# Prioritizing NCDOT Bridge Preservation Projects Using Bridge Element Inspection Data

NCDOT Project 2023-05
FHWA/NC/2023-05

Min Liu, Ph.D.
Chuanni He, Ph.D.
Chase Nicholas
Weilin He
Simon M. Hsiang, Ph.D., P.E., CPE
Brad C. McCoy, Ph.D., P.E., ENV SP
Daniel J. Findley, Ph.D.
George List, Ph.D.

RESEARCH & DEVELOPMENT

**Technical Report Documentation Page**

| 1. Report No. **FHWA/NC/2023-05** | 2. Government Accession No. | 3. Recipient's Catalog No. |
|---|---|---|
| 2. Title and Subtitle **Prioritizing NCDOT Bridge Preservation Projects Using Bridge Element Inspection Data** | | 5. Report Date **August 15th, 2024** |
| | | 6. Performing Organization Code |
| 7. Author(s) Min Liu, Chuanni He, Chase Nicholas, Weilin He, Simon M. Hsiang, Brad C. McCoy, Daniel J. Findley, and George List | | 8. Performing Organization Report No. |
| 9. Performing Organization Name and Address **Department of Civil and Environmental Engineering Syracuse University Syracuse, NY 13244** | | 10. Work Unit No. (TRAIS) |
| | | 11. Contract or Grant No. |
| 12. Sponsoring Agency Name and Address **North Carolina Department of Transportation Research and Development Unit 104 Fayetteville Street Raleigh, North Carolina 27601** | | 13. Type of Report and Period Covered **Final Report August 16, 2022 to August 15, 2024** |
| | | 14. Sponsoring Agency Code **RP 2023-05** |

Supplementary Notes:

16. Abstract

This research aimed to develop a comprehensive framework with which to assist the North Carolina Department of Transportation (NCDOT) in prioritizing bridge preservation activities based on bridge inspection data, preservation cost, and individual bridges' criticality to local business. Focusing on the 442 bridges in Division 10, the research team worked with the experts in the department's Structures Management Unit to collect data on such items as bridge condition status, decision trees, overwriting rules, unit cost, and extended service life. The traffic volume for vehicles and trucks, detour length, and detour travel time cost were also collected. Employing that data, the research team established three core models. The preservation activity triggering model develops preservation plans using routine element inspection data from Structure Safety Reports. The preservation cost estimation model enables accurate budgeting, strategic planning, and timely maintenance. The bridge criticality assessment model calculates the criticality index for bridges based on traffic volume and detour length. An R-based Shiny web application was built to enable NCDOT to efficiently identify bridge preservation activities, estimate cost, and prioritize projects based on the inspection data. With suitable adjustments, the models and web application can be generalized to all bridges in North Carolina. The findings will enhance the maintenance strategy under the conditions of a limited budget for critical bridge infrastructure, ensuring safety and longevity.

| 17. Key Words **Bridge Preservation, Inspection Data, Bridge Criticality, Lifecycle Cost, Prioritization** | 18. Distribution Statement | | |
|---|---|---|---|
| 19. Security Classif. (of this report) **Unclassified** | 20. Security Classif. (of this page) **Unclassified** | 21. No. of Pages 177 | 22. Price |

**Form DOT F 1700.7** (8-72) **Reproduction of completed page authorized**

## DISCLAIMER

## ACKNOWLEDGMENTS

The research team acknowledges the North Carolina Department of Transportation for supporting and funding this project. We extend our thanks to the Steering and Implementation Committee and the managers and engineers of the Structures Management Units, Nick Pierce, Samuel Megahed, Asa Y. Godfrey, Trey Carroll, Tim Sherrill, David Snoke, Gichuru Muchane, and Doug Cantrell.

## EXECUTIVE SUMMARY

The research aims to enhance the North Carolina Department of Transportation's (NCDOT) bridge preservation strategies by developing a comprehensive framework with which to identify, prioritize, and implement preservation activities. The framework includes three core models: the preservation activity triggering model, the preservation cost estimation model, and the bridge criticality assessment model. This integrated approach enables NCDOT to make informed decisions on bridge maintenance, optimizing resource allocation, and extending the service life of bridges effectively.

A thorough literature review was conducted to understand existing methods and factors employed for triggering and prioritizing bridge preservation activities. The review covered reports from 50 state departments of transportation (DOTs) and the Federal Highway Administration (FHWA), as well as state-of-the-art research on geographic information system (GIS) applications in bridge preservation.

This research found that only 20 DOTs have formal bridge preservation manuals or guidelines. DOTs employ various approaches, including (1) ratio-based methods, (2) weighting/scoring, (3) setting goals/objectives, (4) technical specifications, (5) empirical approaches, (6) decision trees, and (7) risk-based methods. The factors considered include bridge condition, traffic volume, economic impact, and potential risks.

This research focused on bridges in Division 10 because they have a good mix of interstate highways, primary routes, and secondary roads. Trigger criteria for preservation activities were gathered from NCDOT Structures Management Unit (SMU) experts and cross-referenced to the Structure Safety Reports. These criteria were used to develop a preservation activity decision tree and overwrite rules, which form the basis of the preservation activity triggering model.

As shown in Table 1, this research developed three models: one to determine preservation activities, one to estimate preservation cost, and one to calculate bridge criticality indexes.

Table 1 Overviews of The Three Models Developed

| Models | Inputs | Outputs |
|---|---|---|
| Preservation activity triggering model | • Bridge element inspection data<br>• Preservation activity decision tree<br>• Implicit preservation activity overwriting rules | Bridge preservation activities |
| Preservation cost estimation model | • Preservation activity list<br>• Preservation activity unit price<br>• Interstate bridge indicator<br>• Inflation rate<br>• Element unit vs. activity unit conversion ratio<br>• Extended service life resulted from preservation | Activity-level preservation cost estimates |
| Bridge criticality assessment model | • Bridge AADT<br>• Bridge truck AADT<br>• Bridge detour length<br>• Unit detour cost | Bridge criticality index according to the traffic volume and detour components |

The preservation activity triggering model develops preservation plans using routine element inspection data from Structure Safety Reports. The model follows a four-step procedure: preprocessing data, calculating defect percentages, triggering preservation activities, and applying overwriting rules. The model processes inspection data to associate defect numbers, removes redundant elements, and calculates defect percentages. Initial preservation activities are triggered using decision trees and further refined through overwriting rules to eliminate redundant activities. The final output is a list of preservation activities ready for cost estimation and lifecycle expenditure analysis, ensuring efficient and targeted preservation efforts. This approach enhances the maintenance strategy for critical bridge infrastructure, ensuring safety and longevity.

The preservation cost estimation model enables accurate budgeting, strategic planning, and timely maintenance. The model assesses costs based on a preservation plan from the preservation activity triggering model. The four-step procedure involves obtaining bridge element units, calculating preservation quantities, matching units and calculating total costs, and determining Net Present Value (NPV) and Equivalent Annual Cost (EAC). The model ensures comprehensive cost estimation by addressing unit discrepancies and applying conversion ratios. Additionally, customizable preservation activities are identified to provide alternative plans for tradeoff analysis. The resulting data foundation supports subsequent cost-benefit analysis, aiding in proactive and efficient bridge management.

The bridge criticality assessment model calculates a criticality index for bridges based on traffic volume and detour length. Critical bridges are those that support high traffic volumes, provide key network connections, or both. The model uses annual average daily traffic (AADT) and Truck AADT data to calculate these factors, filling gaps with imputed values where necessary. The volume component is standardized to a unitless index, while the detour component calculates the cost of detours in dollars per day. Detour costs are adjusted for bridges with no valid detour data. The final criticality index combines the volume and detour components, weighted equally, and scales the result to a 0–100 scale. This model facilitates the stratification of bridges based on their importance to local business.

The final prioritization framework combines a cap approach and a grouping approach to categorize bridges into three groups based on total preservation costs, utilizing customizable thresholds: Group 1 (low cost), Group 2 (intermediate cost), and Group 3 (high cost). Experiments showed that setting thresholds at $10,000 and $500,000 on total preservation cost results in 146 bridges in Group 1, 273 bridges in Group 2, and 22 bridges in Group 3. Group 1 bridges undergo all preservation activities, while Group 2 bridges are ranked by cost-benefit ratio into four priority levels. Group 3 bridges receive detailed preservation reports for case-by-case analysis. All models were assembled in an R-based Shiny web application to facilitate the dissemination and application of the research findings. Detailed instructions for using the R Shiny application and interpreting results are also provided.

**TABLE OF CONTENTS**

1 INTRODUCTION ..... 1
1.1 Research Need Definition ..... 1
1.2 Research Objectives and Tasks ..... 1
2 LITERATURE REVIEW ..... 4
2.1 Definitions ..... 4
2.1.1 Bridge Types ..... 4
2.1.2 Maintenance and Preservation ..... 4
2.1.3 Bridge Elements and Element Defects ..... 7
2.2 Bridge Element Condition ..... 9
2.3 NBI Condition Ratings ..... 9
2.4 Structure Safety Report—Routine Element Inspection ..... 11
2.5 Bridge Preservation Practices ..... 11
2.5.1 DOT Bridge Preservation Programs ..... 11
2.5.2 Methods Used by DOTs for Bridge Preservation Activity Prioritization ..... 16
2.6 Extended Service Life ..... 19
2.6.1 Asphalt Patch ..... 19
2.6.2 Replacing Wearing Surface ..... 19
2.6.3 Penetrating Sealer ..... 19
2.6.4 Painting ..... 20
2.6.5 Repairing Prestressed Concrete Girders ..... 20
2.6.6 Summary ..... 22
2.7 Bridge Preservation Prioritization Research ..... 22
2.8 GIS Application in Bridge Preservation Research ..... 24
3 DATA COLLECTION ..... 26
3.1 Datasets for Preservation Activity Triggering ..... 26
3.1.1 Element Inspection Data for Superstructures and Substructures ..... 26
3.1.2 Preservation Activity Decision Tree ..... 28
3.1.3 Activity Overwriting Rules ..... 29
3.2 Datasets for Preservation Cost Estimation ..... 30
3.2.1 Activity Unit Price ..... 30
3.2.2 Activity & Element Unit Conversion Ratio ..... 32
3.2.3 Activity Extended Service Life ..... 33
3.3 Datasets for Bridge Criticality Assessment ..... 35
3.3.1 Datasets for Traffic Volume Component ..... 35
3.3.2 Datasets for Detour Cost Component ..... 36
3.3.3 Data for Time Cost ..... 37
4 PRESERVATION ACTIVITY TRIGGERING MODEL ..... 38
4.1 Data Preparation ..... 38
4.1.1 Join Defect Number to Element Inspection Data ..... 39
4.1.2 Remove Elements 510, 515, and 520 ..... 39
4.2 Calculate Element Defect Percentage ..... 39
4.2.1 Apply the Maintenance Quantity True/False Rule ..... 40
4.2.2 Calculate Total Element Quantity ..... 40
4.2.3 Calculate the Defect Percentage ..... 41

4.3 Apply Decision Tree to Trigger Initial Activities....42
4.4 Applying Overwriting Rules....43
4.5 Summary....45
5 PRESERVATION COST ESTIMATION MODEL....47
5.1 Data Acquisition and Preprocessing....48
5.1.1 Preservation Activity Application Scope....48
5.1.2 Miscellaneous Cost Estimation Parameters....48
5.2 Step 1: Obtain Bridge Element Unit....49
5.3 Step 2: Obtain Preservation Quantity....49
5.4 Step 3: Match Unit and Calculate Total Cost....50
5.5 Step 4: Calculate NPV and EAC....52
5.6 Summary....55
6 BRIDGE CRITICALITY ASSESSMENT MODEL....58
6.1 Method....58
6.1.1 Volume Component....59
6.1.2 Detour Component....59
6.1.3 Final Criticality Index....60
6.1.4 Example Calculation....60
6.2 Results....62
6.3 Summary....62
7 BRIDGE PRESERVATION PRIORITIZATION....64
7.1 Group 1: Bridges with Low Preservation Costs....64
7.2 Group 2: Bridges with Intermediate Preservation Cost....64
7.3 Group 3: Bridges with High Preservation Cost....65
7.4 Summary....66
8 CONCLUSIONS....67
8.1 Overall Profile of Bridge Preservation....67
8.2 Sensitivity Analysis....68
8.2.1 Weighting of the Index Components....68
8.2.2 Minimum and Maximum Detour Times....69
9 FUTURE STUDIES....72
APPENDIXES....73
APPENDIX A Superstructure Element Inspection Dataset....74
APPENDIX B Substructure Element Inspection Dataset....79
APPENDIX C Preservation Activity Decision Tree (Original)....83
APPENDIX D Preservation Activity Decision Tree (Tidy Format)....89
APPENDIX E Meeting Minutes_October 20, 2022....91
APPENDIX F Meeting Minutes_February 13, 2023....100
APPENDIX G Meeting Minutes_December 8, 2022....103
APPENDIX H Miscellaneous Cost Estimation Parameters....106
APPENDIX I Bridge Element Unit....111
APPENDIX J Meeting Minutes_November 15, 2023....113
APPENDIX K Development Guidelines for Shiny Application....116
1. Development Environment....116
2. App File Structure....116

2.1 Folder Descriptions: ........................................................................................117
2.2 File Descriptions:...........................................................................................117
3. App Module Introduction ....................................................................................118
3.1 App Introduction ..............................................................................................119
3.2 Parameters setting............................................................................................119
3.3 Overall Bridge Profile.......................................................................................121
4. Generate Report for a Particular Bridge ............................................................128
4.1 Input Data.........................................................................................................128
4.2 Bridge Report Calculation ...............................................................................130
4.3 Report Rendering.............................................................................................131
5. View Bridge Report.............................................................................................131
APPENDIX L Shiny Application User Instruction ..................................................133
1. Function Introduction .........................................................................................133
2. App User Manual ...............................................................................................135
2.1. Launching the Shiny App ...............................................................................135
2.2 Parameters Setting ...........................................................................................136
2.3 Generate Overall Bridge Profile.......................................................................139
2.4 Generate Report for A Particular Bridge .........................................................149
2.5 View Bridge Report..........................................................................................151
REFERENCES .........................................................................................................161

**LIST OF FIGURES**

Figure 1.1 Research Framework ........................................................................................2
Figure 2.1 Bridge Action Categories (FHWA 2018) ....................................................................5
Figure 2.2 Percentage of SD Bridges in US (ARTBA 2023) .......................................................12
Figure 2.3 DOTs with and without Bridge Preservation Manuals ...............................................13
Figure 4.1 Preservation Activity Triggering Model Framework ..................................................38
Figure 4.2 Algorithm for Obtaining Defect Number ....................................................................39
Figure 4.3 Algorithm for Removing Redundant Samples ............................................................39
Figure 4.4 Algorithm for Applying Maintenance Quantity True/False Rule ................................40
Figure 4.5 Algorithm for Calculating Defect Percentage .............................................................42
Figure 4.6 Algorithm for Determining Initial Preservation Activity ............................................43
Figure 4.7 Algorithm for Applying Sample Span-level Overwriting Rules .................................44
Figure 5.1 Flowchart for Cost Estimation Model .........................................................................48
Figure 5.2 Algorithm for Applying Sample Span-level Overwriting Rules .................................50
Figure 5.3 Algorithm for Applying Sample Span-level Overwriting Rules .................................51
Figure 5.4 Lifecycle Payment Schedule for Sample Preservation Plan ........................................52
Figure 5.5 Algorithm for Calculating NPV and EAC ...................................................................54
Figure 6.1 Histogram of Final Criticality Index Values for Bridges ............................................62
Figure 7.1 Sample Bridge Preservation Priority ...........................................................................65
Figure 7.2 Snapshot of sample bridge preservation report ...........................................................66
Figure 8.1 Distribution Estimations for Preservation Activity Count, Total Preservation Cost, and Bridge Criticality ...........................................................................................................68
Figure 8.2 Histograms Showing Sensitivity of Final Index Distribution to Component Factor Weighting ...........................................................................................................................69
Figure 8.3 Histograms Showing Sensitivity of Final Index Distribution to Component Factor Weighting ...........................................................................................................................70
Figure A1 File Structure of the BGP App Directory ..................................................................117
Figure A2 The BGP App Structure ............................................................................................119
Figure A3 UI-Introduction of BGP App .....................................................................................119
Figure A4 UI-Parameter Settings (Interest Rate and Activities Unit Price) ...............................121
Figure A5 UI-Upload Data and Customize Bound .....................................................................122
Figure A6 Framework for Calculating Bridge Preservation Costs .............................................122
Figure A7 Calculation Result Visualization Framework ...........................................................124
Figure A8 isualization of All Bridge Calculation Result ...........................................................126
Figure A9 UI-Download Comprehensive Results Table ...........................................................127
Figure A10 UI-Reset the BGP App ............................................................................................128
Figure A11 Generate Bridge Report Framework .......................................................................128
Figure A12 UI-Generate Report for a Particular Bridge ............................................................129

Figure A13 Algorithm for Determining Bridge Interstate Type .......... 130
Figure A14 UI-Customize Preservation Application Scope .......... 132
Figure A15 Bridge Total Preservation Cost .......... 133
Figure A16 Bridge Criticality vs Total Preservation Cost .......... 134
Figure A17 Cost Summary of Bridge 030003 .......... 135
Figure A18 BGP App Introduction Page .......... 136
Figure A19 Parameters Setting: Interest Rate .......... 137
Figure A20 Parameters Setting: Activities Unit Price .......... 138
Figure A21 Steps to Generate Overall Bridge Profile .......... 139
Figure A22 Progress Indicator for Calculating the Total Cost of All Bridges .......... 140
Figure A23 Scatter Plot of Total Cost vs. Criticality .......... 142
Figure A24 Scatter Plot of Preservation EAC vs. Criticality .......... 143
Figure A25 Summary Table of Bridge Preservation Activities and Cost Statistics .......... 144
Figure A26 Bridge Preservation Activity Count and Total Cost .......... 145
Figure A27 Detailed Activity Count for Each Bridge Preservation .......... 146
Figure A28 Download Comprehensive Table (Original) .......... 147
Figure A29 Recalculate and Download Updated Table .......... 148
Figure A30 Reset the BGP App .......... 148
Figure A31 Customize Overlay Type and Steel Beam Repairing Type .......... 149
Figure A32 Generate Individual Bridge Preservation Report .......... 150
Figure A33 Two Ways to View Bridge Preservation Reports .......... 151
Figure A34 Choosing Different Sections of the Report .......... 152
Figure A35 Superstructure Overwritten Activity Table for Bridge 030003 .......... 152
Figure A36 Substructure Overwritten Activity Table for Bridge 030003 .......... 153
Figure A37 Superstructure Defects and Preservation Activity Counts for Bridge 030003 .......... 154
Figure A38 Substructure Defects and Preservation Activity Counts for Bridge 030003 .......... 155
Figure A39 Bridge 030003 Superstructure Required Preservation Quantity and Customization .......... 157
Figure A40 Pay Items per Activity List and Conclusion for Bridge 030003 .......... 159
Figure A41 Cost Estimation Summary for Bridge 030003 .......... 160

**LIST OF TABLES**

Table 2.1 Definitions of Maintenance....5
Table 2.2 Common Actions Based on Bridge Element CS (FHWA 2018)....9
Table 2.3 Bridge Condition Rating Definitions (FHWA 1995)....10
Table 2.4 Number and Percentage of Poor Condition Bridges (NCDOT 2024b)....10
Table 2.5 Bridge Preservation Programs Used by 50 US State DOTs....13
Table 2.6 Seven Prioritization Methods Used by DOTs....16
Table 2.7 Life Expectancy and Usage for Bridge Painting Options (Hopwood II et al. 2018)....20
Table 2.8 Estimated Service Life Yield from Prestressed Concrete Beams (Hearn 2020)....21
Table 2.9 Extended Service Life Yield from Preservation Activities....22
Table 2.10 Bridge Management Systems: Research Summary of Cavalline et al. (2015)....23
Table 2.11 Research Summary of Whelan et al. (2019)....23
Table 3.1 Samples from Superstructure Inspection Dataset....27
Table 3.2 Samples from Substructure Inspection Dataset....28
Table 3.3 Data Samples of Preservation Activity Decision Tree (Original Format)....29
Table 3.4 Preservation Activities Overwriting Rules....30
Table 3.5 Activity Unit Price....31
Table 3.6 Unit Conversion Ratio....33
Table 3.7 Preservation Activity Extended Service Life....34
Table 3.8 NCDOT Route Characteristics Arcs Table Sample....36
Table 3.9 NCDOT Route Characteristics Arcs Table Sample....37
Table 4.1 Sample Observations 1 from Superstructure Dataset....40
Table 4.2 Sample Observations 2 from Superstructure Dataset....41
Table 4.3 Sample Superstructure Dataset Outputs from Preservation Activity Triggering Model....46
Table 5.1 Samples from Preservation Activity Application Scope Dataset....48
Table 5.2 Samples for Miscellaneous Parameters....49
Table 5.3 Sample Preservation Plan....52
Table 5.4 Sample Preservation Activity List with Cost Estimation Breakdown....56
Table 5.5 Sample Preservation Activity Summary....57
Table 6.1 Example Standard Values for AADT (all vehicles) Imputed from Available Data, by Route Class and Land Use Context....58
Table 6.2 Source of Volume Data by Vehicle Type....59
Table 6.3 Data for Calculating Volume and Detour Components of the Criticality Index....60
Table 6.4 Route Segments Table....61
Table 7.1 Sample summary of bridges in Group 1....64
Table 7.2 Preservation priority for bridges in Group 2....65
Table 8.1 Median and Interquartile Range Values for Weighting Sensitivity Scenarios....69

Table 8.2 Detour Values for Bridges in Study and in the State of North Carolina ......................69
Table A1 Superstructure Element Inspection Data (Columns 1-12) ..........................................76
Table A2 Superstructure Element Inspection Data (Columns 13-24) ........................................76
Table A3 Superstructure Element Inspection Data (Columns 25-36) ........................................77
Table A4 Substructure Element Inspection Data (Columns 1-11) .............................................80
Table A5 Substructure Element Inspection Data (Columns 12-22) ...........................................80
Table A6 Substructure Element Inspection Data (Columns 23-33) ...........................................81
Table A7 Data Sample of Preservation Activity Decision Tree (Tidy Format)...........................90
Table A8 The Original Decision Tree Table ...................................................................93
Table A9 The First Interpretation Decision Tree Table ...............................................................93
Table A10 The Second Interpretation Decision Tree Table........................................................94
Table A11 The Third Interpretation Decision Tree Table ..........................................................94
Table A12 Newly Added Decision Table for Element 521 .....................................................101
Table A13 Updated Estimated Service Life for Preservation Activities ..................................102
Table A14 Development Environment and Packages for BGP App .......................................116

# 1 INTRODUCTION

The North Carolina Department of Transportation (NCDOT) manages approximately 13,700 bridges within the state's bridge inventory. Annually, about 9,300 of these structures are inspected by certified bridge inspectors. As of 2024, approximately 1,150 bridges, or 8.4% of the total, are classified as poor condition (NCDOT 2024a). These bridges possess deteriorating components that necessitate significant maintenance to remain in service and may require restrictions on vehicle weights. Bridges in poor condition typically require extensive rehabilitation or replacement, with repair or rehabilitation costs estimated to exceed $4 billion (NCDOT 2024a).

This report presents findings on how the Structures Management Unit (SMU) and Division Bridge Maintenance Engineers can effectively identify specific bridge preservation activities using routine element inspection data, estimate costs for bridge preservation plans, assess bridge criticality in terms of impact on local communities and the freight network, and ultimately adjust bridge preservation priorities to maximize value for the local economy and the public.

## 1.1 Research Need Definition

Currently, NCDOT utilizes the Bridge Management System (BMS) to select bridge preservation projects. The BMS employs a system-wide estimation approach based on an overall bridge distribution profile, operating at the component level to target the deck, superstructure, and substructure of bridges. Additionally, the bridge management system includes models for user costs, integrating algorithms that use historical data to forecast changes in average daily traffic (ADT) and other metrics to estimate costs related to vehicle operation, vehicle type distribution, weight, height, and the likelihood of accident-related injuries.

However, the BMS is inadequate for determining preservation priorities based on individual bridge element conditions and does not consider social or economic impacts, preventing a holistic approach to asset management. Consequently, preservation projects are often suboptimal. Therefore, SMU and Division Bridge Maintenance Engineers need a tool to determine the triggering criteria for bridge preservation activities and to prioritize preservation projects based on individual bridge conditions. This tool should aim to provide the lowest overall lifecycle cost, the best return on investment, and greater value to local businesses and the public.

## 1.2 Research Objectives and Tasks

The objectives of this research are to:

- Identify appropriate preservation activities for bridges based on their element inspection results.
- Evaluate the criticality level for each bridge, considering traffic volume and detour costs for cars and trucks.
- Develop a mechanism to prioritize preservation plans based on preservation cost and bridge criticality.

This research comprises six tasks to achieve these objectives, as illustrated in Figure 1.1.

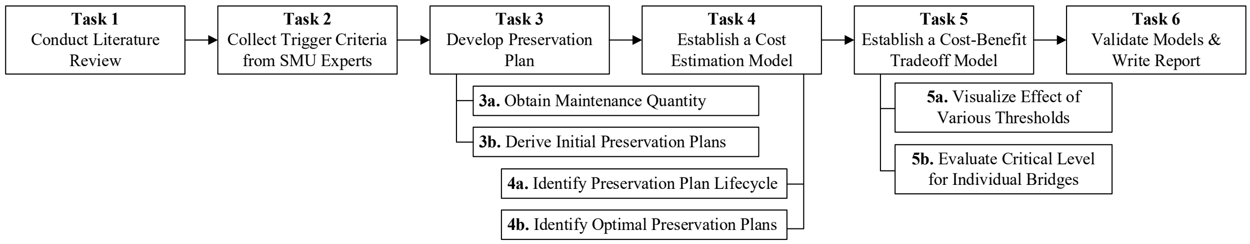



Figure 1.1 Research Framework

**Task 1. Conduct a comprehensive literature review.** A thorough literature review was conducted on methods used and factors considered for triggering and prioritizing bridge preservation activities. The research team reviewed relevant reports from all departments of transportation (DOTs) and the Federal Highway Administration (FHWA), as well as state-of-the-art research on geographic information system (GIS) applications in bridge preservation. The results are summarized in Chapter 2.

**Task 2. Collect trigger criteria from SMU experts.** The research focused on 442 bridges from five counties in Division 10. Trigger criteria, decision trees, and overwriting rules for preservation activities on bridge elements were collected from SMU. Chapter 3 describes the data collection process and results.

**Task 3. Develop a preservation activity triggering model based on Structure Safety Reports.** Routine element inspection records from Structure Safety Reports were used to develop preservation activities. The Equivalent Annual Cost (EAC) of preservation activities was calculated, and the optimum preservation plan was determined in two steps: (1) obtaining preservation quantities based on bridge conditions and user preferences, and (2) developing the initial preservation plan. Chapter 4 elaborates on the technical details of the preservation activity triggering model.

**Task 4. Establish a cost estimation model for bridge preservation plans.** A cost estimation database was created. The estimated preservation quantities from Task 3 were customized according to bridge engineers' preferences on preservation scopes per activity. Activity unit costs were obtained from NCDOT. The most economic preservation plans were determined through two steps: (1) identifying the extended service life of each preservation plan, and (2) calculating the EAC of each plan and identifying the optimal plan with the lowest annual cost. The cost estimation model is documented in Chapter 5.

**Task 5. Establish a cost-benefit tradeoff model for bridge preservation plans.** The cost-benefit analysis was based on preservation cost and bridge criticality. A bridge criticality assessment model was developed, synthesizing traffic volume and detour costs to determine bridge criticality. A cost-benefit tradeoff model was proposed, categorizing bridges into three groups based on two thresholds. Bridges in the first group have relatively low preservation costs and are included in the preservation plan. Bridges in the second group have medium preservation costs and are prioritized based on their cost-benefit ratio. Bridges in the third group have high preservation costs and require detailed reports for case-by-case evaluation. Chapter 6 explains the calculation process for the bridge criticality indexes. Chapter 7 discusses the final bridge preservation priority results.

**Task 6. Validate the models and prepare the final report.** All models and findings were presented to SMU experts for their feedback and validation. This final project report documents all findings and recommendations in Chapter 8. Instructions and user manuals for the proposed tools and models are included in the Appendixes.

# 2 LITERATURE REVIEW

This chapter reviews bridge types, definitions of bridge maintenance and preservation, and bridge element types. It also reviews bridge element condition classification systems and National Bridge Inventory (NBI) bridge condition ratings. It describes the main items recorded in structure safety reports featuring routine element inspections. It reviews bridge preservation practices across the US, including the programs and methods used for prioritizing decisions by 50 state DOTs. The extended service life yield of six types of preservation activities is identified. At the end, two studies in bridge preservation prioritization modeling and GIS application in this area are reviewed.

## 2.1 Definitions

This section reviews bridge types and definitions of bridge maintenance and preservation used by various DOTs and federal agencies. It also reviews definitions for nine types of bridge elements. Given the considerable variation in definitions and terminology adopted by the engineering profession and government bodies engaged in bridge preservation, clarifying the key concept is important.

### 2.1.1 Bridge Types

NCDOT is responsible for the safety of 13,700 bridges and 4,800 culverts and pipes along North Carolina's highways. Based on the materials used in their main structure, bridges can be classified into four primary types: concrete bridges, steel bridges, timber (wood-truss) bridges, and metal-truss bridges (NCDOT 2020a).

In NC, reinforced concrete bridges were most prevalent. Reinforced concrete slabs, T-beams, and through girders were the most important reinforced concrete bridge construction components used by the State Highway Commission in its early years. They proved ideally suited to the preparation of standard plans that could be used in a variety of site conditions, with the result that hundreds of nearly identical bridges were built.

Steel bridges are widely chosen due to their strength, ductility, easy fabrication, and rapid construction (Lin and Yoda 2017). Steel has a much higher strength in both tension and compression than concrete and a relatively good strength-to-cost ratio and stiffness-to-weight ratio. However, steel bridges exposed to air and water are susceptible to corrosion and should be painted regularly. The strength of steel reduces substantially when heated in fires. NC has steel-girder-and-floor-beam bridges and steel stringer multibeam bridges. Steel stringer bridges are the most common in the state's Historic Bridge Inventory (NCDOT 2020b).

Timber's light weight and energy-absorbing properties made it desirable for bridges. But timber bridges are also limited in span length (about 25 feet maximum) and can deteriorate rapidly (NCDOT, 2020c). Timber bridges are often covered with siding and a roof to protect the load-carrying trusses. Iron was then added for greater strength and capacity. This research focuses on concrete and steel bridges because those make up the majority of bridges in NC.

### 2.1.2 Maintenance and Preservation

Bridge maintenance is a primary means by which a highway agency keeps the transportation network a safe, efficient facility for the public road user. Bridge maintenance includes all activity in a facility's life that does not require a redesign and development project (AASHTO 2007). According to the Federal Highway Administration (FHWA 2018), 'maintenance' describes work that is performed to maintain the transportation system or respond to specific conditions or events that restores the highway system to a functional state of operations. Routine Maintenance (RM) encompasses work that is performed in reaction to an event, season, or activities for short-term operational needs that do not have preservation value. Preventive maintenance is a cost-effective means of extending the service life of highway bridges. As shown in Figure 2.1, preservation/preventive maintenance includes cyclical maintenance (performed at predetermined intervals) and condition-based maintenance (in response to known defects) (FHWA 2018).

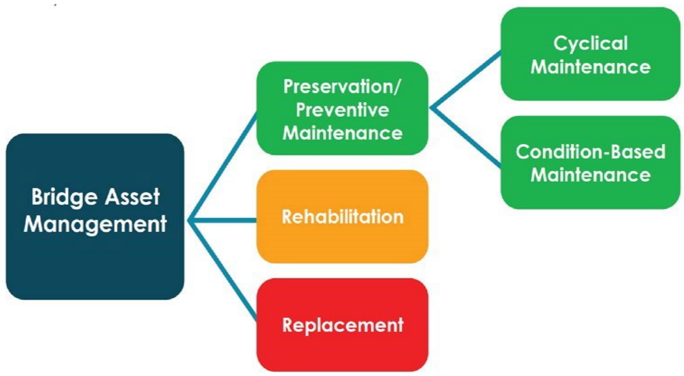



Figure 2.1 Bridge Action Categories (FHWA 2018)

The NCDOT Asset Management Plan (NCDOT 2019) describes bridge maintenance activities including spot painting, repairing structural steel, vegetation removal, sweeping/washing bridge decks, cleaning of bridge deck drains, spot deck repairs, navigation light maintenance/replacement, concrete spall repairs, timber component repairs, minor steel repairs, and lubrication of bearings. Table 2.1 summarizes the definitions or scopes of maintenance employed by 10 DOTs.

Table 2.1 Definitions of Maintenance

| Agency | Definition | Reference |
|---|---|---|
| **FHWA** | **Bridge preservation** involves actions or strategies designed to prevent, delay, or reduce deterioration of bridges or bridge elements; restore the function of existing bridges; keep bridges in good or fair condition; and extend their service life. | (FHWA2018) |
| California | **Bridge maintenance** includes repairing damage or deterioration in various bridge components; removing debris and drift from piers, bearing seats, abutments, etc.; cleaning out drains; repairing expansion joints; cleaning and painting structural steel; sealing concrete surfaces, etc. Also included are the maintenance of electrical and mechanical equipment on moveable span bridges and the operation of the moveable span. | (Caltrans 2014) |
| Montana | **Maintenance** is work that is performed to care for and maintain the highway and associated features so that it substantially retains its original intended use and function. | (MDT 2002) |
| Oregon | **Maintenance** includes the activities associated with keeping up, preserving, repairing, or restoring existing transportation infrastructure, generally on the State Highway System. | (ORDOT 2021a) |
| New Hampshire | **Maintenance** includes washing and sealing bridges, cleaning drainage ways, and controlling vegetation. | (NHDOT 2015) |

| | | |
|---|---|---|
| Idaho | **Preventive maintenance** is a planned strategy of cost-effective treatments to an existing roadway system and its appurtenances that preserves the system, retards future deterioration, and maintains or improves the functional condition of the system. | (ITD 2022) |
| Michigan | **Scheduled maintenance** includes activities that maintain the existing serviceability and reduce deterioration rates on bridges. Priority should be given to corridors where the same small task can be performed on many bridges. | (MDOT 2005) |
| Ohio | **RM** is a way to keep a highway, including all of its elements, in or as close as possible to its original constructed condition or its subsequently improved condition and includes those traffic services and operations which provide safe, convenient, and economic highway transportation for the public. **Preventive maintenance** is the act of keeping a structure in its as-built condition and/or protecting it from inevitable deterioration due to the environment, traffic vibration, and deicing chemicals. | (OHDOT 2022) |
| Texas | **Maintenance** includes RM, preventive maintenance, and major maintenance: **RM** includes the repair of substructures, superstructures, decks, joints, approach slabs, and railings; spot painting; repair and operation of movable bridges; installation of temporary bridges; repair and installation of fender systems.<br>**Preventive maintenance** includes steel structure cleaning and repainting or applying other coatings; bridge deck protection installation, joint cleaning, and sealing or replacement.<br>**Major maintenance** includes bridge rehabilitation, reconstruction, or replacement. Replacement of structures only as a result of a major disaster when no other funds or programs are available. | (TxDOT 2005) |
| Virginia | **Preventive maintenance** includes planned activities performed in advance of a need for repair or in advance of accumulated deterioration to avoid such occurrences and reduce or arrest the rate of future deterioration. The activities may correct minor defects as a secondary benefit. | (Brown and Ahmad 2006) |
| New York | **Preventive maintenance** includes activities that will preserve bridge components in their present (or intended) condition, forestalling the development of a structural deficiency. Preventive maintenance activities (PMA) can be classified into two groups: scheduled and response. | (NYSDOT 2008a) |

FHWA (2018) defines bridge preservation as actions or strategies that prevent, delay, or reduce deterioration of bridges or bridge elements; restore the function of existing bridges; keep bridges in good or fair condition; and extend their service life. Preservation actions can be cyclic or condition driven. The American Association of State Highway and Transportation Officials (AASHTO) and other DOTs (Illinois, Indiana, Iowa, Vermont, Wisconsin, Michigan, and others) have adopted the same definition as FHWA. Washington DOT's preservation strategies include rehabilitation, repairing, replacing bridge elements, repainting steel bridges, repairing concrete bridge decks, and seismic retrofitting (Khaleghi 2014). The Ohio DOT has emphasized the desirability of retaining the existing fabric whenever possible or, when it is too deteriorated and must be replaced, that new material be an in-kind replacement of the existing and/or historic feature (OHDOT 2010). The New Hampshire DOT preservation program includes replacing expansion joints, sealing cracks, and replacing the bridge deck membrane (NHDOT 2015). The Minnesota DOT defines preservation as a program of cyclical and condition-based maintenance activities that slow bridge deterioration, restore a bridge's function, keep bridges in sound condition, and extend their life (MnDOT 2019).

