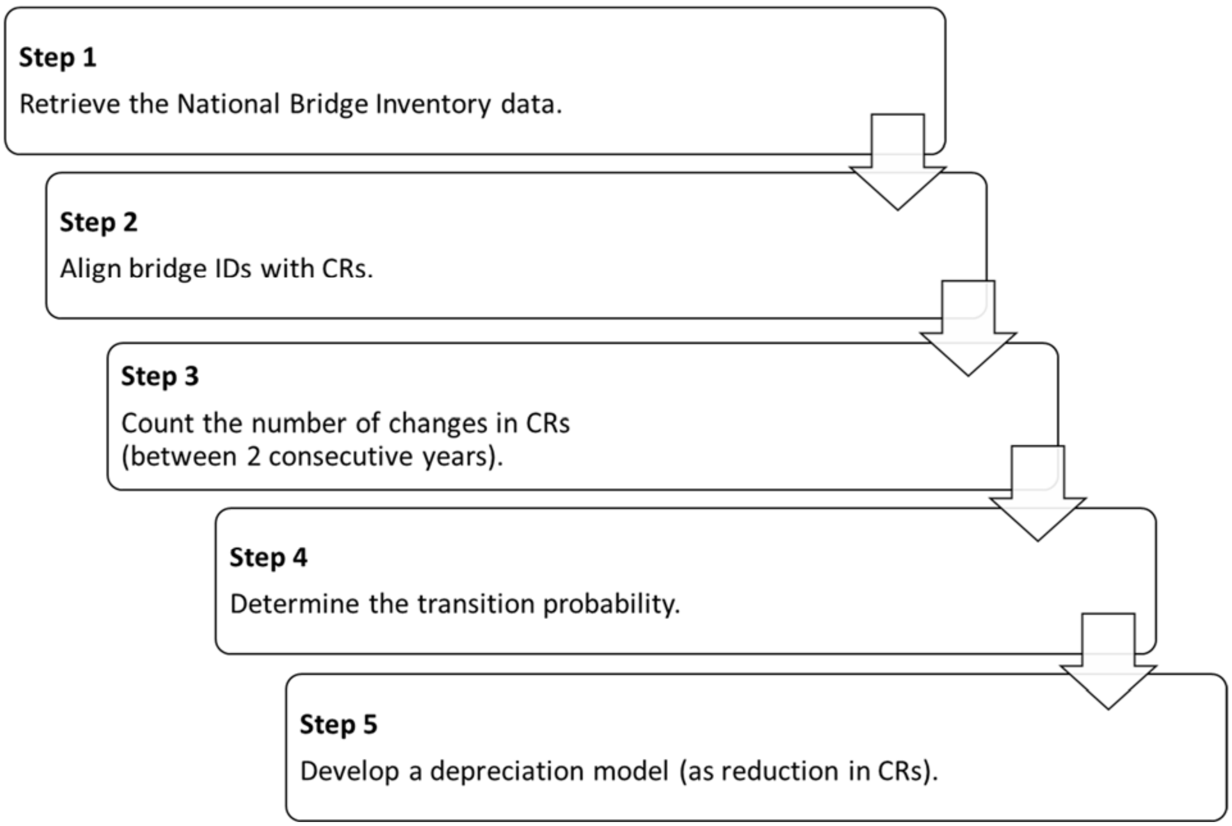


Figure 1 – A Process Chart.

2.1 Step No. 1 – Retrieve the NBI data

The National Bridge Inventory (NBI) database represents “bridge data submitted annually to the Federal Highway Administration (FHWA) by the States, Federal agencies, and Tribal governments” (FHWA, 1995). A total of 26 NBI data sets exist for the past 26 years (1992-2017). Each data set contains bridge identifications (IDs) and condition ratings (CR). For example, a bridge ID appears as ‘29000101’. It is a unique identifier for each bridge within a state.

