Bridge Element Deterioration of Concrete Substructures

WA-RD 893.1

Micaylla O'Leary
Jill Walsh

September 2018

Washington State Department of Transportation
Office of Research & Library Services

WSDOT Research Report

19-04-0247

Research Report
Agreement T 2311, Task 01

BRIDGE ELEMENT DETERIORATION OF CONCRETE SUBSTRUCTURES

by

Micaylla O'Leary
Graduate Student Researcher

Jill Walsh, Ph.D., P.E.
Assistant Professor

The Hal and Inge Marcus School of Engineering
Department of Civil Engineering
Saint Martin's University
5000 Abbey Way SE
Lacey WA 98503

Washington State Department of Transportation
Technical Monitor
DeWayne Wilson, P.E.
Bridge Asset Management Engineer

Prepared for

The State of Washington
Department of Transportation
Roger Millar, Secretary

September 22, 2018

TECHNICAL REPORT DOCUMENTATION PAGE

1. REPORT NO. WA-RD 893.1	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE BRIDGE ELEMENT DETERIORATION OF CONCRETE SUBSTRUCTURES		5. REPORT DATE September 2018 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Micaylla O'Leary, Bridge Engineer, Oregon Department of Transportation Jill Walsh, Assistant Professor, Saint Martin's University		8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Hal and Inge Marcus School of Engineering Department of Civil Engineering Saint Martin's University 5000 Abbey Way SE Lacey WA 98503		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO. Agreement T2311 Task 01
12. SPONSORING AGENCY NAME AND ADDRESS Research Office Washington State Department of Transportation Transportation Building, MS 47372 Olympia, Washington 98504-7372 Project Manager: Rhonda Brooks, 360-705-7945		13. TYPE OF REPORT AND PERIOD COVERED Final Research Report 14. SPONSORING AGENCY CODE
15. SUPPLEMENTARY NOTES		

16. ABSTRACT:

This research project determines the average age of a concrete substructure element at transition from one condition state to the next. Because of necessary frequent repair, the state has accurate asset preservation models for elements such as bridge decks and steel coating to assist in bridge maintenance. However, no statistical or data driven model currently exists for predicting the deterioration of concrete bridge substructure elements.

This research develops a statistically driven model for deterioration of concrete columns. Specifically, Concrete Pile/Column (National Bridge/WSDOT Element 205) and Concrete Submerged Pile/Column (National Bridge/WSDOT Element 227) for both Eastern and Western Washington climates. The research demonstrates there is no significant deterioration difference between columns in Eastern and Western Washington. The research outcome is a Probability Transition Matrix and age of transition for dry and submerged concrete Pile/Column elements.

17. KEY WORDS Concrete, substructures, deterioration, asset management, transition, Markov, inspection	18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22616

19. SECURITY CLASSIF. (of this report) None	20. SECURITY CLASSIF. (of this page) None	21. NO. OF PAGES 53	22. PRICE

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Washington State Department of Transportation or Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Table of Contents

EXECUTIVE SUMMARY ..... **viii**

1 INTRODUCTION, MOTIVATION AND OBJECTIVES **1**

1.1 INTRODUCTION 1

1.2 MOTIVATION 4

1.3 OBJECTIVE 9

2 REVIEW OF PREVIOUS WORK **10**

2.1 INTRODUCTION 10

2.2 DEVELOPMENT OF HAZARD RATIOS 10

2.3 DETERMINISTIC AND STOCHASTIC MODELING 11

2.4 ARTIFICIAL INTELLIGENCE AND BACKWARDS PREDICTION MODELING 12

2.5 ASSESSMENT MANAGEMENT METHODS OF OTHER STATES 13

3 RESEARCH APPROACH **15**

3.1 INITIAL DATA ANALYSIS 15

3.2 INITIAL CALCULATIONS AND DATA FILTRATION 16

3.3 DEVELOPMENT OF OVERVIEW: BRIDGE AGE VS CONDITION STATE 17

3.4 DEVELOPMENT OF PROBABILITY TRANSITION MATRICES 21

3.5 CALCULATIONS OF PROBABILITY TRANSITION MATRICES 23

3.6 DISCUSSION OF PROBABILITY TRANSITION MATRICES 25

4 CONCLUSIONS **27**

4.1 EASTERN WASHINGTON VS WESTERN WASHINGTON 27

4.2 SUBMERGED VS DRY ELEMENTS 27

5 APPLICATION and RECOMMENDATIONS **28**

5.1 APPLICATION 28

5.2 RECOMMENDATIONS 28

REFERENCES **30**

Appendix A **32**

Appendix B **38**

LIST OF FIGURES

Figure 1-1 Minnesota DOT Inspection Field Manual (MnDOT, 2018) 3

Figure 1-2 Location Map of Mud Bay Bridge (Image taken from Google Maps) 5

Figure 1-3 Deterioration of Mud Bay Columns in Pier 6 (taken at 2001 inspection) 7

Figure 1-4 Column Cracking in Mud Bay Bridge (taken at 2001 inspection)..... 7

Figure 1-5 East Mud Bay Bridge Jackets (taken at 2008 inspection)..... 8

Figure 1-6 WSDOT Regions (WSDOT.WA.gov)..... 9

Figure 3-1 NW Region, Element ID 205: Bridge Age vs Condition State..... 17

Figure 3-2 Bridge Age vs Condition State: Element ID 205 18

Figure 3-3 Bridge Age vs Condition State: Element ID 227 19

Figure 3-4 Bridge Age vs Number of Bridges (per Condition State) 20

Figure 3-5 Standard Transition Probability Matrix Format..... 23

Figure 3-6 Transition Probability Matrices Independent of Bridge Age..... 25

LIST OF TABLES

Table 1 Mud Bay Inspection Records: East Bridge, Element ID 227 6

Table 2 Average Age of Condition States per WSDOT Region and Element ID 21

Table 3 Average Years in Each Condition State, Element ID 205 22

Table 4 Average Years in Each Condition State, Element ID 227 23

Table 5 Total Number of Element ID 205 Transitioning 24

Table 6 Total Number of Element ID 227 Transitioning 24

Table 7 Percentage of Transitions, Element ID 205 24

Table 8 Percentage of Transitions, Element ID 227 24

ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AI	Artificial Intelligence
BEISt	Bridge Engineering Information System
BMS	Bridge Management System
BPM	Backwards Prediction Modeling
BrM	AASHTOWare- Bridge Management
CDOT	Colorado Department of Transportation
CS	Condition State
CS1	Condition State 1
CS2	Condition State 2
CS3	Condition State 3
CS4	Condition State 4
DOT	Department of Transportation
EA	Eastern Region
Element ID 205	Concrete Pile/Column
Element ID 227	Concrete Submerged Pile/Column
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
HR	Hazard Ratio
IDOT	Indiana Department of Transportation
MBE	AASHTO Manual for Bridge Evaluations
MnDOT	Minnesota Department of Transportation
MPM	Migration Probability Matrix
MR&R	Maintenance, Repair and Rehabilitation
NBI	National Bridge Inventory
NBIS	National Bridge Inventory Standards
NC	North Central Region
NCDOT	North Carolina Department of Transportation
NW	Northwest Region
NYDOT	New York Department of Transportation
OL	Olympic Region
PHM	Proportional Hazard Modeling
SC	South Central Region
SW	Southwest Region
WA	Washington State
WSBIM	Washington State Bridge Inspection Manual
WSBIS	Washington State Bridge Information System
WSDOT	Washington State Department of Transportation

EXECUTIVE SUMMARY

Objectives

The objective of this research is to develop deterioration rate models for reinforced concrete bridge substructure elements (columns and piles) in two environmental conditions, dry and submerged, and two climate ranges, eastern and western Washington.

Background

The Washington State Bridge and Structures office biannually inspects Washington State's bridge inventory to identify and prioritize repair and maintenance needs. To forecast future needs based on expected deterioration, the Bridge and Structures Office must establish deterioration rates for each bridge element. Accurate deterioration rate models for elements such as bridge decks, joints and steel coating exist due to their recurrent replacement and repair. However, no statistical or data driven prediction model currently exists for deterioration of concrete bridge substructures.

Research Activities

This research summarizes deterioration modeling and forecasting methods used by other state departments of transportation. Washington's bridge inspection data for dry and submerged concrete columns/piles was analyzed and sorted to develop reinforced concrete substructure deterioration models.

Conclusions

Probability Transition Matrices for the deterioration of dry and submerged concrete columns are provided for both Eastern and Western Washington. There is significant difference of concrete bridge column deterioration between Eastern and Western Washington. In both regions, transition to CS3 and CS4 is higher for submerged elements.

1 INTRODUCTION, MOTIVATION AND OBJECTIVES

1.1 Introduction

The Federal Highway Act of 1956, signed by President Eisenhower, provided 65,000-km of the national interstate system and increased federal funding for public roads (Weingroff, 1966). This sparked the creation of the current public roads system during which construction and design standards were developed. At the time, 62 years ago, a bridge design life was 75 years, meaning large portion national highway infrastructure is approaching its design life. Since replacement of the entire system is not feasible, a method is necessary for prioritizing repairs, replacement and maintenance.

The National Bridge Inventory Standards (NBIS) are published in the Code of Federal Regulations 23 CFR 650, Subpart C (WSBIM, 2018). The NBIS sets a national standard that applies to all reportable structures located on all public roads (WSBIM, 2018). NBIS defines a reportable structure as "...including supports erected over a depression or an obstruction, such as, 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…" (WSBIS, 2018). Section 650.315 of the code states: "each state or federal agency must prepare and maintain an inventory of all bridges for collection by the Federal Highway Administration (FHWA) as requested" (FHWA, 2014). Compliance with federal laws is necessary for departments of transportation to be eligible for federal funding. Today, all state departments of transportation are required by federal laws 23CFR 650.315 and 23 CFR 515.007 to maintain bridge inspection files and implement some type of bridge management system using deterioration models (WSBIM, 2018; Thompson, 2017). Additionally, the

Intermodal Surface Transportation Efficiency Act in 1991 mandated bridge management systems (BMS) as a part of all state departments of transportation (Agrawal, 2009). Deterioration models are used as inputs for bridge management software.

There are roughly 7,300 bridges in the state of Washington, of which 74% are concrete structures. The average age of existing bridges in Washington State is 45 years old, over half the expected life-cycle (Bridges, 2015). The Washington State Department of Transportation (WSDOT) Bridge and Structures Office is responsible for managing Washington State's bridge inventory following federal inspection and bridge management regulations. Managing the bridge inventory includes performing routine inspections and identifying and prioritizing repair and maintenance needs.

All federally supported bridges have been inspected biannually since 1978 (Jiang, 1988). Current WSDOT inspection practices outlined in the Washington State Bridge Inspection Manual (WSBIM) align with current NBIS standards. A WSDOT Bridge Inspection Report form includes Bridge Number, Structure ID Number, Bridge Route and mile Post. Also recorded are BMS bridge element condition state (CS) ratings, operating tons, year built, substructure and overall structure evaluation and operating level. Concrete Piles/Columns are assigned BMS element ID 205 and element ID 227 refers to Submerged Concrete Pile/Column.

Element condition requires the inspector to evaluate and quantify defects per bridge element (WSBIM, 2018). The NBI rating-system uses a 0 to 9 scale where 9 indicates a near-perfect condition state (Jaing, 1988). WSDOT uses the federal bridge management system of condition states which range from 1-4. Condition State 1 (CS1) indicates an element is in "Good Condition." The bridge element may have defects, such

as hairline cracks, but they are structurally insignificant. A defect is structural if the defect negatively impacts the bridge's load carrying capacity. If a maintenance repair is made to a structural member and properly completed, Condition State 2 (CS2) is assigned. Condition State 3 (CS3) is assigned if an element is in "Fair Condition" meaning a significant defect is noticed by the inspector, but the defect does not significantly impact the load carrying capacity of the element. Condition State 4 (CS4) defines an element in "Poor Condition" (WSBIM, 2018). If a bridge has a concrete column in CS4, the bridge's load carrying capacity is reduced, which may force bridge restriction of overload vehicles. A rating of CS4 is rare as maintenance repairs and needs are usually met to ensure the bridge remains in service.

The Minnesota Department of Transportation (MnDOT) uses a four-point condition state system similar to WSDOT. MnDOT has developed a comprehensive Bridge Inspection Field Manual that includes pictorial examples alongside written condition state descriptions (Figure 1-1.).

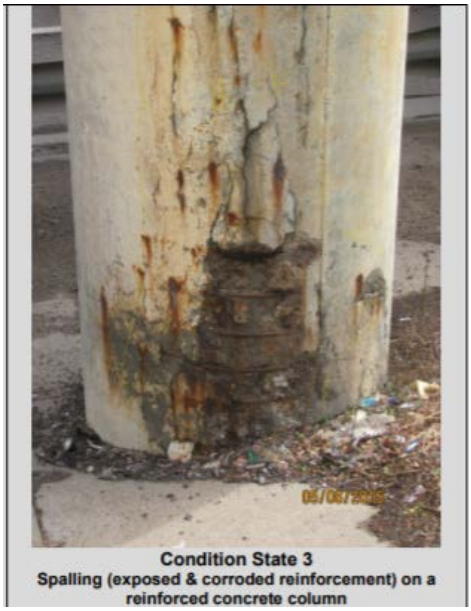


Figure 1-1 Minnesota DOT Inspection Field Manual (MnDOT, 2018)

Biannual inspections provide a means of monitoring bridge inventory. Inspection records can describe life cycles for elements that require frequent maintenance and consequently support deterioration modeling for trends like deck deterioration and steel bridge painting. The models and trends developed from current data strengthen the stakeholder confidence when funding is needed.