The NCDOT Asset Management Plan (NCDOT 2019) provides a comprehensive set of bridge elements that was designed to be flexible for all agencies. It features a list of bridge preservation activities, including repainting structural steel, deck repairs and waterproofing the deck surface (with membrane, thin epoxy overlay, polymer-modified concrete, or a reinforced concrete overlay), object marker replacement, and cleaning and sealing or replacement of expansion joints.

### 2.1.3 Bridge Elements and Element Defects

National Bridge Elements (NBEs) comprise the primary structural components of bridges to allow for the determination of the overall condition and safety of the primary load carrying members. NBEs were designed to remain consistent from agency to agency across the country to facilitate and standardize the capture of bridge element conditions at the national level. Bridge Management Elements (BMEs) were defined with a recommended condition assessment terminology that can be modified to suit the agencies' needs, as these elements are not intended to be utilized for the purposes of national policymaking. In the second edition of its manual for Bridge Element Inspection (AASHTO 2019), AASHTO delineated a bridge element set that can be universally adopted, with modifications as called for, countrywide. Agency Developed Elements (ADEs) provide the flexibility for an agency to define custom elements in accordance with the defined element framework that may be sub-elements of NBEs or BMEs (AASHTO 2019).

The AASHTO *Manual for Bridge Element Inspection* includes an element location matrix covering six element types in the NBE category and three element types in the BME category (AASHTO 2019). The six NBE types are decks and slabs, railings, superstructure, bearings, substructure, and culverts. The three BME types are joints, approach slabs, and wearing surfaces; protective coating; and concrete-reinforcing steel protective systems.

- *Decks and Slabs*: A deck is the surface of a bridge. These elements describe the component that is transferring load from the vehicle to the bridge. This section does not include secondary deck elements such as joints, deck/slab protection systems, or wearing surfaces. Deck structures transmit the loads into superstructure systems. The measuring unit is 'area, square foot' for all nine elements under this category.
- *Railings*: Bridge railings are guardrail systems that prevent people or vehicles from falling off the bridge. They can be made of concrete or steel. The obvious function of a bridge railing is to protect traffic and pedestrians at the edges of structures. In performing this function, the railing must have the strength to withstand the vehicular impact and the geometry and details to safely redirect the vehicle without serious snagging or overturning (NYSDOT 2008b). The measuring unit is 'length, foot' for all five elements under this category.
- *Superstructure*: Superstructures are defined by AASHTO as 'structural parts of the bridge that provide the horizontal span' (FHWA 2019). Superstructure elements described in this section transmit the load from decks into the substructure. These elements include girders, trusses, arches, and floor systems. The floor systems include floor beams and stringers. Additional elements in this group include cables, gusset plates, and pin and hanger assemblies. These elements do not include bracing components such as diaphragms, cross bracing, or portal sway bracing. The measuring unit is 'length, foot' for girder/beam, closed web/box girder, stringer, truss, arch, floor beam, and cable. The unit is 'each' for cable—secondary, gusset plate, pin, and hanger assembly, or both.

- *Bearings*: AASHTO defines a bearing as 'a structural device that transmits loads while facilitating translation and/or rotation' (AASHTO 2010). A bridge bearing carries the loads or movement in both vertical and horizontal directions from the bridge superstructure and transfers those loads to the bridge piers and abutments. The loads can be classified as live load or dead load in vertical directions and as wind load, earthquake load, etc., in horizontal directions. The unit is 'each' for all seven elements in this category.
- *Substructure*: The bridge's substructure consists of the portion of the bridge that supports the entire structure on the surrounding soil. Substructure elements described in this section transmit the load from the superstructure into the ground. These elements include columns, piles, pile caps, pile extensions, caps, pier walls, and abutments. These elements consist of steel, concrete, timber, masonry, and other materials. The measuring unit is 'each' for columns and piles. The unit is 'length, foot' for column tower, pier wall, abutment, pier cap, and pile cap/footing.
- *Joints*: A joint is an engineered space between segments of a bridge, allowing for horizontal and vertical movement. Bridge temperatures change more rapidly than road temperatures due to the lack of base underneath it, and bridges experience higher deflection and thermal movement at the joint while the two pavement surfaces expand and contract at different rates. Without bridge joints, the two different pavements would begin to destroy each other, damaging the bridge structure. To prevent water and debris from entering bridge joints, they need to be sealed with an airtight, waterproof, and flexible material. The measuring unit is 'length, foot' for all seven elements in this category.
- *Approach Slabs*: There are two elements in this category: prestressed concrete approach slab and reinforced concrete approach slab. The approach slab provides a transition between the roadway pavement and the bridge. The approach slab acts as an intermediate bridge to span the embankment portion directly behind the abutment/back wall, which was excavated to construct the abutment/back wall. This area is difficult to compact after constructing the abutment/back wall and is prone to settlement. The approach slab bridges the gap between the rigid abutment and the undisturbed embankment beyond the area excavated. The measuring unit is 'area, square foot' for the elements under this category.
- *Wearing Surface and Protective Systems*: A wearing surface is a layer placed on the bridge deck to form the roadway surface. It is the only portion of the bridge in direct contact with vehicle traffic. The measuring unit is 'area, square foot' for all elements under this category.
- *Culverts*: A pipe or small structure used for drainage under a road, railroad, or other embankments. The measuring unit is 'length, foot.'

A unique element number is assigned to every element. The data items to be collected and reported for bridge elements are state code, structure number, element number, element parent number, element total quantity, and element quantity condition states (CS) 1, 2, 3, or 4.

Currently, most DOTs use the AASHTO Manual for Bridge Element Inspection to define element defects (AASHTO 2019). NCDOT follows AASHTO's defect definitions and codes: Delamination/Spall/Patched Area (1080) and Delamination/Spall/Patched Area/Pothole (Wearing Surfaces) (3210). NCDOT dissects 1080 into two items: Delamination/Spall (1080) and Patched Area (1085) and dissects 3210 into Delamination/Spall (3210) and Patched Area (3215). These two added defect numbers (1085 and 3215) are the only difference.

## 2.2 Bridge Element Condition

According to (FHWA 2014), all elements exist in one of four defined CS: CS 1 – Good, CS 2 – Fair, CS 3 – Poor, and CS 4 – Severe. A higher CS indicates a higher severity of the element's damage and/or deterioration. This definition follows the AASHTO Bridge Element Inspection Guide Manual (AASHTO 2010b). AASHTO states that all the elements, whether they are NBEs or BMEs, have the same general requirements for inspection: 1) the standard CS designation, and 2) the standard number of the CS comprising 'good,' 'fair,' 'poor,' or 'severe' general descriptions. Most of the DOTs, including NCDOT, use the same definitions above.

CS definitions vary, depending on the element. For example, reinforced concrete has different types of defects. For the defect Delamination/Spall/Patched Area (1080), CS 1 – Good is defined as 'None.' CS 2 – Fair is defined as 'Delaminated. Spall 1 in. or less deep or 6 in. or less in diameter. The patched area is sound.' CS 3 – Poor is defined as 'Spall greater than 1 in. deep or greater than 6 in. in diameter. The patched area that is unsound or showing distress. Does not want a structural review.' CS 4 – Severe is defined as 'The condition warrants a structural review to determine the effect on strength or serviceability of the element or bridge; OR a structural review has been completed and the impact of the defect strength or serviceability of the element or bridge' (FHWA 2014).

(FHWA 2018) has set down the common actions to be implemented for different CS levels, shown in Table 2.2. Bridge inspectors should refer to the details of the AASHTO manual (AASHTO 2010b) to identify the CS level of the bridge element.

Table 2.2 Common Actions Based on Bridge Element CS (FHWA 2018)

| Condition State | Description | Common Actions[1] |
|---|---|---|
| 1 | Varies depending on the element – Good | Preservation/Cyclic Maintenance. |
| 2 | Varies depending on the element – Fair | Cyclic Maintenance or Condition-Based Maintenance when cost-effective. Condition-Based. |
| 3 | Varies depending on the element – Poor | Condition-Based Maintenance, or Rehabilitation—when the quantity of poor exceeds a limit that condition-based maintenance is not cost-effective, or Replacement—when rehabilitation is not cost-effective. |
| 4 | Varies depending on the element – Severe | Rehabilitation or Replacement. |

1 The appropriate action for an element will also be dependent on the element quantity in each CS.

## 2.3 NBI Condition Ratings

The NBI is a database that aggregates structure inventory and appraisal data to fulfill the requirements of the National Bridge Inventory Standards (NBIS; FHWA 1995). NBI data has been used to measure the functionality, safety, feasibility, and cost-effectiveness of the preservation of bridges based on their condition (INDOT 2010; VDOT 2022). The NBI includes a structural evaluation of the deck, superstructure, substructure, and culvert on a 0–9 scale, as shown in Table 2.3. Code 'N' (Not Applicable) is used for item 62 (culvert rating) when the structure is a bridge or for items 58, 59, and 60 (deck, superstructure rating, and substructure rating, respectively) when the structure is a bridge-length (i.e., 20 ft.) culvert.

Table 2.3 Bridge Condition Rating Definitions (FHWA 1995)

| Description | Code |
|---|---|
| NOT APPLICABLE | N |
| EXCELLENT CONDITION | 9 |
| VERY GOOD CONDITION—No problems noted. | 8 |
| GOOD CONDITION—Some minor problems. | 7 |
| SATISFACTORY CONDITION—Structural elements show some minor deterioration. | 6 |
| FAIR CONDITION—All primary structural elements are sound but may have minor section loss, cracking, spalling, or scour. | 5 |
| POOR CONDITION—Advanced section loss, deterioration, spalling, or scour. | 4 |
| SERIOUS CONDITION—Loss of section, deterioration, spalling, or scour have seriously affected primary structural components. | 3 |
| Local failures are possible. Fatigue cracks in steel or shear cracks in concrete may be present. | - |
| CRITICAL CONDITION—Advanced deterioration of primary structural elements. Fatigue cracks in steel or shear cracks in concrete may be present, or scour may have removed substructure support. Unless the bridge is closely monitored, it may be necessary to close the bridge until corrective action is taken. | 2 |
| ‘IMMINENT’ FAILURE CONDITION—Major deterioration or section loss presents in critical structural components or obvious vertical or horizontal movement affecting structure stability. The bridge is closed to traffic, but corrective action may put it back in light service. | 1 |
| FAILED CONDITION—Out of service—beyond corrective action. | 0 |

At the component level, a bridge is considered in good condition if its deck, superstructure, and substructure are rated at least 7. If any of these bridge elements is rated 5 or 6, a bridge is considered in fair condition. A bridge is considered in poor condition if any element is rated 4 or less. The NBI can classify bridges as poor condition. A rating of 4 or lower on any of items 58, 59, 60, or 62 (deck, superstructure, substructure, and culverts, respectively) qualifies a bridge as poor condition.

Table 2.4 lists the percentage of poor condition state-maintained bridges in 14 Divisions in NC. The percentage of interstate, primary, and secondary poor condition bridges is also detailed for each Division, which indicates it is in relatively poor condition or has insufficient load-carrying capacity. The fact that a bridge is in poor condition does not imply that it is likely to collapse or that it is unsafe. NCDOT aims at reducing the poor condition rate to below 2.3%, 5.6%, and 12.4% for interstate, primary, and secondary bridges respectively.

Table 2.4 Number and Percentage of Poor Condition Bridges (NCDOT 2024b)

| Division | Interstate (%) | Primary (%) | Secondary (%) | Total (%) |
|---|---|---|---|---|
| **1** | 0.0 | 3.7 | 6.7 | 5.3 |
| **2** | 0.0 | 3.9 | 3.6 | 3.8 |
| **3** | 0.0 | 4.5 | 5.2 | 4.5 |
| **4** | 2.6 | 5.0 | 3.2 | 3.8 |
| **5** | 2.7 | 5.5 | 5.5 | 5.1 |
| **6** | 1.1 | 1.2 | 0.5 | 0.8 |

| | | | | |
|---|---|---|---|---|
| **7** | 1.1 | 17.2 | 8.8 | 8.7 |
| **8** | 0.0 | 0.4 | 3.6 | 2.6 |
| **9** | 7.4 | 6.5 | 6.2 | 6.4 |
| **10** | 2.6 | 5.0 | 5.9 | 5.1 |
| **11** | 0.0 | 11.9 | 19.0 | 17.5 |
| **12** | 9.0 | 8.0 | 11.1 | 10.3 |
| **13** | 2.2 | 9.5 | 16.5 | 14.2 |
| **14** | 13.2 | 7.7 | 15.2 | 13.7 |
| **Statewide** | 3.0 | 5.8 | 10.0 | 8.3 |

## 2.4 Structure Safety Report—Routine Element Inspection

A structure safety report serves as the primary source of information for NCDOT in assessing the condition of bridges. The report documents the existing physical and functional conditions of the structure. The inspection report for these bridges includes photographs, a record of maintenance needs, and recommendations for major improvements. Load capacity analyses are completed based on findings from the routine inspection. The items recorded include sufficient field observations, measurements, and condition scores of bridge elements to determine the condition of the structure; changes from previously recorded conditions; the need to establish or revise a weight restriction; maintenance needs; comments and observations on existing problems, including on changes potentially impacting the problem; and any inventory changes from the previous inspection.

Fifteen topside teams, four underwater teams, three special inspection teams, and twenty-three private engineering firms are responsible for inspecting an estimated 18,000 structures (bridges and culverts) statewide. During a routine inspection, all elements of a structure typically receive a hands-on inspection. Routine inspections are conducted from the bridge deck, ground, and/or water level, and by way of such equipment as ladders. As in an initial inspection, the structure type, size, design, and location will determine if the inspection may require traffic control or special access equipment. Routine inspections generally occur on a 24-month cycle for all bridges. Routine inspections may have a reduced interval or may be extended to a 48-month cycle if approved criteria are met. Damage inspection occurs immediately after an incident once traffic control measures are in place and access to the damaged area is provided. Damaged concrete structures are typically inspected by topside personnel and damaged steel structures are inspected by special inspection personnel. The frequency of follow-up inspections is determined on a case-by-case basis and is dependent upon the level of service and the severity of damage.

## 2.5 Bridge Preservation Practices

Every DOT needs to develop work plans to prioritize bridge preservation activities. But every DOT prioritizes bridge preservation differently. The prioritization methods and decision criteria for preservation activities vary from state to state. This section reviews bridge preservation programs and methods adopted by DOTs.

### 2.5.1 DOT Bridge Preservation Programs

More than 42% of all bridges in the US are over 50 years old and in constant need of maintenance. Budget constraints led to a bridge repair backlog of $125 billion, resulting in 178 million trips taken across SD bridges daily (ASCE 2021). FHWA statistics found that in 36 states, 5% or more of bridges are SD, as shown in Figure 2.2 (ARTBA 2023).

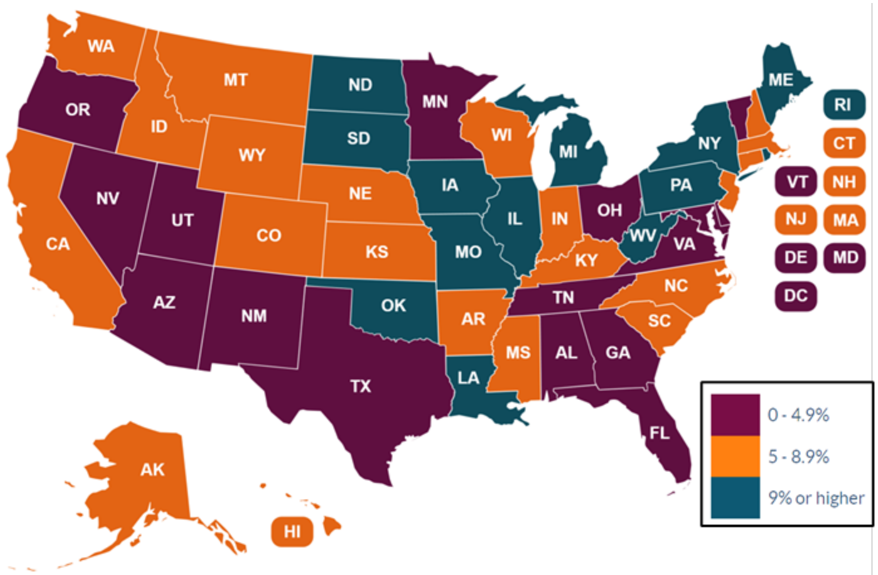



Figure 2.2 Percentage of SD Bridges in US (ARTBA 2023)

To ensure the longevity and safety of bridges, preservation activities must be prioritized effectively. The process of prioritizing bridge preservation activities is a complex undertaking that requires careful consideration of various factors, such as bridge condition, traffic volume, and economic impact. In recent years, different DOTs have developed various methods to aid decision-makers in prioritizing bridge preservation activities. These methods utilize various techniques, such as data analysis, statistical modeling, and optimization algorithms, to provide objective and quantitative assessments of bridge conditions and prioritization of preservation activities.

FHWA has published guidance on bridge preservation to promote the best use and understanding of data collection and to improve existing bridge preservation programs (FHWA 2011, 2018). The research team searched all US state DOTs' websites and found that 20 out of 50 DOTs have formal bridge preservation manuals or guidelines that are posted on their websites (highlighted in green in Figure 2.3). DOTs without any formal bridge preservation manuals or guidelines posted on their websites are identified in red. There is no manual or guideline enabling the NCDOT SMU or Division Bridge Maintenance Engineers to make preservation decisions based on individual bridge conditions.

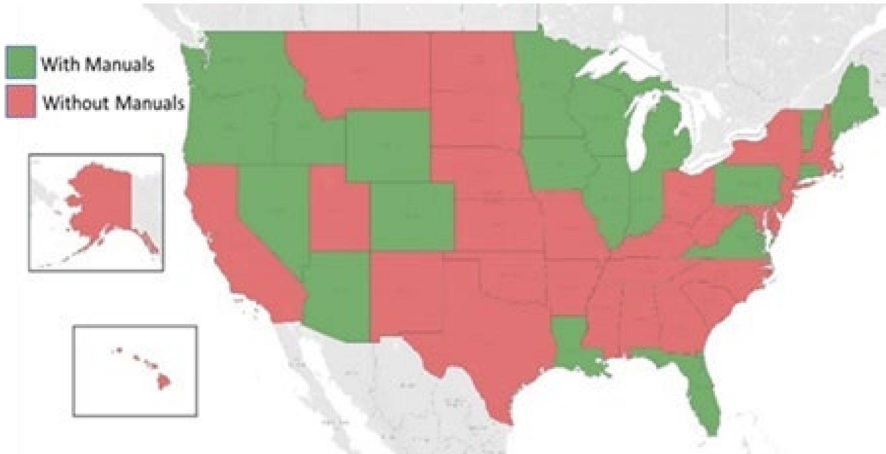



Figure 2.3 DOTs with and without Bridge Preservation Manuals

A bridge preservation program is developed to aid decision-making, ensuring that inspections and maintenance activities are carried out in a cost-effective manner that extends the service life of bridges. By deferring the need for more extensive rehabilitation or complete replacement, such a program seeks to reduce overall infrastructure costs. Currently, several DOTs have adopted bridge preservation programs, which prioritize preservation activities, encourage innovation in preservation techniques, and improve the safety and durability of bridges. These programs include detailed bridge condition measurement systems, formalized descriptions of maintenance activities, and analysis of prioritization methods. A summary of the bridge preservation programs of 50 US state DOTs is presented in Table 2.5.

Table 2.5 Bridge Preservation Programs Used by 50 US State DOTs

| # | State | Use Preservation Manuals? | Bridge Condition Measurements | Maintenance Activities | Prioritization Methods |
|---|---|---|---|---|---|
| 1 | Alabama (ALDOT 2017) | Yes | NBI rating | Detailed activity code and descriptions | Empirical Approach |
| 2 | Alaska (AKDOT 2017) | No | NBI rating | - | - |
| 3 | Arizona (ADOT 2016) | Yes | SD, Functionally Obsolete (FO), Sufficiency Rating (SR) | Cyclical PMA & condition-based PMA | Ratio-Based |
| 4 | Arkansas (ARDOT 2020) | No | CF = Critical Finding<br>A = Safety Deficiency<br>B = Pressing<br>C = Important<br>D = Routine<br>G = General/Preventive Maintenance | Maintenance activity database | Priority based on urgency |
| 5 | California (Caltrans 2014) | No | Minor defects and major defects | - | No decision criteria found |
| 6 | Colorado (CDOT 2015) | Yes | NBI rating | Bridge Preventive Maintenance Program | Weighting /Scoring |

| | | | | | |
|---|---|---|---|---|---|
| 7 | Connecticut (CTDOT 2011) | Yes | NBI rating | Cyclical PMA & condition-based PMA | Weighting /Scoring |
| 8 | Delaware (DelDOT 2012) | No | Deficiency rating | - | Ratio-based Methods |
| 9 | Florida (FDOT 2018) | Yes | NBI, State of Good Repair (SGR) Program | Inspectors provide maintenance activities | Ratio-based Methods |
| 10 | Georgia (GDOT 2013) | No | CS & condition code | Cyclical PMA & condition-based PMA | Setting Goals/Objectives |
| 11 | Hawaii (HDOT 2017) | No | NBI rating | Rehabilitate, strengthen, widen existing structures, scour | No decision criteria |
| 12 | Idaho (FHWA 2013) | Yes | NBI rating | - | Setting Goals/Objectives |
| 13 | Illinois (IDOT 2019) | Yes | NBI rating | Condition-based activities objectives, schedule-based activities objectives | Setting Goals/Objectives |
| 14 | Indiana (INDOT, 2013) | Yes | Detailed CS | - | Technical Specifications |
| 15 | Iowa (IADOT 2014) (Lu 2018) | Yes | Defect CS | - | Empirical Approach |
| 16 | Kansas (KSDOT 2022) | No | SD, NBI rating | Replace or rehabilitate | Setting Goals/Objectives |
| 17 | Kentucky (FHWA 2011) | No | NBI rating, SGR, SD, FO | Cyclical PMA & condition-based PMA | Setting Goals/Objectives |
| 18 | Louisiana (LaDOTD 2020) | Yes | CS & associated defects | - | Weighting /Scoring |
| 19 | Maine (MEDOT 2011) | Yes | NBI rating | Cyclical PMA & condition-based PMA | Weighting /Scoring |
| 20 | Maryland (MDDOT 2012) | No | SGR | - | Setting Goals/Objectives |
| 21 | Massachusetts (MassDOT 2019) | No | NBI rating | - | - |
| 22 | Michigan (FHWA 2013) | Yes | NBI rating | - | Setting Goals/Objectives |
| 23 | Minnesota (MnDOT 2016) | Yes | NBI rating | Preventive and reactive maintenance | Setting Goals/Objectives |
| 24 | Mississippi (MSDOT 2012) | No | NBI rating | Final maintenance and repair recommendations and priorities determined by district bridge inspection engineers (DBIEs) | Empirical Approach |
| 25 | Missouri (Washer et al. 2017) | No | NBI standards | - | Risk-based Method |

| | | | | | |
|---|---|---|---|---|---|
| 26 | Montana (MDT 2019) | No | NBI rating | - | Decision Tree |
| 27 | Nebraska (NEDOT 2010) | No | NBI rating | - | Empirical Approach |
| 28 | Nevada (NVDOT 2021) | Yes | Condition ratings and SD | - | Ratio-based Methods |
| 29 | New Hampshire | No | - | - | - |
| 30 | New Jersey (NJDOT 2014) | No | NBE | Maintenance methods for each element | Technical Specifications |
| 31 | New Mexico | No | - | - | - |
| 32 | New York (NYSDOT 2017) | No | CS | Maintenance methods for each element | Technical Specifications |
| 33 | North Carolina (NCDOT 2019c) | No | NBI rating | Determined by the SMU | Setting Goals/Objectives & Weighting/Scoring |
| 34 | North Dakota (NDDOT 2021) | No | NBI rating | Typical preservation actions | Setting Goals/Objectives |
| 35 | Ohio (OHDOT 2010) | No | CS | Maintenance methods for each element | Technical Specifications |
| 36 | Oklahoma | No | - | - | - |
| 37 | Oregon (ORDOT 2021b) | Yes | NBI rating | PMA | Setting Goals/Objectives |
| 38 | Pennsylvania (PennDOT 2012) | Yes | BMS | - | Empirical Approach |
| 39 | Rhode Island (RIDOT 2016) | No | NBI rating | Maintenance methods for each element | Technical Specifications |
| 40 | South Carolina (SCDOT 2020) | No | NBI rating | Maintenance methods for each element | Ratio-based Methods |
| 41 | South Dakota (Thompson 2006) | No | SR | - | Empirical Approach |
| 42 | Tennessee (TDOT 2019) | No | NBI rating | - | Ratio-based Methods |
| 43 | Texas (TxDOT 2022) | No | Condition rating, appraisal rating | - | Empirical Approach |
| 44 | Utah (UDOT 2017) | No | SR, SD, FO, Bridge Health Index, Bridge Planning Index | Routine/responsive maintenance activities | Ratio-based Methods |
| 45 | Vermont (VTrans 2020) | Yes | Stability, structural integrity, safety | Cyclical PMA & condition-based PMA | Setting Goals/Objectives |
| 46 | Virginia (FHWA 2013) | Yes | NBI rating | - | Setting Goals/Objectives |
| 47 | Washington (Khaleghi 2014) | Yes | Determined by bridge engineers | - | Empirical Approach |
| 48 | West Virginia (WVDOT 2012) | No | SR | - | Weighting /Scoring |

| | | | | | |
|---|---|---|---|---|---|
| 49 | Wisconsin (WIDOT 2016) | Yes | NBI rating | Cyclical PMA, condition-based PMA, rehabilitation, improvement or major rehabilitation, replacement, new bridge construction | Decision Tree |
| 50 | Wyoming (WYDOT 2018) | Yes | Structure standards | - | - |

### 2.5.2 Methods Used by DOTs for Bridge Preservation Activity Prioritization

The decision criteria for preservation activities vary from state to state. For example, the Arizona DOT derived its priorities for preservation activities from the NBI bridge scoring system; the final priority of bridge weights is based on 20 factors, including daily traffic, truck traffic percentages, and detour lengths (ADOT 2016). The Wisconsin DOT defined several condition-based performance objectives to promote its maintenance goals, such as maintaining 95% of bridge decks in good or fair condition and maintaining expansion joints along 90% of the overall length in good or fair condition. The Michigan DOT developed decision matrices for preventive maintenance based on the identified repair options and the expected duration achieved by each repair. Its goal is to ensure that 95% of freeway bridges are in good or fair condition. Other state DOTs use decision trees or NBI ratings as preservation decision rules. Table 2.6 summarizes the seven methods used by DOTs to prioritize bridge preservation activities.

Table 2.6 Seven Prioritization Methods Used by DOTs

| Decision Method | Description | State DOTs |
|---|---|---|
| **Ratio-based Methods** | Assigns a BCI or BCN based on the ratio of the current condition to the condition of the structure when it was new. | Connecticut, Delaware, Massachusetts, Colorado, Nevada, Arkansas, California, Kentucky, New York, Pennsylvania, Utah |
| **Weighting/Scoring** | Weighs several measurements, such as structure conditions, daily traffic, truck travel rate, and detour length of a bridge to determine the bridge criticality. | Arizona, West Virginia, Colorado, Ohio |
| **Setting Goals/Objectives** | Sets the maintenance goal for bridge preservation: for example, 82% of pavements should be in good or fair condition. | Idaho, Illinois, Vermont, Maine, Tennessee, Arizona, Wisconsin |
| **Technical Specifications** | Provides preservation/maintenance specifications. Technical measurements function as decision rules to trigger preservation activity. | Indiana, Michigan, Virginia |
| **Empirical Approach** | Discusses and determines the priority of preservation needs based on bridge inspection reports. | Iowa, Washington |
| **Decision Tree** | Considers bridge years, dimensions of the defects, and bad joints percentage in a hierarchical structure to trigger various preservation/maintenance activities. | Montana, New York, Wisconsin |
| **Risk-Based Method** | Weighs the risks associated with the condition and fatigue of the bridge structure, potential damage from flooding and trucks, and impacts of detours. | Minnesota, New Jersey |

*Ratio-Based Methods*: This method assigns a bridge condition index (BCI) or bridge condition number (BCN) based on the ratio of the current condition to the condition of the structure when it was new (FHWA 2016). The index can be incorporated into prioritization models used to allocate funds for the repair and rehabilitation of bridges with a low health index. Currently, 11 DOTs use ratio-based methods, including Connecticut, Delaware, Massachusetts, Colorado, Nevada, Arkansas, California, Kentucky, New York, Pennsylvania, and Utah. For example, Pennsylvania DOT (PennDOT 2022) has developed a numerical index—the Critical Ranking Factor (CRF)—to prioritize the bridges within each of the fracture critical groups. The CRF is the sum of four digits that characterize the Nonredundant Steel Tension Member (NSTM) groups; each NSTM member will receive a CRF. The member with the lowest number CRF controls the bridge's CRF. For the majority of the bridge structures, rule-based standards from the BMS are applied to determine preservation needs.

*Weighting/Scoring*: Weighting methods not only consider the bridge structure conditions, but also integrate other conditions such as daily traffic, truck travel rate, detour length, and so forth. Each condition has a corresponding weighting factor to determine the final ranking. A detailed table and score for each criterion need to be provided for preservation. Currently, four DOTs use weighting/scoring methods. For example, Arizona DOT (ADOT 2016) considers the applicable factors obtained from NBI data and has developed the following ranking criteria:

$$Bridge\ Priority\ Ranking = \sum_{i=1}^{20} (NBI_i) \times Weighting\ Factor_i \tag{2.1}$$

Each factor has a maximum weight of one point. Each NBI item is assigned a factor of 2.25, 2.5, 2.75, or 1 based on its relative importance. For example, for N19-Detour Length, its weighting factor is 2.25 if the length is 0–5 miles, 2.5 if the length is 6–10 miles, 2.75 if the length is 11–15 miles, and 1 if the length is greater than 15 miles.

*Setting Goals/Objectives*: The goals of the action prioritization portion are to provide a catalog of possible actions with performance parameters, whether available or approximated, and a practical method for selecting the most cost-effective actions in particular situations. In turn, these goals form the basis of a priority-ranking system. If the goals are not specifically stated, they are implied by the factors and methods used to determine the needs and priorities. The goal of a bridge preservation program is to maximize the useful life of bridges in a cost-effective way, resulting in long service life at an optimal life cycle cost. Currently, seven DOTs and the National Cooperative Highway Research Program (NCHRP) use setting goals/objectives methods. For example, the Illinois DOT aims to maintain 93% of bridges on the National Highway System (NHS) and 90% of the state-owned bridges not on the NHS in acceptable condition (IDOT 2019). They measure the bridge condition's performance and ensure that bridges with a primary condition rating of poor (NBI rating < 5) and that are open for operations are safe. Maintaining safe and dependable operations is a high priority for the department.

*Technical Specifications*: DOTs provide preservation/maintenance specifications. Technical measurements are listed as decision rules to trigger preservation activity. Funding is usually the specific requirement for prioritization decisions (FHWA 2013). For example, Idaho, Michigan, and Virginia first measure the performance of the bridges and culverts; based on their general conditions, the structures are identified as good, fair, or poor, hence becoming candidates for maintenance to preserve good conditions, for repairs to avoid poor conditions, or for rehabilitations to remedy poor conditions. Because funding is always limited, each state's strategy for the management of structures is characterized by a mix of funding directed to preventive maintenance of healthy structures, repair of structures with defects, and rehabilitation of structures with major defects.

*Empirical Approach*: This approach identifies the maintenance needs through district and bridge office engineers and reports. Needs are assessed and prioritized annually during district meetings. It is the inspector's responsibility to determine the priority of each work candidate, taking into account the severity of the maintenance needed and whether the member needing attention is fracture-critical. Currently, two DOTs use the empirical approach, Iowa, and Washington. For example, the Iowa DOT (Lu 2018) relies on subjective experience (that is, they rely on the professional judgment of the individual engineers) and performance data to conduct bridge preservations. They have aimed to incorporate best practices and research results and expect a periodic update from the routine inspection results. Maintenance needs are identified by district and bridge office engineers and recorded in the Structure Inventory and Inspection Management System. The identified needs are assessed/prioritized annually during district meetings.

*Decision Tree*: This approach considers bridge years, fault depth, bad joint percentage, and so forth in a hierarchical structure to trigger various preservation/maintenance activities. For example, Montana DOT applies a series of decision trees when selecting bridge preservation, repair, and rehabilitation treatments (MDT 2019). It determines the candidate treatments for superstructure and substructure conditions using the bridge improvement decision process.

*Risk-Based Method*: This approach often weighs the risks associated with such factors as the condition and fatigue of the bridge structure, the potential damage from flooding and trucks, and the impacts of detours. This not only provides decision-makers with a more complete picture of the uncertainty associated with various assessment procedures but also promotes the use of more reliable approaches while still allowing states some freedom regarding implementation. For example, the New Jersey DOT proposed a bridge assessment methodology based on the concept of relative risk, which extends the reliability-based assessment approach to explicitly consider the consequences of not performing maintenance (Moon et al. 2009). The framework takes into consideration a more partitioned definition of perceived relative risk as a combination of hazard, vulnerability, exposure, and an uncertainty premium. The formula is as follows:

$$\begin{gathered} Perceived\ Relative\ Risk\ (H) = \\ (Hazard) \times (Vulnerability) \times (Exposure) \times (Uncertainty\ Premium) \end{gathered} \tag{2.2}$$

Where Hazard is the probability of a hazard occurring. Vulnerability is the probability of failure (to perform adequately) with the given hazard. Exposure consists of the consequences associated with a failure to perform adequately. The Uncertainty Premium is a factor to account for the level of uncertainty associated with the selected assessment approach, including the quality control measures employed. The New Jersey DOT also provided a detailed table to illustrate and summarize the relevant performance limit states, hazards, vulnerabilities, and exposures for bridges.

## 2.6 Extended Service Life

NCDOT uses 64 activities to preserve the bridges, including 22 activities for preserving decks, 21 for superstructures, 12 for substructures, and nine in general. Among the 64 activities, NCDOT has developed an estimation of the extended service life yielded by 57 activities. The seven remaining activities are 1) asphalt patches, 2) replacing wearing surface, 3) penetrating sealer, 4) cleaning and repainting bridge, 5) cleaning and painting substructure, 6) steel repairs, and 7) repairs to prestressed girders. The research team reviewed and found estimations of the extended service life of asphalt patches, replacing wearing surface, and penetrating sealer. Estimations for similar activities were made for cleaning and painting the substructure, cleaning and repainting the bridge, and repairs to prestressed girders. No estimation was arrived at for steel repairs.

### 2.6.1 Asphalt Patch

Asphalt pavement is a durable and cost-effective material commonly used for roads and bridges. Over time, asphalt can deteriorate and develop cracks, potholes, or other forms of damage due to traffic, weathering, or other factors. Asphalt patching is a common repair technique used to address these issues and restore the pavement to a safe and functional condition. It involves the removal of damaged pavement and the application of new asphalt material to the affected area. NCDOT bridge preservation uses two main types of asphalt patching: hot mix asphalt (HMA) and cold mix asphalt (CMA).

In general, HMA patching has a longer service life than CMA patching. This is because HMA has a higher asphalt content and better adhesion properties, which allows it to withstand heavy traffic and weathering over time. The expected service life of HMA techniques is 4–5 years. The expected service life for CMA patches can range from a few weeks to a year (Hafezzadeh et al. 2021).

However, it is important to note that the service life of both HMA and CMA patches can vary depending on several factors, such as the quality of the materials used, the depth and extent of the patch, the traffic conditions, and the climate in which it is located.

### 2.6.2 Replacing Wearing Surface

Replacement of wearing surfaces on bridges is an important maintenance activity that helps ensure the longevity and safety of bridge infrastructure. Cracking must be minimized to prevent water and chlorides from penetrating the deck. It is also essential to minimize rutting and pavement erosion to ensure a smooth and safe ride. Performing preservation and replacement treatments on wearing surfaces can be a cost-effective solution if integrated into a highway paving project.

The process involves the removal of the existing surface layer and the installation of a new layer using materials such as asphalt or concrete. The new surface is designed to improve the ride quality for vehicles and extend the service life of the bridge. In general, the extended service life of a properly installed and maintained wearing surface system is around 25 years (MEDOT 2011). However, the lifespan of the new surface may be shorter or longer depending on a variety of factors, such as the level of traffic and the severity of environmental conditions.

### 2.6.3 Penetrating Sealer

A penetrating sealer is a type of concrete sealer that is designed to penetrate deeply into the pores and capillaries of concrete surfaces, forming a chemical bond that helps to prevent the intrusion of water, moisture, and other contaminants. Unlike surface sealers, which sit on top of the concrete, penetrating sealers work below the surface, protecting the concrete from within. Silane and siloxane sealers are often recommended for use on bridges as they are highly effective at preventing water intrusion and can reduce the risk of corrosion caused by salt and other chemicals.

Past studies have shown that the effectiveness of penetrating sealers decreases due to abrasion, weathering, and UV degradation. The extended service life of silane and siloxane is estimated at five to eight years, depending on traffic abrasion (Cady 1994; Żemajtis and Weyers 1996).