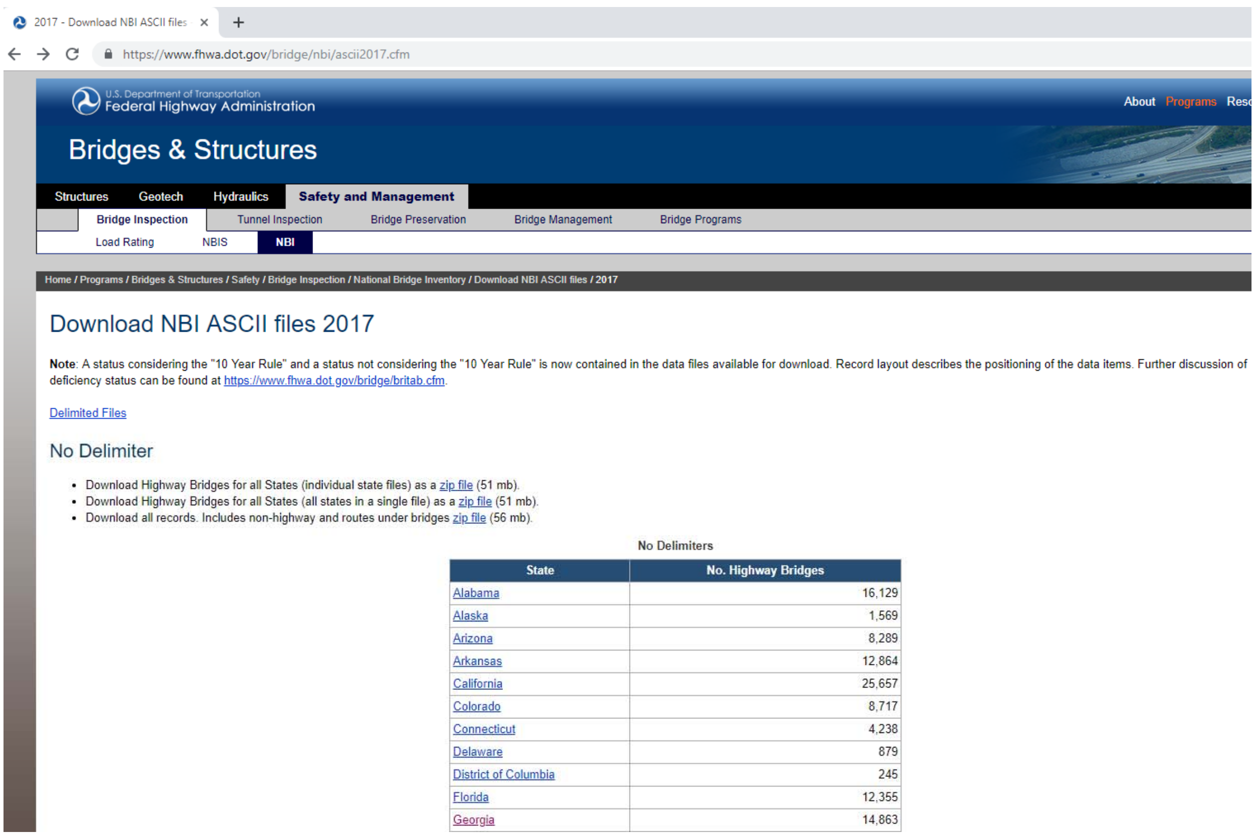


Figure 2 – A Screen Capture of NBI Data Download (Source: FHWA, 2019).

2.2 Step No. 2 – Align Bridge IDs with CRs

Over the last 26 years, state DOTs have constructed new bridges as well as replaced or decommissioned old bridges. As a result, bridge IDs in a bridge inventory vary every year. Table 1 shows realigned bridge IDs and CRs.

Table 1 – Alignment of Bridge IDs and CRs (for Illustration Only).

Bridge ID \ Year	Condition Rating (CR)							
	1992	1993	1994	…	2014	2015	2016	2017
29000101	8	8	8	…	8	7	7 Count#2	6
29000500(a)	NA(b)	NA	NA	…	NA	8	8	8
39011101(c)	3	8	8 Count#1	…	8	8	7	7
39011102	8	7	7	…	6	6	6 Count #3	6
39011103(d)	6	6	6	…	4	D	D	D

Notes: (a) new bridge; (b) NA – not applicable; (c) replaced; (d) D-decommissioned.

2.3 Step No. 3 – Count the Number of Transitions in CRs

A transition indicates the change from one CR to another CR between two consecutive years. For example, in Table 1, three transitions from CR 8 to CR 7 occur.