Historical bridge data, including inspection reports, are catalogued in WSBIS and WSDOT's Bridge Engineering Information System (BEISt). The inspection records provide data for the bridge asset management program, AASHTOWare Bridge Management (BrM) software and to develop element deterioration rates.

1.2 Motivation

Bridge asset managers make decisions based on public safety, but must also consider the economic impact when prioritizing the bridge repair and rehabilitation programs. Because of their recurrent replacement intervals, Washington State has adequate asset preservation models for bridge decks and steel coating. However, there is currently no statistical or data driven model that exists for monitoring the deterioration of bridge substructures (Joint Legislative Audit and Review Committee, 2015). Deterioration modeling for concrete columns can enable data driven predictions of the overall bridge inventory.

Challenges of deterioration model development, inspection practice and use of BMS occur for several reasons: (1) commercial BMS software has been in practice for less than 20 years, and even agencies that implemented BMSs early have only 7 to 9 inspection records available; (2) bridge condition ratings usually only change slightly

over short periods of time; (3) previously conducted inspections are incompatible with what is required as input values for typical BMSs and; (4) frequent maintenance work causes variation in distribution of inspection records (Bu, 2014). Asset management methodologies incorporated economic assessments to validate cost-effective long-term decisions of maintenance, repair and rehabilitation (MR&R) (Lee *et al.*, 2011). An understanding of the probability of column transitioning through condition states enables better estimates of financial needs for the state's bridge inventory.

WSDOT's Mud Bay identical bridges, built in 1958, experienced column deterioration that warranted major structural repairs. Mud Bay Bridges are located in WSDOT's Olympic region, serving both Northbound and Southbound of US101, and span over the Eld Inlet (Map shown in Figure 1-2).

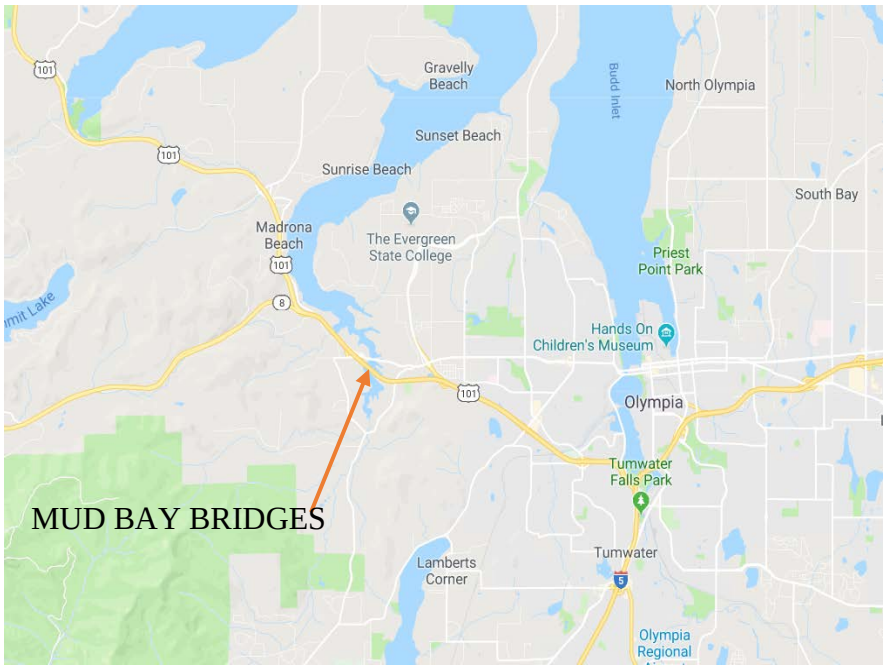


Figure 1-2 Location Map of Mud Bay Bridge (Image taken from Google Maps)

Each bridge consists of 9 piers with 11 columns per pier. Columns of piers 4, 5, and 6 on both bridges are submerged in the Eld Inlet and experienced significant deterioration. The earliest inspection records available in BEISt were recorded in 1996, when the bridge was 38 years old. At the time of the 1996 inspection, all 33 non-submerged columns were still in CS1, while the submerged columns had 14 in CS2, 20 in CS3 and 10 in CS4. Table 1 shows the number of submerged columns on the east bridge in each condition state from the initial 1996 inspection record through 2008 inspection (before major repair work was performed).

Table 1 Mud Bay Inspection Records: East Bridge, Element ID 227

	Number of Columns per Condition State			
Inspection Date	**CS1**	**CS2**	**CS3**	**CS4**
1996-04-04	0	14	20	10
1998-06-02	0	15	29	0
2000-03-29	9	12	13	10
2002-03-29	12	4	18	10
2004-08-19	10	4	18	12
2006-07-19	12	9	10	13
2006-12-15	11	3	18	12
2007-11-19	12	9	10	13
2008-06-02	8	0	32	4

Inspection notes specify bridges with longitudinal cracks, ring cracks and rusting rebar. Notes do not identify which columns were identified as being in CS3 or CS4. Figure 1-3 shows significant loss of concrete cover and exposed, rusted spiral and longitudinal rebar. Figure 1-4 shows deep longitudinal cracking, marine growth and spalling.

Figure 1-3 Deterioration of Mud Bay Columns in Pier 6 (taken at 2001 inspection)

Figure 1-4 Column Cracking in Mud Bay Bridge (taken at 2001 inspection)

Maintenance repair work, including patching concrete cracks, occurred between 1998-2007. With recurrent repair work not stopping concrete deterioration progression, special repair work was done on the 66 submerged concrete columns.

Repair work included removing the existing marine growth, cleaning and coating exposed rebar with epoxy to prevent rust, use of polymer material to return the column to the original shape and fiberglass polymer column jackets (shown in Figure 1-5). The Mud Bay Bridge Special Repair project received federal funding and bid was awarded for $521,721.

Figure 1-5 East Mud Bay Bridge Jackets (taken at 2008 inspection)

The Mud Bay Bridges demonstrate the importance for bridge inspections and repairs to continue to provide safe transportation for the public. A bridge deterioration model has potential to support bridge asset managers in their economic decisions of

continuous minor repairs versus initiating major repairs. Early repair work, that which may require immediate funding, could be quantitatively justified if deterioration models could show they offset the financial impact of future repairs.

1.3 Objective

The objective of this research is to develop deterioration models for both dry and submerged concrete columns as well as examine the deterioration variation due to climate. WSDOT divides the state into six different regions as shown in Figure 1-6. For this research, initial data analysis is on all six regions. Refined analysis is for the regions combined into Eastern and Western Washington as divided by the Cascade Mountain Range. Eastern WA is made up of WSDOT's Eastern (EA), South Central (SC) and North Central (NC) regions which have similar extreme climate. Eastern WA climate consists of hot, dry summers and freezing, snowy winters, hence the bridges experience freeze/thaw cycles. Western WA consists of WSDOT Northwest (NW), Southwest (SW) and Olympic (OL) regions. Western WA does not experience similar freeze/thaw cycles, but does experience high rainfall and harsh coastal environments.

Figure 1-6 WSDOT Regions (WSDOT.WA.gov)

2 REVIEW OF PREVIOUS WORK

2.1 Introduction

The following deterioration modeling methods are discussed in this chapter: 1) variable bridge design and construction specifications and environmental elements to develop hazard ratios, 2) stochastic and deterministic processes and 3) Artificial Intelligence (AI) with backward prediction modeling (BPM). This chapter concludes with a review of deterioration modeling methods used by other departments of transportation.

2.2 Development of Hazard Ratios

Recognizing there are more factors involved in deterioration than just bridge ages, researchers developed an approach to account for variables that may significantly influence deterioration. Each bridge is designed and constructed with specific design parameters and requirements based on bridge location and year of construction, which may vary between code revisions. Some examples include minimum concrete cover or the required strength of concrete.

Hazard ratios account for the risks which may impact bridge deterioration. Using North Carolina's (NCDOT) statewide bridge database, a model was developed using aggregated hazard ratios (HR). This identified variables that most significantly influence deterioration rates of different bridge components (Goyal et al., 2016). Deterioration may result in an unexpected significant decrease in load carrying capacity. Historical records and inspection reports contain descriptive information for each structure including design type, functional classification, geographical region, average daily traffic, maximum span length, type of wearing surface and other variables that could be considered to significantly influence deterioration rates (Goyal et al, 2016). Through unique statistical

regression methodology which correlates a proportional hazard model of NCDOT'S bridge inventory, transition probability matrices were formed (Cavalline, 2015).

To account for the variable hazard influence on deterioration, the Cox proportional hazard modeling (PHM) defines the hazard rate, at a specific time in two components (Goyal et al, 2016). The two components consist of a non-parametric baseline hazard rate function and a time-independent multiplier which uses an exponential function to model the effect of covariates (Goyal *et al.*, 2016). Unlike the standard Markov chain approach, hazard ratios account for multiple variable influence on deterioration. The similarities of the PHM and other deterioration models is that their effectiveness depends on inspection data quantity and quality.

2.3 Deterministic and Stochastic Modeling

Deterministic and stochastic models have been used to develop deterioration rate models since the early 1970s (Agrawal, 2010). Deterministic models describe the relationship between variables affecting deterioration and condition states by using simple statistical calculations (Jaing, 1988; Agrawal 2010). Stochastic models consider multiple variables and recognize the uncertainty and randomness of deterioration processes (Agrawal, 2010). The benefit of both models is that they do not require an overwhelming amount of data to be completed.

Markov chain approach can predict percentage of bridges at specific condition ratings through deterministic methods (Jiang, 1988). The deterministic processes categorize and group bridges together that have similar environments, construction process, and material types. Categorizing similar bridges enables isolation of the bridge age as a variable. This means deterioration transition probability can be conducted with

simple statistical analysis. The probabilities for the Markov chain approach are represented in a matrix form that is referred to as the probability transition matrix or, more simply, the transition matrix (Jiang *et al.*, 1988). This model uses a linear approach, assuming the bridge moves consecutively between condition states (i.e., the bridge will not jump from CS1 to CS3 or CS4) and condition state deteriorates linearly as the bridge ages. The total number of bridge condition state transitions are described by the transition probability matrix. A vector of initial conditions is multiplied by the matrix to determine transition times.

Weibull distribution enables calculation of bridge service-life behaviors, failure rate, reliability function, mean duration and quantile statistics. Weibull distributions are capable of modeling deterioration and service life years. Synthetic data can be produced using a Weibull distribution and Latin hypercube simulations. From the produced data, a final probability matrix and deterioration curve is developed (Riveros, 2010). Production of synthetic data is completed from original data and altered to account for pure deterioration and can provide abundant, accurate data needed for development of deterioration curves. Maintenance repairs and bridge rehabilitation significantly impact deterioration rates. Weibull distribution method produces accurate data when limited inspection data is available (Riveros, 2010).

2.4 Artificial Intelligence and Backwards Prediction Modeling

Artificial Intelligence (AI) and Backwards Prediction Modeling (BPM) generate synthetic data for more complete deterioration curve development. BPM and AI provide missing historical data, using the model to start deterioration rate from the date of construction and then check the assumption by matching the deterioration curve

developed from synthetic data to current condition ratings. This establishes a correlation between existing condition rating datasets and corresponding years' non-bridge factors (Lee *et al.*, 2011). Non-bridge factors account for nonstructural components that influence deterioration such as traffic volume and surrounding environment and can reflect true deterioration models for "Do-Nothing" bridges (no maintenance repairs). This approach simplifies the overly complex problem that arises after bridge maintenance is preformed through computerized generated correlation of both structural and non-structural bridge variables which influence deterioration.

2.5 Assessment Management Methods of Other States

The New York Department of Transportation (NYDOT) used Weibull distribution to develop deterioration rates. NYDOT codes their bridge conditions in accordance to NBI condition state ratings and uses PONTIS bridge management software developed in 1992 by AASHTO (Agrawal, 2010). PONTIS management software was the early version of BrM.

To account for changing software inputs and requirements, the Florida Department of Transportation (FDOT) uses Migration Probability Matrix (MPM). Historical inspections formats and criteria did not correspond exactly to the new 2013 AASHTO Manual Bridge Element inspection criteria. Hence, the matrix is a connection between the old and new manual definitions. The MPM is multiplied by a vector developed for each condition state. This method compares the probability for an element to change stages between old and new inspection methods (Thompson, 2016). As a result,

this does not require computerized generation of data to replace old, incompatible inspection records.