### 2.6.4 Painting

Over time, bridges are subject to environmental factors such as weather, pollution, and UV radiation, which can cause them to deteriorate and require maintenance. Bridge cleaning and painting are essential maintenance activities that not only improve the aesthetic appearance of a bridge but also extend its lifespan by protecting it from corrosion and other forms of deterioration. In this section, the details of overcoating and painting systems are reviewed, and then different painting options are compared.

Various bridge cleaning and painting systems are available, and the choice of system depends on factors such as the type of bridge, accessibility, and budget. Three commonly used painting practices are blast & repaint, overcoating, and zone painting. The most frequent method of maintaining painted surfaces is to remove the existing coating entirely and apply a new one, commonly known as 'blast & repaint.' This approach is used when repairing or rehabilitating the existing coating. Another method, called 'overcoating,' is a form of rehabilitation that does not involve removing the entire existing coating but relies on it for some degree of steel protection. This process includes cleaning the surface to remove debris and reduce contaminants, fixing areas where the coating has failed, applying spot coatings to corroded or intercept failure areas, and adding one or more layers of topcoat over the existing coating. Zone painting is a localized coating repair option that typically involves removing and replacing broad areas of existing coating in specific environments requiring frequent maintenance, such as beam ends, splash zones, and the fascia girders of overpass bridges. Table 2.7 summarizes the life expectancy and usage for each painting option.

Table 2.7 Life Expectancy and Usage for Bridge Painting Options (Hopwood II et al. 2018)

| Painting Option | Usage | Life Expectancy |
| --- | --- | --- |
| Blast & repaint | Majority of painting projects | 15–20 years |
| Overcoating | Small percentage of painting projects | 10–20 years |
| Zone painting | Rarely used | 10–20 years |

### 2.6.5 Repairing Prestressed Concrete Girders

Prestressed concrete girders are an essential component of modern bridge construction. They are designed to withstand heavy loads and provide a durable, long-lasting support structure for bridges. Repairing prestressed concrete girders is crucial to ensure the continued safety and functionality of bridges. The repair process involves identifying the extent and nature of the damage, determining the appropriate repair method, and applying the necessary repairs. In this section, the research group conducted a literature review on the repairing methods based on damage classification.

NCHRP Report 226 (Shanafelt and Horn 1980) provides guidance on assessing, inspecting, and repairing damaged prestressed concrete bridge girders. The report emphasizes the importance of differentiating between the tasks of assessing damage (inspection) and evaluating engineering factors such as load rating. Frequently, unsuitable repair methods or replacement decisions are made due to incorrect assessment of the damage, leading to ineffective and inappropriate repairs (Harries et al. 2009). A damage classification system is proposed, allowing users to quantify the present damage into one of three categories (Harries et al. 2009):

- Minor damage is defined as concrete with shallow spalls, nicks and cracks, scrapes, and some efflorescence, rust, or water stains. Damage at this level does not affect member capacity. Repairs are for aesthetic or preventive purposes.
- Moderate damage includes larger cracks and sufficient spalling or loss of concrete to expose strands. Moderate damage does not affect member capacity. Repairs are intended to prevent further deterioration.
- Severe damage is any damage requiring structural repairs. Typical damage at this level includes significant cracking and spalling, corrosion, and exposed and broken strands.

Repair methods considered in (Shanafelt and Horn 1980) are external post-tensioning, metal sleeve splicing (to avoid confusion, this method will be referred to as 'steel jacketing' in the present work), strand splicing, a combination of these methods, and replacement.

External post-tensioning is effected using steel rods, strands, or bars anchored by corbels or brackets (typically referred to as 'bolsters') that are cast or mounted onto the girder, typically on the girder's side (although occasionally on the soffit). The steel rods, strands, or bars are then tensioned by jacking against the bolster or preload (which will be discussed later).

Steel jacketing is the use of steel plates to encase the girder to restore girder strength. With this repair technique, post-tensioning force can only be introduced by preloading.

Strand splices are designed to reconnect severed strands. Methods of reintroducing prestress force into the spliced strand include preloading, strand heating, and torquing the splice is tightened to reconnect and introduce tension into the strand (Harries et al. 2009).

The extended service life for prestressed concrete girder repair was not identified. Hearn (2020) has summarized the extended service life for repairing, replacing, and retrofitting prestressed concrete beams (see Table 2.8). The Ohio DOT found that the extended service life of repairing prestressed concrete I-beams is 20 years and that of replacing and retrofitting prestressed concrete box beams is 40 and 30 years, respectively. According to Michigan DOT documents, the extended service life of replacing prestressed concrete box beams is 40 years (Hearn 2020).

Table 2.8 Estimated Service Life Yield from Prestressed Concrete Beams (Hearn 2020)

| Activities | Detail | Interval (Years) | State |
|---|---|---|---|
| Repair | Prestressed concrete I-beam | 20 | OH |

| | | | |
|---|---|---|---|
| Replace | Prestressed concrete box beam | 40 | MI, OH |
| Retrofit | Prestressed concrete box beam | 30 | OH |

### 2.6.6 Summary

Table 2.9 summarizes the extended service life yield from asphalt patch, replacing the wearing surface, and applying penetrating sealer, as well as the estimated service life of painting and overcoating, and repairing and retrofitting prestressed concrete beams.

Table 2.9 Extended Service Life Yield from Preservation Activities

| **Activity** | **Detail** | **Extended Service Life** |
|---|---|---|
| Asphalt patch | HMA | 4–5 years |
| | Cold mix asphalt | Up to 1 year |
| Replacing wearing surface | — | 25 years |
| Penetrating sealer | Silane and siloxane | 5–8 years |
| Painting and overcoating | Blast & repaint | 15–20 years |
| | Zone painting | 10–20 years |
| | Overcoating | 10–20 years |
| Repairing prestressed concrete beams | Prestressed concrete I-beam | 20 years |
| Replacing prestressed concrete beams | Prestressed concrete box beam | 40 years |
| Retrofitting prestressed concrete beams | Prestressed concrete box beam | 30 years |

## 2.7 Bridge Preservation Prioritization Research

Cavalline et al. (2015) revised and updated deterioration models and user cost tables for use in the BMS software. They reviewed the data in NCDOT's Bridge Management System software and took steps to address data anomalies. They updated deterministic deterioration models and developed a statistical regression methodology by applying survival analysis techniques to better address characteristics of the historical condition rating data. The research developed probabilistic deterioration models for bridge components and culverts. These models include transition probability matrices that account for the effects of design, geographic, and functional characteristics on deterioration rates over different condition ratings. However, while this model was found to best fit the historical condition rating data and provided unique insight into factors influencing deterioration over the life cycle of each bridge component, it was also discovered that a simplified implementation of the probabilistic deterioration model was able to achieve similar performance without rigorously incorporating the effects of external factors on deterioration rates. Table 2.10 summarizes the study's data collection, methods, results, and limitations.

Table 2.10 Bridge Management Systems: Research Summary of Cavalline et al. (2015)

| Data Collection | Methods | Findings | Limitations |
|---|---|---|---|
| NCDOT's data inventory of bridge structures. | • Updated the deterministic model based on bridge structures.<br>• Developed probabilistic deterioration models based on proportional hazards regression analysis.<br>• Updated user costs and analyzed user cost sensitivity by analyzing ADT and its growth rate, vehicle operation costs, and accident costs. | • Statistical models show improvements in prediction over the traditional planning horizons.<br>• A simplified implementation of the probabilistic deterioration model can achieve similar performance without incorporating external factors.<br>• Seven bridge characteristics identified that are most associated with bridge related crashes.<br>• User costs are most sensitive to accident costs. | • Limitations associated with the ADT dataset resulting in a constant growth rating.<br>• Limited data included on crashes resulting from vertical clearance issues.<br>• Lack of deterioration model validation due to inaccessible concrete components and the higher cost for acquisition of the materials performance data.<br>• The accuracy and precision of deterministic deterioration models is limited because of censoring and the nonnormal distribution of condition rating durations. |

Whelan et al. (2019) revised NCDOT's bridge performance criteria and established a transparent and objective relative weighting of measures to develop a revised bridge replacement priority index. Two approaches directed this research: practitioner-informed development of relative weighting for performance measures and data-driven analysis of performance measures' significance to the bridge replacement classification. Statistical analysis was performed to develop an alternative formula for bridge condition classifications and provide a means of arriving at the probability that a bridge will be replaced.

Table 2.11 summarizes the research's data collection, methods, results, and limitations. The data were collected through two rounds of practitioner surveys to identify the performance criteria. The results showed that Priority Replacement Index (PRI) has a higher classification but suffers from duplicated counting and lacks transparency. All the statistical models consistently match the preference structure elicited from the practitioner surveys. However, this research suffers from the limited number of consistent survey responses. The data in the BMS lacks detailed information on conditions and factors for each bridge that would allow for better distinction.

Table 2.11 Research Summary of Whelan et al. (2019)

| Data Collection | Methods | Findings | Limitations |
|---|---|---|---|
| • Initial practitioner survey with initial performance criteria.<br>• Final practitioner survey with revised performance criteria.<br>• 23 responses, including 14 Division Bridge Program Engineers, 6 bridge maintenance engineers, and 3 engineers from the SMU. | • Two-round practitioner surveys.<br>• Statistical analysis to develop an alternative formula for bridge condition classification.<br>• Binary logistic regression provides the means of probability that a bridge will be replaced. | • PRI shows a higher accuracy classification from a purely statistical perspective.<br>• PRI suffers from duplicated counting and lacks transparency.<br>• Binary logistic regression produces a better distribution of scores.<br>• The statistical models show consistency with the preference | • The number of consistent survey responses was limited.<br>• The descriptive granularity of the data in the BMS often does not accurately capture the condition, history, and other factors specific to each bridge to permit reliable distinction and ranking of individual bridge projects. |

| | | | |
|---|---|---|---|
| | | structure elicited from the practitioner surveys. | |

## 2.8 GIS Application in Bridge Preservation Research

This research endeavored to incorporate a GIS to introduce georeferenced data in decision-making processes for bridge prioritization. Thus, it is imperative to explore how prior research and DOTs have employed this technology in their bridge preservation programs. Therefore, this section reviews academic research and DOT reports with the purpose of discerning various integration methodologies. The overarching goal is to comprehend the potential advantages and limitations of implementing GIS in bridge preservation programs and to identify the principal obstacles that DOTs may encounter when attempting to incorporate this technology. By gaining an understanding of previous research and the DOTs' experiences, this research can contribute to the development of a framework for the effective implementation of GIS in bridge preservation programs.

According to Esri (2022), a GIS is a system that creates, manages, analyzes, and maps all types of data. GIS connects data to a map, integrating location data (where things are) with all types of descriptive information (what things are like there). The benefits include improved communication and efficiency as well as better management and decision-making. Due to superior spatial data handling capabilities, GIS technology is increasingly being considered for implementation in many infrastructure planning and management systems, including bridge management systems (She et al. 1999).

Liu et al. (2018) developed and implemented a web- and GIS-based BMS that allows for advanced geospatial visualization and potential data integration on a centralized cloud platform. The research team used Esri's technology-based ArcGIS Online as the major development tool, and the resulting BMS was designed as a bi-level platform. The upper level manages the overall bridge network based on two-dimensional (2D) vectors or images, while the lower level handles three-dimensional (3D) spatial information and real-time data streams for monitoring the health of individual bridges. One of the major outcomes of this project is an open-source BMS prototype that can create custom applications, provide a platform for integrating GIS with other business systems, and enable cross-organizational collaboration.

Contreras-Nieto et al. (2019) presented a GIS-integrated decision-making framework to prioritize bridge maintenance by using aggregated bridge ratings and ADT. The aggregated bridge ratings were the weighted average of deck, substructure, superstructure, and scour ratings; the weights were determined by analyzing a group of bridge experts' comparisons of the relative importance of deck, substructure, superstructure, and scour with respect to bridge resiliency, riding comfort, safety, and serviceability using the analytic hierarchy process (AHP). A GIS user interface that integrated Google Fusion Tables, Google Maps, and the decision-making criteria was created to visualize the priority of the bridges for maintenance. With the assistance of the GIS interface, bridge maintenance engineers can combine maintenance schedules for bridges that are adjacent to each other. Users can also narrow down the bridge candidates by adding additional filters.

Arkansas DOT provides a full GIS service; the public can use their GIS map to locate historic bridges, view their inventories, and select groups of bridges by type with beautiful photographs, a detailed GIS map, and a thumbnail sketch of bridge features.

Ohio DOT has an innovative method of enabling the public to access information about its bridges. Buckeye Assets (www.buckeyeassets.org) enables the public to find bridges within a given area on its GIS map. One can look specifically for historic bridges, select one from the map, and read through the information compiled on the bridge.

New Hampshire DOT (NHDOT 2019) provides specific information about its maps in the NHDOT GIS Data Catalog for bridge maintenance. The GIS section (Planning and Community Assistance Bureau) manages the Data Catalog website and production of standard printed and online maps. In 2018, a reorganization of the data catalog was completed with new standards adopted for website content and layout, data links, and standard maps, as well as a process for updates.

Wyoming DOT (WVDOT 2012) presented a GIS enhancement project and project prioritization process. WVDOT prioritized potential projects based on a combined project score and a benefit/cost index to assist the department with programming projects. It then integrated the approach into the GIS Project Mapping Application in order to display all potential projects, their scores, locations, history, and other characteristics. The finalized tool will develop a project prioritization function within the GIS mapping tool. WVDOT also aims to populate its project prioritization GIS tool with projects currently included in the WVDOT Multimodal Statewide Transportation Plan and experiment with different funding allocation scenarios.

NCDOT maintains a variety of GIS resources, including data layers and applications, that support bridge and structure data management and decision-making activities. A keystone source of GIS data is the "NCDOT Bridges & Other Structures" geodatabase and map service, a dataset of structure locations (including bridges) that combines spatial location information in point format with important structure attribute information like maintenance responsibility, construction characteristics, weight rating, and detour length. This data is updated quarterly and supports public online applications like the NCDOT Structures Map. Likewise, extensive road characteristics data is maintained in spatial format and updated quarterly. Notable applications designed to support decision-making maintenance activities include the NCDOT Pavement Conditions Map, the NCDOT AADT Web Map, and the Highway Maintenance Improvement Program maps. These resources and others can be used as a foundation for additional analyses and prioritization activities, as further detailed in the following sections of this report.

# 3 DATA COLLECTION

Prioritizing bridge preservation plans is a data-intensive and complex task. Accurately identifying preservation needs, triggering appropriate activities, estimating preservation lifecycle costs, and assessing bridge criticality in terms of local communities require detailed, case-by-case information for each bridge.

The research team collaborated with the NCDOT SMU to collect data on bridge conditions, preservation costs, and bridge traffic. This preliminary study focused on bridges managed by NCDOT Division 10, which includes a mix of interstate highways, primary routes, and secondary roads. The study targets typical bridges preserved by SMU and Divisions, excluding culverts and bridges with timber, steel plank decks, or trusses. Only bridges with General Condition Ratings (GCR) between 5 and 7 were considered, as bridges with GCR scores above 7 are assigned cyclic activities and bridges with GCR scores below 5 are designated for replacement. This criterion resulted in a total of 442 bridges, which constituted the research scope of this project.

This chapter describes each dataset used in the project and any associated data preprocessing steps. The datasets are organized into three categories aimed at developing three models, as described below.

1. **Datasets for Preservation Activity Triggering**: Focused on bridge element inspection results and preservation triggering rules essential for determining specific preservation activities.
2. **Datasets for Preservation Cost Estimation**: Associated with preservation activity unit costs, unit conversion, preservation activity lifecycle, and local inflation ratios to determine lifecycle preservation costs.
3. **Datasets for Bridge Criticality Assessment**: Related to bridge AADT, Truck AADT, detour length, and hourly costs of detours to assess bridge criticality in terms of local traffic and freight.

## 3.1 Datasets for Preservation Activity Triggering

This section introduces datasets used for triggering preservation activities, specifically including:

- Two bridge inspection datasets (Superstructure Element Inspection dataset and Substructure Element Inspection dataset). These form the basis for developing bridge preservation plans.
- Two datasets regarding the rules for triggering preservation activities: the Preservation Activity Decision Tree dataset and the Activity Overwrite Rules dataset. These datasets record the logic for triggering bridge preservation activities.
- Bridge interstate indicator, which indicates whether a bridge is an interstate bridge, aiding in determining specific preservation activities associated with route type.

### 3.1.1 Element Inspection Data for Superstructures and Substructures

These two datasets contain bridge superstructure and substructure inspection data extracted from NCDOT's Structure Safety Report—Routine Element Inspection. The reports record each bridge element's location, defects, severity, required preservation quantity, and observation dates.

Inspection data are the foundation for developing preservation plans. The defect and element information in the inspection data, combined with the preservation activities decision tree, are used to trigger the preservation activities.

Table 3.1 shows the first 10 samples of the superstructure inspection dataset, displaying partial columns. The superstructure dataset also includes inspection records for bridge deck elements. Each row in the dataset represents a specific defect record found on a bridge element. If the defect name value is "NA", it indicates no defects on that element.
For example, the first row in Table 3.1 indicates that span number 1 in bridge 030003 has a defect of "Cracking" on the "Reinforced Concrete Deck" element. Specifically, CS level 2 (CS 2) requires a preservation quantity of 5 square feet, while CS level 3 (CS 3) requires a preservation quantity of 10 square feet. The value of 0 for Level 4 Maintenance indicates that no preservation is needed at CS level 4 (CS 4). Since level 1 indicates that the bridge's CS is "Good" and requires no preservation, it is not recorded in the table. For more information on bridge CS, refer to Section 2.3. The unit of preservation quantity depends on the element. The unit for the reinforced concrete deck is square feet; the units for other elements are detailed in APPENDIX I.

The structures of the superstructure inspection dataset and substructure inspection dataset are similar. Table 3.2 shows a partial view of the substructure inspection data. The complete structure and metadata descriptions of these two inspection datasets are detailed in APPENDIX A and APPENDIX B. The datasets are stored in the files "Step 0_new_super.csv" and "Step 0_new_sub.csv".

Table 3.1 Samples from Superstructure Inspection Dataset

| Number (1) | Span Number (2) | Element Name (3) | Inspection Date (4) | Defect Name (5) | Level2 Maintenance (6) | Level3 Maintenance (7) | Level4 Maintenance (8) | … |
|---|---|---|---|---|---|---|---|---|
| 030003 | 1 | Reinforced Concrete Deck | 4/14/2022 | Cracking (RC and Other) | 5 | 10 | 0 | … |
| 030003 | 1 | Reinforced Concrete Deck | 4/14/2022 | Delamination/Spall | 3 | 0 | 0 | … |
| 030003 | 1 | Reinforced Concrete Deck | 4/14/2022 | Exposed Rebar | 0 | 1 | 0 | … |
| 030003 | 1 | Prestressed Concrete Open Girder/Beam | 4/14/2022 | NA | NA | NA | NA | … |
| 030003 | 1 | Other Bearings | 4/14/2022 | Corrosion | 0 | 7 | 0 | … |
| 030003 | 1 | Reinforced Concrete Bridge Railing | 4/14/2022 | NA | NA | NA | NA | … |
| 030003 | 1 | Steel Protective Coating | 4/14/2022 | Effectiveness (Steel Protective Coatings) | 0 | 5 | 7 | … |
| 030003 | 2 | Reinforced Concrete Deck | 4/14/2022 | Abrasion/Wear (PSC/RC) | NA | 0 | 0 | … |
| 030003 | 2 | Reinforced Concrete Deck | 4/14/2022 | Cracking (RC and Other) | 1000 | 0 | 0 | … |
| 030003 | 2 | Reinforced Concrete Deck | 4/14/2022 | Delamination/Spall | 0 | 4 | 0 | … |
| … | … | … | … | … | … | … | … | |

Table 3.2 Samples from Substructure Inspection Dataset

| Number | Bent Number | Element Name | Inspection Date | Defect name | Level2 Maintenance | Level3 Maintenance | Level4 Maintenance | … |
|---|---|---|---|---|---|---|---|---|
| 030003 | 1 | Reinforced Concrete Column | 4/14/2022 | Delamination/Spall | NA | 0 | 0 | … |
| 030003 | 1 | Reinforced Concrete Pier Cap | 4/14/2022 | Cracking (RC and Other) | 0 | 1 | 0 | … |
| 030003 | 1 | Reinforced Concrete Abutment | 4/14/2022 | Delamination/Spall | 3 | 0 | 0 | … |
| 030003 | 1 | Reinforced Concrete Pier Cap | 4/14/2022 | Delamination/Spall | 0 | 2 | 0 | … |
| 030003 | 1 | Reinforced Concrete Pier Cap | 4/14/2022 | Exposed Rebar | 0 | 12 | 0 | … |
| 030003 | 1 | Reinforced Concrete Column | 4/14/2022 | NA | NA | NA | NA | … |
| 030003 | 2 | Reinforced Concrete Column | 4/14/2022 | Delamination/Spall | 0 | 1 | 0 | … |
| 030003 | 2 | Reinforced Concrete Column | 4/14/2022 | Exposed Rebar | 1 | 0 | 0 | … |
| 030003 | 2 | Reinforced Concrete Column | 4/14/2022 | Abrasion/Wear (PSC/RC) | NA | 0 | 0 | … |
| 030003 | 2 | Reinforced Concrete Pier Cap | 4/14/2022 | Cracking (RC and Other) | 0 | NA | 0 | … |
| … | … | … | … | … | … | … | … | |

### 3.1.2 Preservation Activity Decision Tree

The preservation activity decision tree records the logic for triggering bridge preservation activities. This dataset was provided by SMU. The preservation activity decision tree can trigger preservation activities based on bridge elements, defect types, and severity.

Table 3.3 illustrates an example of a preservation activity decision tree in its original format. All preservation activity decision trees are detailed in APPENDIX C. The table is divided into two portions. The upper portion shows that the decision tree applies to "Reinforced Concrete Deck" elements, specifying corresponding to element numbers 12, 38, 16, 60, and 65. The lower portion is a matrix recording the preservation activities to be taken for different defects on the bridge element. The left side of the matrix lists specific defect numbers and defect names. The top of the matrix displays the severity levels of the defects. According to CS levels, defect severity is categorized into three types: CS 2, CS 3, and CS 4. CS 4 is further divided into two categories based on the percentage of the deck surface affected: $<$ 10% of "Deck Surface" and $\geqslant$ 10% of "Deck Surface". The middle portion of the matrix indicates the required preservation activities.

For example, if "Delamination/Spall" defects are found on a "Reinforced Concrete Decks" element at CS 4 level with the defect percentage at more than 10%, the preservation activity can be determined by locating the intersection of the "Delamination/Spall" row and the "CS4 with $\geqslant$ 10%" of "Deck Surface" column, which indicates that the preservation activity should be "Replace the Concrete Deck". Note that the triggering of preservation activities is from a higher level to a lower level. For example, if CS 3 and CS 2 criteria are met, CS 3 activity will be triggered. In addition, if element conditions exceed the threshold, a higher-level activity will be triggered. For example, if the CS 3 percentage for defect 1080 reaches 30%, it triggers the activity "Overlay".

Table 3.3 Data Samples of Preservation Activity Decision Tree (Original Format)

<table>
<tr><td colspan="6">Reinforced Concrete Decks</td></tr>
<tr><td colspan="2">Applies to Element #'s:</td><td>12</td><td>38</td><td>16</td><td>60</td><td>65</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="2"></td><td>CS2</td><td>CS3</td><td>CS4</td><td>CS4</td></tr>
<tr><td>Defect #</td><td>Defect Name</td><td>< 40% of Deck Surface</td><td>< 20% of Deck Surface</td><td>< 10% of Deck Surface</td><td>≥ 10% of Deck Surface</td></tr>
<tr><td>1080</td><td>Delamination/Spall</td><td>Concrete for Deck Repair</td><td>Concrete for Deck Repair</td><td>Overlay</td><td>Replace Concrete Deck</td></tr>
<tr><td>1085</td><td>Patched Area</td><td>Nothing</td><td>Concrete for Deck Repair</td><td>Overlay</td><td>Replace Concrete Deck</td></tr>
<tr><td>1090</td><td>Exposed Rebar</td><td>Concrete for Deck Repair</td><td>Overlay</td><td>Overlay</td><td>Replace Concrete Deck</td></tr>
<tr><td>1120</td><td>Efflorescence/Rust Staining</td><td>Nothing</td><td>Overlay</td><td>Overlay</td><td>Replace Concrete Deck</td></tr>
<tr><td>1130</td><td>Cracking (RC and Other)</td><td>Silane</td><td>HMWM</td><td>Overlay</td><td>Overlay</td></tr>
<tr><td>1190</td><td>Abrasion/Wear (PSC/RC)</td><td>Nothing</td><td>Overlay</td><td>Overlay</td><td>Overlay</td></tr>
</table>

Table 3.3 illustrates the original format of the decision tree obtained from SMU. However, this format is not directly readable by computers and is not conducive to subsequent coding work. Therefore, this dataset was converted to a tidy format during the preprocessing stage. In a tidy format, each row of the table specifies a preservation activity instance with its triggering conditions. The maintenance matrix in Table 3.3 contains 24 scenarios (6 defects × 4 CS levels), which correspond to the 24 rows in the tidy table. Detailed metadata descriptions for the tidy format table of the decision tree are provided in APPENDIX D. The tidy dataset is stored in the file "Step 0_DT_Activity.csv".

### 3.1.3 Activity Overwriting Rules

NCDOT indicates that certain preservation activities can overwrite their corresponding lower-level activities. This is because some activities can address multiple defects on an element, making the activities triggered by these defects redundant. The Activity Overwrite Rules dataset records the logic for overwriting redundant preservation activities. This dataset was compiled based on multiple meetings between the research team and SMU experts. The details for developing this dataset can be found in the meeting minutes listed in APPENDIX E.

Table 3.4 presents all activity overwrite rules used in this research. The first column lists the higher-level activities, and the second column lists the lower-level activities that are overwritten. The third column is the application granularity of the overwrite rules. If the application granularity is at the span/bent level, and there are both higher-level and lower-level activities on the same span/bent, the higher-level activity replaces the lower-level activity. For example, if bridge 030003, span 1, has two preservation activities, "Replace Concrete Deck" and "Overlay", then according to the first row of Table 3.4, "Replace Concrete Deck" replaces "Overlay". If the application granularity is at the bridge level, and there are both higher-level and lower-level activities on the same bridge, the higher-level activity can overwrite the lower-level activity.

Table 3.4 Preservation Activities Overwriting Rules

| Higher-level Activity (1) | Lower-level Activity (2) | Application Granularity (3) |
|---|---|---|
| Replace Concrete Deck | Overlay | Span/bent level |
| | Concrete for Deck Repair | |
| | HMWM | |
| | Silane | |
| Overlay | HMWM | Bridge level |
| | Silane | |
| Replace Section of Concrete Barrier | Shotcrete Repair | Span/bent level |
| | Concrete Repair | |
| | Silane | |
| Joint Replacement | Joint Cleaning | Span/bent level |
| | Bridge Joint Demolition | |
| Replace Reinforced Concrete Superstructure Element | Shotcrete Repair | Span/bent level |
| | FRP Beam Repair | |
| | Epoxy Resin Injection | |
| Replace Prestressed Superstructure Element | Repairs to Prestressed Girders | Span/bent level |
| | Shotcrete Repair | |
| | FRP Beam Repair | |
| | Repairs to Prestressed Girders with Strand Splice | |
| | Epoxy Resin Injection | |
| Replace Steel Superstructure Element | Steel Beam Repair | Span/bent level |
| | Steel Crack Arrest | |
| | Replace missing or broken fasteners | |
| | Heat Straightening | |
| | Spot Painting | |
| Replace Timber Superstructure Element | Replace missing or broken fasteners | Span/bent level |
| | Penetrating sealer | |
| Replace Bearing | Paint and Maintain Bearings | Span/bent level |
| | Replace missing or broken fasteners | |
| | Jack and Repair Bearing/Bearing Area | |

## 3.2 Datasets for Preservation Cost Estimation

This section introduces the three datasets used for preservation cost estimation. Specifically, these are the Activity Unit Price dataset, which records the unit price of each preservation activity; the Activity & Element Unit Conversion Ratio dataset, which addresses inconsistent unit measures between preservation activity and bridge element; and the Activity Extended Service Life dataset, which records the duration each preservation activity lasts after being performed.

### 3.2.1 Activity Unit Price

The Activity Unit Price dataset records the unit price of each bridge preservation activity. It serves as the basis for calculating the preservation cost of each bridge. This dataset was provided by NCDOT SMU.

Table 3.5 presents the Activity Unit Price dataset. It consists of four columns: The first column, "Activities", lists the names of various preservation activities. The second column, "Element Number", indicates the specific bridge element that the activity will be applied to. An empty value indicates no restriction by the bridge element is imposed on the activity. The third column, "Unit", specifies the unit of measurement for the preservation activity. The abbreviations for the units are as follows: SF (square feet), LF (linear feet), EA (each), LS (lump sum), and LBS (pounds). The fourth column, "Price", records the unit price of the bridge preservation activity in US dollars.

Table 3.5 Activity Unit Price

| Activity (1) | Element Number (2) | Unit (3) | Price (4) |
|---|---|---|---|
| Asphalt Patch | - | | NA |
| Bridge Joint Demolition | - | SF | $57.92 |
| Clean and Paint Substructure | - | SF | $20.27 |
| Clean and Recoating | - | SF | $20.27 |
| Clean and Repaint Bridge | - | SF | $64.17 |
| Concrete for Deck Repair | - | LF | $410.00 |
| Concrete Repair | - | LF | $701.70 |
| Epoxy Resin Injection | - | LF | $119.47 |
| FRP Beam Repair | - | SF | $65.00 |
| Heat Straightening | - | LF | $1,340.00 |
| HMWM | - | SF | $20.21 |
| Jack and Repair Bearing/Bearing Area | - | EA | $20,000.00 |
| Joint Cleaning | - | LF | $1.33 |
| Joint Replacement | 302 | LF | $531.50 |
| Joint Replacement | 304 | LF | $531.50 |
| Joint Replacement | 301 | LF | $49.16 |
| Joint Replacement | 305 | LF | $1,668.12 |
| Joint Replacement | 303 | LF | $706.43 |
| Nothing | - | | $- |
| Overlay (Epoxy) | - | SF | $925.91 |
| Overlay (PPC) | - | SF | $1,091.00 |
| Overlay (LMC) | - | SF | $823.00 |
| Paint and Maintain Bearings | - | EA | $600.00 |
| Penetrating sealer | - | SF | $9.38 |
| Pile Jacket | - | LF | $500.00 |
| Repair Section of Metal Barrier/Rail | - | LF | $429.29 |
| Repair Steel Substructure Element | - | SF | $71.11 |
| Repairs to Prestressed Girders | - | LF | $1,178.66 |
| Repairs to Prestressed Girders with Strand Splice | - | LF | $1,543.75 |
| Replace Bearing | - | EA | $20,600.00 |
| Replace Concrete Deck | - | SF | $1,345.62 |
| Replace Concrete Substructure Element | - | LF | $2,264.70 |
| Replace Defective Masonry | - | SF | $118.00 |

| | | | |
|---|---|---|---|
| Replace Masonry Mortar | - | SF | $118.00 |
| Replace missing or broken fasteners | - | EA | $700.00 |
| Replace Prestressed Superstructure Element | - | LF | $925.00 |
| Replace Reinforced Concrete Superstructure Element | - | LF | $2,264.70 |
| Replace Section of Concrete Barrier | - | LF | $107.23 |
| Replace Section of Metal Barrier/Rail | - | LF | $429.29 |
| Replace Section of Steel Deck | - | SF | $151.82 |
| Replace Section of Timber Barrier/Rail | - | | NA |
| Replace Section of Timber Deck | - | | NA |
| Replace Steel Deck | - | LS | $3,600,000.00 |
| Replace Steel Substructure Element | - | LF | $125.00 |
| Replace Steel Superstructure Element | - | LBS | $2.88 |
| Replace Timber Deck | - | LF | $18.20 |
| Replace Timber Substructure Element | - | LF | $68.20 |
| Replace Timber Superstructure Element | - | | NA |
| Replace Wearing Surface | - | | NA |
| Scour Countermeasures | - | LF | $5.10 |
| Shotcrete Repair | - | LF | $627.45 |
| Silane | - | SF | $8.22 |
| Spot Painting | - | SF | $85.33 |
| Steel Beam Repair (Bolted) | - | LF | $3,168.00 |
| Steel Beam Repair (Cut-out) | - | LF | $6,686.37 |
| Steel Beam Repair (Welding) | - | LF | $1,631.16 |
| Steel Crack Arrest | - | EA | $125.00 |
| Steel Repairs | - | LF | $6,685.37 |
| Temporary Shoring | - | SF | $56.00 |
| Zone Paint | - | SF | $71.11 |

### 3.2.2 Activity & Element Unit Conversion Ratio

The activity conversion ratio is used to convert units when the measurement units of bridge elements and preservation activities differ. This is because the preservation activity unit cost data obtained from SMU are based on historical bid averages of subcontractors who perform the preservation projects. Their measuring units as used in their contracts may differ from the bridge element units defined by FHWA.

For example, if bridge element 330, "Metal Bridge Railing", has a connection defect, a preservation activity such as "replace missing or broken fasteners" can be triggered. Note that the element unit for a bridge railing is "linear feet", while the measurement unit for the "replace missing or broken fasteners" activity is "each". To address this issue, the research matched bridge element inspection records with the activity bid average dataset to identify all inconsistent units. As a result, 25 inconsistent "bridge element–preservation activity" pairs were identified. The research team then consulted with SMU experts to determine the average conversion ratios for each pair. For example, a conversion ratio of 3.5 between the element "Other Bridge Railing (linear feet)" and the activity "Silane (square feet)" indicates that fixing one linear foot defect for the element will require 3.5 square feet of the silane activity.

Table 3.6 presents the conversion ratios for the 25 identified "bridge element–preservation activity" pairs. This dataset contains five columns: The first column lists the element name. The second column lists the element unit. The third column lists the preservation activity for the element. The fourth column lists the preservation activity unit. The fifth column lists the conversion ratio for the "bridge element–preservation activity" pair. The dataset is stored in the file "Step 0_unit_match.csv".

Table 3.6 Unit Conversion Ratio

| Element Name (1) | Element Unit (2) | Activity (3) | Unit (4) | Conversion Ratio (5) |
|---|---|---|---|---|
| Metal Bridge Railing | Feet | Replace missing or broken fasteners | EA | 1 |
| Other Bridge Railing | Feet | Replace missing or broken fasteners | EA | 1 |
| Other Bridge Railing | Feet | Silane | SF | 3.5 |
| Other Bridge Railing | Feet | Steel Crack Arrest | EA | 1 |
| Other Pile | Feet | Repair Steel Substructure Element | SF | 1 |
| Prestressed Concrete Closed Web/Box Girder | Feet | FRP Beam Repair | SF | 1 |
| Prestressed Concrete Open Girder/Beam | Feet | FRP Beam Repair | SF | 1 |
| Prestressed Concrete Top Flange | Square Feet | Concrete for Deck Repair | LF | 1 |
| Reinforced Concrete Abutment | Feet | Scour Countermeasures | LF | 1 |
| Reinforced Concrete Bridge Railing | Feet | Silane | SF | 3.5 |
| Reinforced Concrete Column | Each | Epoxy Resin Injection | LF | 1 |
| Reinforced Concrete Column | Each | Pile Jacket | LF | 1 |
| Reinforced Concrete Column | Each | Replace Concrete Substructure Element | LF | 1 |
| Reinforced Concrete Column | Each | Scour Countermeasures | LF | 1 |
| Reinforced Concrete Column | Each | Shotcrete Repair | LF | 1 |
| Reinforced Concrete Deck | Square Feet | Concrete for Deck Repair | LF | 1 |
| Reinforced Concrete Pile Cap/Footing | Feet | Scour Countermeasures | LF | 1 |
| Steel Abutment | Feet | Replace missing or broken fasteners | EA | 1 |
| Steel Floor Beam | Feet | Replace Steel Superstructure Element | LBS | 490 |
| Steel Open Girder/Beam | Feet | Replace Steel Superstructure Element | LBS | 490 |
| Steel Open Girder/Beam | Feet | Replace missing or broken fasteners | EA | 1 |
| Steel Pile | Feet | Clean and Paint Substructure | SF | 1 |
| Steel Pile | Feet | Repair Steel Substructure Element | SF | 1 |
| Steel Pile | Feet | Replace missing or broken fasteners | EA | 1 |
| Steel Pile | Feet | Scour Countermeasures | LF | 1 |

### 3.2.3 Activity Extended Service Life

The activity extended service life refers to the duration each preservation activity lasts after being performed. NCDOT uses 64 activities to preserve bridges, including 22 activities for preserving decks, 21 for superstructures, 12 for substructures, and 9 in general. Of those 64 activities, NCDOT has developed an estimation of the extended service life yielded by 57 activities. The seven remaining activities are (1) "Asphalt Patch", (2) "Replace Wearing Surface", (3) "Penetrate Sealer, (4) "Clean and Repaint Bridge", (5) "Clean and Paint Substructure", (6) "Steel Repairs", and (7) "Repairs to Prestressed Girders". The research team reviewed and found estimations of the extended service life for asphalt patches, replacing the wearing surface, and penetrating sealer (see Table 2.9). Estimations for similar activities were made for cleaning and painting the substructure (10 years), cleaning and repainting the bridge (20 years), and repairs to prestressed girders (20 years). The estimation for steel repairs (8 years) was determined by interviewing SMU engineers during progress report meetings. The Activity Extended Service Life dataset records the extended life of these bridge preservation activities.