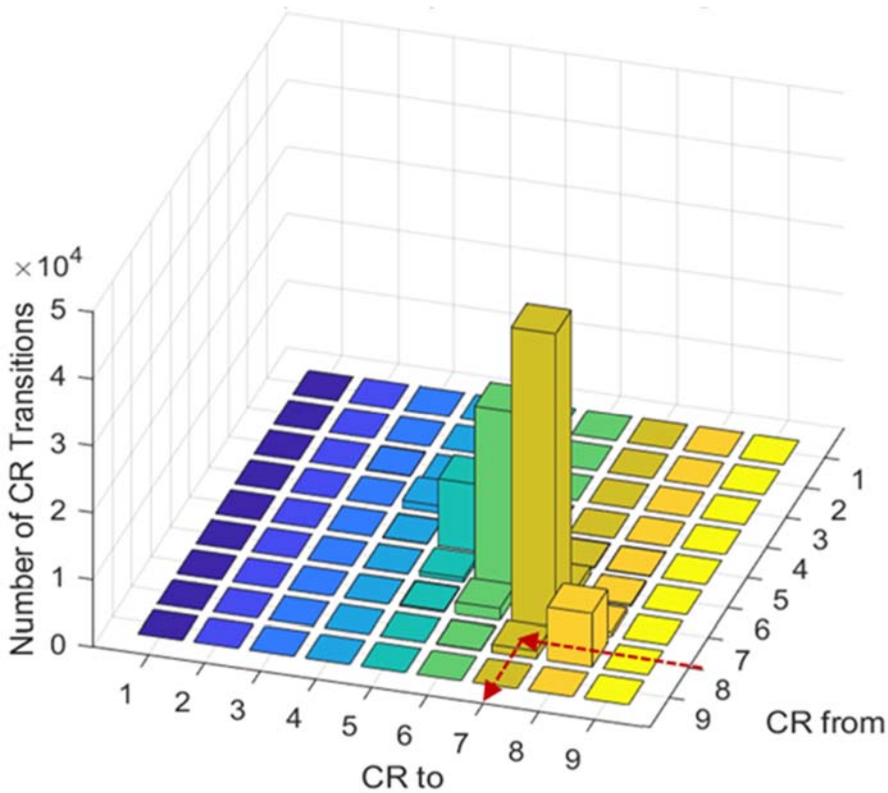


Figure 3 – CR Transition Counts in a 3-Dimensional Bar Chart.

Figure 3 shows the number of CR transitions in the vertical axis. The other two axes represent 'CR from' and 'CR to', respectively. For instance, this chart contains an analysis 8,000 bridges. Between years 1992 and 2017, 1,500 transitions occur from CR 8 to CR 7 (illustrated above). A total of 14,900 transitions from CR 8 to CR8 or the other CRs occur. 13,400 instances from CR 8 to CR 8 occur. This means that nearly 10% (=1,500/14,900) of the bridges with a CR 8 transition to a CR 7.

2.4 Step No. 4 – Determine the Transition Probability

The transition probability determines a probability of transitioning from one CR to another CR. For example, in Figure 3, the probability of a CR 8 transitioning to a CR 7 is 10%. As a result, the probability of a CR 8 remaining in CR 8 is 90%. Table 2 shows a transition probability matrix for the bridges presented in Figure 3. No CR 9 exists in the bridge inventory.

Table 2 – Transition Probability Matrix (%), P.

Probability (%)		Transitioning to CR								
	CR	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
Transitioning from CR	**1**	1	0	0	0	0	0	0	0	0
	2	1	99	0	0	0	0	0	0	0
	3	0	2	98	0	0	0	0	0	0
	4	0	0	1	99	0	0	0	0	0
	5	0	0	0	2	98	0	0	0	0
	6	0	0	0	0	2	98	0	0	0
	7	0	0	0	0	0	3	97	0	0
	8	0	0	0	0	0	0	10	90	0
	9	0	0	0	0	0	0	0	0	0

2.5 Step No. 5 – Develop a Depreciation Model

The Markov-chain method (Agrawal et al., 2010) uses a matrix analysis shown in Eq. (1) and evaluates CR predictions. P is the transition probability matrix shown in the previous section. YR represents the future years.