Colorado Department of Transportation (CDOT) models deterioration with Markov chains. Bid Tabulations were analyzed to determine costs related to element repairs. Colorado developed models for specific bridge elements and calculated median years an element stayed in each condition state. Transition probabilities determined by CDOT are imported into their PONTIS BMS and are expressed as vectors of transition probabilities (Hearn, 2012).

North Carolina Department of Transportation (NCDOT) uses Markov Chain approach for their deterioration modeling. NCDOT's research team developed probabilistic deterioration models using proportional hazard assumptions to incorporate deterioration factors such as design, geographic location and functional bridge features to determine component rate deterioration (Cavalline, 2014). NCDOT broke the deterioration model down into element levels including substructure, superstructure and decks. The model addresses issues in project levels of new designs and maintenance, repair and rehabilitation of structures (Cavalline, 2014).

The Indiana Department of Transportation (IDOT) uses probability-based Markov Chain approach with determining transition probability matrices both dependent and independent of bridge ages. The analytical development of the deterioration model determined in this project was conducted in a similar method as previously completed by IDOT.

3 RESEARCH APPROACH

3.1 Initial Data Analysis

Current and historical bridge condition data from bridge inspections are maintained for each bridge in the WSDOT BMS. To develop a pure deterioration model, the data set needs to be confirmed for each variable of interest. WSDOT provided an Excel file of historical inspection data. The data included: Bridge Number, Bridge Name, Region Code, Built Year, Rebuilt Year, Inspection Date, Element ID, Element Name, Total Quantity of Element, Number of Elements in each condition state CS1, CS2, CS3, CS4, and Inspection Notes.

The research scope is to develop deterioration models for four categories:

1. Eastern Washington for dry concrete column/pile (Element ID 205)
2. Western Washington for dry concrete column/pile (Element ID 205)
3. Eastern Washington for submerged concrete column/pile (Element ID 227)
4. Western Washington for submerged concrete column/pile (Element ID 227)

The separation of these variables aligns with current inspection and bridge asset management practice. Initially, the effects on deterioration due to partially wet columns was a desired parameter as well as sea water vs fresh water. These two parameters were eliminated for reasons described below.

As noted in the Mud Bay deterioration analysis, current inspection practice of concrete columns only differentiates between submerged and non-submerged concrete columns (Element IDs 227 and 205, respectively). Data currently does not include indicator of submerged water type (salt or and fresh water).

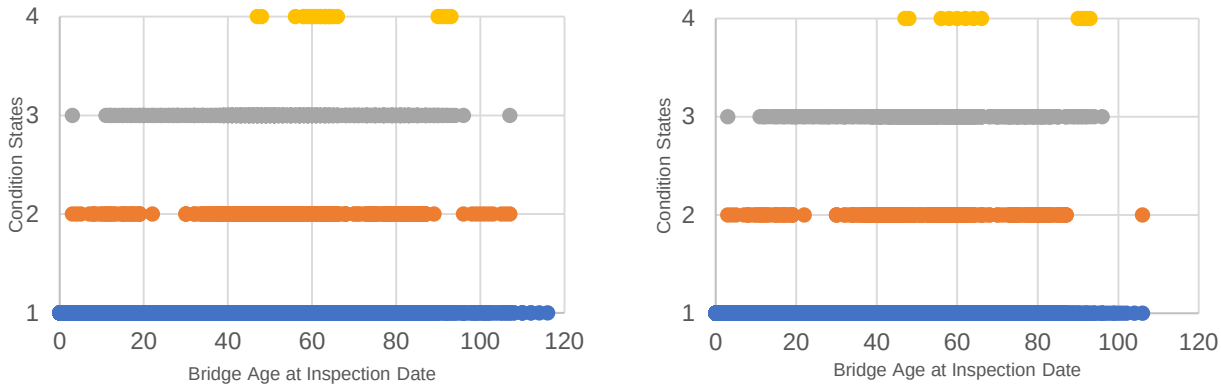
As pointed out in the Mud Bay deterioration analysis, inspection reports only identify the quantity of elements in each condition state, while inspection notes only indicate the deterioration (i.e. size of cracks and spalling) of specific columns. Inspection notes do not distinguish which CS that specific columns are assigned during specific inspections. Therefore, there is no way of determining what column is transitioning, or tracking a particular column's deterioration profile. The only indicator of specific column deterioration was if the inspector noted it in the comments. This was seen only when one column deteriorated significantly faster than the rest.

3.2 Initial Calculations and Data Filtration

The WSDOT provided Microsoft Excel database was imported to Microsoft Access. The query function of Microsoft Access retrieved: Bridge Number, Built Year, Rebuilt Year, Region Code, Inspection Date, Element ID, Total Quantity, Number of Elements in CS1, CS2, CS3 and CS4. Since individual bridge columns are not typically assigned specific CS, all columns for that condition were combined. For example, if there are 6 columns in CS2 and 3 columns in CS3, the tables were edited to indicate 1 in CS2 and 1 in CS3

When a bridge is retrofitted, the bridge's age is not adjusted in the inspection database. While the bridge age could theoretically be adjusted from the retrofit date, the whole bridge age would be adjusted as opposed to only the columns that were retrofitted, due to the current reporting methods described above. Looking at WSDOT Northwest Region data only, Figure 3-1 compares bridge age vs condition state for all bridges (Figure 3-1a) and rebuilt bridges removed (Figure 3-1b). When bridges with a rebuilt year are included, the maximum bridge age in condition state 1 is 116 years, there is a

cluster of bridges around 100 years old in condition state 2 and an outlier 107 year old bridge in condition state 3. When the rebuilt year bridges are removed, the maximum bridge age in condition state 1 is 106 years, the cluster around 100 years in condition state 2 disappears, and the maximum age in condition state 3 is 96. This trend was evident for all regions in both dry and submerged columns. Therefore, including retrofitted bridges gives an impression of artificially high bridge age for condition states and thus were removed from the data set.



a. With "Rebuilt Year"

b. Without "Rebuilt Year"

Figure 3-1 NW Region, Element ID 205: Bridge Age vs Condition State

Bridges with an unexplained improved condition rating were also removed. These removals condensed the data set from 19,404 to 16,608 data points. Bridges that were removed from the data set are listed in Appendix A.

3.3 Development of Overview: Bridge Age vs Condition State

Initial data analysis is performed on the six WSDOT defined regions with data combined into the two categories (Eastern/Western) for matrix development. Graphs of Bridge Age vs Condition States Graphs for condensed date set for Element ID 205 (Dry Concrete

Pile/Column) and Element ID 227 (Submerged Concrete Pile/Column) are shown in Figure 3-2 and Figure 3-3, respectively.

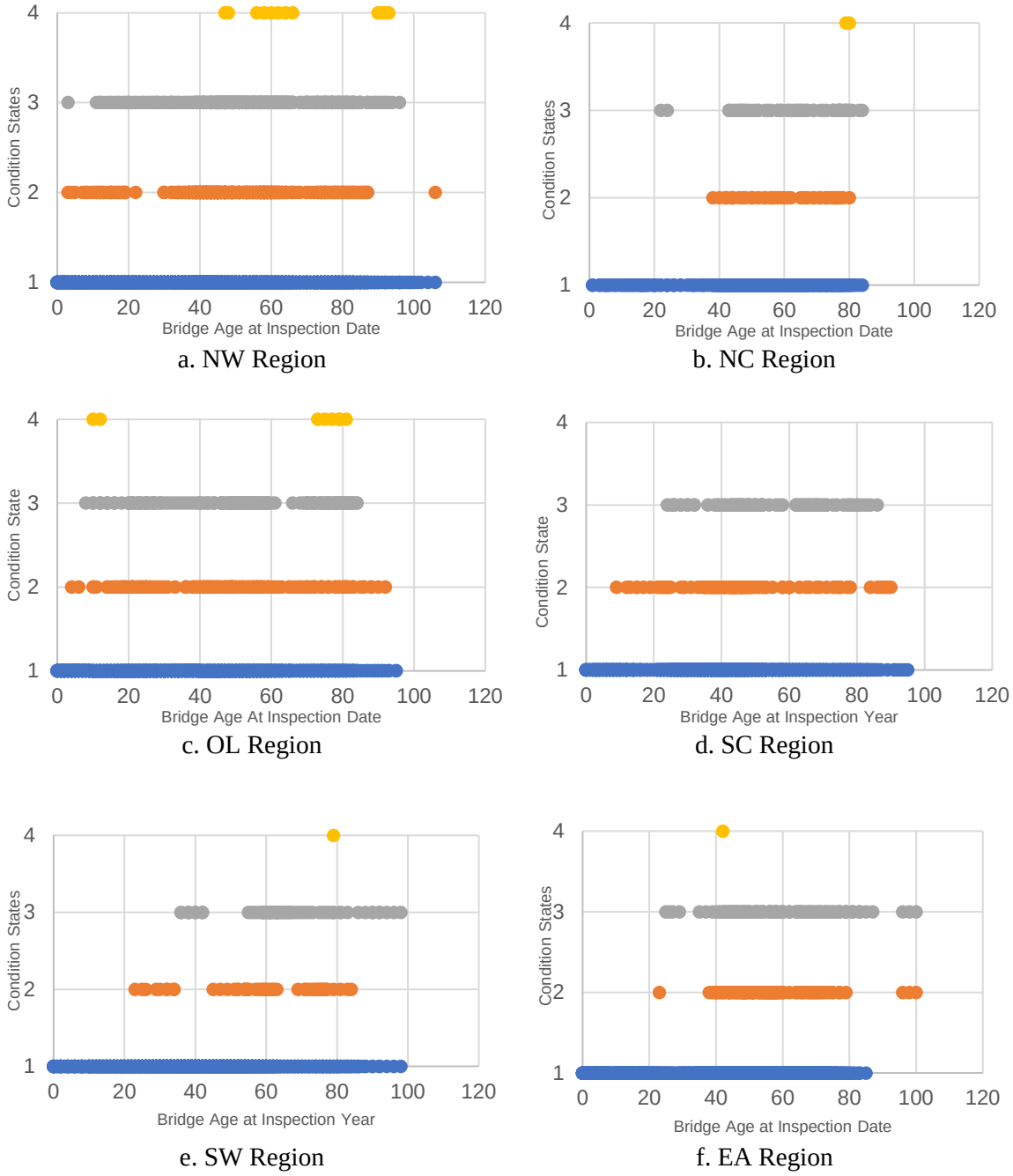
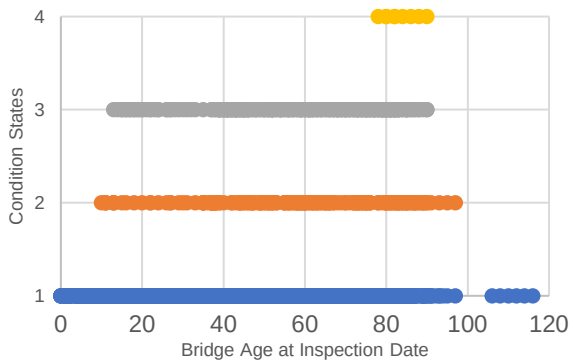
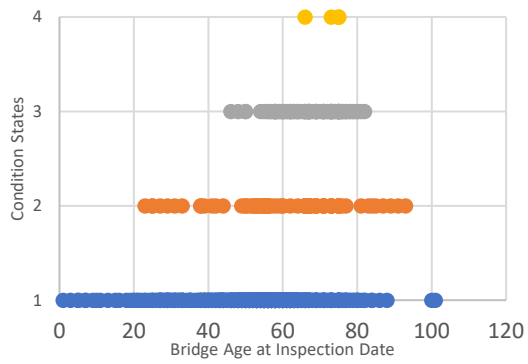


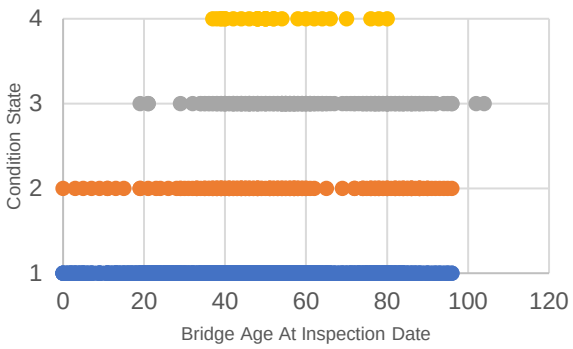
Figure 3-2 Bridge Age vs Condition State: Element ID 205