Table 3.7 shows the service life of the 55 preservation activities incorporated in this research. The table contains two columns. The first column lists all preservation activities, and the second column indicates the activity extended service life. The Activity Extended Service Life dataset is stored in the file "Step 0_Activity_Extended_Life.csv".

Table 3.7 Preservation Activity Extended Service Life

| Activity<br>(1) | Extended Service Life<br>(2) |
|---|---|
| Shotcrete Repair | 10 |
| Replace Section of Concrete Barrier | 10 |
| Concrete Repair | 8 |
| Silane | 5 |
| Replace missing or broken fasteners | 10 |
| Replace Timber Superstructure Element | 5 |
| Clean and Paint Substructure | 10 |
| Repair Steel Substructure Element | 8 |
| Replace Steel Substructure Element | 10 |
| Steel Crack Arrest | 5 |
| Temporary Shoring | 4 |
| Scour Countermeasures | 6 |
| Concrete for Deck Repair | 10 |
| Overlay (Epoxy) | 10 |
| Overlay (PPC) | 20 |
| Overlay (LMC) | 25 |
| Replace Concrete Deck | 30 |
| HMWM | 8 |
| Replace Reinforced Concrete Superstructure Element | 15 |
| FRP Beam Repair | 15 |
| Epoxy Resin Injection | 10 |
| Replace Concrete Substructure Element | 10 |
| Pile Jacket | 10 |
| Repairs to Prestressed Girders | 20 |
| Replace Prestressed Superstructure Element | 15 |
| Repairs to Prestressed Girders with Strand Splice | 12 |
| Replace Section of Steel Deck | 15 |
| Replace Steel Deck | 30 |
| Steel Beam Repair (Bolted) | 8 |
| Steel Beam Repair (Cut-out) | 8 |
| Steel Beam Repair (Welding) | 8 |

| | |
|---|---|
| Replace Steel Superstructure Element | 15 |
| Heat Straightening | 15 |
| Replace Timber Deck | 15 |
| Replace Section of Timber Deck | 5 |
| Spot Painting | 15 |
| Repair Section of Metal Barrier/Rail | 8 |
| Replace Section of Metal Barrier/Rail | 10 |
| Replace Section of Timber Barrier/Rail | 5 |
| Replace Defective Masonry | 10 |
| Replace Masonry Mortar | 5 |
| Joint Replacement | 8 |
| Joint Cleaning | 2 |
| Bridge Joint Demolition | 8 |
| Paint and Maintain Bearings | 8 |
| Replace Bearing | 10 |
| Jack and Repair Bearing/Bearing Area | 6 |
| Penetrating sealer | 5 |
| Asphalt Patch | 4 |
| Replace Wearing Surface | 20 |
| Replace Timber Substructure Element | 5 |
| Zone Paint | 15 |
| Clean and Repaint Bridge | 20 |
| Steel Repairs | 8 |
| Clean and Recoating | 8 |

## 3.3 Datasets for Bridge Criticality Assessment

The datasets utilized for bridge criticality assessment include two components: the traffic volume component and the detour cost component. This section introduces the datasets in each component, as well as other data required for the model generally.

### 3.3.1 Datasets for Traffic Volume Component

Data for the volume component of the index is sourced from traffic counts produced annually by the NCDOT Traffic Survey Group for compliance with FHWA reporting standards. These counts describe AADT by highway network segment. In addition to traffic counts for all vehicles, AADT is also available for trucks. Employing truck counts helps to refine the detour component, as detour costs differ for different vehicle types and trip purposes. Where truck counts are not available for certain segments, route class and land use context information are used to impute traffic volume values. This concept is described in greater detail in the following sections.

Route segment AADT, Truck AADT, route class, and land use context information are available in the NCDOT Road Characteristics Arcs File Geodatabase. The research team exported the attribute table of the most recent version of the routes feature class for use in this project. It is provided with research materials as “allNCRoutes24.csv”. Table 3.8 presents a sample of rows and key fields from this table that are used to formulate the criticality index. Route ID, Begin Milepost1, and End Milepost1 are used to identify the specific route segment on which a bridge is located; fields AADT and AADT Truck store traffic volume counts; field Urban Type stores three categories of land use context information. Blanks in traffic volume fields connote a lack of data; blanks in the Urban Type field connote a non-urban land use context.

Table 3.8 NCDOT Route Characteristics Arcs Table Sample

| Route Name (1) | Route ID (2) | Begin Milepost1 (3) | End Milepost1 (4) | AADT (5) | AADT Truck (6) | Route Class (7) | Urban Type (8) | … |
|---|---|---|---|---|---|---|---|---|
| US-19 | 20000019044 | 0 | 0.006 | 5000 | 235 | 2 | - | … |
| NS-99098 | 50099098026 | 0.097 | 0.104 | - | - | 5 | Urbanized Area | … |
| NS-99713 | 50099713065 | 0.097 | 0.16 | - | - | 5 | Urbanized Area | … |
| NC-50 | 30000050096 | 0 | 0.018 | 3100 | 480 | 3 | - | … |
| I-73 | 10000073062 | 0 | 0.024 | 10000 | 1880 | 1 | - | … |
| NC-98 | 30000098064 | 0 | 0.448 | 2600 | 200 | 3 | - | … |
| I-85 | 10000085013 | 0.525 | 0.53 | 157000 | 16800 | 1 | Urbanized Area | … |
| NC-120 | 30000120081 | 0.069 | 0.154 | 2700 | 160 | 3 | - | … |
| NS-98323 | 50098323071 | 0.097 | 0.228 | - | - | 5 | Urban Cluster | … |
| NC-125 | 30000125042 | 1.22 | 1.301 | 1300 | 104 | 3 | - | … |
| NC-11 | 30000011071 | 0 | 0.141 | 1500 | 370 | 3 | - | … |
| NS-96231 | 50096231051 | 0.097 | 0.269 | - | - | 5 | Urbanized Area | … |
| NC-24 | 30000024013 | 0 | 0.001 | 29500 | 3060 | 3 | - | … |
| US-221 | 20000221006 | 0 | 0.06 | 2100 | 218 | 2 | - | … |
| I-40 | 10600040001 | 0 | 0.419 | - | - | 1 | Urbanized Area | … |
| I-240 | 10000240011 | 0 | 0.171 | 60000 | 2520 | 1 | Urbanized Area | … |
| NS-93867 | 50093867065 | 0.097 | 0.157 | - | - | 5 | Urbanized Area | … |
| NC-105 | 30000105095 | 0 | 0.081 | 13000 | 830 | 3 | - | … |
| SR-1528 | 40001528001 | 0.096 | 0.163 | - | - | 4 | Urbanized Area | … |
| NS-96797 | 50096797080 | 0.096 | 0.25 | - | - | 5 | - | … |
| SR-2578 | 40002578034 | 0.097 | 0.139 | 12000 | - | 4 | Urbanized Area | … |
| … | … | … | … | … | … | … | … | … |

### 3.3.2 Datasets for Detour Cost Component

Data for the detour component is sourced from NCDOT's structures GIS data layer and from time cost estimation factors produced by the U.S. Department of Transportation for use economic evaluations (USDOT 2016). NCDOT's structure GIS layer contains an estimate of detour time by bridge structure. It is important to note that these detour times may not reflect full traffic conditions and that in some cases no detour exists for a bridge (the bridge serves as a dead-end). This issue is described and addressed in greater detail in the following sections. Additionally, the structure data contains bridge route information that is used to locate the specific route segment on which a bridge is located.

Bridge detour and route information is available in the NCDOT Structure Locations Statewide Geodatabase maintained by the SMU. The research team exported the attribute table of the most recent version of the structures features class for bridges included in the study for use in this project. It is provided with research materials as "studyBridges24.csv". Table 3.9 presents a sample of rows and key fields from this table that are used to formulate the criticality index. Bridge Number is used as a unique bridge identifier. Route ID and Milepost are used to identify route network segments on which bridges are located for joining route data to bridges. Detour Length stores the detour length information for each bridge; values of 0 and 99 in this field are recorded using methods described in the following section.

Table 3.9 NCDOT Route Characteristics Arcs Table Sample

| Bridge Number (1) | Frontage Road Intersection (2) | Frontage Road Carried (3) | Route ID (4) | Detour Length (5) | Milepost (6) | … |
|---|---|---|---|---|---|---|
| 120121 | ADAMS CREEK | NC73 | 30000073013 | 2 | 16.36 | … |
| 120148 | ROCKY RIVER | SR1132 | 40001132013 | 2 | 9.23 | … |
| 120193 | CODDLE CREEK | SR1304 | 40001304013 | 4 | 3.28 | … |
| 590188 | MCALPINE CREEK | US74 WBL | 20600074060 | 2 | 5.00 | … |
| 030006 | LANES CREEK | NC218 | 30000218004 | 4 | 5.33 | … |
| 590450 | ELIZABETH AVE. | I277 & US74 | 10000277060 | 0 | 2.17 | … |
| 830025 | LAKE TILLERY | SR1740 | 40001740084 | 2 | 4.49 | … |
| 830052 | BIG BEAR CREEK | SR1134 | 40001134084 | 2 | 8.47 | … |
| … | … | … | … | … | … | … |

### 3.3.3 Data for Time Cost

The detour component of the criticality index also utilizes time cost estimates produced by USDOT. These time cost estimates reflect the cost per hour of travel time savings for a variety of vehicle types and trip purposes. These values were used to stratify and monetize costs incurred to bridge traffic in the event a detour is required. The criticality index uses the General Travel Time value for All Purposes of $18.80/hour with general traffic volume (AADT) and uses Commercial Vehicle Operators value for Truck Drivers of $32.40/hour with truck traffic volume (AADT Truck).

# 4 PRESERVATION ACTIVITY TRIGGERING MODEL

The research team developed a bridge preservation activity triggering model for the 442 bridges in Division 10. The model employed the following three datasets provided by NCDOT:

- Superstructure Inspection Data: This dataset contains inspection data for the superstructure elements of 442 bridges.
- Substructure Inspection Data: This dataset includes inspection data for the substructure elements of the same 442 bridges.
- Bridge Interstate Indicator: A binary variable indicating whether a bridge is part of the interstate system.

The triggering mechanism is based on the preservation activity decision tree and preservation activity overwrite rules (rules designed to overwrite initial preservation activities).

The model has a four-step procedure. The steps are (1) data preprocessing; (2) calculate defect percentage for bridge elements; (3) trigger the preservation activities for each span according to the decision trees; and (4) apply the overwrite rules. All codes in this chapter are available from the "TotalData.Rmd" file. An overview of the preservation activity triggering model can be visualized in Figure 4.1. The framework first preprocessed the element inspection datasets, and then calculated the preservation activities for each bridge in iteration. A detailed breakdown of the modules in the model is provided in the discussion in the subsequent sections.

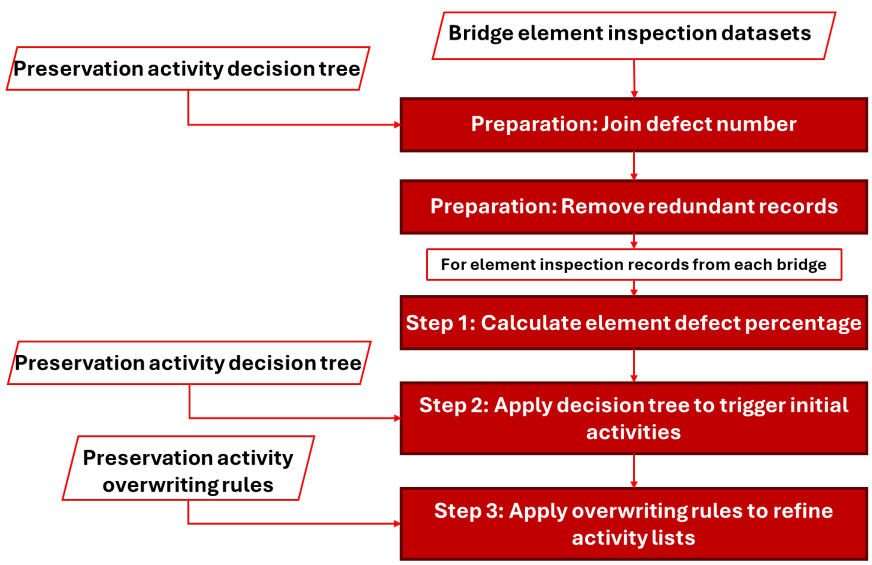



Figure 4.1 Preservation Activity Triggering Model Framework

## 4.1 Data Preparation

The research team collaborated with the experts from NCDOT SMU to gather their requirements and specifications for triggering specific preservation activities. The bridge preservation plan is derived iteratively for each individual bridge, triggering the preservation activities based on the element defect percentage and decision tree, then aggregating the same activity per span or bent, and finally using overwriting rules to adjust. The inspection data referenced is derived from a subset of the element inspection data for the 442 bridges, containing only the inspection records relevant to a specific bridge.

### 4.1.1 Join Defect Number to Element Inspection Data

Each element defect is associated with a defect number, as defined in the preservation decision tree dataset. The initial step involved associating the defect numbers with the defect names in the element inspection data. This was accomplished by joining the element inspection datasets with the preservation decision rule dataset, as illustrated in Figure 4.2.

**Algorithm 4.1**: associate defect name with defect number

**Inputs**: superstructure inspection dataset, substructure inspection dataset, preservation decision tree
**Outputs**: revised superstructure inspection dataset, revised substructure inspection dataset

Read in superstructure inspection dataset *superstructure*
Read in substructure inspection dataset *substructure*
Read in preservation decision tree *DT*
*revised_superstructure* = left join *superstructure* and *DT* by *defect_name*, then only keep defect_*number* as newly added column
*revised _substructure* = left join *substructure* and *DT* by *defect_name*, then only keep defect_*number* as newly added column
return *revised_superstructure*, *revised_substructure*

Figure 4.2 Algorithm for Obtaining Defect Number

### 4.1.2 Remove Elements 510, 515, and 520

Due to NCDOT's data collection and storage schema, the defects of elements 510 (wearing surface), 515 (steel protective coating), and 520 (concrete reinforcing steel protective system) are accounted for by parent element 521 (concrete protective coating). Detailed information is provided in APPENDIX F. Consequently, the research team considered only the defect quantities listed under element 521 and removed elements 510, 515, and 520 from the datasets. This was accomplished by applying a filter function in R. The pseudocode for this step is supplied in Figure 4.3.

**Algorithm 4.2**: remove redundant elements from inspection datasets

**Inputs**: superstructure inspection dataset from previous step, substructure inspection dataset from previous step
**Outputs**: cleaned superstructure inspection dataset, cleaned substructure inspection dataset

Read in superstructure inspection dataset *superstructure*
Read in substructure inspection dataset *substructure*
*revised_superstructure* = filter superstructure where *superstructure.elemen_number* not in (510, 515, 520)
*revised_substructure* = filter substructure where *substructure.elemen_number* not in (510, 515, 520)
return *revised_superstructure*, *revised_substructure*

Figure 4.3 Algorithm for Removing Redundant Samples

The preceding steps completed the data preprocessing procedures. The processed datasets serve as part of the input datasets for the activity triggering model, as discussed in the following sections.

## 4.2 Calculate Element Defect Percentage

This step involved calculating the percentage of each defect relative to the total element quantity. This calculation is essential as the preservation decision rule is applied based on the defective percentage of each element defect. Several procedures are included in this step.

### 4.2.1 Apply the Maintenance Quantity True/False Rule

The research team confirmed with NCDOT that maintenance/preservation activities will only be triggered for defects that have a corresponding maintenance quantity. If the "Level#maintenance" quantity equals 0 or if the value of the "Level#maintenance" quantity is missing, it means that the defects have already been addressed (see APPENDIX E). Using the superstructure dataset as an example, the data pipeline for this procedure is described in Figure 4.4.

**Algorithm 4.3**: apply maintenance quantity true/false rule

**Inputs**: superstructure inspection dataset from previous step
**Outputs**: revised superstructure inspection dataset

```
Read in superstructure inspection dataset superstructure
for i in superstructure.row_index:
    if superstructure[row_i].level2maintenance==0 then superstructure[row_i].level2AASHTO=0
    if superstructure[row_i].level3maintenance==0 then superstructure[row_i].level3AASHTO=0
    if superstructure[row_i].level4maintenance==0 then superstructure[row_i].level4AASHTO=0
end for
return superstructure
```

Figure 4.4 Algorithm for Applying Maintenance Quantity True/False Rule

Once this procedure is finished, the variables "level2maintenance", "level3maintenance", and "level4maintenance" are removed from the datasets for clearer representation.

### 4.2.2 Calculate Total Element Quantity

The defect percentage is calculated using equation 4.1. The total quantity refers to the element quantity per span (for superstructure elements) or per bent (for substructure elements). Since the element inspection dataset only lists element quantities associated with specific defects rather than bridge spans or bents, the total element quantity must be aggregated from the element inspection dataset before calculating the percentage.

$$Defect\ percentage = \frac{Defect\ Quantity}{Total\ Element\ Quantity} \times 100\% \qquad (4.1)$$

The research team combed the data samples manually and identified two types of observations.

- Type I: Different elements with the same type of defects. For example, as shown in Table 4.1, there are six bearing devices in span 1 of bridge 030003. All have corrosion.

Table 4.1 Sample Observations 1 from Superstructure Dataset

| No | Bridge number | Span number | Location name | Element number | Element quantity | Defect name |
|---|---|---|---|---|---|---|
| 1 | 030003 | 1 | Bearing Device | 316 | 1 | Corrosion |
| 2 | 030003 | 1 | Bearing Device | 316 | 1 | Corrosion |
| 3 | 030003 | 1 | Bearing Device | 316 | 1 | Corrosion |
| 4 | 030003 | 1 | Bearing Device | 316 | 1 | Corrosion |
| 5 | 030003 | 1 | Bearing Device | 316 | 1 | Corrosion |
| 6 | 030003 | 1 | Bearing Device | 316 | 1 | Corrosion |
| … | … | … | … | … | … | … |

- Type II: Same element with different types of defects. See Table 4.2. There is one deck in span 1 of bridge 030003. It has three types of defects: “Cracking”, “Delamination/Spall”, and “Exposed Rebar”.

Table 4.2 Sample Observations 2 from Superstructure Dataset

| No | Bridge number | Span number | Location name | Element number | Element quantity | Defect name |
|---|---|---|---|---|---|---|
| 1 | 030003 | 1 | Deck | 12 | 2108 | Cracking (RC and Other) |
| 2 | 030003 | 1 | Deck | 12 | 2108 | Delamination/Spall |
| 3 | 030003 | 1 | Deck | 12 | 2108 | Exposed Rebar |

For Type I elements, we can sum the element quantities (all bearings in the example) and use it as the denominator to calculate the percentage defect. For example, there are 12 records of element 316 (“Other Bearings”) for span 1 in Table 4.1. As a result, the total element quantity for this element will be 12 pieces. For Type II elements, if we used the same method as we had for Type I, we would count the element quantity multiple times, which would be incorrect. The research team identified all Type I elements (see APPENDIX G): they are elements 302, 310, 311, 312, 313, 314, 315, 316, and 521 (actually element 515, which, according to Section 4.1.2, is taken into consideration by its parent element 521). All other elements were classified as Type II elements. For example, there are three records of element 12 (reinforced concrete deck) for span 1 in Table 4.2. Since they describe three different defects for the same element, the element quantity in this example is 2108 square feet. These element types classify bridge elements according to different aggregating strategies. The following section applies these strategies to obtain total element quantities and defect percentages.

### 4.2.3 Calculate the Defect Percentage

The defect percentage can be obtained with equation 4.1. The defect percentage results for levels 2, 3, and 4 quantities for each inspection data sample were represented as variables and appended to the element inspection dataset. Using the superstructure dataset as an example, this process is illustrated in Figure 4.5.

**Algorithm 4.4**: calculate defect percentage

**Inputs**: superstructure inspection dataset from previous step
**Outputs**: revised superstructure inspection dataset

Read in superstructure inspection dataset *superstructure*
Define *super_typeI* and *super_TypeII* based on specific *ElementNumbers*:
    *super_typeI* includes specific element numbers
    *super_TypeII* includes all other element numbers not in *super_typeI*

Calculate total quantities for typeI elements in *super_typeI*:
    Group by multiple identifiers (*Number*, *SpanNumber*, *ElementNumber*, *ParentElementNumber*)
    Summarize to calculate total quantities (*ElementQuantity*)

Calculate total quantities for *typeII* elements in *super_typeII*:
    Group and summarize first by detailed identifiers to average *ElementQuantity*
    Then regroup by (*Number*, *SpanNumber*, *ElementNumber*, *ParentElementNumber*) to sum *ElementQuantity*

Calculate total defect quantities and store it as *super_defect_quantity*:
    Filter for non-NA defect names from *superstructure*

```
    Group by (Number, SpanNumber, ElementNumber, ElementName, ParentElementNumber, ComponentID,
        ComponentName, DefectName, DefectNumber)
    Summarize to calculate defect quantities (sum of AASHTO levels)

Calculate defect percentages:
    Combine total span data from both super_typeI and super_typeII into a single dataset super_span_with_total
    Join dataset super_span_with_total with super_defect_quantity as super_defect_percentage
    Calculate defect percentages for each level by according to equation 4.1 in super_defect_percentage

return super_defect_percentage
```

Figure 4.5 Algorithm for Calculating Defect Percentage

This algorithm first separates Type I and Type II elements into different data frames by filtering the element numbers. It then calculates the total element quantity, as specified in Section 4.2.2. Concurrently, the defect quantities at different CS levels are calculated by aggregating the same defects belonging to the same element. The two data frames are subsequently merged to restore the complete inspection dataset. A final dataset with element defect quantities at various CS levels and total element quantities is obtained. The defect percentage at different CS levels can then be derived using equation 4.1. Up to this point, we have obtained the measurements specified in the activity decision tree. The next procedure is to compare the measurements with the decision tree and trigger the initial preservation activity.

## 4.3 Apply Decision Tree to Trigger Initial Activities

At this stage, the processed element inspection dataset can be matched with the preservation decision tree dataset to identify the appropriate preservation activities for each defect instance. The research team developed data pipelines to facilitate this task. The activity triggering process for the superstructure dataset is illustrated in Figure 4.6.

**Algorithm 4.5**: triggering initial preservation activity

**Inputs**: superstructure inspection dataset from previous step, preservation decision tree

**Outputs**: superstructure inspection dataset with preservation activity

```
Read in superstructure inspection dataset superstructure
Read in preservation decision tree dataset DT

Initialize the Activity column in superstructure to 'NA'
Initialize an empty list errors

for each row (i) in superstructure:
    Read the defect details for the current row
    if the ElementNumber is 521:
        if the sum of Level3Percentage and Level4Percentage is greater than 0:
            Set Activity for this row to 'Clean and Recoating'
        else:
            Set Activity for this row to 'Nothing'
        Continue to the next iteration

    Query the DT for matching ElementNumber and DefectName
    if the result has fewer than 4 rows:
        Append an error message indicating the defect and element are not found
        Continue to the next iteration
```

```
    Retrieve percentage thresholds and logic from DT based on CS level and logic
    Determine applicable activity based on the defect percentages relative to thresholds:
        if Level4Percentage meets or exceeds the threshold (CS4 'Greater or Equal'):
            Set Activity based on Level 4 'Greater or Equal' activity
        else if conditions for Level 3 activity are met:
            Set Activity based on Level 4 'Less Than' activity
        else if conditions for Level 2 activity are met:
            Set Activity based on Level 3 'Less Than' activity
        else if conditions for Level 1 activity are met:
            Set Activity based on Level 2 'Less Than' activity
        else:
            Set Activity to 'Nothing'
    Record the determined Activity in superstructure for this row

if there are any errors:
    print unique errors

Filter superstructure to include only rows where Activity is not 'Nothing'

return superstructure
```

Figure 4.6 Algorithm for Determining Initial Preservation Activity

Initially, the algorithm loads both the superstructure dataset and the decision tree. It prepares the dataset by setting the "Activity" column to "NA" and initiates an empty error log. A special condition checks elements with a specific element number (521); according to the discussion with SMU experts, if the sum of their CS 3 percentage and CS 4 percentage is higher than zero, the activity is set to "Clean and Recoating". Otherwise, the activity is set to "Nothing" (see Section 4.1.2). For other elements, the algorithm queries the preservation decision tree using the element number and defect name to find applicable rules. If the query results in fewer than four matches, an error indicating the absence of data for the defect and element is logged, and the algorithm proceeds to the next element without setting an activity. This is because a decision tree rule should have at least four restricting criteria (CS 2, CS 3, and two thresholds at CS 4). For rows with adequate decision criteria, the algorithm retrieves percentage thresholds and decision logic from the decision tree and assigns an activity based on how defect percentages compare to these thresholds. After iterating through all the entries, the algorithm prints any logged errors. It then filters the dataset to exclude rows where the activity is "Nothing". The final dataset, annotated with assigned non-empty preservation activities, is then returned.

Up to this point, an initial preservation activity can be assigned for each defect instance. Next, the research team applies the implicit overwriting rules to refine the preservation activity list.

## 4.4 Applying Overwriting Rules

NCDOT uses overwrite rules to adjust the initial triggered preservation activities. This is because some activities can address multiple defects on the same elements, rendering the rest of the activities triggered by these defects redundant. The overwriting rules specify that if a higher-level activity exists, the corresponding lower-level activity will be substituted by the higher-level one. For example, if bridge 030003, span 1, has two preservation activities—"Joint Cleaning" and "Joint Replacement"—then "Joint Replacement" will overwrite "Joint Cleaning". The research team collaborated with SMU to develop a list of overwriting rules, as discussed in Section 3.1.3.

In the R-based activity triggering model, this step is executed through a set of user-defined functions. It is important to note that the overwriting rules are divided into two categories. The first category contains rules that apply at the bridge span/bent level, indicating that a higher-level activity only replaces lower-level activities that are to be applied to the elements in the same span/bent. The second category includes rules that operate at the bridge level, meaning that if the rule is triggered, the higher-level activity will substitute all lower-level activities within the bridge.

The research team presents the algorithm that applies the span-level overwriting rules to the dataset, as illustrated in Figure 4.7 Algorithm for Applying Sample Span-level Overwriting Rules. Two sample overwrite rules are included in the example. The same principle is applied to bent-level overwriting. For bridge-level overwriting rules, a simple "replace" function can accomplish the task, since only inspection data from a single bridge are fed to the algorithm in each iteration.

---

**Algorithm 4.6**: apply activity overwriting rules (span level)

---

**Inputs**: superstructure inspection dataset from previous step, preservation activity overwriting rules
**Outputs**: superstructure inspection dataset after applying overwriting rules

---

Read in superstructure inspection dataset *superstructure*
Read in preservation preservation activity overwriting rules

Initialize the *super_overwrite* data frame to store the final list of updated bridge activities

for each *SpanNumber* in unique (*superstructure.SpanNumber*):
    *SpanActivities* = Filter Activities by *SpanNumber* from *superstructure*

    if 'Replace Concrete Deck' in *SpanActivities.Activities*:
        Replace activities ('Overlay', 'Concrete for Deck Repair', 'HMWM', 'Silane') with 'Replace Concrete Deck'

# Apply additional overwriting rules in the for loop
    if 'Replace Reinforced Concrete Superstructure Element' in *SpanActivities.Activities*:
        Replace activities ('Shotcrete Repair', 'FRP Beam Repair', 'Epoxy Resin Injection') with 'Replace Reinforced Concrete Superstructure Element'

# Apply the rest of overwriting rules in the for loop
    ……

    Append *SpanActivities* to *super_overwrite*

return *super_overwrite*

---

Figure 4.7 Algorithm for Applying Sample Span-level Overwriting Rules

This algorithm subsets the inspection report into spans. The algorithm iterates through each span and checks for the presence of specific activities that will trigger an overwrite. If such activities are present, other lower-level activities are overwritten based on predefined rules. Eventually, all updated inspection datasets per span are collected into a dataset named "super_overwrite" and returned.

## 4.5 Summary

So far, the list of preliminary preservation activities has been prepared by automatically matching the element inspection records with the predefined preservation activity decision tree and the SMU experts–defined implicit overwriting rules. This list serves as the basis for further cost estimation, lifecycle expenditure assessment, and cost-benefit tradeoff analysis. A sample outcome dataset is shown in Table 4.3. Compared with the initial element inspection dataset, several changes can be observed:

1. Redundant columns such as "Span Length", "Continuous Span", and "Inspection Date" have been removed.
2. Element inspection records with missing CS quantities have been removed.
3. CS maintenance quantities have been removed.
4. CS repair quantities have been removed.
5. CS severity quantities have been removed.
6. The "number of Preservation Activity Records" (PARs), "PAR quantities", "Preventive Maintenance (PM) quantities", and "Critical Found (CF) quantities" have been removed.
7. The dataset has been grouped at the element level, with the total element quantity per span/bent added to the dataset.
8. CS percentages per defect have been calculated and added.
9. A preservation activity has been derived for each defect, and defect records that will not trigger a preservation activity have been removed from the dataset.

Several columns in Table 4.3 should be highlighted. Column 10 represents the total element quantity calculated according to the method listed in Section 4.2.2. Columns 12, 14, and 16 are the corresponding CS percentages obtained from Section 4.2.3. Lastly, column 19 lists the preservation activities being triggered after applying the overwriting rules listed in Section 4.4.

Table 4.3 Sample Superstructure Dataset Outputs from Preservation Activity Triggering Model

| Bridge Number (1) | Span Number (2) | Element Number (3) | Element Name (4) | Parent Element Name (5) | Component ID (6) | Component Name (7) | Defect Name (8) | Defect Number (9) | Total Span Quantity (10) | CS 2 Quantity (11) | CS 2 Percentage (12) | CS 3 Quantity (13) | CS 3 Percentage (14) | CS 4 Quantity (15) | CS4 Percentage (16) | Total PM Count (17) | Total CF Count (18) | Preservation Activity (19) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 030003 | 1 | 12 | Reinforced Concrete Deck | NA | 37 | Reinforced Concrete Deck | Cracking (RC and Other) | 1130 | 2108 | 1005 | 48 | 1 | 0 | 0 | 0 | 6 | 0 | HMWM |
| 030003 | 1 | 316 | Other Bearings | NA | 123 | Other Bearing | Corrosion | 1000 | 12 | 0 | 0 | 7 | 58 | 0 | 0 | 0 | 0 | Paint and Maintain Bearings |
| 030003 | 2 | 12 | Reinforced Concrete Deck | NA | 37 | Reinforced Concrete Deck | Cracking (RC and Other) | 1130 | 2133 | 1000 | 47 | 0 | 0 | 0 | 0 | 0 | 0 | HMWM |
| 030003 | 2 | 109 | Prestressed Concrete Open Girder/Beam | NA | 73 | Prestressed Concrete Girder | Cracking (PSC) | 1110 | 100 | 1 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | Epoxy Resin Injection |
| 030003 | 2 | 109 | Prestressed Concrete Open Girder/Beam | NA | 73 | Prestressed Concrete Girder | Delamination/Spall | 1080 | 100 | 4 | 4 | 2 | 2 | 0 | 0 | 0 | 0 | Repairs to Prestressed Girders |
| 030003 | 2 | 109 | Prestressed Concrete Open Girder/Beam | NA | 73 | Prestressed Concrete Girder | Exposed Rebar | 1090 | 100 | 1 | 1 | 1 | 1 | 0 | 0 | 0 | 0 | Shotcrete Repair |
| 030003 | 2 | 301 | Pourable Joint Seal | NA | 24 | Standard Joint | Adjacent Deck or Header | 2360 | 39 | 0 | 0 | 1 | 3 | 0 | 0 | 0 | 0 | Joint Replacement |
| 030003 | 2 | 316 | Other Bearings | NA | 123 | Other Bearing | Corrosion | 1000 | 12 | 0 | 0 | 12 | 100 | 0 | 0 | 0 | 0 | Paint and Maintain Bearings |
| 030003 | 3 | 12 | Reinforced Concrete Deck | NA | 37 | Reinforced Concrete Deck | Cracking (RC and Other) | 1130 | 2122 | 1000 | 47 | 1 | 0 | 0 | 0 | 0 | 0 | HMWM |
| 030003 | 3 | 109 | Prestressed Concrete Open Girder/Beam | NA | 73 | Prestressed Concrete Girder | Delamination/Spall | 1080 | 225 | 6 | 3 | 1 | 0 | 0 | 0 | 2 | 0 | Shotcrete Repair |
| 030003 | 3 | 316 | Other Bearings | NA | 123 | Other Bearing | Corrosion | 1000 | 12 | 0 | 0 | 12 | 100 | 0 | 0 | 0 | 0 | Paint and Maintain Bearings |
| 030003 | 4 | 12 | Reinforced Concrete Deck | NA | 37 | Reinforced Concrete Deck | Cracking (RC and Other) | 1130 | 2125 | 1000 | 47 | 0 | 0 | 0 | 0 | 0 | 0 | HMWM |
| 030003 | 4 | 109 | Prestressed Concrete Open Girder/Beam | NA | 73 | Prestressed Concrete Girder | Cracking (PSC) | 1110 | 100 | 1 | 1 | 0 | 0 | 0 | 0 | | | Epoxy Resin Injection |

# 5 PRESERVATION COST ESTIMATION MODEL

A preservation cost estimation is essential for bridge management as it enables accurate budgeting, strategic planning, and timely maintenance of infrastructure. By estimating the costs associated with preserving a bridge, bridge management teams can allocate resources efficiently, prioritize repair and rehabilitation efforts, and extend the bridge's lifespan. This proactive approach helps in identifying potential issues early and mitigating risks, thus ensuring the safety and reliability of the bridge.

The research team developed a cost estimation model to assess the cost of a given preservation plan obtained from the preservation activity triggering model in Chapter 4. The core idea is to obtain the preservation quantity from the preservation plan and the preservation unit cost from historical bidding records to determine the total cost. This model primarily uses the following input datasets:

- Bridge Preservation Activity List: The preservation activity list per bridge, which is the output of the preservation activity triggering model in Chapter 4.
- Preservation Activity Application Scope: The preservation quantity per bridge listed under three CS levels: CS 2, CS 3, and CS 4 quantities. This dataset lists the quantities that should be considered in the preservation plan for each activity. For example, if the activity "Silane" has a preservation scope of CS 3, it will address all the corresponding defects in CS 3 and above.
- Preservation Activity Unit Price: The unit price obtained from SMU based on historical bid averages for preservation projects.
- Preservation Activity Extended Service Life: The extended service life to be achieved by preservation activities.
- Bridge Element Unit: The unit of bridge elements, utilized to match the preservation quantity with the bridge element quantity.
- Inflation Ratio: The NCDOT inflation ratio used for budgeting.
- Activity & Element Unit Conversion Ratio: The ratio for converting bridge element defect quantity to preservation activity quantity.

The cost estimation model follows a five-step procedure, as illustrated in Figure 5.1

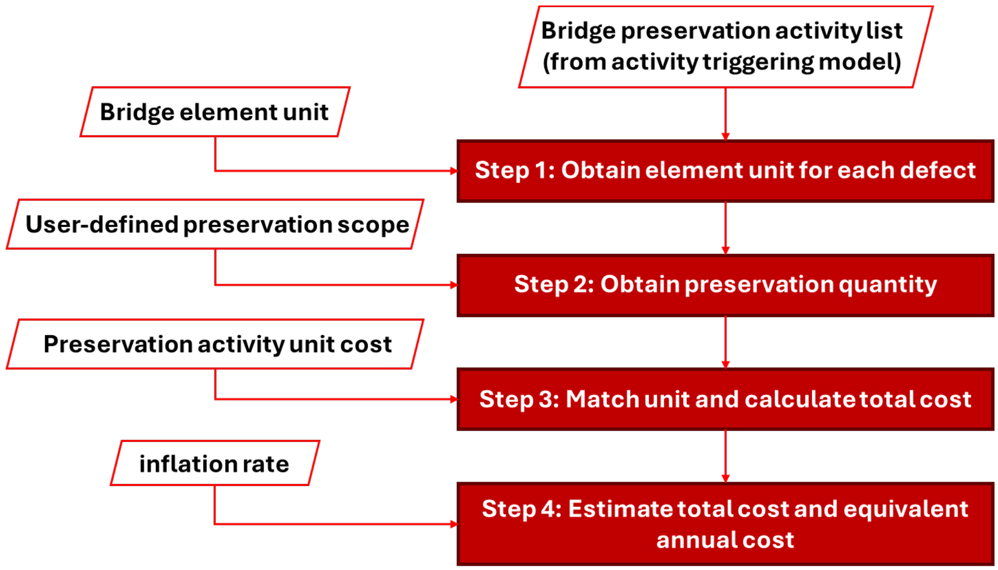



Figure 5.1 Flowchart for Cost Estimation Model

## 5.1 Data Acquisition and Preprocessing

A cost estimation model should be highly customizable to accommodate the needs of the bridge management team regarding changes in preservation scope, quantity, unit cost, and market dynamics. This section describes the data schema and acquisition process for the dataset created by the research team. Additional datasets used in this model are discussed in Section 3.2.