CR 8 predictions in YR = [0,1,0,0,0,0,0,0,0] P^{YR} [9,8,…,2,1]' ………………………. Eq. (1)

CR 7 predictions in YR = [0,0,1,0,0,0,0,0,0] P^{YR} [9,8,…,2,1]' ………………….…… Eq. (2)

For instance, in the next 10 years, CR 8 will transition to a condition rating = [0,1,0,0,0,0,0,0,0] P^{10} [9,8,…,2,1]'. A similar process is used for the other CRs. Eq. (2) predicts CRs for bridges currently with CR 7.

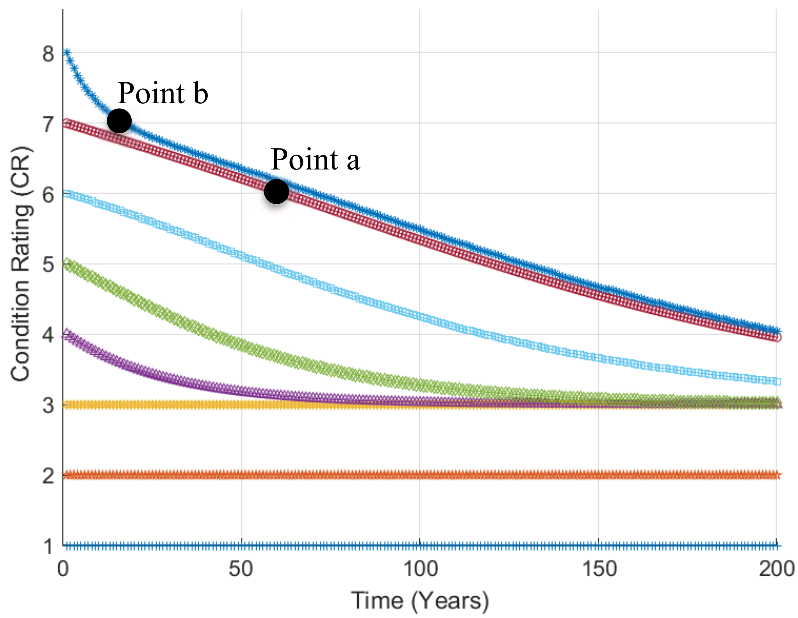


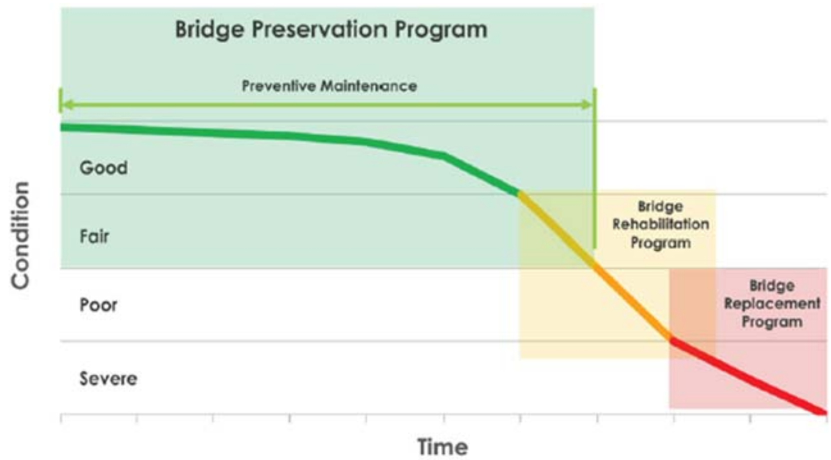
Figure 4 – Depreciation Predictions (for Illustration Only).

Figure 4 illustrates depreciation prediction models in terms of reduction in CRs. This figure indicates that it takes about 60 years for bridges with CR 7 to transition to CR 6 (Point a). On the other hand, it takes approximately 15 years for bridges with CR 8 to transition to CR 7 (Point b).