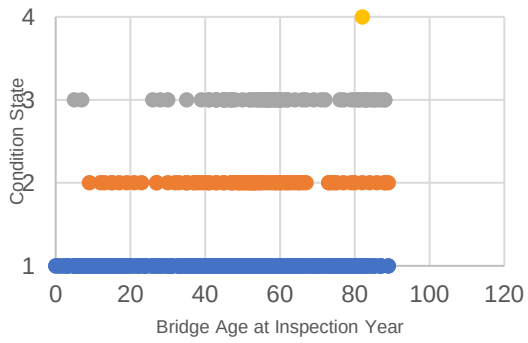
a. NW Region



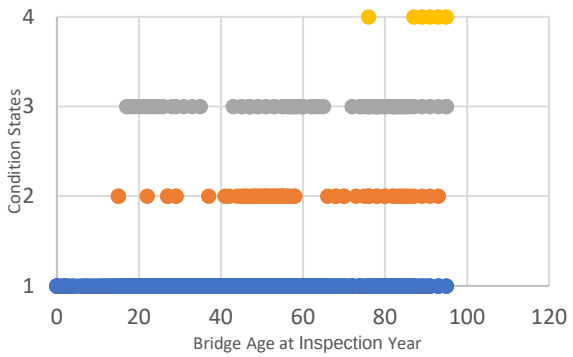
b. NC Region



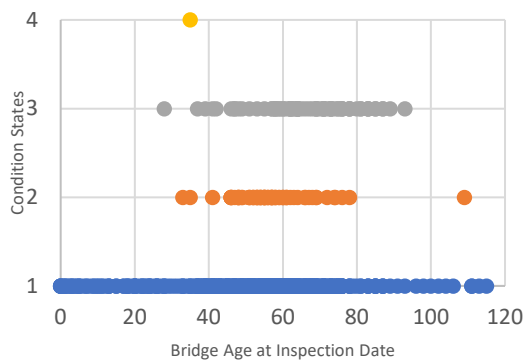
c. OL Region



d. SC Region



e. SW Region



f. EA Region

Figure 3-3 Bridge Age vs Condition State: Element ID 227

To capture predominate age per condition state, bridges from each region were separated by condition state and plotted against age at inspection. Figure 3-4 shows the condition state distribution for dry concrete columns/piles (Element ID 205) for the WSDOT defined Eastern Region. For this region, the majority of WSDOT bridge inventory is in CS1. The highest quantity of bridges in CS1 (38 bridges) is at Bridge Age 45. The youngest bridge in CS2 is 23 years, the majority being between 47 – 58 years old. The graphs for EA Region Element ID 205 continue to skew to the left as the CS moves from 1-4. This is to be expected since bridges deteriorate as they age. These trends were evident in all regions, for both Element ID 205 and 227. Similar graphs for each remaining region are presented in Appendix B.

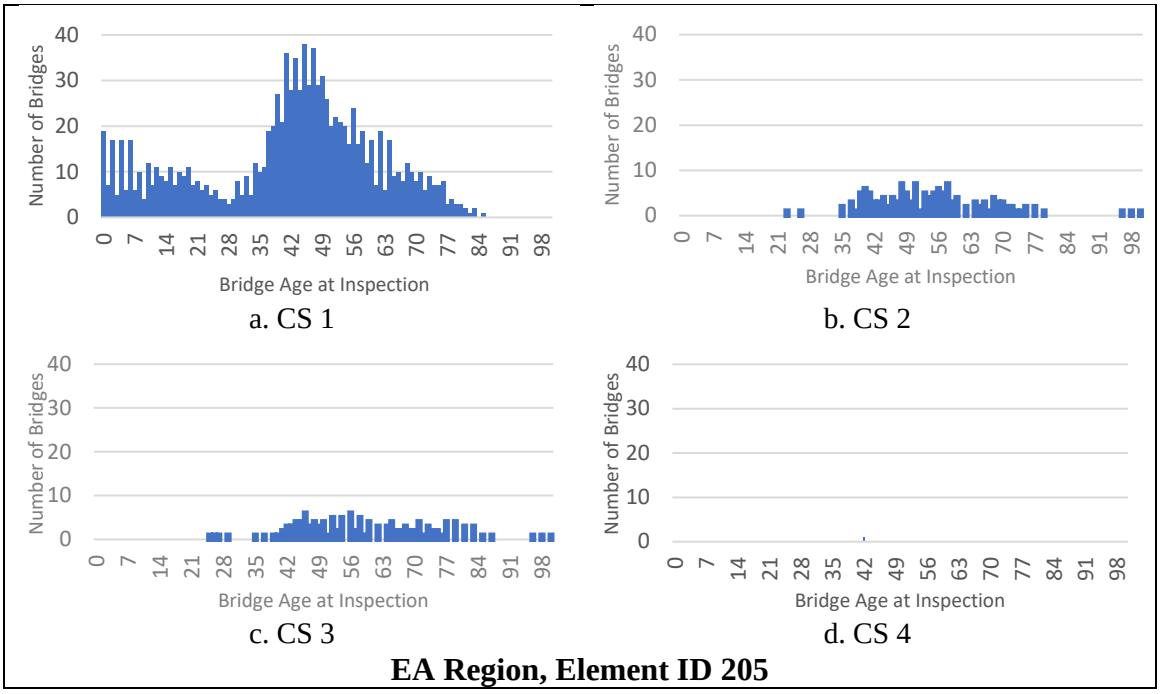


Figure 3-4 Bridge Age vs Number of Bridges (per Condition State)

3.4 Development of Probability Transition Matrices

While the graphs of the previous section provide a good overview of WSDOT bridge inventory condition state, the only information of importance for developing transition matrices is when the element transitions between condition states. For example, if a bridge has columns in CS 1 at initial inspection then moves to CS 2 at the next inspection date, it is considered to have "Column Transition". The final step of data analysis is to determine average number of years concrete columns spend in each condition state before transitioning to the next. The average age of condition states per WSDOT regions and Element ID are plotted in Table 2.

Table 2 Average Age of Condition States per WSDOT Region and Element ID

Region & Element ID	CS1	CS2	CS3	CS4
Element ID 205 – Dry Concrete Column/Pile				
EA	42	54	59	42
NC	52	60	62	80
NW	41	51	55	69
OL	37	50	51	61
SC	40	46	54	-
SW	40	55	56	80
Element ID 227 – Submerged Concrete Column/Pile				
EA	49	55	65	35
NC	52	56	66	73
NW	44	56	57	83
OL	44	50	56	51
SC	46	50	59	82
SW	43	52	57	84

The transitioning ages were then identified by flagging data with a change in condition state. For example, if a bridge had columns in CS1 at inspection year 2000 and CS2 at inspection year 2002, the data was flagged. From flagged transition points, the

average age of the bridges for each transitioning condition state per region and Element ID were calculated. Once the average transitioning ages were determined, the average year bridge columns remain in each condition state was calculated. Final data filtering (i.e., removing data that didn't transition condition states) further condensed the data population from 16,608 to only 546.

Table 3 shows the average year in each condition state per region for dry concrete column/piles (Element ID 205) and Table 4 shows the same for submerged concrete column/piles (Element ID 227). The last two rows of each table combine the regions into Eastern and Western Washington. Eastern Washington is the average of EA, SC and NC regions and Western Washington averages OL, NW and SW regions. A value of '0' in Table 3 and Table 4 indicates the average year in the CS was equal to the previous average year in CS. The results in Table 3 and Table 4 are compatible with input format for BrM Element Deterioration.

Table 3 Average Years in Each Condition State, Element ID 205

Region	CS1	CS2	CS3	CS4
EA	47	6	-	-
NC	59	0	24	-
NW	43	5	-	-
OL	44	3	26	-
SC	40	6.5	-	-
SW	46.5	3.9	28.6	-
Eastern WA	48.67	4.17	8	-
Western WA	44.50	3.97	18.2	-

Table 4 Average Years in Each Condition State, Element ID 227

Region	CS1	CS2	CS3	CS4
EA	56.8	3	-	-
NC	53.2	9	-	-
NW	55	0	-	-
OL	52	7	-	-
SC	36	16	30	-
SW	38	11	22	-
Eastern WA	48.7	9.33	10	-
Western WA	48.33	6.00	7.33	-

3.5 Calculations of Probability Transition Matrices

A typical Transition Probability Matrix takes the form as shown in Figure 3-5. Transition probability matrix development requires the total number of bridges transitioning for each condition state. The method used to determine the transition age and probabilities follows that described by Jiang, Saito and Sinha. q_n equals the number of bridges transitioning in each condition state per region divided by the total transitions in a region.

$$\begin{bmatrix} p_1 & q_1 & 0 & 0 \\ 0 & p_2 & q_2 & 0 \\ 0 & 0 & p_n & q_n \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure 3-5 Standard Transition Probability Matrix Format

Table 5 and Table 6 represent the total number of transitioning bridges, per region for Element ID 25 and 227 respectively. For Example, EA Region had a bridge transition from CS1 to CS2 a total of 11 times. The percentages of transition probability from one initial condition state to the next per region for both Element ID 205 and 227 are shown in Tables 7 and 8 respectively.

Table 5 Total Number of Element ID 205 Transitioning

Region	CS1-CS2	CS2-CS3	CS3-CS4	CS4
EA	11	29	0	-
NC	6	17	1	-
NW	50	100	0	-
OL	24	37	1	-
SC	23	28	0	-
SW	13	38	1	-
Eastern WA	40	74	1	-
Western WA	87	175	2	-

Table 6 Total Number of Element ID 227 Transitioning

Region	CS1-CS2	CS2-CS3	CS3-CS4	CS4
EA	6	15	0	-
NC	5	18	3	-
NW	9	25	0	-
OL	14	19	0	-
SC	5	13	1	-
SW	5	27	2	-
Eastern WA	16	46	4	-
Western WA	28	71	2	-

Table 7 Percentage of Transitions, Element ID 205

Region	CS1-CS2	CS2-CS3	CS3-CS4	CS4
Eastern WA	34.78	64.35	0.87	-
Western WA	32.95	66.29	0.76	-

Table 8 Percentage of Transitions, Element ID 227

Region	CS1-CS2	CS2-CS3	CS3-CS4	CS4
Eastern WA	24.24	69.70	6.06	-
Western WA	27.72	70.30	1.98	-

p_n is the probability that the column will not transition to the next condition state. Therefore, p_n is equal to one minus the probability it will transition, q_n. Once p_n and q_n are determined a Transition Probability Matrix that is independent of the bridge ages is created. The four transition probability matrices area shown in Figure 3-6. These

transition probability matrices can be used with the initial condition state vector to determine the probability for a bridge to transition from one CS to the next.

I. *Eastern, WA Element ID 205*					**III.** *Eastern, WA Element ID 227*				
	CS1	CS2	CS3	CS4		CS1	CS2	CS3	CS4
CS1	0.652	0.348	0	0	CS1	0.758	0.242	0	0
CS2	0	0.357	0.643	0	CS2	0	0.303	0.697	0
CS3	0	0	0.991	0.009	CS3	0	0	0.939	0.061
CS4	0	0	0	1	CS4	0	0	0	1
II. *Western, WA Element ID 205*					**IV.** *Western, WA Element ID 227*				
	CS1	CS2	CS3	CS4		CS1	CS2	CS3	CS4
CS1	0.670	0.330	0	0	CS1	0.723	0.277	0	0
CS2	0	0.337	0.663	0	CS2	0	0.297	0.703	0
CS3	0	0	0.992	0.008	CS3	0	0	0.980	0.020
CS4	0	0	0	1	CS4	0	0	0	1

Figure 3-6 Transition Probability Matrices Independent of Bridge Age

3.6 Discussion of Probability Transition Matrices

The transition probability matrices strictly monitor deterioration, or transitioning, from one condition state to the next, a linear deterioration pattern. The transition matrix does not incorporate the possibility of transitioning from CS1 to CS3, CS1 to CS4 or CS2 to CS4.

As seen in Tables 7 and 8, no significant percentage variation occurs between Eastern and Western WA for either Element ID. The second largest variation in

percentage of transition occurs for Element ID 227 from CS1 to CS2 with Western WA only approximately 3% larger than Eastern WA. While the largest variation in percentage of transition occurs for Element ID 227 from CS3 to CS4 with Eastern WA only approximately 4% larger than Western WA. These slight variations of less than 1% transitioning to the largest of 4% variation is then represented in only slightly different Matrices shown in Figure 3-6.

4 CONCLUSIONS

4.1 Eastern Washington vs Western Washington

Results show no significant difference in deterioration rates between bridges east and west of the Cascade Mountain Range. The only instance of variation between Eastern and Western WA occurs for Element ID 227 transition probability for CS4. For this condition state, Eastern WA had a probability of transition from CS3 to CS4 of 0.061, where Western WA had a probability of 0.020. For Element ID 205 the difference between Western and Eastern WA transition probabilities had a maximum variance of 0.020. For Element ID 227 the difference between Eastern and Western WA had a maximum variance of approximately 0.040. This data shows there is no significant difference of concrete bridge column deterioration between Eastern and Western Washington.

4.2 Submerged vs Dry Elements

Comparing dry and submerged elements, there is higher percentage of transition for dry elements transitioning from CS1 to CS2 however transition to CS3 and CS4 is higher for submerged elements.

5 APPLICATION and RECOMMENDATIONS

5.1 Application

The method of modeling deterioration rate is based on linear deterioration from one CS to the next (a concrete column moving from CS1 to CS2 or CS2 to CS3). The probabilities of transition described in the Research Approach is based on the total inventory of bridges and is independent of the bridge age. The model also does not account maintenance repairs and bridge rehabilitation. WSDOT may use the probability transition matrices to determine the risk of a bridge moving linearly from CS1 to CS4. The probability for calculation is determined by multiplying the known vector matrix by the Transition Probability Matrix for the region and element of interest. The method of data analysis conducted in the study is compatible to the current WSDOT BrM user inputs.