### 5.1.1 Preservation Activity Application Scope

This dataset is stored as a data table in CSV format named "Step 0_Activity_Apply_Scope.csv". The table contains two columns. The first column lists all preservation activities, and the second column lists the preservation scope of the corresponding activity. For example, as shown in Table 5.1, the activity "HMWM" will be preserved until CS 2, indicating that the portion of its corresponding defect with a condition stage greater than or equal to CS 2 (i.e., CS 2, CS 3, and CS 4) will receive HMWM. The default application scope for all activities was set to CS level 2. This is because the element inspection data from SMU listed the defect quantities starting from level 2. Starting from this level makes the preservation plan the most comprehensive and covers all detected defects.

Table 5.1 Samples from Preservation Activity Application Scope Dataset

| Preservation Activity<br>(1) | Preserve Until<br>(2) |
|---|---|
| HMWM | 2 |
| Paint and Maintain Bearings | 2 |
| Epoxy Resin Injection | 2 |
| … | … |

### 5.1.2 Miscellaneous Cost Estimation Parameters

This dataset is stored as a data table in a CSV format named "Step 0_Params.csv". The table contains four columns. The first column lists the bridge numbers of the 442 bridges in Division

10. Column 2 is an indicator of interstate bridges; value "I" means that the corresponding bridge is on an interstate route. The interstate indicator helps the model to determine which types of deck surface treatments can be implemented. The interstate data are obtained from a dataset provided by SMU, which includes the route number with which each of the 442 bridges is associated. According to the numbering rules for the US interstate highway system, a route number starting with "I" denotes an interstate bridge. Therefore, 106 bridges were labeled as interstate bridges. Column 3 indicates the default type of "Overlay" activity to be applied. Value 0 represents "Overlay (LMC)", 1 indicates "Overlay (Epoxy)", and 2 is "Overlay (PPC)". Column 4 lists the inflation rate to calculate the annuity of the preservation expenditure. The default value is 3% per year. Data samples are listed in Table 5.2. This file includes all miscellaneous parameters that can be customized by SMU experts and can be extended in the future. The full dataset is included in APPENDIX H.

Table 5.2 Samples for Miscellaneous Parameters

| Bridge Number (1) | Interstate (2) | Overlay Type (3) | Inflation Ratio (4) |
|---|---|---|---|
| 030003 | 0 | 1 | 0.03 |
| 030004 | 0 | 1 | 0.03 |
| 030006 | 0 | 1 | 0.03 |
| 030010 | 0 | 1 | 0.03 |
| 030012 | 0 | 1 | 0.03 |
| … | … | … | … |

The data described in this section, along with the datasets in Section 3.2, serve as the inputs for preservation cost estimation. The following sections discuss the steps and methods for establishing the cost estimation model.

## 5.2 Step 1: Obtain Bridge Element Unit

Notice that the preservation activity list obtained from Chapter 4 does not contain the measurement unit for bridge elements. Thus, an essential prerequisite in obtaining preservation cost is to identify the bridge element unit of measurement. This step utilizes a temporary dataset named "Step 0_element_unit.csv". This dataset records the units and element numbers for various bridge elements. These units are defined by FHWA and obtained from SMU. The full dataset is available in APPENDIX I.

This research matched the preservation list dataset with the bridge element unit dataset using the bridge element name. The output dataset of this step is the preservation activity list with an additional column named "Element Unit".

## 5.3 Step 2: Obtain Preservation Quantity

By default, the preservation quantity for each defect equals the CS quantities that are at or above CS 2. The research team also added a function in the estimation model to allow users to customize a particular CS level to preserve to, by adjusting the value in column 2 in Table 5.1. The preservation scope is determined at the activity level. Using such logic, Figure 5.2 illustrates the calculation of preservation quantities for defects in the superstructure dataset.

**Algorithm 5.1**: calculate maintenance quantity

**Inputs**: superstructure preservation activity list from previous step, preservation activity application scope dataset
**Outputs**: superstructure inspection dataset with maintenance quantity

```
Read in superstructure preservation activity list superstructure
Read in preservation activity application scope dataset scope

Merge superstructure with scope on the 'Activity' column
Select the following columns from superstructure:
    - 'SpanNumber'
    - 'ElementNumber'
    - 'ElementName'
    - 'Unit'
    - 'ComponentID'
    - 'ComponentName'
    - 'DefectName'
    - 'Activity'
    - 'ExtendedLife'
    - 'TotalSpanQuantity'
    - 'Level2Quantity'
    - 'Level3Quantity'
    - 'Level4Quantity'
    - 'PreserveUntil'

Initialize a new column 'MaintQty' in superstructure with NA values

for each row i in superstructure:
   if 'PreserveUntil' value in row i is 2:
      Set 'MaintQty' in row i to the sum of 'Level2Quantity', 'Level3Quantity', and 'Level4Quantity' in row i
   else if 'PreserveUntil' value in row i is 3:
      Set 'MaintQty' in row i to the sum of 'Level3Quantity' and 'Level4Quantity' in row i
   else if 'PreserveUntil' value in row i is 4:
      Set 'MaintQty in row i to the sum of 'Level4Quantity' in row i

return superstructure
```

Figure 5.2 Algorithm for Applying Sample Span-level Overwriting Rules

First, this algorithm subsets the necessary variables from the preservation activity list. It next initializes a new "MaintQty" variable for storing the preservation quantity per defect. The algorithm then iterates each preservation activity instance and aggregates the preservation quantity from various CS levels by matching the activity instance with the application scope dataset. After this procedure, the "MaintQty" variable will reflect the bridge element quantity of a given preservation activity.

## 5.4 Step 3: Match Unit and Calculate Total Cost

The preservation activity unit cost data obtained from SMU are derived from historical bid averages of contractors involved in preservation projects. Consequently, the units of measurement are based on contractual terms and may differ from the bridge element units defined by FHWA (APPENDIX I). For instance, if bridge element 330, "Metal Bridge Railing", exhibits a "Connection" defect, a preservation activity such as "Replace Missing or Broken Fasteners" may be initiated. The unit for "Metal Bridge Railing" is measured in "linear feet", whereas the unit for the activity of "Replace Missing or Broken Fasteners" is measured in "each".

To address this discrepancy, this research matched the bridge element inspection records with the activity bid average dataset to identify all inconsistent units. Consequently, 25 inconsistent "bridge element–preservation activity" pairs were identified. The research team then consulted with SMU experts to determine the average conversion ratios for each pair.

Subsequently, the preservation quantity is adjusted by multiplying it by this conversion factor. For elements that do not require a unit conversion, a factor of 1 is applied. Finally, the adjusted quantities are multiplied by the preservation activity unit cost to derive the cost estimation. The total preservation cost is the sum of the costs for all preservation activities. The calculation for this step is illustrated in Figure 5.3.

**Algorithm 5.2**: unit match and total cost estimation

**Inputs**: preservation activity lists from previous step, preservation activity unit price, activity-element unit conversion ratio

**Outputs**: inspection dataset with activity cost estimation

```
Read in superstructure preservation activity list superstructure
Read in substructure preservation activity list substructure
Read in preservation activity unit price dataset price
Read in activity-element unit conversion ratio dataset ConversionRatio

Initialize an empty data frame bridge
Combine superstructure and substructure into bridge

Merge bridge with price on the "Activity" column

for each row in bridge:
  if 'ElementNumber.y' is NA:
# ElementNumber.y is the element number from the unit price dataset
    Set 'ElementNumber.y' to the value of 'ElementNumber.x' in the same row

Filter bridge to keep only rows where 'ElementNumber.y' equals 'ElementNumber.x'
Remove the 'ElementNumber.y' column

Rename column 'ElementNumber.x' in bridge to 'ElementNumber'

for each row in bridge:
    if 'Price' is NA:
        Set 'Price' to 0

Join bridge with 'unit_match' on columns "ElementName", "ElementUnit", "Activity", and "Unit"

for each row in bridge:
# If no need for unit conversion, set the ratio to 1
    if 'ConversionRatio' is NA:
        Set 'ConversionRatio' to 1

Calculate 'MaintQty_Converted' as 'MaintQty' multiplied by 'ConversionRatio' for each row in bridge
return bridge
Calculate 'TotalCost' as 'Price' multiplied by 'MaintQty_Converted' for each row in bridge

return superstructure
```

Figure 5.3 Algorithm for Applying Sample Span-level Overwriting Rules

The above algorithm can be broken down into two steps. First, the bridge element preservation quantity is multiplied by the conversion ratio to obtain the real preservation quantity measured by the preservation activity bid price. Second, the subtotal cost per activity is obtained via preservation quantity multiplied by unit cost. Note that the preservation activity lists for superstructure and substructure were concatenated before adjusting preservation quantity to ensure the comprehensiveness of cost estimation per bridge.

## 5.5 Step 4: Calculate NPV and EAC

A preservation plan for a bridge encompasses multiple preservation activities, each with differing extended service lives. Therefore, a fair comparison between various plans necessitates scaling the total expenditure to a uniform timeframe. The research team employed two metrics, Net Present Value (NPV) and EAC, to evaluate economic efficiency.

An example is used below to explain the calculation process. Consider a bridge preservation plan comprising four activities, as detailed in Table 5.3. The extended service life for each activity is indicated in parentheses. The longest extended service life is identified as the service lifecycle of the entire plan, which, in this example, is 10 years. During this 10-year period, all four activities will be performed at the beginning of year 1. Subsequently, at the beginning of year 6, the activities “Paint & Maintain Bearings” and “Deck Sealing” will be performed for a second time, and the activity “Steel Beam Repair” will be performed again at the end of year 8. Given this expenditure schedule, the lifecycle payments can be visualized in Figure 5.4.

Table 5.3 Sample Preservation Plan

| Plan | Preservation Activities | Longest Extended Life (years) |
|---|---|---|
| A | Steel Beam Repair (8) + Paint & Maintain Bearings (5) + Deck Sealing (5) + Asphalt Overlay (10) | 10 |

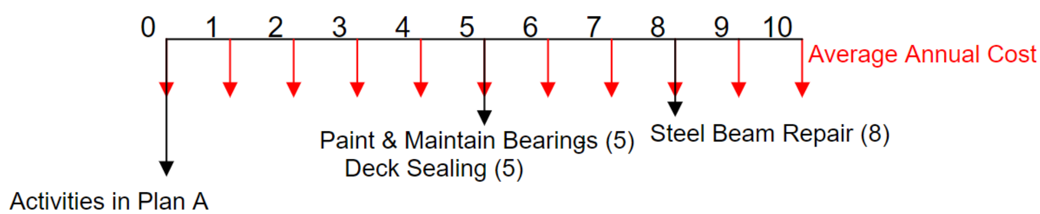



Figure 5.4 Lifecycle Payment Schedule for Sample Preservation Plan

As a result, the NPV and EAC can be obtained through several steps, as follows.

- Convert year 5 expenditure to present value via equation 5.1, where $F_{year5}$ represents the net expenditure at the beginning of year 6, which is the cost for activities “Paint & Maintain Bearings” and “Deck Sealing”, and $r$ represents the inflation ratio.

$$NPV_{year5} = \frac{F_{year5}}{(1+r)^5} \tag{5.1}$$

- Convert the new expenditure at the beginning of year 9 to EAC using equation 5.2, where $F_{year8}$ is the net expenditure for “Steel Beam Repair” at the beginning of year 9. The new expenditure for “Steel Beam Repair” covers years 9 to 16, which exceeds the designed service life of the plan. Therefore, we will only consider the expenditure that covers the period of year 9 and year 10 by first obtaining its EAC.

$$EAC_{Steel\ Beam\ Repair} = \frac{F_{year9} \times r}{1 - \frac{1}{(1+r)^8}} \quad (5.2)$$

- Subsequently, the NPV for years 9 and 10 expenditures can be obtained via equation 5.3, where $EAC_{Steel\ Beam\ Repair\_year8}$ and $EAC_{Steel\ Beam\ Repair\_year9}$ represent the EAC at years 9 and 10.

$$NPV_{year8} = \frac{EAC_{Steel\ Beam\ Repair\_year9}}{(1+r)^8} + \frac{EAC_{Steel\ Beam\ Repair\_year10}}{(1+r)^9} \quad (5.3)$$

- The lifecycle NPV for the entire preservation plan is the sum of three portions, as outlined in equation 5.4, where $IC_{year1}$ is the initial cost for the four activities at the beginning of year 1.

$$NPV = IC_{year1} + NPV_{year6} + NPV_{year9} \quad (5.4)$$

- Finally, the EAC for the entire plan is obtained via equation 5.5.

$$EAC = \frac{NPV \times r}{1 - \frac{1}{(1+r)^{10}}} \quad (5.5)$$

The research teams developed custom functions in R to achieve NPV and EAC calculations. The algorithm can be found in Figure 5.5.

**Algorithm 5.3**: calculate NPV and EAC

**Inputs**: preservation activity lists from previous step, inflation rate
**Outputs**: NPV and EAC of a preservation plan

Read in preservation activity list dataframe *bridge*

Initialize an empty dataframe *bridge_agg_Act*
Initialize a variable ‘longest_life’ with NA
Initialize a variable ‘EAC_Total’ with NA

Aggregate *bridge* data by ‘Activity’ and ‘ExtendedLife’ and calculate the sum of ‘TotalCost’ for each group
Store the result in *bridge_agg_Act*

# ‘ExtendedLife’ represent the extended service life for each activity
Find the maximum value of ‘ExtendedLife’ in *bridge_agg_Act* and store it as ‘longest_life’

Initialize a new column ‘NPV’ in *bridge_agg_Act* with NA values

for each row *i* in *bridge_agg_Act*:
# loop until the last but one year of the longest extended service life
  Calculate a sequence from 0 to (‘longest_life’ - 0.001), with steps of ‘ExtendedLife’ for the current row

# if the activity only requires full-cycle repetitions in the plan

```
    if 'longest_life' is exactly divisible by 'ExtendedLife' of the current row:
        Initialize 'NPV' to 0
        for each year j in the calculated sequence:
            Add to 'NPV' the cost of the current row divided by (1 + interest rate) raised to the power of 'j'
        Update the 'NPV' value of the current row in bridge_agg_Act

# If the activity requires partial cycle repetition
    else:
        Initialize 'NPV' to 0
        for each year j in the calculated sequence except the last one:
            Add to 'NPV' the cost of the current row divided by (1 + interest rate) raised to the power of j
        Calculate the remaining years from the last value in the sequence to ('longest_life' - 0.001), with steps of 1
        Calculate 'EAC' using the formula provided in equation 5.5
        for each year k in the remaining years:
            Add to 'NPV' the 'EAC' divided by (1 + interest rate) raised to the power of k
        Update the 'NPV' value of the current row in bridge_agg_Act

Round the 'NPV' values in bridge_agg_Act to 2 decimal places

Calculate 'EAC_Total' using the provided formula with the sum of 'NPV' values from bridge_agg_Act

return NPV, EAC_Total
```

Figure 5.5 Algorithm for Calculating NPV and EAC

Each activity has an extended service life. This algorithm first groups the preservation activity list from the earlier step by the activity name and its extended service life. The activity cost estimates are summed in each group. Next, the algorithm identifies the activity with the longest service life as the lifecycle of the preservation plan. The next step is to calculate NPV for each activity. It iterates each activity and identifies whether only full cycles are needed. If an activity is performed in full cycles, the NPV can be obtained in a similar way as in equation 5.1. Otherwise, the annual expenditures should be obtained first, before conversion to NPV, as illustrated in equations 5.2 and 5.3. Eventually, the total NPV and EAC are obtained via equations 5.4 and 5.5. This algorithm completes the preservation cost estimation. The total preservation cost, NPV, and EAC of a preservation plan are returned to the R Shiny application for cost-benefit analysis.

Notice that, given the nature of decision tree rules, most preservation activities are deterministic. To provide additional preservation plan candidates for tradeoff analysis, two groups of customizable preservation activities were identified in accordance with deliberations in the meetings with SMU (APPENDIX J). The first group consists of activities for deck overlay. Activities included in this group are:

- No overlay required
- HMWM
- Silane
- Overlay (Epoxy)
- Overlay (PPC)
- Overlay (LMC)

The second group consists of activities for steel beam repairing. Activities included in the group are:

- Steel beam repair (welding)
- Steel beam repair (bolted)
- Steel beam repair (cut-out)

These activities are customizable according to the specific needs of the SMU. The customization has the highest overwriting priority and functions at the bridge level. For example, if the bridge engineer determines that HMWM should be used, all other activities in this group will be replaced by HMWM for a bridge, regardless of other triggering rules. By default, activities with the lowest unit cost will be applied.

In the R Shiny application, this customization is achieved by manually selecting customized activities for each group after the software calculates the preservation plans and costs based on the steps described in preceding chapters. Detailed software architecture and designs for the customization function can be found in APPENDIX K.

## 5.6 Summary

This chapter aims to provide a cost estimation for preservation activities derived from the previous chapter, thereby establishing a data foundation for subsequent cost-benefit analysis. The main outcomes of this chapter are discussed as follows.

First, a comprehensive list of preservation activities per bridge is provided. Once given the scope of the preservation application, the preservation quantity and cost estimation for addressing each defect are detailed. A sample preservation activity list is shown in Table 5.4. Building upon Table 4.3, several newly added columns in Table 5.4 should be noted. Column 5 contains the element measuring units described in Section 5.2. Columns 15 and 16 list the preservation scope per preservation activity and the total preservation quantities that are discussed in Section 5.3. Columns 19 and 20 are the conversion factor and the converted preservation quantities discussed in Section 5.4. Column 21 represents the subtotal cost estimation for the corresponding activities.

Second, as the preservation plan is derived for all bridges, a summary table listing the total number of activities and the total preservation cost is presented. Sample data can be found in Table 5.5.

Additionally, a detailed bridge preservation report for each bridge is provided in HTML format. This report can be accessed via the R Shiny application. The steps to generate the HTML report are discussed in APPENDIX K, and a brief introduction to the report is also included in APPENDIX L.

Table 5.4 Sample Preservation Activity List with Cost Estimation Breakdown

| Bridge Number (1) | Span/Bent Number (2) | Element Number (3) | Element Name (4) | Element Unit (5) | Component ID (6) | Component Name (7) | Defect Name (8) | Preservation Activity (9) | Extended Service Life (10) | Total Span/Bent Quantity (11) | CS 2 Quantity (12) | CS 3 Quantity (13) | CS 4 Quantity (14) | Preserve Until (15) | Preservation Quantity (16) | Activity Unit (17) | Unit Price (18) | Conversion Ratio (19) | Converted Preservation Quantity (20) | Cost (21) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 030003 | Span 1 | 12 | Reinforced Concrete Deck | Square Feet | 37 | Reinforced Concrete Deck | Cracking (RC and Other) | HMWM | 8 | 2108 | 1005 | 1 | 0 | 2 | 1006 | SF | $20 | 1 | 1006 | $20,331 |
| 030003 | Span 1 | 316 | Other Bearings | Each | 123 | Other Bearing | Corrosion | Paint and Maintain Bearings | 8 | 12 | 0 | 7 | 0 | 2 | 7 | EA | $600 | 1 | 7 | $4,200 |
| 030003 | Span 2 | 12 | Reinforced Concrete Deck | Square Feet | 37 | Reinforced Concrete Deck | Cracking (RC and Other) | HMWM | 8 | 2133 | 1000 | 0 | 0 | 2 | 1000 | SF | $20 | 1 | 1000 | $20,210 |
| 030003 | Span 2 | 109 | Prestressed Concrete Open Girder/Beam | Feet | 73 | Prestressed Concrete Girder | Cracking (PSC) | Epoxy Resin Injection | 10 | 100 | 1 | 0 | 0 | 2 | 1 | LF | $119 | 1 | 1 | $119 |
| 030003 | Span 2 | 109 | Prestressed Concrete Open Girder/Beam | Feet | 73 | Prestressed Concrete Girder | Delamination/Spall | Repairs to Prestressed Girders | 20 | 100 | 4 | 2 | 0 | 2 | 6 | LF | $1,179 | 1 | 6 | $7,072 |
| 030003 | Span 2 | 109 | Prestressed Concrete Open Girder/Beam | Feet | 73 | Prestressed Concrete Girder | Exposed Rebar | Shotcrete Repair | 10 | 100 | 1 | 1 | 0 | 2 | 2 | LF | $627 | 1 | 2 | $1,255 |
| 030003 | Span 2 | 301 | Pourable Joint Seal | Feet | 24 | Standard Joint | Adjacent Deck or Header | Joint Replacement | 8 | 39 | 0 | 1 | 0 | 2 | 1 | LF | $49 | 1 | 1 | $49 |
| 030003 | Span 2 | 316 | Other Bearings | Each | 123 | Other Bearing | Corrosion | Paint and Maintain Bearings | 8 | 12 | 0 | 12 | 0 | 2 | 12 | EA | $600 | 1 | 12 | $7,200 |
| 030003 | Span 3 | 12 | Reinforced Concrete Deck | Square Feet | 37 | Reinforced Concrete Deck | Cracking (RC and Other) | HMWM | 8 | 2122 | 1000 | 1 | 0 | 2 | 1001 | SF | $20 | 1 | 1001 | $20,230 |
| 030003 | Span 3 | 109 | Prestressed Concrete Open Girder/Beam | Feet | 73 | Prestressed Concrete Girder | Delamination/Spall | Shotcrete Repair | 10 | 225 | 6 | 1 | 0 | 2 | 7 | LF | $627 | 1 | 7 | $4,392 |
| 030003 | Span 3 | 316 | Other Bearings | Each | 123 | Other Bearing | Corrosion | Paint and Maintain Bearings | 8 | 12 | 0 | 12 | 0 | 2 | 12 | EA | $600 | 1 | 12 | $7,200 |
| 030003 | Span 4 | 12 | Reinforced Concrete Deck | Square Feet | 37 | Reinforced Concrete Deck | Cracking (RC and Other) | HMWM | 8 | 2125 | 1000 | 0 | 0 | 2 | 1000 | SF | $20 | 1 | 1000 | $20,210 |
| 030003 | Span 4 | 109 | Prestressed Concrete Open Girder/Beam | Feet | 73 | Prestressed Concrete Girder | Cracking (PSC) | Epoxy Resin Injection | 10 | 100 | 1 | 0 | 0 | 2 | 1 | LF | $119 | 1 | 1 | $119 |

Table 5.5 Sample Preservation Activity Summary

| Timestamp | Bridge Number | County | Total Activity for Superstructure | Total Activity for Substructure | Total Activity | Total Cost |
|---|---|---|---|---|---|---|
| 2/28/24 13:19 | 030003 | ANSON | 21 | 15 | 36 | $201,888 |
| 2/28/24 13:19 | 030004 | ANSON | 5 | 2 | 7 | $55,190 |
| 2/28/24 13:19 | 030006 | ANSON | 3 | 3 | 6 | $14,952 |
| 2/28/24 13:19 | 030010 | ANSON | 2 | 0 | 2 | $3,765 |
| 2/28/24 13:19 | 030012 | ANSON | 4 | 2 | 6 | $2,479 |
| 2/28/24 13:19 | 030013 | ANSON | 1 | 0 | 1 | $164 |
| 2/28/24 13:19 | 030022 | ANSON | 0 | 0 | 0 | $ - |
| 2/28/24 13:19 | 030024 | ANSON | 7 | 3 | 10 | $6,564 |
| 2/28/24 13:19 | 030027 | ANSON | 5 | 2 | 7 | $78,855 |
| 2/28/24 13:19 | 030028 | ANSON | 14 | 4 | 18 | $127,580 |
| 2/28/24 13:19 | 030032 | ANSON | 37 | 14 | 51 | $278,199 |
| … | … | … | … | … | … | … |

# 6 BRIDGE CRITICALITY ASSESSMENT MODEL

The criticality index model developed for this report frames bridge criticality as a combination of volume and detour factors. The bridge volume factor considers the total amount of traffic carried by a bridge, while the bridge detour factor considers the cost associated with removing the bridge from the transportation network. Bridges may be considered "critical" due to either factor. That is, critical bridges are those that support large traffic volumes, provide key network connections, or do both (Nicholas et al. 2022). This research employs quantitative data to develop an index of criticality based on these factors that can be used to rank and classify bridges for the purposes of maintenance activity prioritization.

## 6.1 Method

The methodology for developing the criticality index uses the data sources described above to calculate volume and detour factors for all bridges, and then combines these values into a final index. The first step in developing both factors is identifying the AADT and Truck AADT for all bridges. For most bridges, these values can be identified using the Route ID and milepost of the bridge found in the structure's GIS data maintained by NCDOT. Matching the route ID and milepost of the structure with the route segment in the latest Route Characteristics file produced by NCDOT yields the AADT and Truck AADT at the precise location of the bridge crossing. However, these values are not available for every bridge. Exceptions include:

- Bridges located on divided highways for which traffic volumes are only reported as the total of both directions, rather than for individual bridges
- Bridges located on roadways for which either AADT or Truck AADT is not recorded/reported

The method developed here divides the traffic volume counts on divided highways at the point of the bridge evenly between the bridges in both directions. In order to do so, it is necessary to first identify and develop a table of the pairs of bridge numbers that exist in these situations through the use of a GIS. This step is not automated but requires completion only one time to generate a table used in the model script.

To fill data gaps for bridges located on routes without reported AADT or Truck AADT values, standard volume values are imputed from routes of similar route class and land use context. These imputed values are calculated using the median values in each combination of route class and land use context to minimize the influence of outliers. Route class and land use context are sourced from the NCDOT Route Characteristics file. An example standard volume value table is shown as Table 6.1 below.

Table 6.1 Example Standard Values for AADT (all vehicles) Imputed from Available Data, by Route Class and Land Use Context

| | Land Use Context | | |
|---|---|---|---|
| **Route Class** | **Non-Urban** | **Urban Cluster** | **Urbanized Area** |
| 1 - Interstate | 30500 | 44500 | 75000 |
| 2 - US Route | 8100 | 12000 | 23000 |
| 3 - NC Route | 4400 | 9100 | 15500 |
| 4 - Secondary Route | 1000 | 2900 | 7200 |

Table 6.2 below describes the source of volume data for all vehicles (left) and trucks (right) using the methods for sourcing volume data and filling gaps described above. Volume data for all vehicles are available for twice as many of the bridges included in the study than truck volumes alone. The gaps in truck volumes must be filled with standard imputed values.

Table 6.2 Source of Volume Data by Vehicle Type

| | Vehicle Type | |
|---|---|---|
| **Data Source** | **All Vehicles** | **Trucks** |
| Volume at Route | 73% | 36% |
| Volume at Paired Bridge | 7% | 6% |
| Imputed | 20% | 58% |

### 6.1.1 Volume Component

The volume component of the final bridge criticality index is the simple count of all vehicles (AADT) at the bridge crossing. Because this component will be combined with the detour factor variable in the final index, it requires standardization to a unitless index, which is accomplished through scaling to the maximum using the formula below:

$$TotalAADT_{Scale} = TotalAADT_i / TotalAADT_{max} \qquad (6.1)$$

where:
$TotalAADT_i$ = the total AADT of all vehicles at bridge *i*
$TotalAADT_{max}$ = the maximum AADT of all vehicles at bridges in the study set

### 6.1.2 Detour Component

The detour component of the criticality index uses bridge volume to calculate the cost of detours when the bridge is removed from the network. This cost estimation treats vehicle and truck time costs separately. These time costs are multiplied by the bridge detour time and summed to produce a total daily cost, in dollars, of the bridge's removal from the network. It is important to note that each bridge is treated as an isolated case; network effects that may stem from interdependent bridges are not considered. The formula below describes the bridge detour cost in dollars per day:

$$DetCost_v = (TotalAADT_i \times DetLength_i \times \frac{TimeCost_v}{60}) \qquad (6.2)$$

where:
$TotalAADT_i$ = the total AADT of all vehicles at bridge *i*
$DetLength_i$ = the detour length of bridge *i*, in minutes
$TimeCost_v$ = the time cost, in dollar per hour, for general vehicle travel time (all purposes)

Similarly, the detour cost in dollars per day for truck traffic is given by the formula:

$$DetCost_t = (TotalAADT_i \times DetLength_i \times \frac{TimeCost_t}{60}) \qquad (6.3)$$

where:
$TotalAADT_i$ = the total AADT of trucks at bridge *i*
$DetLength_i$ = the detour length of bridge *i*, in minutes

$TimeCost_t$ = the time cost, in dollar per hour, for commercial vehicle operators (truck drivers)

The structures GIS data maintained by NCDOT contains detour values of zero for some bridges, indicating no detour time, and a detour length of 99 for some bridges, indicating no available detour. To ensure all bridges have a valid and non-zero detour cost, the research applied minimum and maximum assumptions to these bridges. Bridges were assigned a minimum detour time of 0.5 and a maximum detour time of 45. This aligns bridges with no detours slightly above the maximum valid detour time in the dataset of 33.

The final detour requires summing and standardization to a unitless index for use in the overall criticality score:

$$TotalDetCost_i = DetCost_v + DetCost_t \quad (6.4)$$

$$TotalDetCost_{Scale} = TotalDetCost_i \,/ TotalDetcCost_{\max} \quad (6.5)$$

where:
$TotalDetCost$ = the total detour cost for all vehicles at bridge *i*
$TotalDetCost_{max}$ = the maximum total detour cost of all vehicles at bridges in the study set

### 6.1.3 Final Criticality Index

The unitless indexes for the volume and detour components must be combined to yield a final criticality index that reflects both factors. This research effort gives equal (50%) weight to both components, though alternative weighting schemes could be used in the event one component is intended to be emphasized. The weighted sum of the two components is therefore given by:

$$CompSum = 0.5 \times TotalAADT_{Std} + 0.5 \times TotalDetcCostt_{Std}$$

Following weighting and summation, the final index is calculated with scaling using the following formula:

$$Critical\ Index = \sqrt{CompSum_i / CompSum_{max}} \times 100 \quad (6.6)$$

where:
$CompSum_i$ = the sum of weighted components at bridge *i*
$CompSum_{max}$ = the maximum sum of weighted components for bridges in the study set

The final scaled criticality index therefore provides indexed scores on a scale of 0 to 100, but with no bridges having a criticality level of zero. A discussion of the resulting data is provided in the following section.

### 6.1.4 Example Calculation

In this section, volume and detour components of the criticality index are calculated for a bridge using the data as shown in Table 6.3:

Table 6.3 Data for Calculating Volume and Detour Components of the Criticality Index

| BRDG_NBR | RTE_ID | MP | DETOUR_LEN |
|---|---|---|---|
| 590121 | 30000051060 | 5.037 | 6 |

And its corresponding record from the Table 6.4 route segments table:

Table 6.4 Route Segments Table

| RouteName | RouteID | BeginMp1 | EndMp1 | AADT | AadtTruck | RouteClass | UrbanType |
|---|---|---|---|---|---|---|---|
| NC-51 | 30000051060 | 5.006 | 5.257 | 32500 | 1070 | 3 | Urbanized Area |

In this case, the complete volume data is available for the bridges, and no standard values need to be applied. The volume component ($TotalAADT_{Scale}$) of the criticality for this bridge can be computed using the bridge AADT and the max bridge AADT in the study sample (148,000) or bridges using the following formula:

$$TotalAADT_{Scale} = TotalAADT_i / TotalAADT_{max} \quad (6.7)$$

$$TotalAADT_{Scale} = 32{,}500/148{,}000 \quad (6.8)$$

$$TotalAADT_{Scale} = 0.22 \quad (6.9)$$

The total daily detour cost, $TotalDetCost_i$, can be calculated below as the sum of all vehicle costs ($DetCost_v$) and truck detour costs ($DetCost_t$):

$$DetCost_v = (TotalAADT_i \times DetLength_i \times \frac{TimeCost_v}{60}) \quad (6.10)$$

$$DetCost_v = (32500 \times 6 \times \frac{\$18.80}{60}) \quad (6.11)$$

$$DetCost_v = \$61{,}100 \quad (6.12)$$

$$DetCost_t = (TotalTruckAADTT_i \times DetLength_i \times \frac{TimeCost_v}{60}) \quad (6.13)$$

$$DetCost_v = (1070 \times 6 \times \frac{\$32.40}{60}) \quad (6.14)$$

$$DetCost_v = \$3{,}466.80 \quad (6.15)$$

$$TotalDetCost_i = DetCost_v + DetCost_t \quad (6.16)$$

$$TotalDetCost_i = \$61{,}100 + \$3{,}466.80 \quad (6.17)$$

$$TotalDetCost_i = \$64{,}566.80 \quad (6.18)$$

The scaled detour component can be calculated using the maximum total daily detour cost for bridges in the dataset ($176,973) as follows:

$$TotalDetCost_{Scale} = TotalDetCost_i / TotalDetcCost_{\max} \quad (6.19)$$

$$TotalDetCost_{Scale} = \$64{,}566.80 / \$176{,}973 \quad (6.20)$$

$$TotalDetCost_{Scale} = 0.36 \quad (6.21)$$

The final criticality index is calculated by summing the individual components using equal weighting and scaling using the following formulas (assuming the maximum component sum for bridges in the datasets of 0.79):

$$CompSum = 0.5 \times TotalAADT_{Std} + 0.5 \times TotalDetcCostt_{Std} \quad (6.22)$$

$$CompSum = 0.5 \times 0.22 + 0.5 \times 0.36 \quad (6.23)$$

$$CompSum = 0.29 \quad (6.24)$$

$$Critical\ Index = \sqrt{CompSum_i / CompSum_{max}} \times 100 \quad (6.25)$$

$$Critical\ Index = \sqrt{0.29/0.79} \times 100 \quad (6.26)$$

$$Critical\ Index = 60.6 \quad (6.27)$$

## 6.2 Results

A histogram of final criticality index values for the 442 bridges included in this study is provided in Figure 6.1. The distribution is roughly bimodal but skewed such that there is a large local maximum of criticality values around 20 and a small local maximum of criticality values around 70. These distinct concentrations are likely a reflection of the stark differences in traffic volumes that can be handled between different highway classes. Additionally, the histogram shows there are certain particularly high-frequency values that appear as outliers, such as the high-frequency values around 10, 35, and 65. These outlier peaks are likely to originate from the use of imputed standard traffic volumes described above, which result in groupings of criticality index values for bridges with similar characteristics and no available volume data.

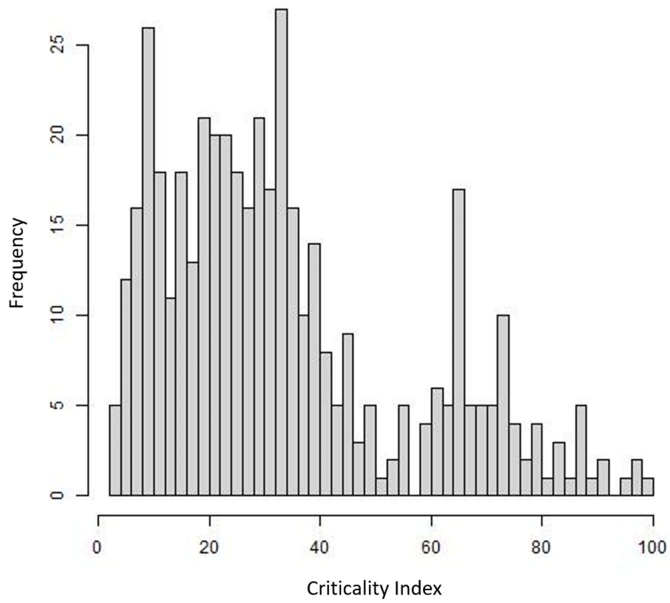


Figure 6.1 Histogram of Final Criticality Index Values for Bridges

## 6.3 Summary

The criticality index model developed for this research is meant to facilitate the stratification of bridges based on their essentialness to the highway network for the purposes of prioritizing maintenance activities. This is accomplished by considering multiple factors (volume and detours) within a single index. This method is based on quantitative observations of traffic, detour lengths, and the cost of time for different vehicles and trip purposes. With the exception of the initial identification of paired bridges on divided highways using a GIS, this model is automated and included as a module scripted in the R programming language within the large project software package.

It is important to note that the model also includes assumptions about the relative importance of each factor to overall criticality, referred to here as "weighting". This research assumes an equal weight will be given to each component, but this assumption can vary with the priorities of an agency. Similar assumptions apply to the maximum and minimum detour times assigned to bridges.