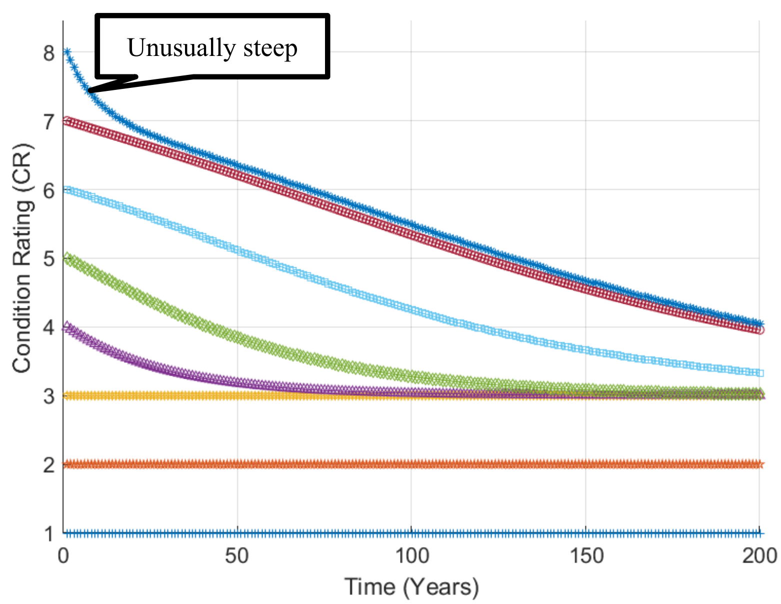
3. ANALYZING RESULTS

3.1 Ideal versus Predicted Depreciation Models

In general, bridge depreciation occurs very slowly when a bridge is new. As the bridge ages, the depreciation occurs at a faster rate, as illustrated in Figure 5(a). In contrast, in Figure 5(b), the depreciation curve for CR 8 is unusually steep in the first 10 years.



(a) Ideal Bridge Performance (Source: FHWA, 2018).

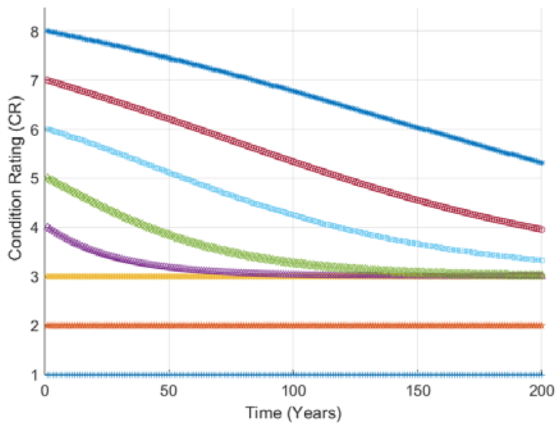


(b) Predicted Bridge Performance.

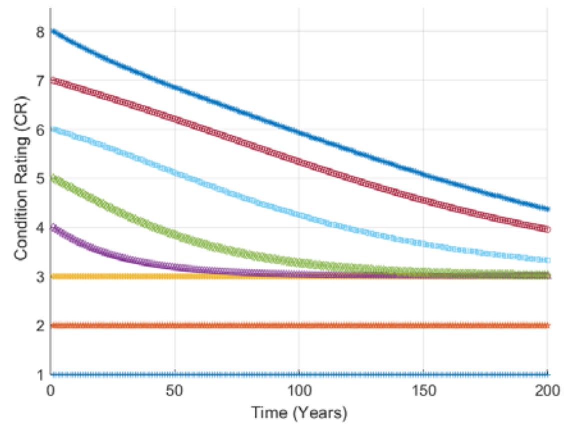
Figure 5 – CR Transition Counts in a 3-Dimensional Bar Chart.

3.2 Sensitivity Analysis on Transition Probability

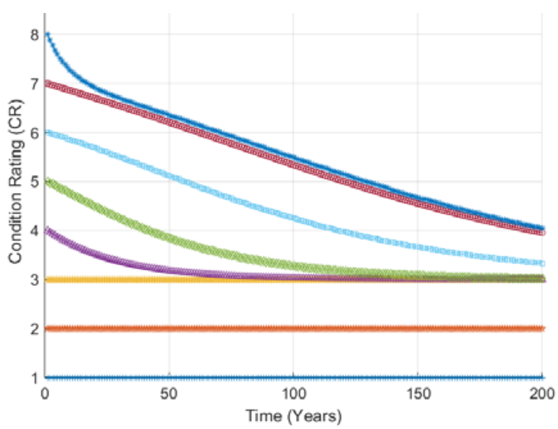
Transition probabilities affect bridge performance forecasting. Figure 6 shows the shapes of depreciation models for varying transition probabilities. For a 'CR8' depreciation model to yield a declining straight line, the transition probability must be less than 3% (Figure 6b). With the transition probability of less than 1% (Figure 6a), the shape approaches to the ideal depreciation curve shown in Figure 5a.