5.2 Recommendations

To account for maintenance repairs further research is needed. One method that allows adjustment for new information is the use of a Neural Network (Lee, 2014). Neural Networks adjust for limited data through Backwards Prediction Modeling. Backwards Prediction Modeling generates synthetic data points for periods before mandatory inspection. Modifying inspection reports to identify the original bridge columns and ones that may have been constructed during a bridge widening would mean inspection data from bridges that were identified with a rebuilt year could be included in the data set. Other inspection practice that may be altered would be a separation of element ID for columns submerged in saltwater vs freshwater to account for this variable.

Chloride testing could quantify the impact of salt water on the western side of the state and use of rock salt on the east side. Chloride testing could provide data to support or disprove that salt contributed to similar eastern and western deterioration rates.

REFERENCES

Agrawal, A. K., Kawaguchi, A., & Chen, Z. (2010). Deterioration Rates of Typical Bridge Elements in New York. *Journal of Bridge Engineering*, *15*(4), 419-429.

Bridges - By the Numbers. (2015, August 04, Retrieved from https://www.wsdot.wa.gov/Bridge/Reporting/BridgesByNumbers.htm). Last access (2017),

Bu, G. P., Lee, J. H., Guan, H., Loo, Y. C., & Blumenstein, M. (2015). Prediction of Long-Term Bridge Performance: Integrated Deterioration Approach with Case Studies. *Journal of Performance of Constructed Facilities*, *29*(3), 04014089. doi:10.1061/(asce)cf.1943-5509.0000591

Cavalline, Tara L., Matthew J. Whelan, Brett Q. Tempest, Raka Goyal, and Joshua D. Ramsey. *Determination of Bridge Deterioration Models and Bridge User Costs for the NCDOT Bridge Management System*. Rep. no. FHWA/NC/2014-07. North Carolina Department of Transportation Research and Development Unit, 26 Oct. 2015. Web.

FHWA (Federal Highway Administration). (2014). "Specification for the National Bridge Inventory" *NBI*, Washington, DC.

Goyal, R., Whelan, M. J., & Cavalline, T. L. (2016). Characterising the effect of external factors on deterioration rates of bridge components using multivariate proportional hazards regression. *Structure and Infrastructure Engineering*, *13*(7), 894-905.

Hearn, G. (2012). *Deterioration and Cost Information for Bridge Management* (pp. 1-352, Rep. No. CDOT-2012-4). Denver, CO: Colorado State Department of Transportation-Research.

Jiang., Y., S., M., & S. (1988, November 30). *Bridge Performance Prediction Model Using the Markov Chain*. Retrieved from https://trid.trb.org/view.aspx?id=300339 Last access (April 20, 2018).

Joint Legislative Audit and Review Committee. (n.d.). Total Highway Maintenance and Preservation Estimates Are Available. Retrieved January, 2015, from http://leg.wa.gov/jlarc/reports/WSDOTCostEst/pf/print-ver.htm). Last access (October 12, 2017).

MnDOT (Minnesota Department of Transportation). (2018). "MnDOTs Bridge Inspection Field Manual" St. Paul MN.

Lee, J., Guan, H., Loo, Y., & Blumenstein, M. (2014). Development of a Long-Term Bridge Element Performance Model Using Elman Neural Networks. *Journal of Infrastructure Systems*, *20*(3).

Riveros, G. A., & Arredondo, E. (2010). Guide to the Development of a Deterioration Rate Curve Using Condition State Inspection Data. *US Army Corps of Engineers,*1-12.

Thompson, P. D. (2017). *Migration Probability Matrix for Bridge Element Deterioration Models* (Publication No. 17-01378). Washington, DC: Transportation Research Board.

Weingroff, R. F. (1966, Summer). Federal-Aid Highway Act of 1956: Creating The Interstate System. Retrieved from https://www.fhwa.dot.gov/publications/publicroads/96summer/p96su10.cfm). Last access (October 12, 2017).

WSDOT (Washington State Department of Transportation). (2018). "Washington State Bridge Inspection Manual" *WSBIM*, Olympia, WA.

Appendix A

List of Bridges Removed (Rebuilt Years)

structure_id	bridge_no	region_code	structure_id	bridge_no	region_code
0014428A	2/5S	NW	0006078B	5/503W	NW
0003163A	2/126	NC	0006094B	5/504E	NW
0003163B	2/127	NC	0006094C	5/504W	NW
0002614B	2/224S	NC	0006124A	5/506E	NW
0004136A	2/238	NC	0006124B	5/506W	NW
0002365A	2/604	EA	0006313A	5/507E	NW
0000451A	3/2	OL	0006313B	5/507W	NW
0003381A	4/106A	SW	0006207B	5/508E	NW
0001442B	4/209	SW	0006207A	5/508W	NW
000000PR	5/1E	SW	0006313C	5/509E	NW
0004375A	5/206	SW	0006313D	5/509W	NW
0004204A	5/216E	SW	0006186A	5/510E	NW
0004204B	5/216W	SW	0006186B	5/510W	NW
0004363A	5/217E	SW	0006820A	5/511E	NW
0004363B	5/217W	SW	0006820B	5/511W	NW
0012597A	5/221	SW	0007090B	5/516E	NW
0011336A	5/222	SW	0007090C	5/516W	NW
0011430A	5/223	SW	0007401B	5/519E	NW
0003936A	5/228	SW	0007401D	5/520W	NW
0003922A	5/230	SW	0007618C	5/525.5E	NW
0013692A	5/314	OL	0007617C	5/531E	NW
0004950A	5/316	OL	0007617D	5/531W	NW
0005090A	5/321	OL	0007990A	5/532W	NW
0005295C	5/325A	OL	0007734A	5/533.5W	NW
0005295D	5/325S-W	OL	0007734C	5/534W	NW
0005455A	5/332	OL	0007816A	5/535E	NW
0008100B	5/337E	OL	0007816B	5/535W	NW
0008100A	5/337W	OL	0007741A	5/536E	NW
0002069A	5/345E	OL	0007741B	5/536W	NW
0005284A	5/407.5	OL	0007741C	5/538E	NW
0004495A	5/411W	OL	0007741E	5/539E	NW
0005523B	5/417	OL	0007741D	5/539W	NW
0006145B	5/433	OL	0007565A	5/540N-W	NW
0006145C	5/434	OL	0007565N	5/541S-W	NW
0006088B	5/437	OL	0007565F	5/542E	NW
0007326B	5/445W	OL	0007565E	5/542S-E	NW
0006792A	5/452E	OL	0007565G	5/542W	NW
0006792B	5/452W	OL	0007504A	5/543E	NW
0006821A	5/453	OL	0007504B	5/543W	NW
0006979B	5/455	OL	0007110K	5/545R	NW
0006379A	5/458E	OL	0007110G	5/545SCD	NW
0006379B	5/458W	OL	0007110B	5/545W	NW
0006361B	5/462E	OL	0007409A	5/549	NW
0006361C	5/462W	OL	0012197A	5/588E	NW
0006379C	5/464E	OL	0012197B	5/588W	NW
0006379D	5/464W	OL	0007299A	5/595E	NW

structure_id	bridge_no	region_code	structure_id	bridge_no	region_code
0007299B	5/595W	NW	0000952A	12/273	SW
0007071A	5/599E	NW	0001287A	12/278	SW
0007071C	5/599NCD	NW	0003762A	12/512N	SC
0007071B	5/599W	NW	0001724B	12/620	SC
0007227A	5/602	NW	0008527A	12/660	SC
0012790A	5/605	NW	0007138A	14/25	SW
0007071G	5/607E	NW	0001151A	14/104	SW
0007071F	5/607W	NW	0009151A	16/12E	OL
0007227B	5/608E	NW	0009151B	16/12W	OL
0007227C	5/608W	NW	0009151C	16/15E	OL
0007118A	5/609E	NW	0009151D	16/15W	OL
0007118B	5/609W	NW	0009415A	16/20E	OL
0007134A	5/612E	NW	0009415B	16/20W	OL
0011598C	5/612W	NW	0012985A	16/24W	OL
0011598D	5/613	NW	0009245A	16/120	OL
0011561A	5/615	NW	0004840A	17/215	NC
0003842A	5/626E	NW	0005433A	18/5	NW
0008132A	5/626W	NW	0005082A	18/9	NW
0008132I	5/630A	NW	0012618B	18/14N	NW
0008132E	5/631E	NW	0006068B	18/16S	NW
0008132F	5/631W	NW	0006068C	18/20N	NW
0008090A	5/633E	NW	0006068D	18/24N	NW
0008090B	5/633W	NW	0009289A	18/26	NW
0008085C	5/638E	NW	0006676A	18/34	NW
0008085D	5/638W	NW	0006787A	20/209N	NW
0004196A	5/650W	NW	0007777A	20/209S	NW
0004352A	5/653E	NW	0003761A	20/277	NW
0005440A	5/663W	NW	0006563A	20/621	NC
0005423A	5/673E	NW	0003722A	20/624	NC
0005423B	5/674E	NW	0005114B	26/111	NC
0005422A	5/675W	NW	0002385A	26/275	EA
0005422B	5/702W	NW	000000LV	28/108	NC
0004563A	5/708	NW	0006744A	82/123	SC
0004768A	5/710	NW	000000PD	82/280S	SC
0004795A	5/711	NW	000000OC	90/10E-S	NW
0004795B	5/713E	NW	0007565P	90/10EB	NW
0004795C	5/713W	NW	0007565C	90/10WB	NW
0004833A	5/714	NW	0007565L	90/10WCD	NW
0007057B	5/842E	NW	0013105A	90/22LID	NW
0005738B	8/104N	OL	000000KO	90/24.5S	NW
0005738A	8/104S	OL	000000KN	90/25S	NW
0006412A	9/130	NW	000000KP	90/25.5S	NW
0004328B	9/311	NW	0008610C	90/43ECD	NW
0002311A	12/12N	OL	0008610B	90/43N	NW
0001679A	12/15	OL	0008610A	90/43S	NW
0002328A	12/230	SW	0002577A	90/50N	NW

structure_id	bridge_no	region_code	structure_id	bridge_no	region_code
0009133C	90/59E-N	NW	0010513C	167/106	NW
0008573F	90/66N	NW	0009236B	167/112E	NW
0006966B	90/78N	NW	0008441A	167/119	NW
0008916A	90/98.6N	SC	0008114A	167/121E	NW
0005702A	90/118N	SC	0008114B	167/121W	NW
0005872B	90/120N	SC	0008114C	167/122E	NW
0005872A	90/120S	SC	0008114D	167/122W	NW
0006868A	90/132N	SC	0008114E	167/123E	NW
0007574B	90/145S	SC	0008114F	167/123W	NW
0008200F	90/162N	SC	0008114G	167/124E	NW
0005688A	90/210	NC	0008114H	167/124W	NW
0005688B	90/214	NC	0008175A	167/125E	NW
0005689B	90/216	NC	0008175B	167/125W	NW
0006875D	90/531N	EA	0008175D	167/126W	NW
0006875C	90/531S	EA	0008175E	167/127E	NW
0003376B	97/118	SC	0008175F	167/127W	NW
0001516B	97/120	SC	0008114I	167/128E	NW
0007683A	97/512	NC	0008114J	167/128W	NW
0007046A	99/500	NW	000000QC	167/129	NW
0004872A	99/530E	NW	0013037C	167/129E-S	NW
0005758A	99/538	NW	0007085B	167/133	NW
0004104B	99/540N-N	NW	0002352A	169/12	NW
0003935A	99/540NB	NW	0012217B	182/7E	SC
0003935B	99/540SB	NW	0012207F	182/14	SC
0007868A	101/54	SW	0012236F	182/21S	SC
0005101A	101/101	OL	0004656B	203/18	NW
0001084A	101/125W	OL	0009241J	205/46	SW
0005534A	101/132	OL	0006279A	240/32W	SC
0003217A	101/147	OL	0008390A	261/125	SC
0003255A	101/164	OL	0007386D	281/1	NC
0005198A	101/167	OL	000000LZ	281/10	NC
0003255D	101/172	OL	0011864A	303/40	OL
0005777B	101/175	OL	0005741A	395/11	SC
0001389A	101/207	OL	0004029A	395/460	EA
0001406A	101/318	OL	0000432A	395/512	EA
0004928A	101/330	OL	0007113A	395/514	EA
0004928B	101/332	OL	000000ET	395/618	EA
0009808A	101/514	OL	08566400	397/10	SC
0011964A	104/5.1	OL	0006968A	405/5	NW
0004752A	141/14	SW	0007249B	405/10	NW
0003507A	153/16	NC	0007079A	405/10B	NW
0006094D	161/102	NW	0007249D	405/11	NW
0008102C	162/2	OL	0007606A	405/12	NW
0008682A	167/16	OL	0007376A	405/15	NW
0010513A	167/102	NW	0007376C	405/16	NW
0010513B	167/104	NW	0006912B	405/22	NW