Additionally, this criticality index considers bridges in isolation on the highway network. There may be some cases in which network segment interdependencies cannot be captured using this isolated approach. An example is the case of truck traffic on weight-restricted bridges. In some cases, bridge detours may create additional complications for heavy trucks if the shortest detours require crossings on weight-restricted bridges. Detour lengths by bridge may therefore vary by vehicle type. Additionally, detours chosen by drivers depend on specific origin and destination objectives, and, in the event bridge crossings are known to be unavailable, outages may result in drivers choosing much different routes than they would otherwise choose to minimize total travel time. This could result in different traffic patterns than simply the shortest circumvention of each bridge.

# 7 BRIDGE PRESERVATION PRIORITIZATION

Based on the comprehensive preservation cost estimations and bridge criticality assessments, this research developed a cost-benefit analysis to prioritize preservation plans for each bridge. The prioritization method employs a two-phase framework by combining a cap approach and a grouping approach. The main idea is described as follows:

1. The cap approach: Decision makers will set a lower bound and an upper bound for the total preservation cost.
2. The grouping approach: All bridges will be divided into three groups. Group 1 consists of bridges with a total preservation cost less than the lower bound; Group 2 contains bridges with a total preservation cost between the lower and upper bounds; Group 3 includes bridges with a preservation cost greater than the upper bound.
3. All preservation activities will be recommended for bridges in Group 1.
4. Bridges in Group 2 will be assigned a 4-point priority level based on the cost-benefit ratio. This ratio is calculated by dividing the bridge criticality score by the total preservation cost. Bridges will be divided into four priority levels based on their cost-benefit ratio quantile.
5. Bridges in Group 3 will be considered on a case-by-case basis. A detailed preservation report will be provided to bridge preservation managers for decision- making.

By default, the lower bound is set at $10,000 and the upper bound is set at $500,000. During our experiments with the 442 bridges, these thresholds resulted in 146 bridges in Group 1, 273 bridges in Group 2, and 22 bridges in Group 3. This chapter discusses the outcomes and results of bridge prioritization for each group.

## 7.1 Group 1: Bridges with Low Preservation Costs

Group 1 includes bridges with relatively low total preservation costs. Therefore, it is unnecessary to separate preservation activities for individual bridges at the implementation stage. This research provides a summary table that documents preservation information for each bridge at Table 7.1.

Table 7.1 Sample summary of bridges in Group 1

| Bridge Number | County | AADT | No. of Superstructure Activities | No. of Substructure Activities | No. of Total Activities | Preservation Cost | Criticality Score | Category |
|---|---|---|---|---|---|---|---|---|
| 030010 | ANSON | 2700 | 2 | 0 | 2 | $3,765 | 15.11 | < $10,000 |
| 030012 | ANSON | 1500 | 4 | 2 | 6 | $2,643 | 14.41 | < $10,000 |
| 030013 | ANSON | 800 | 1 | 0 | 1 | $164 | 7.96 | < $10,000 |
| 030022 | ANSON | 2200 | 0 | 0 | 0 | $0 | 14.64 | No need for preservation |
| 030036 | ANSON | 2300 | 0 | 0 | 0 | $0 | 10.68 | No need for preservation |

The table categorizes the bridges into two sets based on whether a preservation activity is needed. Bridge managers can access overview information such as AADT, the number of required activities, total cost, and bridge criticality. The complete table can be accessed in the R Shiny application, as described in APPENDIX L.

## 7.2 Group 2: Bridges with Intermediate Preservation Cost

This research used equation 7.1 to calculate the cost-benefit ratio for bridges in Group 2. These bridges were then divided into four subsets based on their cost-benefit ratio quantile, as described in Table 7.2. Using these criteria, the preservation priority for individual bridges is shown in Figure 7.1.

$$CostBenifitRatio = \frac{Criticality\ Score}{Preservation\ Cost} \quad (7.1)$$

Table 7.2 Preservation priority for bridges in Group 2

| Quantile | Priority |
|---|---|
| 0% - 25% | Low priority |
| 25% - 50% | Medium priority |
| 50% - 75% | High priority |
| 75% - 100% | Critical priority |

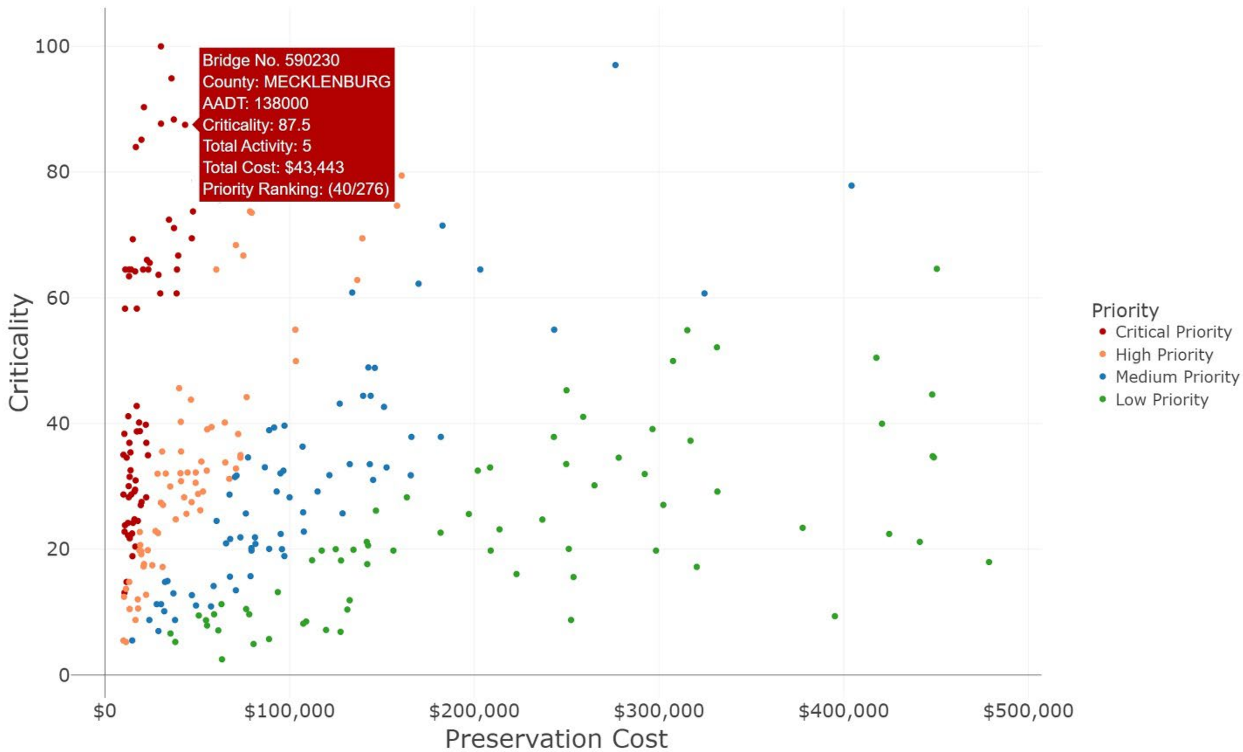


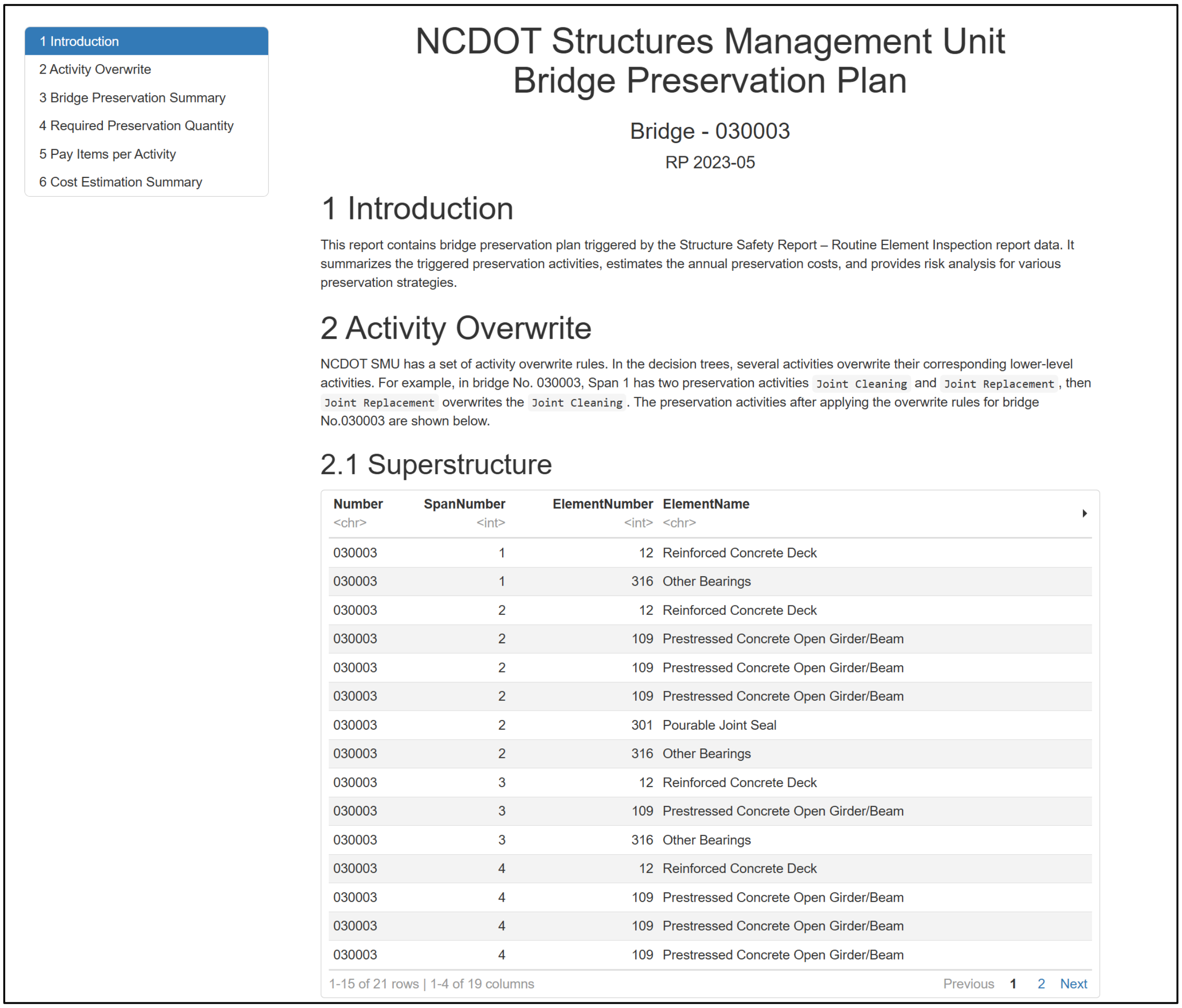
Figure 7.1 Sample Bridge Preservation Priority

This research provides an interactive visualization in the R Shiny application. Detailed information on using the tool can be found in APPENDIX L.

## 7.3 Group 3: Bridges with High Preservation Cost

A more prudent assessment is required for bridges with high preservation costs. Instead of providing a prioritization, this research developed detailed preservation reports for these bridges, enabling managers to fine-tune their preservation plans.

The preservation report is an HTML-based file that includes detailed steps for triggering preservation activities and cost estimates. A snapshot of a sample report is shown in Figure 7.2. The report contains six sections documenting raw element inspection data of superstructures and substructures, the process of applying overwrite rules, a preservation activity summary, the calculation process of preservation quantities, preservation costs, and a cost summarization. It provides step-by-step illustrations for deriving preservation activities and cost estimates. Bridge engineers are advised to review the reports and adjust detailed preservation plans for these high-value bridges. For additional information on the preservation report, please refer to Appendix L.




1 Introduction
2 Activity Overwrite
3 Bridge Preservation Summary
4 Required Preservation Quantity
5 Pay Items per Activity
6 Cost Estimation Summary


NCDOT Structures Management Unit
Bridge Preservation Plan

Bridge - 030003

RP 2023-05

1 Introduction

This report contains bridge preservation plan triggered by the Structure Safety Report – Routine Element Inspection report data. It summarizes the triggered preservation activities, estimates the annual preservation costs, and provides risk analysis for various preservation strategies.

2 Activity Overwrite

NCDOT SMU has a set of activity overwrite rules. In the decision trees, several activities overwrite their corresponding lower-level activities. For example, in bridge No. 030003, Span 1 has two preservation activities `Joint Cleaning` and `Joint Replacement`, then `Joint Replacement` overwrites the `Joint Cleaning`. The preservation activities after applying the overwrite rules for bridge No.030003 are shown below.

2.1 Superstructure

| Number <chr> | SpanNumber <int> | ElementNumber <int> | ElementName <chr> |
|---|---|---|---|
| 030003 | 1 | 12 | Reinforced Concrete Deck |
| 030003 | 1 | 316 | Other Bearings |
| 030003 | 2 | 12 | Reinforced Concrete Deck |
| 030003 | 2 | 109 | Prestressed Concrete Open Girder/Beam |
| 030003 | 2 | 109 | Prestressed Concrete Open Girder/Beam |
| 030003 | 2 | 109 | Prestressed Concrete Open Girder/Beam |
| 030003 | 2 | 301 | Pourable Joint Seal |
| 030003 | 2 | 316 | Other Bearings |
| 030003 | 3 | 12 | Reinforced Concrete Deck |
| 030003 | 3 | 109 | Prestressed Concrete Open Girder/Beam |
| 030003 | 3 | 316 | Other Bearings |
| 030003 | 4 | 12 | Reinforced Concrete Deck |
| 030003 | 4 | 109 | Prestressed Concrete Open Girder/Beam |
| 030003 | 4 | 109 | Prestressed Concrete Open Girder/Beam |
| 030003 | 4 | 109 | Prestressed Concrete Open Girder/Beam |

1-15 of 21 rows | 1-4 of 19 columns    Previous 1 2 Next

Figure 7.2 Snapshot of sample bridge preservation report

## 7.4 Summary

This chapter has synthesized results from previous chapters to derive recommendations for preservation prioritization. Experts can utilize the tools to customize grouping thresholds and prioritize bridges based on specific needs. All the results presented in this chapter are sampled from the R Shiny application. Detailed instructions on using the application and interpreting the results are provided in APPENDIX L.

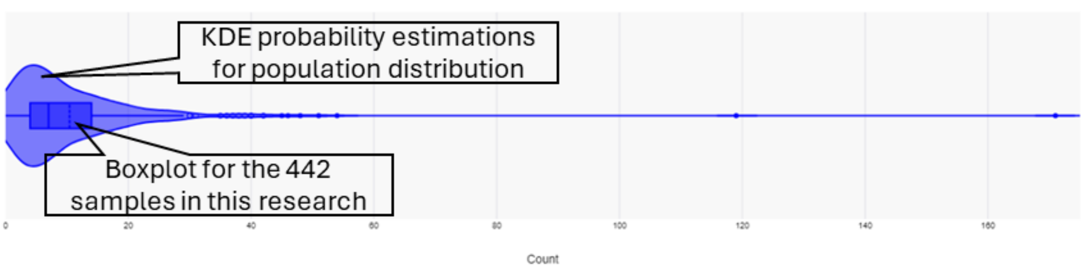
# 8 CONCLUSIONS

This research developed a bridge preservation prioritization framework for NCDOT. The framework includes three submodels: the preservation activity triggering model, the preservation cost estimation model, and the bridge criticality assessment model. This is among the first research efforts to analyze bridge preservation priority by considering both cost and criticality. Several critical conclusions can be drawn from this research.

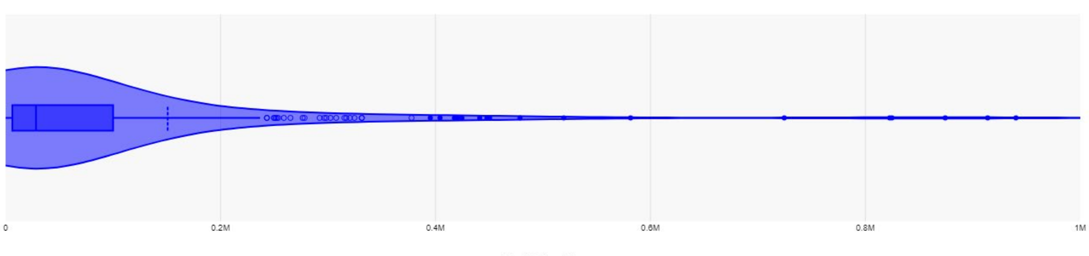
## 8.1 Overall Profile of Bridge Preservation

The bridge preservation situation in North Carolina is complex, encompassing a wide range of bridges. Among the 442 bridge samples analyzed in this preliminary study, our findings indicate that 421 bridges (95%) require preservation. Moreover, the scope of preservation activities varies significantly. For example, 385 bridges require fewer than 20 activities, and their elements can be restored to CS 1, whereas the most complex bridge will require 171 preservation activities to fully recover.

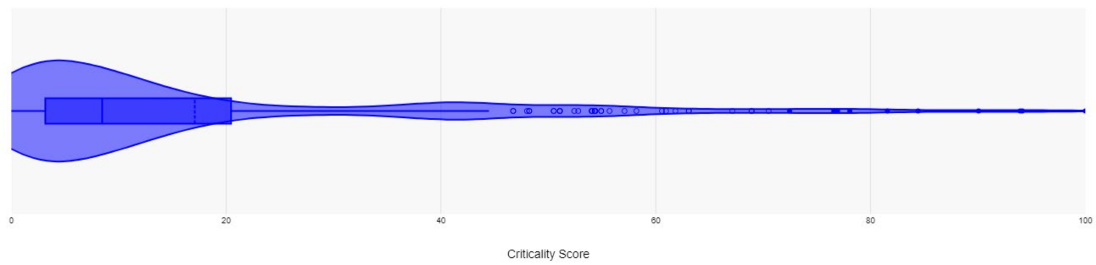
This research identified a long-tail distribution for bridge condition, criticality, and preservation cost. We used the preservation activity count, cost estimates, and bridge criticality scores for the 442 bridges to draw potential distributions for these metrics. The results are shown in Figure 8.1. The violin plots with kernel density estimation lines smoothed the sample distribution, thereby approximating the population distributions in NC. Note that all three metrics have outliers to the right as extremes. Therefore, a preferred approach is to consider these extremes on a case-by-case basis, which is precisely what this research has done in the prioritization process.




(a) Distribution of the Number of Preservation Activities per Bridge




(b) Distribution of the Preservation Cost per Bridge




(c) Distribution of the Bridge Criticality
Figure 8.1 Distribution Estimations for Preservation Activity Count, Total Preservation Cost, and Bridge Criticality

## 8.2 Sensitivity Analysis

The bridge criticality index is sensitive both to the underlying data employed by the research team and to the assumptions applied by the research team to fill gaps in that data and derive the best possible determination of overall criticality for bridges in the study. This sensitivity analysis focuses on key assumptions in the second category – the assumptions used to fill gaps in the data. Specifically,

- The weighting of the index components
- Minimum detour times (to prevent zeros in the detour component)
- Maximum detour times (for bridges with no known detour)

An additional process used to fill gaps is the division of volume evenly across paired bridges at crossings employing two unidirectional bridges. However, sensitivity to this assumption is not explored here because no systematic alternative to an even split of traffic volumes at paired crossings can be informed by the available data.

### 8.2.1 Weighting of the Index Components

The default assumption of the criticality index model is that the two component factors, volumes, and detours, are each given 50% weight. However, it may be desirable to alter this assumption given certain policy objectives. For example, if a stated policy objective is to prioritize maintenance on bridges where the greatest number of trips are affected, it would be reasonable to increase the weight of the volume factor. Alternatively, if a stated policy objective is to first address bridges that provide the greatest economic contribution, it would be reasonable to increase the weight of the detour component. This section explores these scenarios.

Figure 8.2 presents histograms of the final criticality index values resulting from the weighting of three scenarios: 80% Volume / 20% Detour, 50% Volume / 50% Detour, and 20% Volume / 80% Detour. The scenario with high weighting on the volume component has a less-dispersed and more left-skewed distribution when compared to the even weighting scenario. In this scenario, very few bridges obtain criticality index values above 50. In a contrary fashion, the scenario with high weighting on the detour component is shown to have slightly greater dispersion compared to the even-weighting scenario. In this scenario, a greater number of bridges obtain final index values of 80 and higher. Median and interquartile range values for these scenarios, reported in Table 8.1, reinforce this characterization. The median, or central point of the data is closer to 50 and the interquartile range is greater, indicating a more evenly dispersed set of values across the possible range (0-100).

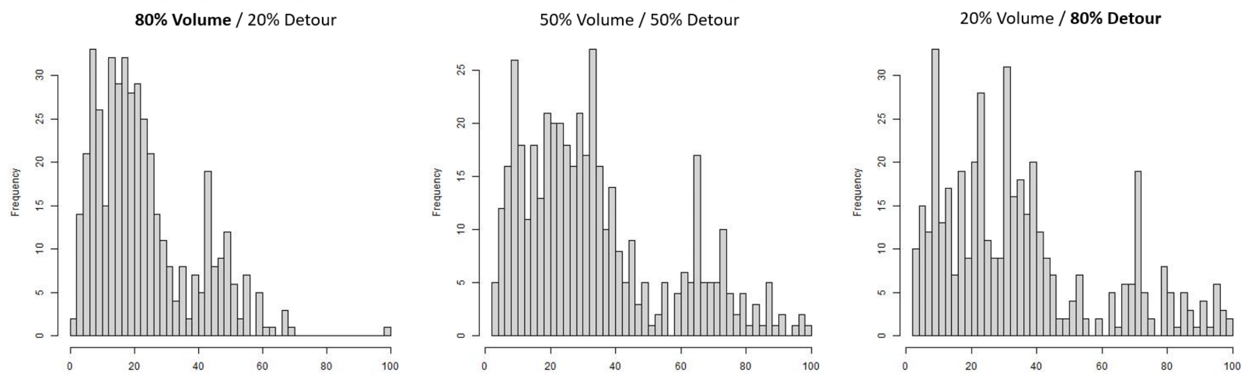



Figure 8.2 Histograms Showing Sensitivity of Final Index Distribution to Component Factor Weighting

Table 8.1 Median and Interquartile Range Values for Weighting Sensitivity Scenarios

| Weighting Factor | Median | IQR |
|---|---|---|
| Less Detour (80V/20D) | 19.2 | 17.8 |
| Even (50V/50D) | 29.7 | 26.9 |
| More Detour (20V/80D) | 30.6 | 27.0 |

These results suggest that more heavily emphasizing the detour component will produce criticality values that more evenly scale between 0 and 100. In this scenario, criticality is more dispersed and absolute criticality values will be greater. Relying more solely on the volume component will reduce the dispersion of the data. If absolute values of criticality, rather than rank-order values of criticality, are used, this will translate to reduced differentiation that the criticality adds to prioritization analyses.

### 8.2.2 Minimum and Maximum Detour Times

Defining minimum and maximum detour times for bridges is necessary because the NCDOT Structures data contains bridge records with detour times of zero (which is unrealistic and would result in a value of zero for the detour component of the criticality index) and bridge records with detour times of 99 (indicating no available detour, rather than a valid numeric value). Table 8.2 shows the number of bridges with different detour values in the study and in the state of North Carolina.

Table 8.2 Detour Values for Bridges in Study and in the State of North Carolina

| Detour Value | Bridges in Study | Bridges in State |
|---|---|---|
| 0 | 99/442 (22%) | 1,162/14,115 (8%) |

| | | |
|---|---|---|
| 99 (“No Detour”) | 3/442 (0.7%) | 1,255/14,115 (9%) |
| Maximum | 33 | 89 |

The research team employed an assumed default minimum value of 0.5. A minimum value of 0.5 was used to position the bridge detour below the lowest valid numeric value (1), while being greater than zero. The range of possible justifiable values for the assumed minimum value is therefore quite narrow, ranging from 0 to 1. However, this assumption affects a large number of bridges in both the study set and the statewide set. As shown in Figure 8.3, the shape of the final criticality index distribution does not change much when altering this value between more extreme values of 0.25 and 0.95.

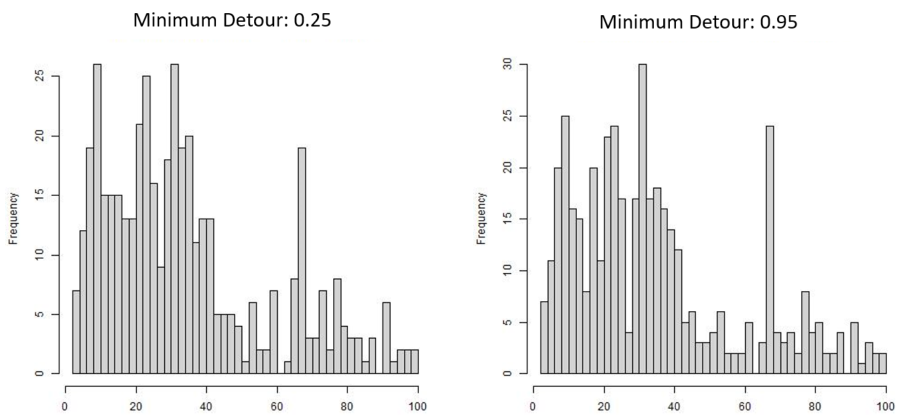



Figure 8.3 Histograms Showing Sensitivity of Final Index Distribution to Component Factor Weighting

A more important question than the appropriate value between 0 and 1 for these bridges is the accuracy of the assumption that detours on the bridges are very short. For example, 40 of the bridges in the study set with detour lengths of 0 have a functional class of “Principal Arterial - Interstate, Urban”, including some that are not located near ramps or other features providing easy detours. It may be worth checking and updating the source data for the DETOUR_LEN value within the NCDOT Structures data.

The research team employed default values of 45 (maximum). A maximum value of 45 was used to position bridges with no valid detours at the highest edge of value numeric values in the dataset. In the set of 442 bridges analyzed, the maximum valid detour time of any bridge was 33. Arguments for using a higher maximum detour time may be justifiable. When looking at all bridges in North Carolina, the maximum valid detour time is 89 though very few bridges have detour times greater than 50. In contrast to the minimum detour time, the maximum detour time affects few bridges but has a high possible range. However, it affects many more bridges in the statewide set. This is because bridges without detours are regionally concentrated in the mountainous west of the state and, to a lesser extent, in eastern coastal areas. Of these bridges, 81% have a functional class of “Local – Rural” and are likely on routes that carry relatively little traffic. Additionally, the 99$^{th}$ percentile detour length for all bridges in the state is 29. It may be helpful to think of increasing the maximum detour length as a way of increasing detour component values for detour-less bridges as a multiple on this value. For example, if the maximum detour value is set to 60, the detour component score for detour-less bridges would be twice the value of a 99th percentile detour length bridge, all else held equal.

# 9 FUTURE STUDIES

There are several avenues worth exploring for future research efforts. First, this project applied a rule-based system to derive preservation activities based on element inspection records. More sophisticated mechanisms, such as machine learning–based approaches, can be employed to improve the level of automation in developing preservation plans. Additionally, the application of overwriting rules relies heavily on domain knowledge. Therefore, a formal knowledge representation, such as an ontology, could be helpful in organizing and formalizing the activity overwriting process.

Second, this project served as preliminary research to prioritize bridge preservation activities. The experiments and evaluation of the developed tools are based on 442 sample bridges across five counties. Future research could focus on a broader range of bridge types and inspection samples across North Carolina to confirm the generalizability and scalability of the framework.

Third, the developed application currently requires manual imports of multiple datasets, as these datasets were provided in text or CSV format during model development. It would be beneficial to explore linking the application to the NCDOT data warehouse so that the system can seamlessly record, track, and share the data among the units across the entire project lifecycle, from planning and design to construction and maintenance.

Fourth, existing bridge criticality scores consider traffic volume and detour costs. Extensive efforts could be made to investigate the socioeconomic impact of a bridge on local communities to expand the applicability of bridge criticality analysis. This would be especially helpful in improving the equity and equality of infrastructure facilities for local communities.

**APPENDIXES**

## APPENDIX A Superstructure Element Inspection Dataset

The original Superstructure Inspection dataset records the inspection data for 442 bridges in Division 10. The complete Superstructure Inspection dataset comprises a data frame with 28,413 rows and 36 columns. The complete dataset is saved in the file “Step 0_new_super.csv”.

Tables A1–A3 list the Superstructure Inspection data samples. Table A1, Table A2, and Table A3 display columns 1–12, 13–24, and 25–36 of the datasets, respectively. Some metadata for the dataset are described as follows. The variables that have been utilized in the model are highlighted with underlines.

- **Number**: String. A unique identifier used to distinguish each row regarding which bridge.
- **SpanNumber**: String. The span number identifying different spans of the bridge.
- **SpanLength**: Numeric. Records the span length.
- **IsContinuousSpan**: Numeric. Indicates whether the span is continuous.
- **ServiceUnder**: Numeric.
- **HeightAtBegin**: Numeric.
- **HeightAtEnd**: Numeric.
- **ElementNumber**: String. Code of the bridge element.
- **ElementName**: String. Name of the bridge element.
- **ParentElementNumber**: String. Parent element number, used to identify the parent structure to which the element belongs. If NA, the element is a top-level element and does not belong to any parent element.
- **ComponentID**: String. Unique identifier for the component.
- **ComponentName**: String. Name of the component.
- **InspectionDate**: DateTime. Date of the bridge inspection.
- **ElementQuantity**: Numeric. Quantity of the element.
- **DefectName**: String. If NA, it indicates that the element has no defects.
- **Level2Count**: Numeric.
- **Level2AASHTO**: Numeric. The AASHTO defect quantity at the CS level 2.
- **Level2Maintenance**: Numeric. The maintenance defect quantity at the CS level 2.
- **Level2Repairs**: Numeric.
- **Level2Severity**: Numeric.
- **Level3Count**: Numeric.
- **Level3AASHTO**: Numeric. The AASHTO defect quantity at the CS level 3.
- **Level3Maintenance**: Numeric. The maintenance defect quantity at the CS level 3.
- **Level3Repairs**: Numeric.
- **Level3Severity**: Numeric.
- **Level4Count**: Numeric.
- **Level4AASHTO**: Numeric. The AASHTO defect quantity at the CS level 4.
- **Level4Maintenance**: Numeric. The maintenance defect quantity at the CS level 4.
- **Level4Repairs**: Numeric.
- **Level4Severity**: Numeric.
- **NumberOfPArs**: Numeric.
- **PARQuantity**: Numeric.
- **CFCount**: Numeric.

- **CFQuantity**: Numeric.
- **PMCount**: Numeric.

## Table A1 Superstructure Element Inspection Data (Columns 1-12)

| Number (1) | Span Number (2) | Span Length (3) | Is Continuous Span (4) | Service (5) | Height At Begin (6) | Height At End (7) | Element Number (8) | Element Name (9) | Parent Element Number (10) | Component ID (11) | Component Name (12) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 030001 | 1 | 8 | 0 | 0 | 0 | 0 | 241 | Reinforced Concrete Culvert | NA | 79 | Reinforced Concrete Box Culvert |
| 030001 | 1 | 8 | 0 | 0 | 0 | 0 | 241 | Reinforced Concrete Culvert | NA | 79 | Reinforced Concrete Box Culvert |
| 030001 | 1 | 8 | 0 | 0 | 0 | 0 | 241 | Reinforced Concrete Culvert | NA | 79 | Reinforced Concrete Box Culvert |
| 030001 | 2 | 8 | 0 | 0 | 0 | 0 | 241 | Reinforced Concrete Culvert | NA | 79 | Reinforced Concrete Box Culvert |
| 030001 | 2 | 8 | 0 | 0 | 0 | 0 | 241 | Reinforced Concrete Culvert | NA | 79 | Reinforced Concrete Box Culvert |
| 030001 | 2 | 8 | 0 | 0 | 0 | 0 | 241 | Reinforced Concrete Culvert | NA | 79 | Reinforced Concrete Box Culvert |
| 030001 | 2 | 8 | 0 | 0 | 0 | 0 | 241 | Reinforced Concrete Culvert | NA | 79 | Reinforced Concrete Box Culvert |
| 030001 | 3 | 8 | 0 | 0 | 0 | 0 | 241 | Reinforced Concrete Culvert | NA | 79 | Reinforced Concrete Box Culvert |
| 030001 | 3 | 8 | 0 | 0 | 0 | 0 | 241 | Reinforced Concrete Culvert | NA | 79 | Reinforced Concrete Box Culvert |
| 030001 | 3 | 8 | 0 | 0 | 0 | 0 | 241 | Reinforced Concrete Culvert | NA | 79 | Reinforced Concrete Box Culvert |
| 030001 | 3 | 8 | 0 | 0 | 0 | 0 | 241 | Reinforced Concrete Culvert | NA | 79 | Reinforced Concrete Box Culvert |
| 030001 | 4 | 8 | 0 | 0 | 0 | 0 | 241 | Reinforced Concrete Culvert | NA | 79 | Reinforced Concrete Box Culvert |
| 030001 | 4 | 8 | 0 | 0 | 0 | 0 | 241 | Reinforced Concrete Culvert | NA | 79 | Reinforced Concrete Box Culvert |
| 030001 | 4 | 8 | 0 | 0 | 0 | 0 | 241 | Reinforced Concrete Culvert | NA | 79 | Reinforced Concrete Box Culvert |
| 030002 | 1 | 41.33 | 0 | 0 | 0 | 0 | 15 | Prestressed Concrete Top Flange | NA | 103 | Prestressed Concrete Cored Slab |
| 030002 | 1 | 41.33 | 0 | 0 | 0 | 0 | 104 | Prestressed Concrete Closed Web/Box Girder | NA | 103 | Prestressed Concrete Cored Slab |
| 030002 | 1 | 41.33 | 0 | 0 | 0 | 0 | 310 | Elastomeric Bearing | NA | 35 | Elastomeric Bearing Pad |
| 030002 | 1 | 41.33 | 0 | 0 | 0 | 0 | 331 | Reinforced Concrete Bridge Railing | NA | 33 | Concrete Railing |
| 030002 | 1 | 41.33 | 0 | 0 | 0 | 0 | 510 | Wearing Surface | NA | 26 | Asphalt Wearing Surface |
| 030002 | 1 | 41.33 | 0 | 0 | 0 | 0 | 521 | Concrete Protective Coating | 15 | 27 | Epoxy Coating |

## Table A2 Superstructure Element Inspection Data (Columns 13-24)

| Inspection Date (13) | ElementQuantity (14) | Defect Name (15) | Level2 Count (16) | Level2 AASHTO (17) | Level2 Maintenance (18) | Level2 Repairs (19) | Level2 Severity (20) | Level3 Count (21) | Level3 Maintenance (22) | Level3 Repairs (23) | Level3 AASHTO (24) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 11/10/2022 | 40 | Cracking (RC and Other) | 2 | 4 | NA | 1 | 163 | 0 | 0 | 0 | 0 |
| 11/10/2022 | 40 | Delamination/Spall | 1 | 5 | 5 | 0 | 98 | 5 | 13 | 0 | 3 |
| 11/10/2022 | 40 | Scour | 1 | 1 | 0 | 0 | 62 | 1 | 16 | 0 | 1 |
| 11/10/2022 | 40 | Cracking (RC and Other) | 1 | 3 | NA | 0 | 97 | 0 | 0 | 0 | 0 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 11/10/2022 | 40 | Delamination/Spall | 2 | 2 | 2 | 0 | 163 | 6 | 8 | 0 | 4 |
| 11/10/2022 | 40 | Patched Area | 1 | 1 | NA | 0 | 93 | 0 | 0 | 0 | 0 |
| 11/10/2022 | 40 | Scour | 2 | 2 | NA | 0 | 99 | 0 | 0 | 0 | 0 |
| 11/10/2022 | 40 | Cracking (RC and Other) | 1 | 2 | 0 | 0 | 108 | 0 | 0 | 0 | 0 |
| 11/10/2022 | 40 | Delamination/Spall | 0 | 0 | 0 | 0 | 0 | 6 | 15 | 0 | 5 |
| 11/10/2022 | 40 | Patched Area | 1 | 2 | NA | 0 | 112 | 0 | 0 | 0 | 0 |
| 11/10/2022 | 40 | Scour | 2 | 2 | NA | 0 | 129 | 0 | 0 | 0 | 0 |
| 11/10/2022 | 40 | Cracking (RC and Other) | 1 | 4 | NA | 0 | 111 | 0 | 0 | 0 | 0 |
| 11/10/2022 | 40 | Patched Area | 1 | 1 | 0 | 1 | 78 | 1 | 9 | 0 | 1 |
| 11/10/2022 | 40 | Scour | 1 | 1 | 0 | 0 | 42 | 0 | 0 | 0 | 0 |
| 4/14/2021 | 1200 | NA | NA | 0 | NA | NA | NA | NA | NA | NA | 0 |
| 4/14/2021 | 400 | NA | NA | 0 | NA | NA | NA | NA | NA | NA | 0 |
| 4/14/2021 | 20 | NA | NA | 0 | NA | NA | NA | NA | NA | NA | 0 |
| 4/14/2021 | 84 | NA | NA | 0 | NA | NA | NA | NA | NA | NA | 0 |
| 4/14/2021 | 1149 | Crack (Wearing Surface) | 2 | 67 | 67 | 0 | 99 | 0 | 0 | 0 | 0 |
| 4/14/2021 | 140 | NA | NA | 0 | NA | NA | NA | NA | NA | NA | 0 |

Table A3 Superstructure Element Inspection Data (Columns 25-36)

| Level3 Severity (25) | Level4 Count (26) | Level4 AASHTO (27) | Level4 Maintenance (28) | Level4 Repairs (29) | Level4 Severity (30) | Number of PArs (31) | PAR Quantity (32) | CF Count (33) | CF Quantity (34) | PM Count (35) | PM Quantity (36) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 340 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 130 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 464 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 551 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 1 | 16 | 0 | 0 | 1 | 16 |
| 163 | 0 | 0 | 0 | 0 | 0 | 2 | 32 | 0 | 0 | 2 | 32 |
| 0 | 0 | 0 | 0 | 0 | 0 | 2 | 32 | 0 | 0 | 2 | 32 |
| NA | NA | 0 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| NA | NA | 0 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| NA | NA | 0 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| NA | NA | 0 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| NA | NA | 0 | NA | NA | NA | NA | NA | NA | NA | NA | NA |

## APPENDIX B Substructure Element Inspection Dataset

The original Substructure Inspection dataset records the inspection data for 442 bridges in Division 10. The complete Substructure Inspection dataset comprises a data frame with 14,037 rows and 33 columns. The complete dataset is saved in the file “Step 0_new_sub.csv”.