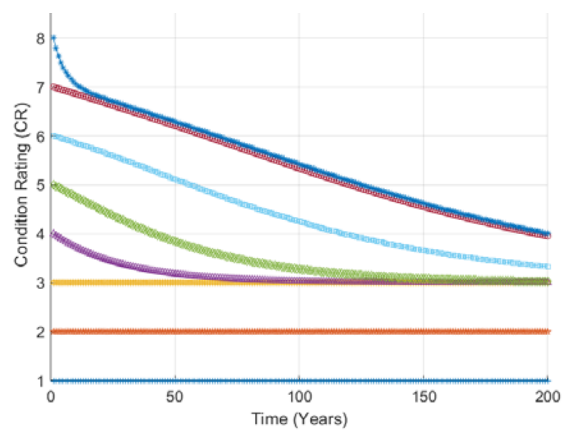
(a) Transition Probability = 1 %
(CR 8 → CR 7)



(b) Transition Probability = 3%
(CR 8 → CR 7)



(c) Transition Probability = 10%
(CR 8 → CR 7)



(d) Transition Probability = 20%
(CR 8 → CR 7)

Figure 6 – Depreciation Models for Varying Transition Probabilities.

3.3 Validation of the 'CR8' Depreciation Model

Figure 7 shows the change in the number of bridges with a CR 8. In 1997, 800 bridges were 10 years old (Point A). By 2007, these bridges were 20 years old (Point B). Only 50% remained in CR 8. In 2017, only 100 bridges maintained a CR 8 (Point C). These changes explain the steep decline in CR8 (see Figure 5b).

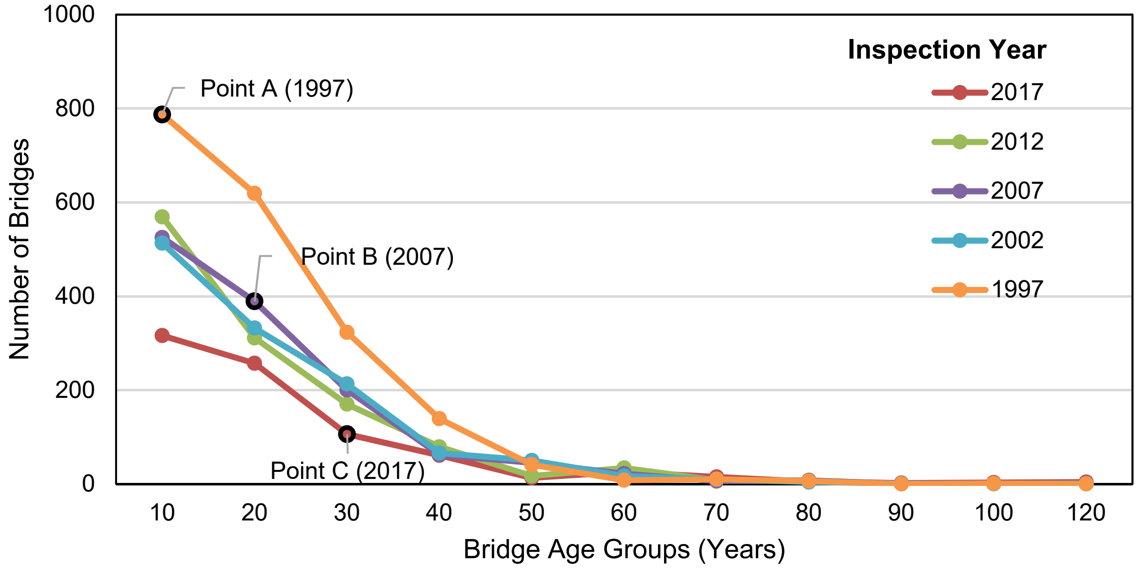


Figure 7 – The Number of Bridges with a CR 8 by Inspection Year.

4. CONCLUSIONS

This guide presents a step-by-step process for developing a deterioration model for bridges. The number of CR changes in the National Bridge Inventory data determines a transition probability. It affects the shape of depreciation models and is a key component in predicting bridge performance. Lastly, reviewing historical data is a good way to validate a depreciation model.

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