structure_id	bridge_no	region_code	structure_id	bridge_no	region_code
0007828A	405/23E	NW	0014407A	519/101FTP	NW
0007828B	405/23W	NW	0007839B	520/16	NW
0005347B	405/25E	NW	0007839B	520/16S	NW
0005347C	405/25W	NW	0008591A	520/21	NW
0007623C	405/30E	NW	0007839C	520/21N	NW
0007623D	405/30W	NW	0008591A	520/21S	NW
0008812B	405/41E	NW	0007839D	520/22N	NW
0009267A	405/41W	NW	0008591B	520/22S	NW
0007596A	405/45E	NW	0009086A	520/25N	NW
0007596B	405/45W	NW	0009086B	520/25S	NW
0007596C	405/46E	NW	0009086C	520/27N	NW
0007596D	405/46W	NW	0009086D	520/27S	NW
0007596E	405/47E	NW	0008744B	520/30	NW
0004609A	405/47W	NW	0008744B	520/30N	NW
0007742A	405/48E	NW	0008744A	520/30S	NW
0007839A	405/48S-W	NW	0009259C	520/34S	NW
0004609B	405/48W	NW	0011314A	520/37	NW
0008674E	405/52E	NW	0010201A	520/42S	NW
0008674F	405/52W	NW	0014444B	520/46	NW
0004978A	405/56E	NW	0014444C	520/48A	NW
0008615C	405/56W	NW	0008257A	522/28N	NW
0008615E	405/59E	NW	0006371A	522/28S	NW
0008615F	405/59W	NW	0008382G	522/30E-N	NW
0008569A	405/64	NW	0012036A	525/3	NW
0008382A	405/70E	NW	0002656A	525/10	NW
0008382B	405/70W	NW	0008286B	527/104	NW
0008375B	405/72	NW	0000965A	529/10E	NW
0008286A	405/73	NW	0000965C	529/20W	NW
0008375C	405/103E	NW	0006897A	530/132	NW
0008375D	405/103W	NW	0006837A	532/6	NW
0008417B	405/105E	NW	08236500	548/5	NW
0008417A	405/105W	NW	08061500	548/10	NW
0008417C	405/108E	NW	0008573H	900/30	NW
0008417D	405/108W	NW	08494200	509/20	OL
0011598A	405/110E	NW	08257600	119	NC
0011598B	405/110W	NW	07963700	316	NC
0002377A	409/10	SW	07990000	382	NC
08127600	411/10	SW	08321600	1	NW
0006321A	432/10S	SW	08077200	3	NW
0005968A	432/12	SW	07963500	11	NW
0003760A	433/1	SW	08298100	15	NW
000000IU	503/26	SW	08298200	17	NW
0005452A	509/5A	OL	08168200	30	NW
000000HY	509/103	NW	08277800	35	NW
0008673E	512/25	OL	08475300	37	NW
000000HH	513/12	NW	08236700	38	NW

structure_id	bridge_no	region_code	structure_id	bridge_no	region_code
08269400	44	NW	08470800	4599/0.2	OL
08297700	56	NW	08397500	506-4.20	SC
08071600	109	EA	08303200	608-8.30	SC
08045800	131	NW	08410400	690-3.92	SC
08464900	17E	OL	08038700	93450-00.3	EA
07977600	212	SW	08488000	9641/1.7	OL
07977600	212	SW	08488000	9641/1.7	OL
08317800	321	NC	08491200	9710/6.1	OL
08317800	321	NC	08491400	9710/6.4	OL
08044800	328	NW	08407600	9740/2.0	OL
07983000	331	NW	08209500	9740/4.1	OL
08476200	334	NW	08192600	9740/5.0	OL
08394100	336	NW	08571700	000000004	EA
08324100	414	NC	08009900	2-1	EA
08652000	654	NW	08181600	002500245	EA
08184700	C-4	NC	08080600	008000284	OL
08315200	16-1	EA	08354400	012000044	EA
08092700	257Z	NW	08442700	210000001	SW
08092700	257Z	NW	08201200	210000012	SW
08224700	3032	NW	08338000	210000032	SW
08224700	3032	NW	08298700	210000079	SW
08138900	3194	NW	08081400	210000093	SW
08138900	3194	NW	08344900	210000099	SW
08224200	411A	NC	08267400	210000105	SW
08071400	927B	NW	08161400	210000135	SW
08071400	927B	NW	08161600	210000136	SW
0007016B	04272	SC	08326000	210000137	SW
08360500	05271	SC	08156600	41000001	SW
08407900	05301	SC	08224200	411A	NC
08066000	1320A	NW	08072500	645000015	OL
08435700	1726A	NW	08367800	720500312	EA
08435700	1726A	NW	08343700	901-15.93	SC
08258900	400-3	EA	08134100	901-18.87	SC
08099000	414-3	EA	08038700	9345-0.30	EA
08302000	416-3	EA	07972700	SPOK-2105	EA
08636800	418-3	EA	08575600	SPOK-2609	EA
08326900	419-3	EA	0004332A	SPOK-3603	EA
08320900	433-3	EA	08011600	SPOK-4651	EA
08019300	439-3	EA	08264500	3143	NW
08158900	78132	SC	08748200	8A	NW
08351300	26205B	OL	08535800	BRG-006	NW
08351300	26205B	OL	08830100	BRG-031E	NW
08134400	492101	SW	08830100	31E	NW
08418800	34750001	SW	08505000	BRG-031W	NW
08364400	370-1.35	SC	08505000	31W	NW
08289500	400-6.96	SC	08504100	BRG-032	NW

structure_id	bridge_no	region_code	structure_id	bridge_no	region_code
08504100	32	NW	08559600	88342	SC
08505300	BRG-034	NW	08560600	EVTB14	NW
08505300	34	NW	08560600	4200703	NW
08527400	BRG-039	NW	07984500	LKW2192C	OL
08527400	39	NW	08522700	000000002	OL
08526200	BRG-090	NW	08535600	3142	NW
08527300	BRG-093	NW	08002500	0000TUK12	NW
08527300	93	NW	08518200	1070000U1	NW
08513000	BRG-094MS	NW	08518200	RENTON-28	NW
08513000	94MS	NW	0005258A	359100816	EA
08548000	BRG-102	NW	08529500	371000815	EA
08535800	006	NW	08528700	373000814	EA
08535800	6	NW	08514600	533000802	EA
08505000	31	NW	08524100	533000819	EA
08504100	32	NW	08552600	864-03-S2	NW
08505300	34	NW	08500900	BELLEVUE8	NW
08527400	039	NW	08507100	CAMAS-010	SW
08527300	93	NW	08494200	F23	OL
08554100	N2	OL	08550000	FRNDALE 2	NW
08555300	N3	OL			
08544600	N4	OL			
08512000	E19	OL			
08501500	F12	OL			
000000JE	3139	NW			
08264500	3143	NW			
08549900	3900	SC			
08513000	94MS	NW			
0002376A	50912	OL			
08559600	ELLNBRG15	SC			