Tables A4–A6 list the Substructure Inspection data samples. Table A4, Table A5, and Table A6 display columns 1–11, 12–22, and 23–33 of the datasets, respectively. Some metadata for the dataset are described as follows. The variables that have been utilized in the model are highlighted with underlines.

- **Number**: String. A unique identifier used to distinguish each row regarding which bridge.
- **BentNumber**: String. The bent number identifying different bents of the bridge.
- **IsEndbent**: Numeric. Indicates whether the bent is an end bent.
- **BentName**: String. Name of the bent.
- **ElementNumber**: String. Code of the bridge element.
- **ElementName**: String. Name of the bridge element.
- **ParentElementNumber**: String. Parent element number, used to identify the parent structure to which the element belongs. If NA, the element is a top-level element and does not belong to any parent element.
- **ComponentID**: String. Unique identifier for the component.
- **ComponentName**: String. Name of the component.
- **InspectionDate**: Date Time. Date of the bridge inspection.
- **ElementQuantity**: Numeric. Quantity of the element.
- **DefectName**: String. If NA, it indicates that the element has no defects.
- **Level2Count**: Numeric.
- **Level2AASHTO**: Numeric. The AASHTO defect quantity at the CS level 2.
- **Level2Maintenance**: Numeric. The maintenance defect quantity at the CS level 2.
- **Level2Repairs**: Numeric.
- **Level2Severity**: Numeric.
- **Level3Count**: Numeric.
- **Level3AASHTO**: Numeric. The AASHTO defect quantity at the CS level 3.
- **Level3Maintenance**: Numeric. The maintenance defect quantity at the CS level 3.
- **Level3Repairs**: Numeric.
- **Level3Severity**: Numeric.
- **Level4Count**: Numeric.
- **Level4AASHTO**: Numeric. The AASHTO defect quantity at the CS level 4.
- **Level4Maintenance**: Numeric. The maintenance defect quantity at the CS level 4.
- **Level4Repairs**: Numeric.
- **Level4Severity**: Numeric.
- **NumberOfPArs**: Numeric.
- **PARQuantity**: Numeric.
- **CFCount**: Numeric.
- **CF_Quantity**: Numeric.
- **PMCount**: Numeric.
- **PM_Quantity**: Numeric.

## Table A4 Substructure Element Inspection Data (Columns 1-11)

| Number (1) | Bent Number (2) | Is End Bent (3) | Bent Name (4) | Element Number (5) | Element Name (6) | Parent Element Number (7) | Component ID (8) | Component Name (9) | Inspection Date (10) | Element Quantity (11) |
|---|---|---|---|---|---|---|---|---|---|---|
| 30002 | 1 | 0 | Bent 1 | 234 | Reinforced Concrete Pier Cap | NA | 66 | Reinforced Concrete Pier Cap | 4/14/2021 | 40 |
| 30002 | 1 | 0 | End Bent 1 | 215 | Reinforced Concrete Abutment | NA | 55 | Reinforced Concrete Abutment | 4/14/2021 | 55 |
| 30002 | 1 | 0 | End Bent 1 | 225 | Steel Pile | NA | 60 | Steel Pile | 4/14/2021 | 5 |
| 30002 | 1 | 0 | End Bent 1 | 233 | Prestressed Concrete Pier Cap | NA | 65 | Prestressed Concrete Pier Cap | 4/14/2021 | 42 |
| 30002 | 1 | 0 | End Bent 1 | 515 | Steel Protective Coating | 225 | 112 | Unknown | 4/14/2021 | 256 |
| 30002 | 2 | 0 | End Bent 2 | 215 | Reinforced Concrete Abutment | NA | 55 | Reinforced Concrete Abutment | 4/14/2021 | 55 |
| 30002 | 2 | 0 | End Bent 2 | 225 | Steel Pile | NA | 60 | Steel Pile | 4/14/2021 | 5 |
| 30002 | 2 | 0 | End Bent 2 | 234 | Reinforced Concrete Pier Cap | NA | 66 | Reinforced Concrete Pier Cap | 4/14/2021 | 42 |
| 30002 | 2 | 0 | End Bent 2 | 515 | Steel Protective Coating | 225 | 112 | Unknown | 4/14/2021 | 325 |
| 30002 | 1 | 0 | Bent 1 | 205 | Reinforced Concrete Column | NA | 47 | Reinforced Concrete Column | 4/14/2021 | 3 |
| 30003 | 2 | 0 | Bent 2 | 205 | Reinforced Concrete Column | NA | 47 | Reinforced Concrete Column | 4/14/2022 | 1 |
| 30003 | 2 | 0 | Bent 2 | 205 | Reinforced Concrete Column | NA | 47 | Reinforced Concrete Column | 4/14/2022 | 1 |
| 30003 | 3 | 0 | Bent 3 | 205 | Reinforced Concrete Column | NA | 47 | Reinforced Concrete Column | 4/14/2022 | 1 |
| 30003 | 3 | 0 | Bent 3 | 205 | Reinforced Concrete Column | NA | 47 | Reinforced Concrete Column | 4/14/2022 | 1 |
| 30003 | 4 | 0 | Bent 4 | 205 | Reinforced Concrete Column | NA | 47 | Reinforced Concrete Column | 4/14/2022 | 1 |
| 30003 | 4 | 0 | Bent 4 | 205 | Reinforced Concrete Column | NA | 47 | Reinforced Concrete Column | 4/14/2022 | 1 |
| 30003 | 1 | 0 | Bent 1 | 205 | Reinforced Concrete Column | NA | 47 | Reinforced Concrete Column | 4/14/2022 | 1 |
| 30003 | 2 | 0 | Bent 2 | 205 | Reinforced Concrete Column | NA | 47 | Reinforced Concrete Column | 4/14/2022 | 1 |
| 30003 | 4 | 0 | Bent 4 | 205 | Reinforced Concrete Column | NA | 47 | Reinforced Concrete Column | 4/14/2022 | 1 |
| 30003 | 1 | 0 | Bent 1 | 234 | Reinforced Concrete Pier Cap | NA | 66 | Reinforced Concrete Pier Cap | 4/14/2022 | 48 |

## Table A5 Substructure Element Inspection Data (Columns 12-22)

| Defect Name (12) | Level2 Count (13) | Level2 AASHTO (14) | Level2 Maintenance (15) | Level2 Repairs (16) | Level2 Severity (17) | Level3 Count (18) | Level3 AASHTO (19) | Level3 Maintenance (20) | Level3 Repairs (21) | Level3 Severity (22) |
|---|---|---|---|---|---|---|---|---|---|---|
| NA | NA | 0 | NA | NA | NA | NA | 0 | NA | NA | NA |
| NA | NA | 0 | NA | NA | NA | NA | 0 | NA | NA | NA |
| NA | NA | 0 | NA | NA | NA | NA | 0 | NA | NA | NA |
| NA | NA | 0 | NA | NA | NA | NA | 0 | NA | NA | NA |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| NA | NA | 0 | NA | NA | NA | NA | 0 | NA | NA | NA |
| NA | NA | 0 | NA | NA | NA | NA | 0 | NA | NA | NA |
| NA | NA | 0 | NA | NA | NA | NA | 0 | NA | NA | NA |
| NA | NA | 0 | NA | NA | NA | NA | 0 | NA | NA | NA |
| NA | NA | 0 | NA | NA | NA | NA | 0 | NA | NA | NA |
| NA | NA | 0 | NA | NA | NA | NA | 0 | NA | NA | NA |
| Delamination/Spall | 0 | 0 | 0 | 0 | 0 | NA | 1 | 1 | 0 | 90 |
| Exposed Rebar | 1 | 1 | 1 | 0 | 144 | 0 | 0 | 0 | 0 | 0 |
| Delamination/Spall | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 168 |
| Exposed Rebar | 2 | 1 | 1 | 0 | 275 | 0 | 0 | 0 | 0 | 0 |
| Delamination/Spall | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 161 |
| Exposed Rebar | 0 | 0 | 0 | 0 | 0 | 1 | 1 | 1 | 0 | 156 |
| Delamination/Spall | 1 | NA | NA | 0 | 106 | 0 | 0 | 0 | 0 | 0 |
| Abrasion/Wear (PSC/RC) | 1 | NA | NA | 0 | 99 | 0 | 0 | 0 | 0 | 0 |
| Cracking (RC and Other) | 1 | 1 | NA | 0 | 70 | 0 | 0 | 0 | 0 | 0 |
| Cracking (RC and Other) | 1 | 3 | 0 | 0 | 66 | 3 | 1 | 1 | 0 | 77 |

## Table A6 Substructure Element Inspection Data (Columns 23-33)

| Level4Count (23) | Level4 AASHTO (24) | Level4 Maintenance (25) | Level4 Repairs (26) | Level4 Severity (27) | Number Of PArs (28) | PAR Quantity (29) | CF Count (30) | CF Quantity (31) | PM Count (32) | PM Quantity (33) |
|---|---|---|---|---|---|---|---|---|---|---|
| NA | 0 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| NA | 0 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| NA | 0 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| NA | 0 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| NA | 0 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| NA | 0 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| NA | 0 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| NA | 0 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| NA | 0 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| NA | 0 | NA | NA | NA | NA | NA | NA | NA | NA | NA |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |
| 0 | 0 | 0 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 1 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

# APPENDIX C Preservation Activity Decision Tree (Original)

## Deck

**Reinforced Concrete Decks**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 12 | 38 | 16 | 60 |
| | | 65 | | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Deck Surface | < 20% of Deck Surface | < 10% of Deck Surface | ≥ 10% of Deck Surface |
| 1080 | Delamination/Spall | Concrete for Deck Repair | Concrete for Deck Repair | Overlay | Replace Concrete Deck |
| 1085 | Patched Area | Nothing | Concrete for Deck Repair | Overlay | Replace Concrete Deck |
| 1090 | Exposed Rebar | Concrete for Deck Repair | Overlay | Overlay | Replace Concrete Deck |
| 1120 | Efflorescence/Rust Staining | Nothing | Overlay | Overlay | Replace Concrete Deck |
| 1130 | Cracking (RC and Other) | Silane | HMWM | Overlay | Overlay |
| 1190 | Abrasion/Wear (PSC/RC) | Nothing | Overlay | Overlay | Overlay |

**Steel Decks**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 28 | 29 | 30 | 60 |
| | | 65 | | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Deck Surface | < 20% of Deck Surface | < 10% of Deck Surface | ≥ 10% of Deck Surface |
| 1000 | Corrosion | Nothing | Nothing | Replace Section of Steel Deck | Replace Steel Deck |
| 1010 | Cracking | Nothing | Steel Crack Arrest | Replace Section of Steel Deck | Replace Steel Deck |
| 1020 | Connection | Nothing | Replace missing or broken fasteners | Replace missing or broken fasteners | Replace Steel Deck |

**Concrete Barrier**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 331 | 333 | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Barrier | < 20% of Barrier | < 10% of Barrier | ≥ 10% of Barrier |
| 1080 | Delamination/Spall | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Section of Concrete Barrier |
| 1085 | Patched Area | Nothing | Nothing | Concrete Repair | Replace Section of Concrete Barrier |
| 1090 | Exposed Rebar | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Section of Concrete Barrier |
| 1120 | Efflorescence/Rust Staining | Nothing | Nothing | Shotcrete Repair | Replace Section of Concrete Barrier |
| 1130 | Cracking (RC and Other) | Nothing | Silane | Silane | Replace Section of Concrete Barrier |

**Prestressed Concrete Decks**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 13 | 15 | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 20% of Deck Surface | < 10% of Deck Surface | < 5% of Deck Surface | ≥ 5% of Deck Surface |
| 1080 | Delamination/Spall | Concrete for Deck Repair | Concrete for Deck Repair | Overlay | Replace Concrete Deck |
| 1085 | Patched Area | Nothing | Concrete for Deck Repair | Overlay | Replace Concrete Deck |
| 1090 | Exposed Rebar | Concrete for Deck Repair | Overlay | Overlay | Replace Concrete Deck |
| 1100 | Exposed Prestressing | Concrete for Deck Repair | Overlay | Overlay | Replace Concrete Deck |
| 1110 | Cracking (PSC) | Silane | HMWM | Overlay | Overlay |
| 1120 | Efflorescence/Rust Staining | Nothing | Overlay | Overlay | Replace Concrete Deck |
| 1190 | Abrasion/Wear (PSC/RC) | Nothing | Overlay | Overlay | Overlay |

**Timber Decks**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 31 | 54 | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Deck Surface | < 20% of Deck Surface | < 10% of Deck Surface | ≥ 10% of Deck Surface |
| 1020 | Connection | Nothing | Replace missing or broken fasteners | Replace missing or broken fasteners | Replace Timber Deck |
| 1140 | Decay/Section Loss | Nothing | Nothing | Replace Section of Timber Deck | Replace Timber Deck |
| 1150 | Check/Shake | Nothing | Nothing | Replace Section of Timber Deck | Replace Timber Deck |
| 1160 | Crack (Timber) | Nothing | Nothing | Penetrating sealer | Replace Timber Deck |
| 1170 | Split/Delamination (Timber) | Nothing | Nothing | Replace Section of Timber Deck | Replace Timber Deck |
| 1180 | Abrasion/Wear (Timber) | Nothing | Nothing | Replace Section of Timber Deck | Replace Timber Deck |

**Metal Barrier**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 330 | 333 | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Barrier | < 20% of Barrier | < 10% of Barrier | ≥ 10% of Barrier |
| 1000 | Corrosion | Nothing | Spot Painting | Repair Section of Metal Barrier/Rail | Replace Section of Metal Barrier/Rail |
| 1010 | Cracking | Nothing | Steel Crack Arrest | Repair Section of Metal Barrier/Rail | Replace Section of Metal Barrier/Rail |
| 1020 | Connection | Nothing | Replace missing or broken fasteners | Replace missing or broken fasteners | Replace Section of Metal Barrier/Rail |
| 1900 | Distortion | Nothing | Nothing | Repair Section of Metal Barrier/Rail | Replace Section of Metal Barrier/Rail |

## Timber Barrier

| | Applies to Element #'s: | 332 | | | |
|---|---|---|---|---|---|
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Barrier | < 20% of Barrier | < 10% of Barrier | ≥ 10% of Barrier |
| 1020 | Connection | Nothing | Replace missing or broken fasteners | Replace missing or broken fasteners | Replace Section of Timber Barrier/Rail |
| 1140 | Decay/Section Loss | Nothing | Nothing | Replace Section of Timber Barrier/Rail | Replace Section of Timber Barrier/Rail |
| 1150 | Check/Shake | Nothing | Nothing | Replace Section of Timber Barrier/Rail | Replace Section of Timber Barrier/Rail |
| 1160 | Crack (Timber) | Nothing | Nothing | Penetrating sealer | Replace Section of Timber Barrier/Rail |
| 1170 | Split/Delamination (Timber) | Nothing | Nothing | Replace Section of Timber Barrier/Rail | Replace Section of Timber Barrier/Rail |
| 1180 | Abrasion/Wear (Timber) | Nothing | Nothing | Replace Section of Timber Barrier/Rail | Replace Section of Timber Barrier/Rail |

## Joints

| | Applies to Element #'s: | 300 | 301 | 302 | 303 |
|---|---|---|---|---|---|
| | | 305 | 306 | 304 | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Joint | < 20% of Joint | < 10% of Joint | ≥ 10% of Joint |
| 2310 | Leakage | Nothing | Joint Replacement | Joint Replacement | Joint Replacement |
| 2320 | Seal Adhesion | Nothing | Joint Replacement | Joint Replacement | Joint Replacement |
| 2330 | Seal Damage | Nothing | Joint Replacement | Joint Replacement | Joint Replacement |
| 2340 | Seal Cracking | Nothing | Joint Replacement | Joint Replacement | Joint Replacement |
| 2350 | Debris Impaction | Nothing | Joint Cleaning | Joint Cleaning | Joint Replacement |
| 2360 | Adjacent Deck or Header | Nothing | Bridge Joint Demolition | Bridge Joint Demolition | Joint Replacement |
| 2370 | Metal Deterioration or Damage | Nothing | Joint Replacement | Joint Replacement | Joint Replacement |

## Masonry Barrier

| | Applies to Element #'s: | 334 | | | |
|---|---|---|---|---|---|
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Barrier | < 20% of Barrier | < 10% of Barrier | ≥ 10% of Barrier |
| 1080 | Delamination/Spall | Nothing | Replace Defective Masonry | Replace Defective Masonry | Replace Defective Masonry |
| 1085 | Patched Area | Nothing | Nothing | Replace Defective Masonry | Replace Defective Masonry |
| 1120 | Efflorescence/Rust Staining | Nothing | Nothing | Replace Defective Masonry | Replace Defective Masonry |
| 1610 | Mortar Breakdown | Nothing | Nothing | Replace Masonry Mortar | Replace Defective Masonry |
| 1620 | Split/Spall (Masonry) | Nothing | Nothing | Replace Defective Masonry | Replace Defective Masonry |
| 1630 | Patched Area (Masonry) | Nothing | Nothing | Replace Defective Masonry | Replace Defective Masonry |
| 1640 | Masonry Displacement | Nothing | Nothing | Replace Defective Masonry | Replace Defective Masonry |
| 1900 | Distortion | Nothing | Nothing | Replace Defective Masonry | Replace Defective Masonry |

# Superstructure

**Reinforced Concrete Superstructure**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 105 | 106 | 110 | 112 |
| | | 118 | 136 | 142 | 144 |
| | | 157 | 116 | 155 | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Reinforced Concrete Member | < 20% of Reinforced Concrete Member | < 10% of Reinforced Concrete Member | ≥ 10% of Reinforced Concrete Member |
| 1080 | Delamination/Spall | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Reinforced Concrete Superstructure Element |
| 1085 | Patched Area | Nothing | Shotcrete Repair | FRP Beam Repair | Replace Reinforced Concrete Superstructure Element |
| 1090 | Exposed Rebar | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Reinforced Concrete Superstructure Element |
| 1120 | Efflorescence/Rust Staining | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Reinforced Concrete Superstructure Element |
| 1130 | Cracking (RC and Other) | Nothing | Epoxy Resin Injection | Epoxy Resin Injection | Replace Reinforced Concrete Superstructure Element |

**Steel Superstructure**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 102 | 106 | 107 | 112 |
| | | 118 | 120 | 1120 | 136 |
| | | 142 | 152 | 157 | 113 |
| | | 141 | | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Steel Member | < 20% of Steel Member | < 10% of Steel Member | ≥ 10% of Steel Member |
| 1000 | Corrosion | Nothing | Steel Beam Repair | Steel Beam Repair | Replace Steel Superstructure Element |
| 1010 | Cracking | Nothing | Steel Crack Arrest | Steel Beam Repair | Replace Steel Superstructure Element |
| 1020 | Connection | Nothing | Replace missing or broken fasteners | Replace missing or broken fasteners | Replace Steel Superstructure Element |
| 1900 | Distortion | Nothing | Steel Beam Repair | Heat Straightening | Replace Steel Superstructure Element |

**Prestressed Concrete Superstructure**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 104 | 109 | 115 | 143 |
| | | 154 | | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 20% of Prestressed Member | < 10% of Prestressed Member | < 5% of Prestressed Member | ≥ 5% of Prestressed Member |
| 1080 | Delamination/Spall | Shotcrete Repair | Repairs to Prestressed Girders | Repairs to Prestressed Girders | Replace Prestressed Superstructure Element |
| 1085 | Patched Area | Nothing | Shotcrete Repair | FRP Beam Repair | Replace Prestressed Superstructure Element |
| 1090 | Exposed Rebar | Nothing | Shotcrete Repair | Repairs to Prestressed Girders | Replace Prestressed Superstructure Element |
| 1100 | Exposed Prestressing | Shotcrete Repair | Shotcrete Repair | Repairs to Prestressed Girders with Strand Splice | Replace Prestressed Superstructure Element |
| 1110 | Cracking (PSC) | Epoxy Resin Injection | Epoxy Resin Injection | Epoxy Resin Injection | Replace Prestressed Superstructure Element |
| 1120 | Efflorescence/Rust Staining | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Prestressed Superstructure Element |

**Steel Superstructure Element**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 147 | 148 | 149 | 161 |
| | | 162 | | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Steel Member | < 20% of Steel Member | < 10% of Steel Member | ≥ 10% of Steel Member |
| 1000 | Corrosion | Nothing | Spot Painting | Replace Steel Superstructure Element | Replace Steel Superstructure Element |
| 1010 | Cracking | Nothing | Steel Crack Arrest | Steel Crack Arrest | Replace Steel Superstructure Element |
| 1020 | Connection | Nothing | Replace missing or broken fasteners | Replace missing or broken fasteners | Replace Steel Superstructure Element |
| 1900 | Distortion | Nothing | Nothing | Replace Steel Superstructure Element | Replace Steel Superstructure Element |

| Timber Superstructure | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 111 | 117 | 135 | 146 |
| | | 156 | | | |
| | | | | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Timber Member | < 20% of Timber Member | < 10% of Timber Member | ≥ 10% of Timber Member |
| 1020 | Connection | Nothing | Replace missing or broken fasteners | Replace missing or broken fasteners | Replace Timber Superstructure Element |
| 1140 | Decay/Section Loss | Nothing | Nothing | Replace Timber Superstructure Element | Replace Timber Superstructure Element |
| 1150 | Check/Shake | Nothing | Nothing | Replace Timber Superstructure Element | Replace Timber Superstructure Element |
| 1160 | Crack (Timber) | Nothing | Nothing | Penetrating sealer | Replace Timber Superstructure Element |
| 1170 | Split/Delamination (Timber) | Nothing | Nothing | Replace Timber Superstructure Element | Replace Timber Superstructure Element |
| 1180 | Abrasion/Wear (Timber) | Nothing | Nothing | Replace Timber Superstructure Element | Replace Timber Superstructure Element |

| Wearing Surface Criteria | | | | | |
|---|---|---|---|---|---|
| | Applies to concrete deck bridges | 510 | | | |
| | | | | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 20% of Deck Surface | < 10% of Deck Surface | < 5% of Deck Surface | ≥ 5% of Deck Surface |
| 3210 | Delamination/Spall | Asphalt Patch | Replace Wearing Surface | Overlay | Overlay |
| 3215 | Patched Area | Nothing | Asphalt Patch | Replace Wearing Surface | Overlay |
| 3220 | Crack | Nothing | Replace Wearing Surface | Replace Wearing Surface | Overlay |
| 3230 | Effectiveness | Nothing | Replace Wearing Surface | Replace Wearing Surface | Overlay |

| Bearings | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 310 | 311 | 312 | 313 |
| | | 315 | 316 | 314 | |
| | | | | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Bearing Line | < 20% of Bearing Line | < 10% of Bearing Line | ≥ 10% of Bearing Line |
| 1000 | Corrosion | Nothing | Paint and Maintain Bearings | Paint and Maintain Bearings | Replace Bearing |
| 1020 | Connection | Nothing | Replace missing or broken fasteners | Replace missing or broken fasteners | Replace Bearing |
| 2210 | Movement | Nothing | Jack and Repair Bearing/Bearing Area | Jack and Repair Bearing/Bearing Area | Replace Bearing |
| 2220 | Alignment | Nothing | Jack and Repair Bearing/Bearing Area | Jack and Repair Bearing/Bearing Area | Replace Bearing |
| 2230 | Bulging, Splitting or Tearing | Nothing | Nothing | Replace Bearing | Replace Bearing |
| 2240 | Loss of Bearing Area | Nothing | Jack and Repair Bearing/Bearing Area | Jack and Repair Bearing/Bearing Area | Jack and Repair Bearing/Bearing Area |

# Substructure

**Reinforced Concrete Substructure Element**

Applies to Element #'s: 203, 205, 210, 211, 218, 227, 229, 215

| Defect # | Defect Name | CS2<br>< 40% of Reinforced Concrete Member | CS3<br>< 20% of Reinforced Concrete Member | CS4<br>< 10% of Reinforced Concrete Member | CS4<br>≥ 10% of Reinforced Concrete Member |
|---|---|---|---|---|---|
| 1080 | Delamination/Spall | Shotcrete Repair | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1085 | Patched Area | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1090 | Exposed Rebar | Shotcrete Repair | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1120 | Efflorescence/Rust Staining | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1130 | Cracking (RC and Other) | Nothing | Epoxy Resin Injection | Epoxy Resin Injection | Replace Concrete Substructure Element |
| 1190 | Abrasion/Wear (PSC/RC) | Nothing | Nothing | Pile Jacket | Replace Concrete Substructure Element |
| 4000 | Settlement | Nothing | Nothing | Temporary Shoring | Replace Concrete Substructure Element |
| 6000 | Scour | Nothing | Scour Countermeasures | Scour Countermeasures | Replace Concrete Substructure Element |

**Prestressed Substructure Element**

Applies to Element #'s: 204, 226

| Defect # | Defect Name | CS2<br>< 20% of Prestressed Member | CS3<br>< 10% of Prestressed Member | CS4<br>< 5% of Prestressed Member | CS4<br>≥ 5% of Prestressed Member |
|---|---|---|---|---|---|
| 1080 | Delamination/Spall | Shotcrete Repair | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1085 | Patched Area | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1090 | Exposed Rebar | Shotcrete Repair | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1100 | Exposed Prestressing | Shotcrete Repair | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1110 | Cracking (PSC) | Epoxy Resin Injection | Epoxy Resin Injection | Epoxy Resin Injection | Replace Concrete Substructure Element |
| 1120 | Efflorescence/Rust Staining | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1190 | Abrasion/Wear (PSC/RC) | Nothing | Nothing | Pile Jacket | Replace Concrete Substructure Element |
| 4000 | Settlement | Nothing | Nothing | Temporary Shoring | Replace Concrete Substructure Element |
| 6000 | Scour | Nothing | Scour Countermeasures | Scour Countermeasures | Replace Concrete Substructure Element |

**Reinforced Concrete Substructure Cap**

Applies to Element #'s: 220, 234, 235

| Defect # | Defect Name | CS2<br>< 40% of Reinforced Concrete Member | CS3<br>< 20% of Reinforced Concrete Member | CS4<br>< 10% of Reinforced Concrete Member | CS4<br>≥ 10% of Reinforced Concrete Member |
|---|---|---|---|---|---|
| 1080 | Delamination/Spall | Concrete Repair | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |
| 1085 | Patched Area | Nothing | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |
| 1090 | Exposed Rebar | Concrete Repair | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |
| 1120 | Efflorescence/Rust Staining | Nothing | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |
| 1130 | Cracking (RC and Other) | Nothing | Epoxy Resin Injection | Epoxy Resin Injection | Replace Concrete Substructure Element |
| 1190 | Abrasion/Wear (PSC/RC) | Nothing | Nothing | Pile Jacket | Replace Concrete Substructure Element |
| 4000 | Settlement | Nothing | Nothing | Temporary Shoring | Replace Concrete Substructure Element |
| 6000 | Scour | Nothing | Scour Countermeasures | Scour Countermeasures | Replace Concrete Substructure Element |

**Prestressed Substructure Cap**

Applies to Element #'s: 233

| Defect # | Defect Name | CS2<br>< 20% of Prestressed Member | CS3<br>< 10% of Prestressed Member | CS4<br>< 5% of Prestressed Member | CS4<br>≥ 5% of Prestressed Member |
|---|---|---|---|---|---|
| 1080 | Delamination/Spall | Concrete Repair | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |
| 1085 | Patched Area | Nothing | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |
| 1090 | Exposed Rebar | Concrete Repair | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |
| 1100 | Exposed Prestressing | Concrete Repair | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |
| 1110 | Cracking (PSC) | Epoxy Resin Injection | Epoxy Resin Injection | Epoxy Resin Injection | Replace Concrete Substructure Element |
| 1120 | Efflorescence/Rust Staining | Nothing | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |

**Steel Substructure Element**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 202 | 203 | 207 | 211 |
| | | 219 | 225 | 229 | 231 |
| | | 218 | 235 | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Steel Member | < 20% of Steel Member | < 10% of Steel Member | ≥ 10% of Steel Member |
| 1000 | Corrosion | Nothing | Clean and Paint Substructure | Repair Steel Substructure Element | Replace Steel Substructure Element |
| 1010 | Cracking | Nothing | Steel Crack Arrest | Repair Steel Substructure Element | Replace Steel Substructure Element |
| 1020 | Connection | Nothing | Replace missing or broken fasteners | Replace missing or broken fasteners | Replace Steel Substructure Element |
| 1900 | Distortion | Nothing | Repair Steel Substructure Element | Temporary Shoring | Replace Steel Substructure Element |
| 4000 | Settlement | Nothing | Nothing | Temporary Shoring | Replace Steel Substructure Element |
| 6000 | Scour | Nothing | Scour Countermeasures | Scour Countermeasures | Replace Steel Substructure Element |

**Masonry Substructure Element**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 213 | 217 | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Masonry Member | < 20% of Masonry Member | < 10% of Masonry Member | ≥ 10% of Masonry Member |
| 1120 | Efflorescence/Rust Staining | Nothing | Nothing | Replace Defective Masonry | Replace Defective Masonry |
| 1610 | Mortar Breakdown | Nothing | Nothing | Replace Defective Masonry | Replace Defective Masonry |
| 1620 | Split/Spall (Masonry) | Nothing | Nothing | Replace Defective Masonry | Replace Defective Masonry |
| 1630 | Patched Area (Masonry) | Nothing | Nothing | Replace Defective Masonry | Replace Defective Masonry |
| 1640 | Masonry Displacement | Nothing | Nothing | Replace Defective Masonry | Replace Defective Masonry |
| 4000 | Settlement | Nothing | Nothing | Temporary Shoring | Replace Defective Masonry |
| 6000 | Scour | Nothing | Nothing | Scour Countermeasures | Replace Defective Masonry |

**Timber Substructure Element**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 206 | 208 | 212 | 216 |
| | | 235 | 228 | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Timber Member | < 20% of Timber Member | < 10% of Timber Member | ≥ 10% of Timber Member |
| 1020 | Connection | Nothing | Replace missing or broken fasteners | Replace missing or broken fasteners | Replace Timber Substructure Element |
| 1140 | Decay/Section Loss | Nothing | Nothing | Replace Timber Substructure Element | Replace Timber Substructure Element |
| 1150 | Check/Shake | Nothing | Nothing | Replace Timber Substructure Element | Replace Timber Substructure Element |
| 1160 | Crack (Timber) | Nothing | Nothing | Penetrating sealer | Replace Timber Substructure Element |
| 1170 | Split/Delamination (Timber) | Nothing | Nothing | Replace Timber Substructure Element | Replace Timber Substructure Element |
| 1180 | Abrasion/Wear (Timber) | Nothing | Nothing | Pile Jacket | Replace Timber Substructure Element |
| 4000 | Settlement | Nothing | Nothing | Temporary Shoring | Replace Timber Substructure Element |
| 6000 | Scour | Nothing | Nothing | Scour Countermeasures | Replace Timber Substructure Element |

**Steel Protective Coating Criteria**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to steel superstructure bridges | 515 | | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Steel Surface | < 20% of Steel Surface | < 10% of Steel Surface | ≥ 10% of Steel Surface |
| 3410 | Chalking | Nothing | Zone Paint | Zone Paint | Clean and Repaint Bridge |
| 3420 | Peeling/Bubbling/Cracking | Spot Painting | Zone Paint | Zone Paint | Clean and Repaint Bridge |
| 3430 | Oxide Film Degradation Color/Texture Adherence | Zone Paint | Zone Paint | Clean and Repaint Bridge | Steel Repairs |
| 3440 | Effectiveness | Spot Painting | Zone Paint | Zone Paint | Clean and Repaint Bridge |

## APPENDIX D Preservation Activity Decision Tree (Tidy Format)

The Preservation Activity Decision Tree dataset in tidy format was converted from the original format. The tidy format of the Preservation Activity Decision Tree can be directly read by the computer. The complete Preservation Activity Decision Tree (Tidy Format) is a data frame with 2492 rows and 10 columns. The complete dataset can be found in the file "Step 0_DT_Activity.csv".

Table A7 lists a sample of the Preservation Activity Decision Tree (Tidy Format) dataset. Below are the metadata descriptions of the dataset.

- **Type**: String. The type of bridge component.
- **Subtype**: String. The subtype of the bridge component.
- **ElementNumber**: String. The code of the bridge element.
- **DefectNo**: String. The unique identifier for the specific defect.
- **DefectName**: String. The name of the defect.
- **CS**: Numeric. The CS level of the defect.
- **Percentage**: Numeric. The percentage of the element affected by the defect.
- **Logic**: String. The logical operator used to determine if the percentage meets a certain condition. LT represents Less Than, and GT represents Greater Than.
- **Object**: String.
- **Activity**: String. The preservation activity to be undertaken if the specified conditions are met.

Table A7 Data Sample of Preservation Activity Decision Tree (Tidy Format)

| Type | Subtype | ElementNumber | DefectNo | DefectName | CS | Percentage | Logic | Object | Activity |
|---|---|---|---|---|---|---|---|---|---|
| Deck | Reinforced Concrete Decks | 12 | 1080 | Delamination/Spall | 2 | 40 | LT | Deck Surface | Concrete for Deck Repair |
| Deck | Reinforced Concrete Decks | 12 | 1085 | Patched Areas | 2 | 40 | LT | Deck Surface | Nothing |
| Deck | Reinforced Concrete Decks | 12 | 1090 | Exposed Rebar | 2 | 40 | LT | Deck Surface | Concrete for Deck Repair |
| Deck | Reinforced Concrete Decks | 12 | 1120 | Efflorescence/Rust Staining | 2 | 40 | LT | Deck Surface | Nothing |
| Deck | Reinforced Concrete Decks | 12 | 1130 | Cracking (RC and Other) | 2 | 40 | LT | Deck Surface | Silane |
| Deck | Reinforced Concrete Decks | 12 | 1190 | Abrasion/Wear (PSC/RC) | 2 | 40 | LT | Deck Surface | Nothing |
| Deck | Reinforced Concrete Decks | 12 | 1080 | Delamination/Spall | 3 | 20 | LT | Deck Surface | Concrete for Deck Repair |
| Deck | Reinforced Concrete Decks | 12 | 1085 | Patched Areas | 3 | 20 | LT | Deck Surface | Concrete for Deck Repair |
| Deck | Reinforced Concrete Decks | 12 | 1090 | Exposed Rebar | 3 | 20 | LT | Deck Surface | Overlay |
| Deck | Reinforced Concrete Decks | 12 | 1120 | Efflorescence/Rust Staining | 3 | 20 | LT | Deck Surface | Overlay |
| Deck | Reinforced Concrete Decks | 12 | 1130 | Cracking (RC and Other) | 3 | 20 | LT | Deck Surface | HMWM |
| Deck | Reinforced Concrete Decks | 12 | 1190 | Abrasion/Wear (PSC/RC) | 3 | 20 | LT | Deck Surface | Overlay |
| Deck | Reinforced Concrete Decks | 12 | 1080 | Delamination/Spall | 4 | 10 | LT | Deck Surface | Overlay |
| Deck | Reinforced Concrete Decks | 12 | 1080 | Delamination/Spall | 4 | 10 | GE | Deck Surface | Replace Concrete Deck |
| Deck | Reinforced Concrete Decks | 12 | 1085 | Patched Areas | 4 | 10 | LT | Deck Surface | Overlay |
| Deck | Reinforced Concrete Decks | 12 | 1085 | Patched Areas | 4 | 10 | GE | Deck Surface | Replace Concrete Deck |
| Deck | Reinforced Concrete Decks | 12 | 1090 | Exposed Rebar | 4 | 10 | LT | Deck Surface | Overlay |
| Deck | Reinforced Concrete Decks | 12 | 1090 | Exposed Rebar | 4 | 10 | GE | Deck Surface | Replace Concrete Deck |
| Deck | Reinforced Concrete Decks | 12 | 1120 | Efflorescence/Rust Staining | 4 | 10 | LT | Deck Surface | Overlay |
| Deck | Reinforced Concrete Decks | 12 | 1120 | Efflorescence/Rust Staining | 4 | 10 | GE | Deck Surface | Replace Concrete Deck |
| Deck | Reinforced Concrete Decks | 12 | 1130 | Cracking (RC and Other) | 4 | 10 | LT | Deck Surface | Overlay |
| Deck | Reinforced Concrete Decks | 12 | 1130 | Cracking (RC and Other) | 4 | 10 | GE | Deck Surface | Overlay |
| Deck | Reinforced Concrete Decks | 12 | 1190 | Abrasion/Wear (PSC/RC) | 4 | 10 | LT | Deck Surface | Overlay |
| Deck | Reinforced Concrete Decks | 12 | 1190 | Abrasion/Wear (PSC/RC) | 4 | 10 | GE | Deck Surface | Overlay |
| … | … | … | … | … | … | … | … | … | |

## APPENDIX E Meeting Minutes_October 20, 2022

**Project No.:** **RP 2023-05**
**Title:** **Prioritizing NCDOT Bridge Preservation Projects Using Bridge Element Inspection Data**
**Meeting:** **Data Clarification & Decision Trees**
**Location:** **1000 Birch Ridge Dr. Raleigh, NC 27610**
**DOT CCA Structures Conference Room Col. C4**
**Date:** **October 20, 2022**
**Time:** **1:00 p.m.–3:00 p.m.**

**Meeting Attendees**

| **Steering and Implementation Committee** | **NCDOT Bridge Maintenance System Managers** | **Research Team** |
|---|---|---|
| Nicholas Pierce – Chair | | Min Liu |
| Trey Carroll | | Simon Hsiang |
| | | Chuanni He |

1) **The new data file, Division 10 Elements_20220930:**

a. There are 574 bridges in the latest file "Division 10 Elements_20220930" received on September 30, 2022, which is a sharp increased from the 442 bridges in the file "div10elements_090222" received on September 2, 2022. The 574 bridges include timber bridges and bridges with steel planks that are outside of the research scope. It was confirmed that the research team would only focus on the 442 bridges and use the inspection data from the "Division 10 Elements_20220930" file.

b. It was confirmed that all elements of the bridges are in the "Division 10 Elements_20220930" file, including the elements without defects identified.