Appendix B

Bridge Age vs Number of Bridges, per WSDOT Regions

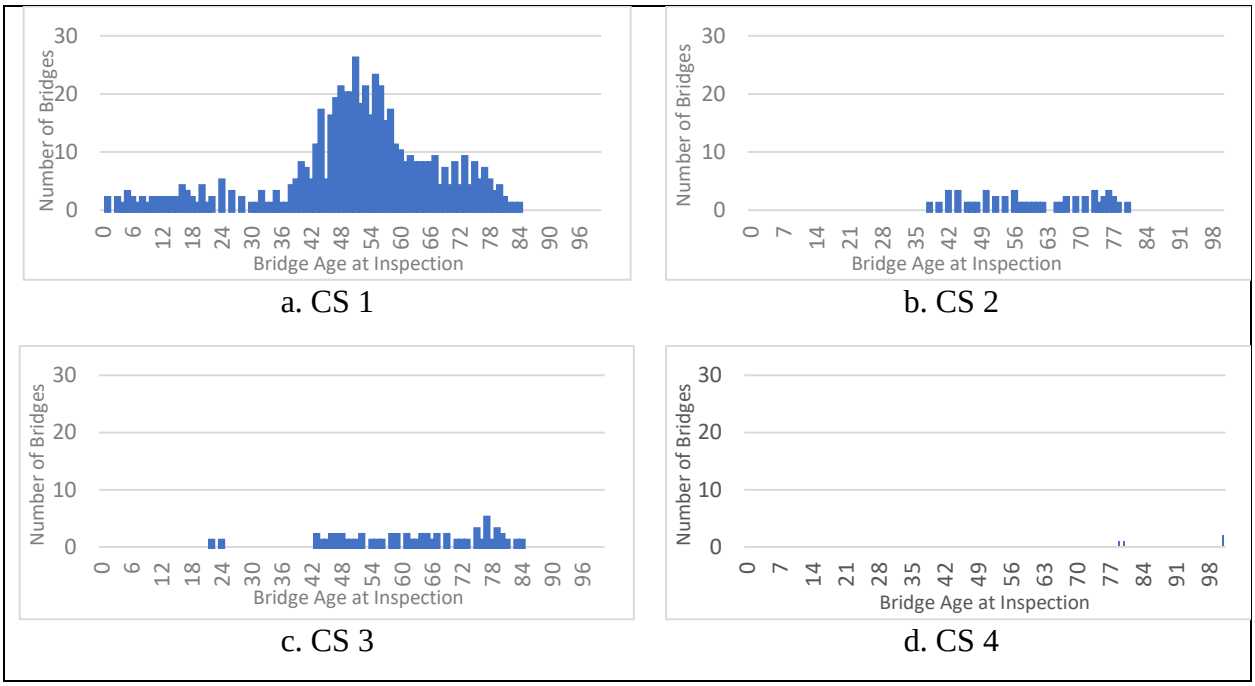


Figure B - 1 Bridge Age vs Number of Bridges: NC Region, Element ID 205

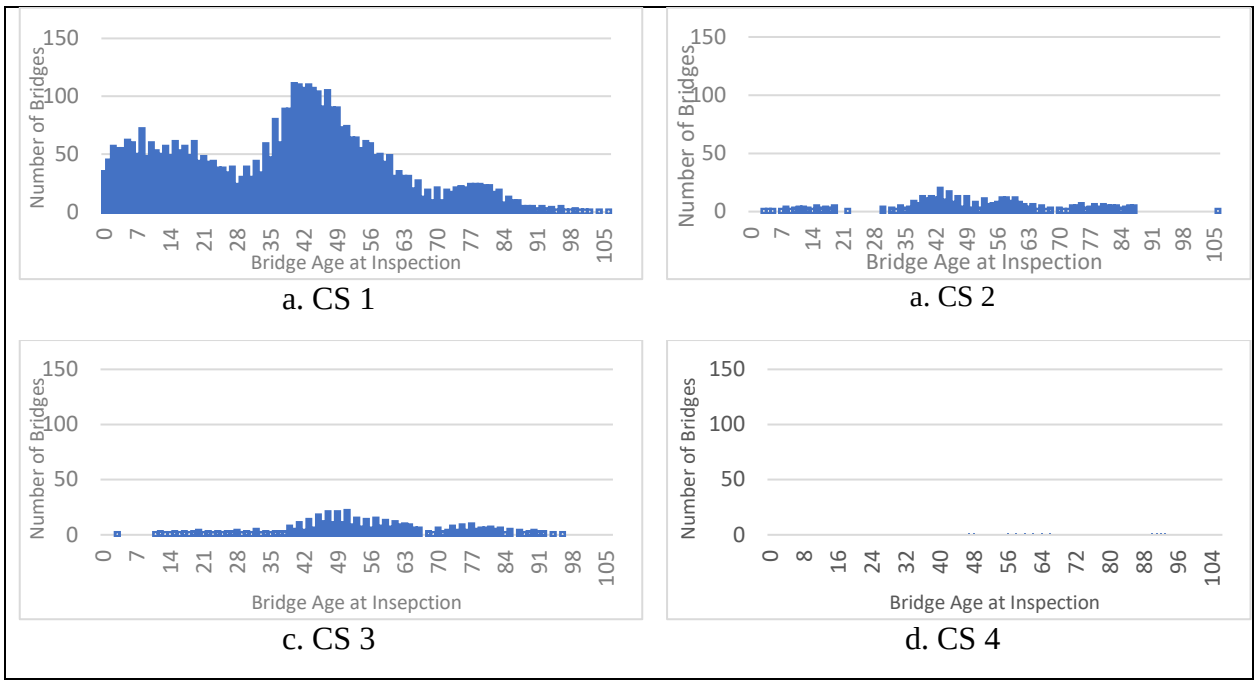


Figure B- 2 Bridge Age vs Number of Bridges: NW Region, Element ID 205

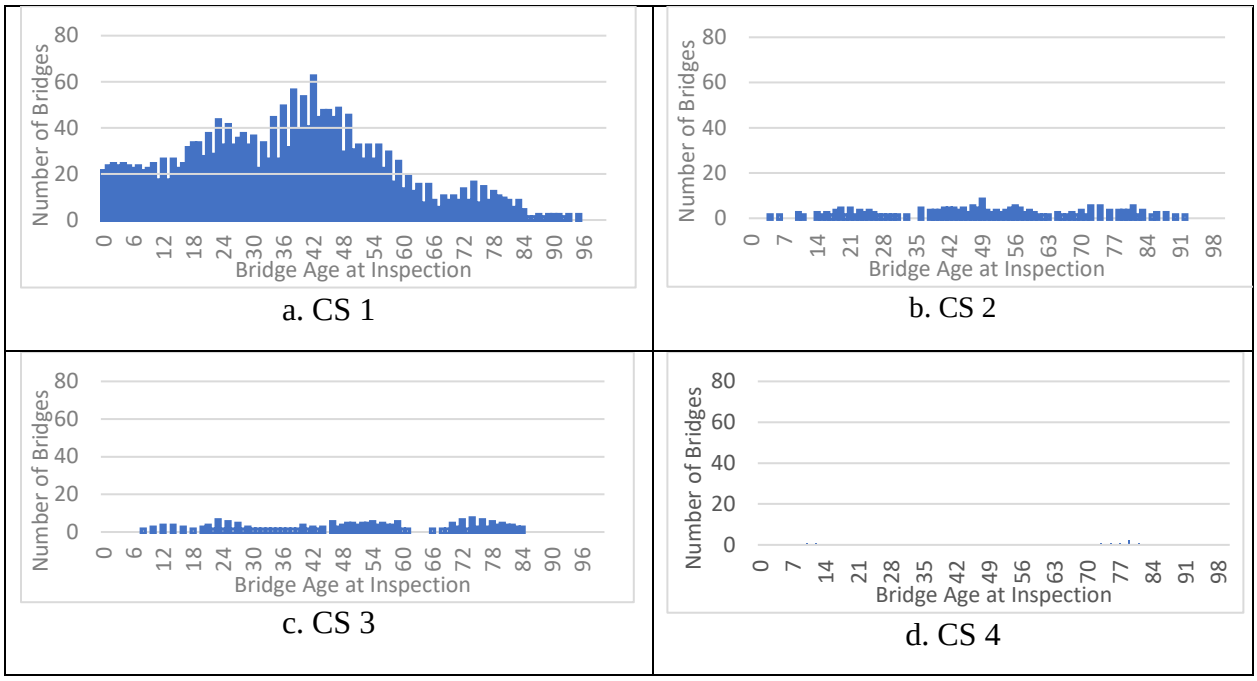


Figure B- 3 Bridge Age vs Number of Bridges: OL Region, Element ID 205

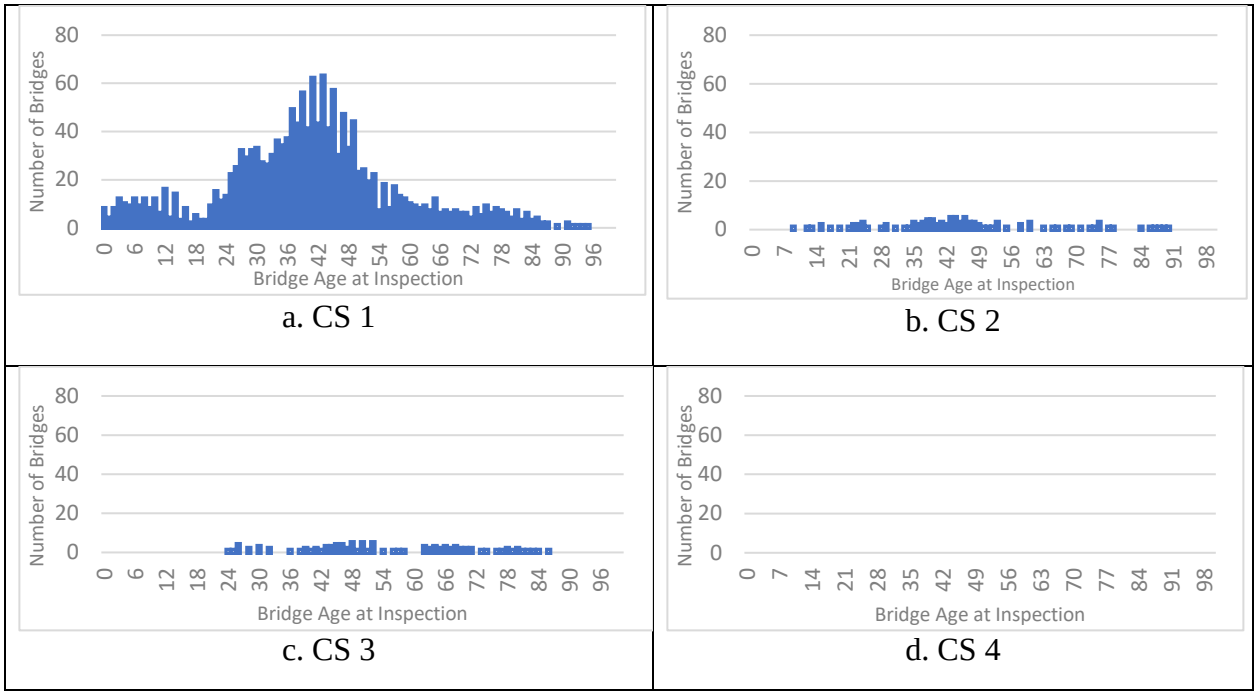


Figure B- 4 Bridge Age vs Number of Bridges: SC Region, Element ID 205

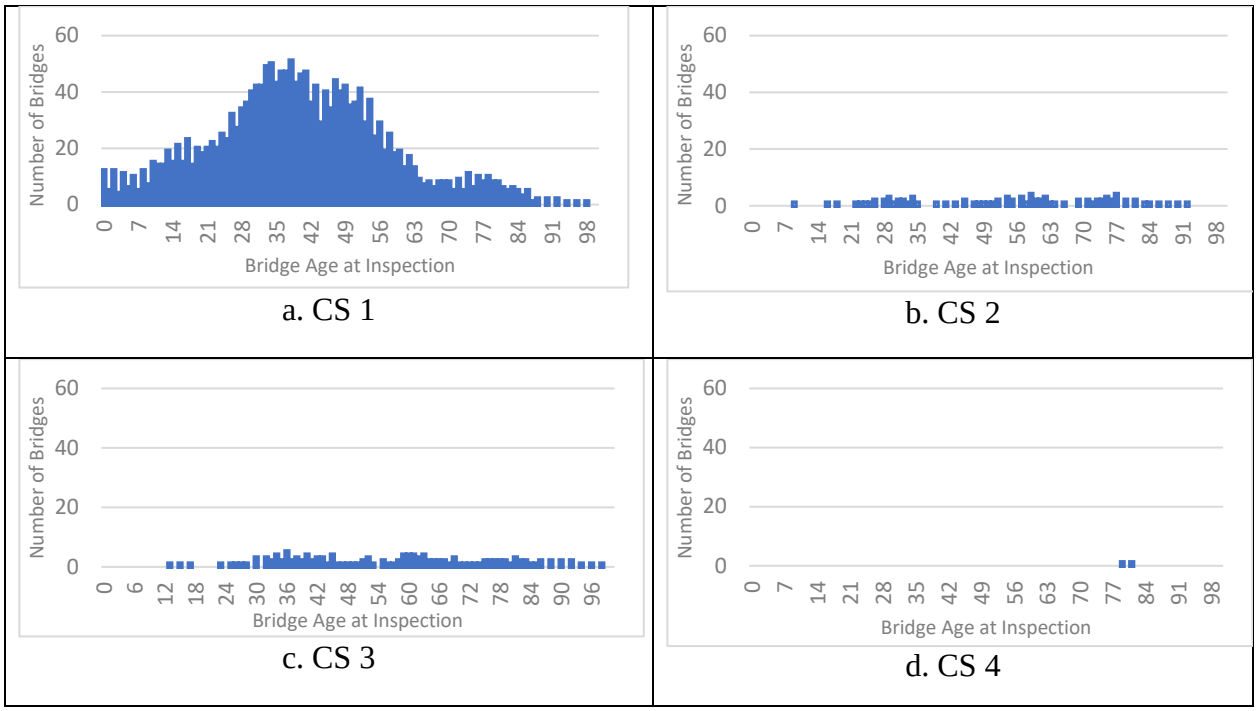


Figure B- 5 Bridge Age vs Number of Bridges: SW Region, Element ID 205

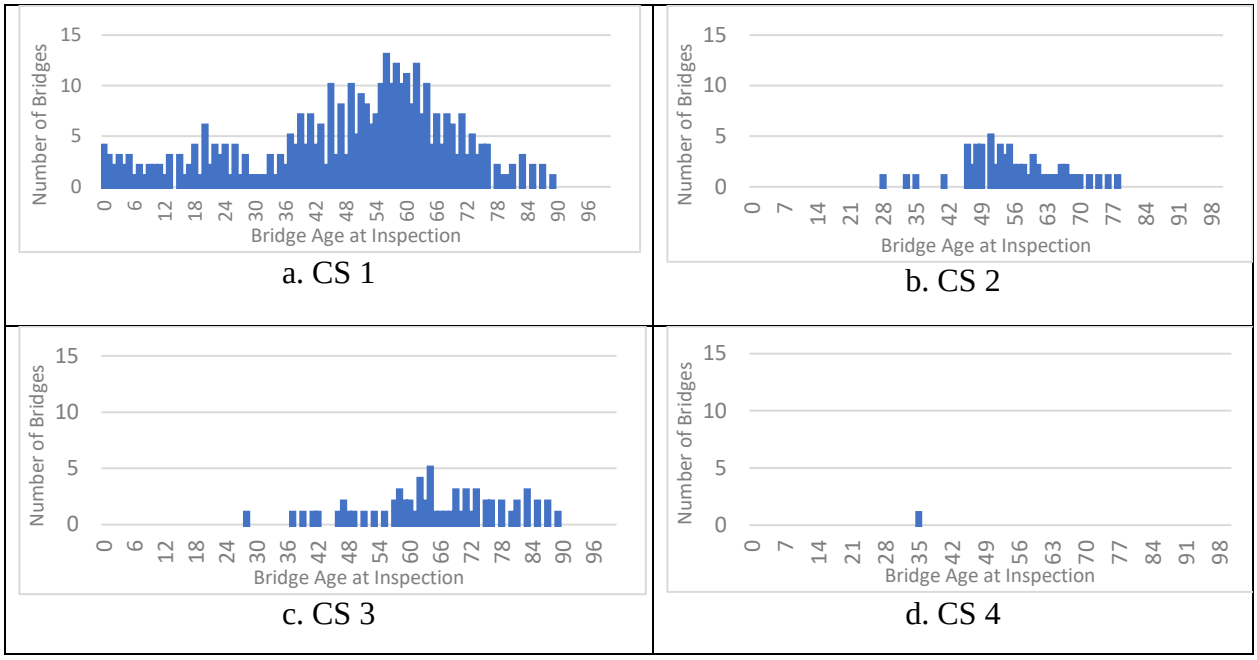


Figure B- 6 Bridge Age vs Number of Bridges: EA Region, Element ID 227

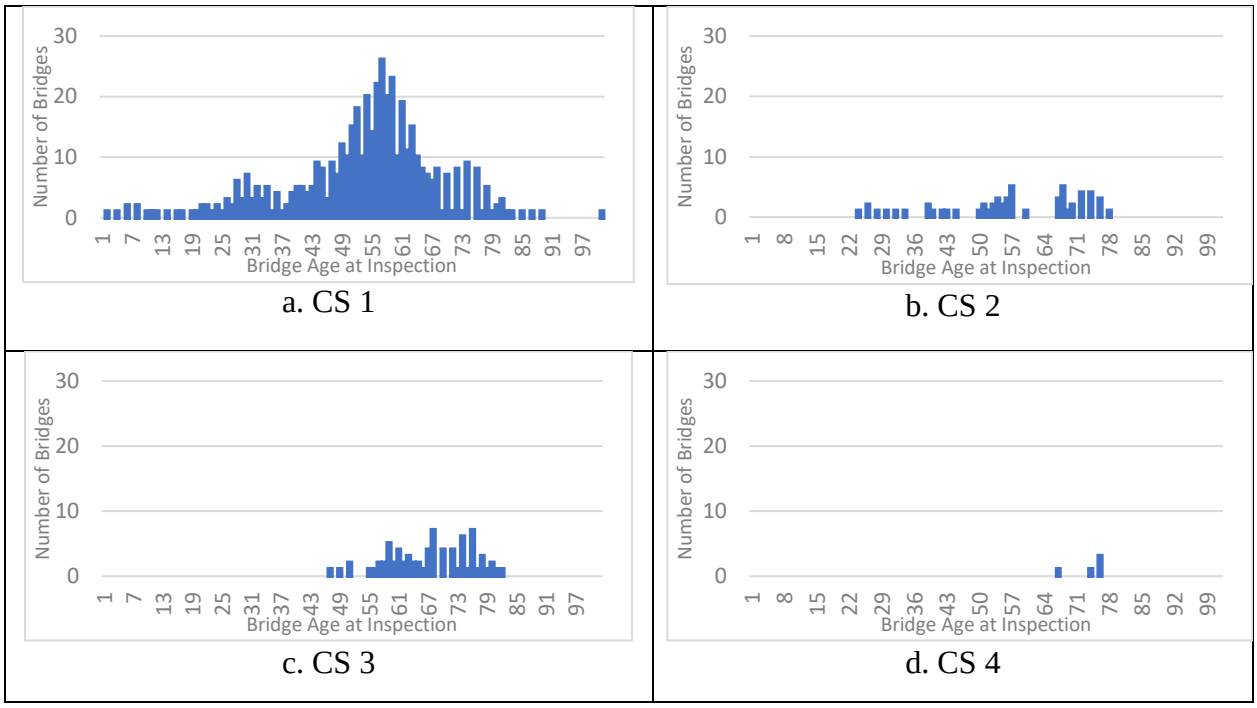


Figure B- 7 Bridge Age vs Number of Bridges: NC Region, Element ID 227

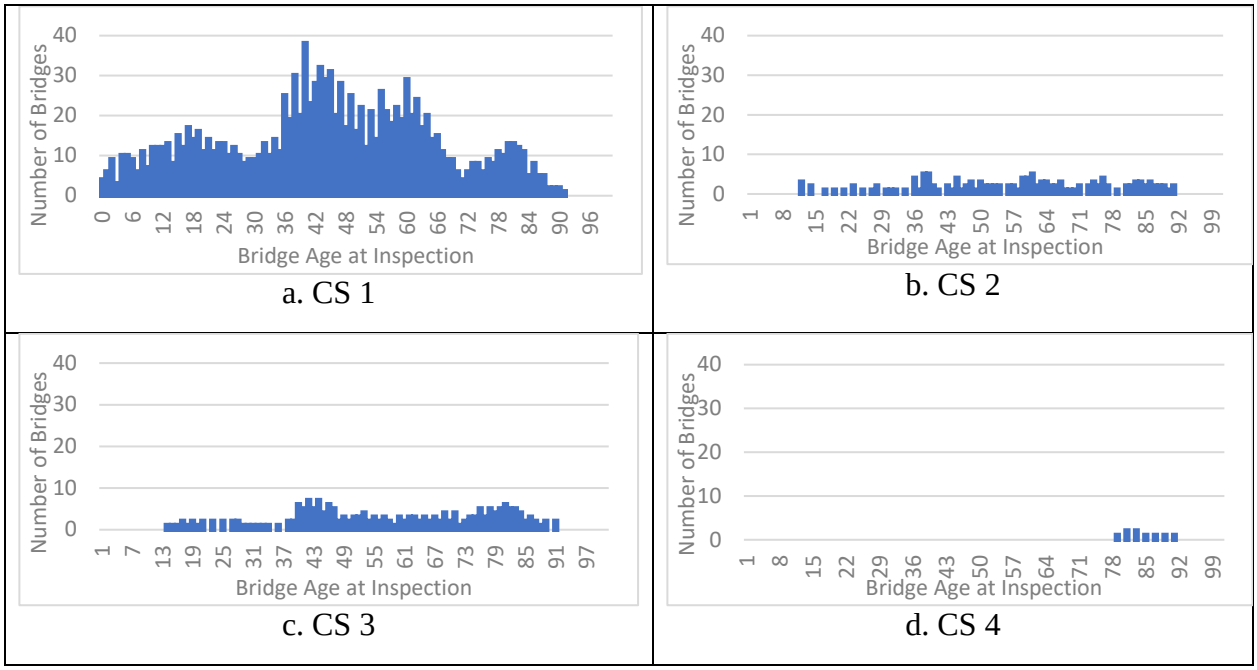


Figure B- 8 Bridge Age vs Number of Bridges: NW Region, Element ID 227

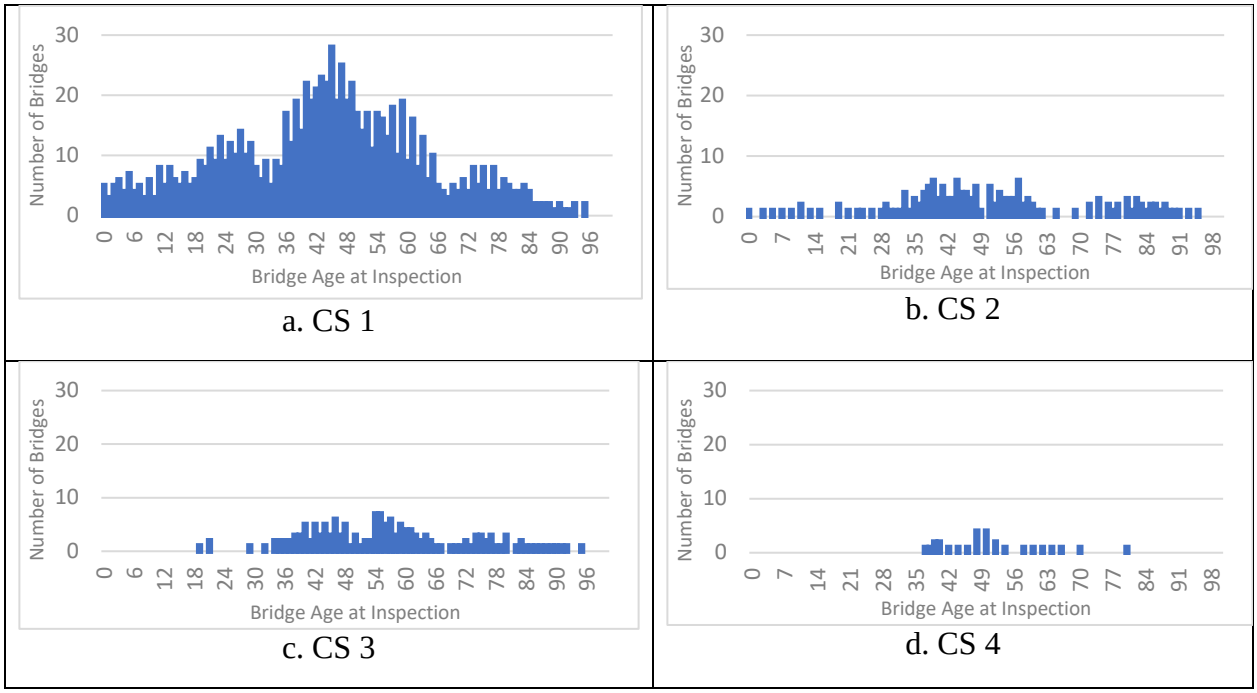


Figure B- 9 Bridge Age vs Number of Bridges: OL Region, Element ID 227

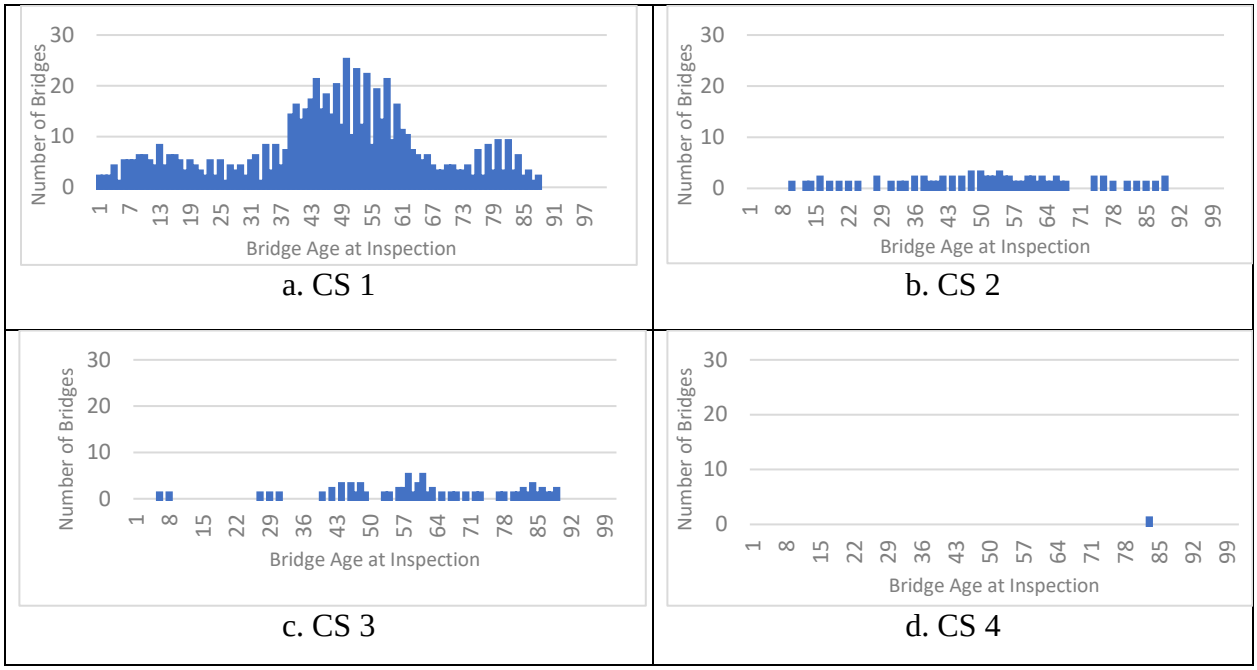


Figure B- 10 Bridge Age vs Number of Bridges: SC Region, Element ID 227

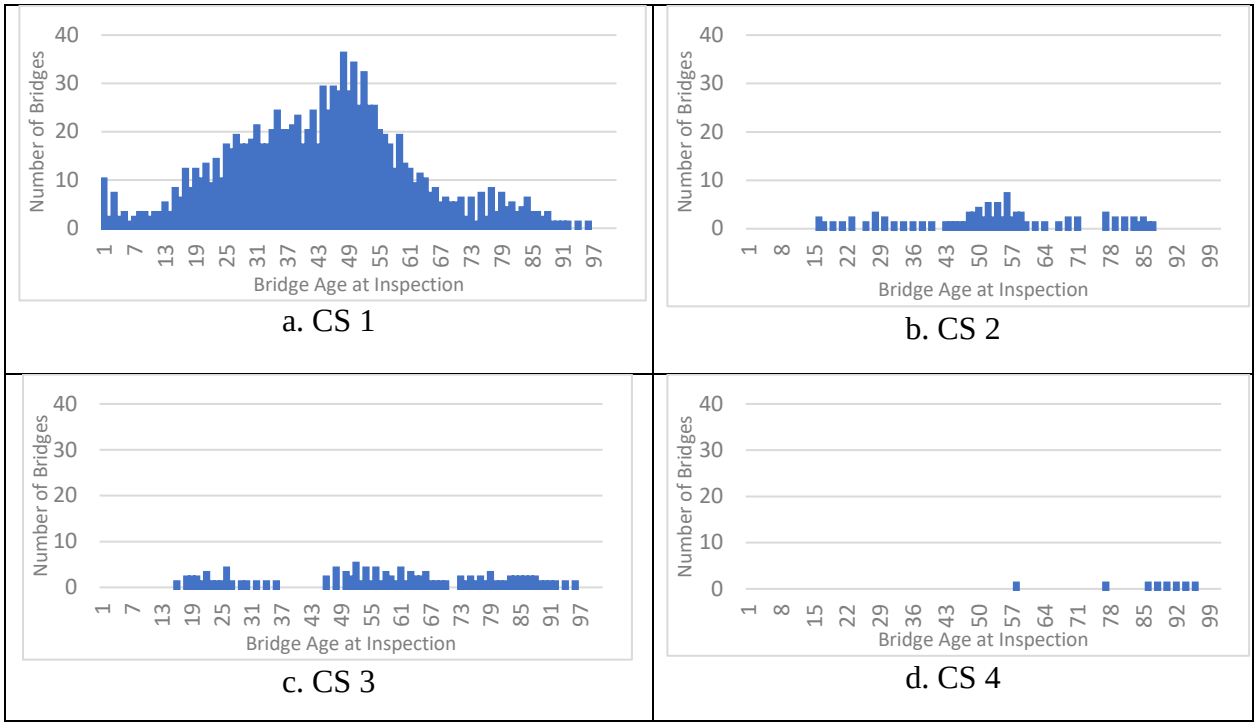


Figure B- 11 Bridge Age vs Number of Bridges: SW Region, Element ID 227

Americans with Disabilities Act (ADA) Information:
This material can be made available in an alternate format by emailing the Office of Equal Opportunity at wsdotada@wsdot.wa.gov or by calling toll free, 855-362-4ADA(4232). Persons who are deaf or hard of hearing may make a request by calling the Washington State Relay at 711.

Title VI Statement to Public:
It is the Washington State Department of Transportation's (WSDOT) policy to assure that no person shall, on the grounds of race, color, national origin or sex, as provided by Title VI of the Civil Rights Act of 1964, be excluded from participation in, be denied the benefits of, or be otherwise discriminated against under any of its federally funded programs and activities. Any person who believes his/her Title VI protection has been violated, may file a complaint with WSDOT's Office of Equal Opportunity (OEO). For additional information regarding Title VI complaint procedures and/or information regarding our non-discrimination obligations, please contact OEO's Title VI Coordinator at (360) 705-7082.