2) **Decision Tree**:

Regarding the calculations for using decision trees, the following were confirmed:

a. The research will use Level #AASHTO as the nominator to calculate percentage defects for the deck and superstructure elements.
b. The research will use the total quantity of a span for the same defect as the denominator to calculate the percentage defect for the deck and superstructure elements.
c. The units in "a" and "b" are the same and are always consistent.
d. Maintenance/preservation activities will only be triggered for defects with a corresponding maintenance quantity. If Level#maintenance quantity = 0 or the value of the Level#maintenance quantity is missing, this means that the defects have been addressed before. Therefore, Level #AASHTO should be regarded as zero. This rule should be checked at each CS level.
e. Therefore, the research will first check the Level#maintenance quantity for each element. If Level#maintenance = 0, then the Level #AASHTO (the nominator) will be regarded as zero. If Level#maintenance ≠ 0, then Level #AASHTO can be used as the nominator to calculate percentage defect for deck and superstructure elements.

f. The maintenance/preservation activities will be triggered at the span level. The percentage of defects at each CS level will be calculated using the equation below.

$$\%CS\#\ defect = \frac{\sum_i Level\#AASHTO\ for\ defect_i\ in\ span_j}{\sum_i Elements\ for\ defect_i\ in\ span_j} \times 100\%.$$

g. The SMU group approved the decision tables provided by the research team (see Appendix 3).

h. The SMU group approved adding the new overwrite rule for "Replace concrete deck" activity (see Appendix 4).

i. There might be some extreme high costs for overlay activities for bridges with more than five spans. For these bridges, overwriting rules may need to be enacted. NCDOT will assess the condition, and the research team will then revise the rules based on NCDOT's feedback.

j. The SMU group will further determine the defect percentage calculation method for the substructure elements. The unit of those elements is reported as "each" in the "Division 10 Elements_20220930."

3) **"FHWA_Element Sheet" File**

a. The SMU group shared a new file, "FHWA_Element Sheets," which lists all the bridge elements with their element numbers and units used in the report. The file also contains all defects with defect numbers and their CS descriptions. This file can be used as an index for searching for bridge elements and defects.

4) **Miscellaneous**

a. There is no specific file format requirement for the tool to be developed. The research team should clearly describe the logic behind the analysis. NCDOT can develop its own applications based on logic.

b. NCDOT is preparing a bridge preservation manual. The research team can use the definitions for preservation and maintenance based on the new manual.

c. Simon recommended considering urgency, recency, and frequency of preservation activities.

| **Action Items** | |
|---|---|
| 1 | The SMU group will check on the defect percentage calculation method for bridge substructures and get back to the research team. They will also help to find definitions for preservation and maintenance based on the most recent bridge preservation manual. |
| 2 | The research team will first focus on the bridge deck and substructures to develop a prototype to automate the bridge preservation plans according to the new dataset "Division 10 Elements," the decision tree, and the FHWA element sheets. The research plan includes four steps: 1) clean up the "Division 10 Elements" dataset and only include the 442 bridges; 2) calculate percentage defect for deck and superstructure elements; 3) determine the preservation activities for each span according to the decision trees; and 4) apply the overwrite rules to develop a final preservation activity list for the 442 bridges. The research team will develop a software program to implement the steps. The initial results are expected to be available to NCDOT by November 18, 2022. |
| 3 | The research team will send the definitions of "urgency," "recency," and "frequency" proposed by Dr. Simon Hsiang to the SMU group. |

**Follow-up 1: Definitions for Urgency, Frequency, and Recency**
**Urgency**: a measure of how quickly the incident needs to be resolved.
**Frequency**: a measure of how many times something happens within a certain period.
**Recency**: a measure of how recent the last action was taken.

**Follow-up 2: Interpretation for the Decision Tables**
It was confirmed that each decision table in the decision tree file can be interpreted by three tables. A sample decision table is given below in Table A8.

Table A8 The Original Decision Tree Table

| | | CS2 | CS3 | CS4 | CS4 |
|---|---|---|---|---|---|
| Defect # | Defect Name | < 40% of Deck Surface | < 20% of Deck Surface | < 10% of Deck Surface | ≥ 10% of Deck Surface |
| 1080 | Delamination/Spall | Concrete for Deck Repair (1) | Concrete for Deck Repair (2) | Overlay (3) | Replace Concrete Deck (4) |

The following three decision tables (Table A9, Table A10, and Table A11) list the corresponding action items based on percentage defect for different CS. The three tables are equivalent to the Table A8.

Table A9 The First Interpretation Decision Tree Table

| CS2=0% | | CS3 | | |
|---|---|---|---|---|
| | | 0% | (0%,20%) | [20%,100%] |
| CS4 | 0% | Nothing | Concrete for Deck Repair (2) | Overlay (3) |
| | (0%,10%) | Overlay (3) | Overlay (3) | Overlay (3) |
| | [10%,100%] | Replace Concrete Deck (4) | Replace Concrete Deck (4) | Replace Concrete Deck (4) |

Table A10 The Second Interpretation Decision Tree Table

| CS2<40% | | CS3 0% | CS3 (0%,20%) | CS3 [20%,100%] |
|---|---|---|---|---|
| CS4 | 0% | Concrete for Deck Repair (1) | Concrete for Deck Repair (2) | Overlay (3) |
| CS4 | (0%,10%) | Overlay (3) | Overlay (3) | Overlay (3) |
| CS4 | [10%,100%] | Replace Concrete Deck (4) | Replace Concrete Deck (4) | Replace Concrete Deck (4) |

Table A11 The Third Interpretation Decision Tree Table

| CS2>=40% | | CS3 0% | CS3 (0%,20%) | CS3 [20%,100%] |
|---|---|---|---|---|
| CS4 | 0% | Concrete for Deck Repair (2) | Concrete for Deck Repair (2) | Overlay (3) |
| CS4 | (0%,10%) | Overlay (3) | Overlay (3) | Overlay (3) |
| CS4 | [10%,100%] | Replace Concrete Deck (4) | Replace Concrete Deck (4) | Replace Concrete Deck (4) |

**Follow-up 3: Activity Overwrite Rules**

The following activities highlighted in red, once triggered, will overwrite activities triggered by the corresponding lower-level CS criteria.

| **Reinforced Concrete Decks** | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 12<br>65 | 38 | 16 | 60 |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Deck Surface | < 20% of Deck Surface | < 10% of Deck | ≥ 10% of Deck Surface |
| 1080 | Delamination/Spall | Concrete for Deck Repair | Concrete for Deck Repair | Overlay | Replace Concrete Deck |
| 1085 | Patched Area | Nothing | Concrete for Deck Repair | Overlay | Replace Concrete Deck |
| 1090 | Exposed Rebar | Concrete for Deck Repair | Overlay | Overlay | Replace Concrete Deck |
| 1120 | Efflorescence/Rust Staining | Nothing | Overlay | Overlay | Replace Concrete Deck |
| 1130 | Cracking (RC and Other) | Silane | HMWM | Overlay | Overlay |
| 1190 | Abrasion/Wear (PSC/RC) | Nothing | Overlay | Overlay | Overlay |

**Prestressed Concrete Decks**

| | Applies to Element #'s: | 13 | 15 | | |
|---|---|---|---|---|---|
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 20% of Deck Surface | < 10% of Deck Surface | < 5% of Deck Surface | ≥ 5% of Deck Surface |
| 1080 | Delamination/Spall | Concrete for Deck Repair | Concrete for Deck Repair | Overlay | Replace Concrete Deck |
| 1085 | Patched Area | Nothing | Concrete for Deck Repair | Overlay | Replace Concrete Deck |
| 1090 | Exposed Rebar | Concrete for Deck Repair | Overlay | Overlay | Replace Concrete Deck |
| 1100 | Exposed Prestressing | Concrete for Deck Repair | Overlay | Overlay | Replace Concrete Deck |
| 1110 | Cracking (PSC) | Silane | HMWM | Overlay | Overlay |
| 1120 | Efflorescence/Rust Staining | Nothing | Overlay | Overlay | Replace Concrete Deck |
| 1190 | Abrasion/Wear (PSC/RC) | Nothing | Overlay | Overlay | Overlay |

**Concrete Barrier**

| | Applies to Element #'s: | 331 | 333 | | |
|---|---|---|---|---|---|
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Barrier | < 20% of Barrier | < 10% of Barrier | ≥ 10% of Barrier |
| 1080 | Delamination/Spall | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Section of Concrete Barrier |
| 1085 | Patched Area | Nothing | Nothing | Concrete Repair | Replace Section of Concrete Barrier |
| 1090 | Exposed Rebar | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Section of Concrete Barrier |
| 1120 | Efflorescence/Rust Staining | Nothing | Nothing | Shotcrete Repair | Replace Section of Concrete Barrier |
| 1130 | Cracking (RC and Other) | Nothing | Silane | Silane | Replace Section of Concrete Barrier |

**Joints**

| | Applies to Element #'s: | 300 | 301 | 302 | 303 |
|---|---|---|---|---|---|
| | | 305 | 306 | 304 | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Joint | < 20% of Joint | < 10% of Joint | ≥ 10% of Joint |
| 2310 | Leakage | Nothing | Joint Replacement | Joint Replacement | Joint Replacement |
| 2320 | Seal Adhesion | Nothing | Joint Replacement | Joint Replacement | Joint Replacement |
| 2330 | Seal Damage | Nothing | Joint Replacement | Joint Replacement | Joint Replacement |
| 2340 | Seal Cracking | Nothing | Joint Replacement | Joint Replacement | Joint Replacement |
| 2350 | Debris Impaction | Nothing | Joint Cleaning | Joint Cleaning | Joint Replacement |
| 2360 | Adjacent Deck or Header | Nothing | Bridge Joint Demolition | Bridge Joint Demolition | Joint Replacement |
| 2370 | Metal Deterioration or Damage | Nothing | Joint Replacement | Joint Replacement | Joint Replacement |

**Reinforced Concrete Superstructure**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 105 | 106 | 110 | 112 |
| | | 118 | 136 | 142 | 144 |
| | | 157 | 116 | 155 | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Reinforced | < 20% of Reinforced | < 10% of Reinforced | ≥ 10% of Reinforced |
| 1080 | Delamination/Spall | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Reinforced Concrete Superstructure Element |
| 1085 | Patched Area | Nothing | Shotcrete Repair | FRP Beam Repair | Replace Reinforced Concrete Superstructure Element |
| 1090 | Exposed Rebar | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Reinforced Concrete Superstructure Element |
| 1120 | Efflorescence/Rust Staining | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Reinforced Concrete Superstructure Element |
| 1130 | Cracking (RC and Other) | Nothing | Epoxy Resin Injection | Epoxy Resin Injection | Replace Reinforced Concrete Superstructure Element |

**Prestressed Concrete Superstructure**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 104 | 109 | 115 | 143 |
| | | 154 | | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 20% of Prestressed Member | < 10% of Prestressed Member | < 5% of Prestressed Member | ≥ 5% of Prestressed Member |
| 1080 | Delamination/Spall | Shotcrete Repair | Repairs to Prestressed Girders | Repairs to Prestressed Girders | Replace Prestressed Superstructure Element |
| 1085 | Patched Area | Nothing | Shotcrete Repair | FRP Beam Repair | Replace Prestressed Superstructure Element |
| 1090 | Exposed Rebar | Nothing | Shotcrete Repair | Repairs to Prestressed Girders | Replace Prestressed Superstructure Element |
| 1100 | Exposed Prestressing | Shotcrete Repair | Shotcrete Repair | Repairs to Prestressed Girders with Strand Splice | Replace Prestressed Superstructure Element |
| 1110 | Cracking (PSC) | Epoxy Resin Injection | Epoxy Resin Injection | Epoxy Resin Injection | Replace Prestressed Superstructure Element |
| 1120 | Efflorescence/Rust Staining | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Prestressed Superstructure Element |

**Steel Superstructure**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 102 | 106 | 107 | 112 |
| | | 118 | 120 | 1120 | 136 |
| | | 142 | 152 | 157 | 113 |
| | | 141 | | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Steel | < 20% of Steel Member | < 10% of Steel Member | ≥ 10% of Steel Member |
| 1000 | Corrosion | Nothing | Steel Beam Repair | Steel Beam Repair | Replace Steel Superstructure Element |
| 1010 | Cracking | Nothing | Steel Crack Arrest | Steel Beam Repair | Replace Steel Superstructure Element |
| 1020 | Connection | Nothing | Replace missing or broken fasteners | Replace missing or broken fasteners | Replace Steel Superstructure Element |
| 1900 | Distortion | Nothing | Steel Beam Repair | Heat Straightening | Replace Steel Superstructure Element |

**Steel Superstructure Element**

This is for steel elements like steel cables and gusset plates, that do not act like girders

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 147 | 148 | 149 | 161 |
| | | 162 | | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Steel | < 20% of Steel Member | < 10% of Steel Member | ≥ 10% of Steel Member |
| 1000 | Corrosion | Nothing | Spot Painting | Replace Steel Superstructure Element | Replace Steel Superstructure Element |
| 1010 | Cracking | Nothing | Steel Crack Arrest | Steel Crack Arrest | Replace Steel Superstructure Element |
| 1020 | Connection | Nothing | Replace missing or broken fasteners | Replace missing or broken fasteners | Replace Steel Superstructure Element |
| 1900 | Distortion | Nothing | Nothing | Replace Steel Superstructure Element | Replace Steel Superstructure Element |

**Timber Superstructure**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 111 | 117 | 135 | 146 |
| | | 156 | | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Timber Member | < 20% of Timber Member | < 10% of Timber Member | ≥ 10% of Timber Member |
| 1020 | Connection | Nothing | Replace missing or broken fasteners | Replace missing or broken fasteners | Replace Timber Superstructure Element |
| 1140 | Decay/Section Loss | Nothing | Nothing | Replace Timber Superstructure Element | Replace Timber Superstructure Element |
| 1150 | Check/Shake | Nothing | Nothing | Replace Timber Superstructure Element | Replace Timber Superstructure Element |
| 1160 | Crack (Timber) | Nothing | Nothing | Penetrating sealer | Replace Timber Superstructure Element |
| 1170 | Split/Delamination (Timber) | Nothing | Nothing | Replace Timber Superstructure Element | Replace Timber Superstructure Element |
| 1180 | Abrasion/Wear (Timber) | Nothing | Nothing | Replace Timber Superstructure Element | Replace Timber Superstructure Element |

**Bearings**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 310 | 311 | 312 | 313 |
| | | 315 | 316 | 314 | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Bearing Line | < 20% of Bearing Line | < 10% of Bearing Line | ≥ 10% of Bearing Line |
| 1000 | Corrosion | Nothing | Paint and Maintain Bearings | Paint and Maintain Bearings | Replace Bearing |
| 1020 | Connection | Nothing | Replace missing or broken fasteners | Replace missing or broken fasteners | Replace Bearing |
| 2210 | Movement | Nothing | Jack and Repair Bearing/Bearing Area | Jack and Repair Bearing/Bearing Area | Replace Bearing |
| 2220 | Alignment | Nothing | Jack and Repair Bearing/Bearing Area | Jack and Repair Bearing/Bearing Area | Replace Bearing |
| 2230 | Bulging, Splitting or Tearing | Nothing | Nothing | Replace Bearing | Replace Bearing |
| 2240 | Loss of Bearing Area | Nothing | Jack and Repair Bearing/Bearing Area | Jack and Repair Bearing/Bearing Area | Jack and Repair Bearing/Bearing Area |

**Reinforced Concrete Substructure Element**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 203 | 205 | 210 | 211 |
| | | 218 | 227 | 229 | 215 |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Reinforced | < 20% of Reinforced | < 10% of Reinforced | ≥ 10% of Reinforced |
| 1080 | Delamination/Spall | Shotcrete Repair | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1085 | Patched Area | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1090 | Exposed Rebar | Shotcrete Repair | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1120 | Efflorescence/Rust Staining | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1130 | Cracking (RC and Other) | Nothing | Epoxy Resin Injection | Epoxy Resin Injection | Replace Concrete Substructure Element |
| 1190 | Abrasion/Wear (PSC/RC) | Nothing | Nothing | Pile Jacket | Replace Concrete Substructure Element |
| 4000 | Settlement | Nothing | Nothing | Temporary Shoring | Replace Concrete Substructure Element |
| 6000 | Scour | Nothing | Scour Countermeasures | Scour Countermeasures | Replace Concrete Substructure Element |

**Reinforced Concrete Substructure Cap** — Substructure concrete caps have been separated, as concrete repairs would be typically used on caps,

Applies to Element #'s: 220, 234, 235

| Defect # | Defect Name | CS2<br>< 40% of Reinforced | CS3<br>< 20% of Reinforced | CS4<br>< 10% of Reinforced | CS4<br>≥ 10% of Reinforced |
|---|---|---|---|---|---|
| 1080 | Delamination/Spall | Concrete Repair | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |
| 1085 | Patched Area | Nothing | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |
| 1090 | Exposed Rebar | Concrete Repair | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |
| 1120 | Efflorescence/Rust Staining | Nothing | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |
| 1130 | Cracking (RC and Other) | Nothing | Epoxy Resin Injection | Epoxy Resin Injection | Replace Concrete Substructure Element |
| 1190 | Abrasion/Wear (PSC/RC) | Nothing | Nothing | Pile Jacket | Replace Concrete Substructure Element |
| 4000 | Settlement | Nothing | Nothing | Temporary Shoring | Replace Concrete Substructure Element |
| 6000 | Scour | Nothing | Scour Countermeasures | Scour Countermeasures | Replace Concrete Substructure Element |

**Prestressed Substructure Element**

Applies to Element #'s: 204, 226

| Defect # | Defect Name | CS2<br>< 20% of Prestressed | CS3<br>< 10% of Prestressed | CS4<br>< 5% of Prestressed | CS4<br>≥ 5% of Prestressed |
|---|---|---|---|---|---|
| 1080 | Delamination/Spall | Shotcrete Repair | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1085 | Patched Area | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1090 | Exposed Rebar | Shotcrete Repair | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1100 | Exposed Prestressing | Shotcrete Repair | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1110 | Cracking (PSC) | Epoxy Resin Injection | Epoxy Resin Injection | Epoxy Resin Injection | Replace Concrete Substructure Element |
| 1120 | Efflorescence/Rust Staining | Nothing | Shotcrete Repair | Shotcrete Repair | Replace Concrete Substructure Element |
| 1190 | Abrasion/Wear (PSC/RC) | Nothing | Nothing | Pile Jacket | Replace Concrete Substructure Element |
| 4000 | Settlement | Nothing | Nothing | Temporary Shoring | Replace Concrete Substructure Element |
| 6000 | Scour | Nothing | Scour Countermeasures | Scour Countermeasures | Replace Concrete Substructure Element |

**Prestressed Substructure Cap** — Substructure concrete caps have been separated, as concrete repairs would be typically used on caps, rather than shotcrete.

Applies to Element #'s: 233

| Defect # | Defect Name | CS2<br>< 20% of Prestressed | CS3<br>< 10% of Prestressed | CS4<br>< 5% of Prestressed | CS4<br>≥ 5% of Prestressed |
|---|---|---|---|---|---|
| 1080 | Delamination/Spall | Concrete Repair | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |
| 1085 | Patched Area | Nothing | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |
| 1090 | Exposed Rebar | Concrete Repair | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |
| 1100 | Exposed Prestressing | Concrete Repair | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |
| 1110 | Cracking (PSC) | Epoxy Resin Injection | Epoxy Resin Injection | Epoxy Resin Injection | Replace Concrete Substructure Element |
| 1120 | Efflorescence/Rust Staining | Nothing | Concrete Repair | Concrete Repair | Replace Concrete Substructure Element |

**Steel Substructure Element**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 202 | 203 | 207 | 211 |
| | | 219 | 225 | 229 | 231 |
| | | 218 | 235 | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Steel Member | < 20% of Steel Member | < 10% of Steel Member | ≥ 10% of Steel Member |
| 1000 | Corrosion | Nothing | Clean and Paint Substructure | Repair Steel Substructure Element | Replace Steel Substructure Element |
| 1010 | Cracking | Nothing | Steel Crack Arrest | Repair Steel Substructure Element | Replace Steel Substructure Element |
| 1020 | Connection | Nothing | Replace missing or broken fasteners | Replace missing or broken fasteners | Replace Steel Substructure Element |
| 1900 | Distortion | Nothing | Repair Steel Substructure Element | Temporary Shoring | Replace Steel Substructure Element |
| 4000 | Settlement | Nothing | Nothing | Temporary Shoring | Replace Steel Substructure Element |
| 6000 | Scour | Nothing | Scour Countermeasures | Scour Countermeasures | Replace Steel Substructure Element |

**Timber Substructure Element**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 206 | 208 | 212 | 216 |
| | | 235 | 228 | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Timber Member | < 20% of Timber Member | < 10% of Timber Member | ≥ 10% of Timber Member |
| 1020 | Connection | Nothing | Replace missing or broken fasteners | Replace missing or broken fasteners | Replace Timber Substructure Element |
| 1140 | Decay/Section Loss | Nothing | Nothing | Replace Timber Substructure Element | Replace Timber Substructure Element |
| 1150 | Check/Shake | Nothing | Nothing | Replace Timber Substructure Element | Replace Timber Substructure Element |
| 1160 | Crack (Timber) | Nothing | Nothing | Penetrating sealer | Replace Timber Substructure Element |
| 1170 | Split/Delamination (Timber) | Nothing | Nothing | Replace Timber Substructure Element | Replace Timber Substructure Element |
| 1180 | Abrasion/Wear (Timber) | Nothing | Nothing | Pile Jacket | Replace Timber Substructure Element |
| 4000 | Settlement | Nothing | Nothing | Temporary Shoring | Replace Timber Substructure Element |
| 6000 | Scour | Nothing | Nothing | Scour Countermeasures | Replace Timber Substructure Element |

**Masonry Substructure Element**

| | | | | | |
|---|---|---|---|---|---|
| | Applies to Element #'s: | 213 | 217 | | |
| | | CS2 | CS3 | CS4 | CS4 |
| Defect # | Defect Name | < 40% of Masonry Member | < 20% of Masonry Member | < 10% of Masonry Member | ≥ 10% of Masonry Member |
| 1120 | Efflorescence/Rust Staining | Nothing | Nothing | Replace Defective Masonry | Replace Defective Masonry |
| 1610 | Mortar Breakdown | Nothing | Nothing | Replace Defective Masonry | Replace Defective Masonry |
| 1620 | Split/Spall (Masonry) | Nothing | Nothing | Replace Defective Masonry | Replace Defective Masonry |
| 1630 | Patched Area (Masonry) | Nothing | Nothing | Replace Defective Masonry | Replace Defective Masonry |
| 1640 | Masonry Displacement | Nothing | Nothing | Replace Defective Masonry | Replace Defective Masonry |
| 4000 | Settlement | Nothing | Nothing | Temporary Shoring | Replace Defective Masonry |
| 6000 | Scour | Nothing | Nothing | Scour Countermeasures | Replace Defective Masonry |

## APPENDIX F Meeting Minutes_February 13, 2023

**Project No.:** **RP 2023-05**
**Title: Prioritizing NCDOT Bridge Preservation Projects Using Bridge Element Inspection Data**
**Meeting: Preservation Activity Triggering Model Progress Report & Data Clarification**
**Location: 1000 Birch Ridge Dr. Raleigh, NC 27610**
**DOT CCA Structures Conference Room Col. C4**
**Date: February 13, 2023**
**Time: 1:00 p.m. – 3:00 p.m.**

**Meeting Attendees**

| **Steering and Implementation Committee** | **NCDOT Bridge Maintenance System Managers** | **Research Team** |
|---|---|---|
| Nicholas Pierce – Chair | | Min Liu |
| Asa Godfrey | | Chuanni He |

**1) Preservation activity triggering model:**

a. The research team has completed the first version of the triggering model for superstructures and substructures and submitted it to NCDOT for validation.
b. Chuanni demonstrated the model and explained the coding and functions.
c. NCDOT suggested that the defects of wearing surfaces and protective system elements (listed below) be reported as defects of their parent elements in the version 3 datasets (3"Div_10_sub_january23.csv" and "Div_10_super_january23.csv"). The research team will revise the triggering model to remove these elements from triggering preservation activities. NCDOT also suggested that the defect quantities for wearing surface and protective system elements can be used for cost estimation since they are measured by area ($ft.^2$).

- Element 510 (wearing surface)
- Element 515 (steel protective coating)
- Element 520 (concrete reinforcing steel protective system)
- Element 521 (concrete protective coating)

d. NCDOT suggested that if element 521 has an associated CS3 and CS4 quantity, the model should directly trigger a "clean and recoating" activity. The newly added decision table is shown in Table A12.

Table A12 Newly Added Decision Table for Element 521

| Applies to steel superstructure bridges | | 521 | | |
|---|---|---|---|---|
| | | CS2 | CS3 | CS4 |
| Defect # | Defect Name | < 100% of Steel Surface | > 0% of Concrete Surface | > 0% of Concrete Surface |
| 3510 | Wear (Concrete Protective Coatings) | Nothing | Clean and Recoating | Clean and Recoating |
| 3540 | Effectiveness (Concrete Protective Coatings) | Nothing | Clean and Recoating | Clean and Recoating |
| 7000 | Damage | Nothing | Clean and Recoating | Clean and Recoating |

**2) Version 3 datasets ("Div_10_sub_january23.csv" and "Div_10_super_january23.csv"):**

a. In the new datasets, the PAR columns indicate that inspectors have raised concerns about the defect for the further attention of NCDOT SMU experts. The SMU experts assign the corresponding PAR requests to RM, PM, or CF. RM means that the defect is not cause for extra concern, PM means that the defects require higher-priority action, and CF means urgent treatment is needed. The corresponding quantity ("PARQuantity", "PMQuantity", and "CFQuantity") measures the defect quantity of the related PAR requests, and its unit is consistent with the ASSTO defect quantity.

b. The "levelXrepairs" columns indicate to the inspectors that they are to identify whether the defect has been repaired; the "levelXseverity" columns suggest whether the defect still applies. Both variables should be Boolean. NCDOT will investigate why the values in current datasets are continuous instead of Boolean.

**3) Bid average dataset:**

NCDOT will associate the bid average records with pay items for each preservation activity and send the results to the research team to develop the cost estimation model.

**4) Inflation rate data:**

The research team will send the inflation data provided by the NCDOT 2020–2029 Current STIP program to NCDOT SMU for confirmation.

**5) Miscellaneous:**

a. The as-built bridge preservation history record is managed by SMU's construction sector.

b. NCDOT suggested the research team continue the literature review on preservation activity's impact on extended service life and report to NCDOT if there is a huge difference between the literature and the items in "Preservation Activities with Estimated Service Life.xls".

c. NCDOT corrected the estimated service life for some preservation activities. The corrected data are listed in Table A13.

Table A13 Updated Estimated Service Life for Preservation Activities

| | Activities Name | Estimated Service Life (Year) | Name of similar activities in DOT Data file |
|---|---|---|---|
| 1 | Asphalt Patch | 5 | - |
| 2 | Clean and Paint Substructure | 20 | - |
| 3 | Clean and Repaint Bridge | - | Paint Existing Structure (20 Year) |
| 4 | Overlay | - | LMC Overlay (25 Years) |
| | | | PPC Overlay (25 Years) |
| | | | Epoxy Overlay (10 Years) |
| 5 | Replace Wearing Surface | 25 | - |
| 6 | Repairs to Prestressed Girders | 20 | - |
| 7 | Replace Wearing Surface | 25 | - |
| 8 | Steel Repairs | 50 | |
| 9 | Penetrating sealer | 4 | |
| 10 | Penetrating sealer | 4 | |

| Action Items | |
|---|---|
| 1 | NCDOT will check and clarify the data observations discrepancy between version 2 "Division10_Elements_20220930.xlsx" and version 3 "Div_10_sub_january23.csv", "Div_10_super_january23.csv" datasets. |
| 2 | NCDOT will check the "levelXrepairs" and "levelXseverity" columns of the version 3 datasets to confirm the meaning of these variables. |
| 3 | NCDOT will associate the bid average records with pay items for each preservation activity and send the results to the research team. |
| 4 | NCDOT will confirm the inflation rate with NCDOT STIP program. |
| 5 | The research team will revise the triggering model to remove elements 510, 515, 520, and 521 from triggering activities. |
| 6 | The research team will check the version 3 datasets to ensure the defects for elements 510, 515, 520, and 521 have been reported in their parent elements and will report to NCDOT if any discrepancy is found. |
| 7 | The research team will continue reviewing literature on preservation activity extended service life. The research team will report to NCDOT if a large discrepancy is found between the literature and data in the "Preservation Activities with Estimated Service Life.xls" file. |
| 8 | The research team will send the inflation rate data to NCDOT SMU for their validation. |

**Follow up:**

1. The research team will remove elements 510, 515, 520 from the datasets, and use element 521 to match the decision rules listed in section 1(d) to trigger the corresponding preservation activities for elements in wearing surfaces, protective coatings, and concrete reinforcing steel protective systems.

## APPENDIX G Meeting Minutes_December 8, 2022

**Project No.:** **RP 2023-05**
**Title: Prioritizing NCDOT Bridge Preservation Projects Using Bridge Element Inspection Data**
**Meeting:** **Preservation Activity Triggering Model Progress Report**
**Location:** **1000 Birch Ridge Dr. Raleigh, NC 27610**
**DOT CCA Structures Conference Room Col. C4**
**Date:** **December 8, 2022**
**Time:** **10:00 a.m.–12:00 a.m.**

**Meeting Attendees**

| **Steering and Implementation Committee** | **NCDOT Bridge Maintenance System Managers** | **Research Team** |
|---|---|---|
| Nicholas Pierce – Chair | | Min Liu |
| Asa Godfrey | | Simon Hsiang |
| Sam Megahed | | Chuanni He |
| Tim Sherrill | | |
| David Snoke | | |

**1) Preservation Activity Triggering Model for Superstructures:**

a. NCDOT confirmed that the structure of the model is correct and that the research team can use the same structure and method to build the triggering model for substructure defects.

b. The rules for differentiating Type I observations (different elements with the same type of defects) and Type II observations (same elements with different types of defects) will be verified by NCDOT, which will provide a new dataset to distinguish different types of observations.

c. The element 515 “Steel Protective Coating” applies to multiple bridge objects. The decision model should distinguish the unit for reporting those defects associated with element 515. NCDOT will compile a set of rules to associate element 515 with different objects and calculate the total element quantity accordingly.

d. The overwrite rule of “Deck Overlay” should be considered at the bridge level instead of the span level.

**2) Preservation Activity Triggering Model for Substructures:**

a. The research team confirmed with NCDOT that maintenance/preservation activities would only be triggered for defects with a corresponding maintenance quantity. This rule should be checked at each CS level for the substructures.
b. The research will use the total quantity of a bent for the same defect as the denominator to calculate the percentage defect for substructure elements.
c. NCDOT will provide a new dataset to distinguish between Type I and Type II observations for substructures.
d. The research team will compile a list of defects that do not exist in the decision tree. NCDOT will provide feedback regarding how to address these defects.

e. The research team has confirmed with NCDOT that the same overwrite rules would be applied to substructures with no updates.

**3) Bridge Criticality vs. Local Economy**

a. NCDOT does not track historical preservation activity logs. A detailed budget plan for urgent fix of bridge defects is unavailable.

b. The research team will contact Mustan to arrange a meeting with the steering and implementation committee to brainstorm the data source for this topic and discuss whether to expand the project or have it as a new research project.

**4) Miscellaneous**

The research team will conduct preliminary research on Task 4: Establish a cost estimation model. The research team will use the unit cost data from the "2021 BID AVERAGES.xlsm" file.

| Action Items | |
|---|---|
| 1 | NCDOT will confirm/clarify that the following elements are Type I (different elements with the same type of defects): Element 301; Element 302; Element 310; Element 311; Element 312; Element 313; Element 314; Element 315; Element 316; and Element 515. |
| 2 | NCDOT will provide a new dataset to distinguish between Type I and Type II observations for superstructures and substructures. |
| 3 | NCDOT will confirm the proper way to deal with defect "Damage" for all elements, "Abrasion/Wear (PSC/RC)" for element 104; "Deterioration (Other)" for element 333; all defects for element 521; and "Wear (Concrete Protective Coatings)" for element 234 because they do not exist in the decision tree. |
| 4 | NCDOT will provide a set of rules to determine the total quantity calculation rules for element 515. |
| 5 | The research team will revise the overwrite rules of the existing model for superstructures. |
| 6 | The research team will revise the model to accommodate the revised total quantity for element 515 once receiving feedback from NCDOT. |
| 7 | The research team will continue working on the triggering model for substructure elements. |
| 8 | The research team will list those activities that do not exist in the decision tree and send them to NCDOT for feedback (see Appendix 1 below). |
| 9 | The research team will list the elements of Type I and Type II observations used in the model and send it to NCDOT for feedback (see Appendix 2 below). |

**Follow-up 1: Defect Items do not Exist in Decision Tree**

The following defect items were not found in the decision tree file.

Superstructures:

1. Defect "Damage" for all elements.
2. Defect "Abrasion/Wear (PSC/RC)" for element 104.
3. Defect "Deterioration (Other)" for element 333.
4. All the defects for element 521.

Substructures:

1. Defect "Damage" for all elements.
2. Defect "Effectiveness (Concrete Protective Coatings)" for element 521.

3. Defect “Wear (Concrete Protective Coatings)” for element 521.
4. Defect “Wear (Concrete Protective Coatings)” for element 234.

**Follow-up 2: Element List for Type I and Type II Observations**
**Superstructures:**
1. Type I observations (different elements with the same type of defects): Element 301; Element 302; Element 310; Element 311; Element 312; Element 313; Element 314; Element 315; Element 316; Element 515.
2. Type II observations (same element with different types of defects): all the other elements.

**Follow-up 3: Responses from NCDOT**
**1) Type I and Type II observations clarification.**

a. NCDOT confirmed to send a new dataset containing a column called “Parent Element Number”, which can be used to look at the defects and connect them back to the element they are associated with. This will eliminate the issue where defect 515 (Steel Protective Coating) was on bearings for prestressed girders flagged “clean and repaint structure” on top of the “clean and paint bearings” triggered by defect 15 (Corrosion) the bearings had.
b. NCDOT will provide a new item to indicate if repairs have been made to previously reported defects, along with lines for PARs Submitted, Critical Quantities and Priority Quantities which can help answer the questions about Urgency, Frequency and Recency.
c. NCDOT confirmed that observations for Element 300, 301, 302, 303, 304, 305, and 306 are in type II (same element with different types of defects).
d. NCDOT confirmed that observations for Element 310, 311, 312, 313, 314, 315, and 316 are in type I (different element types with the same types of defects).
e. NCDOT confirmed that observations for Element 510, 515, 520, and 521 are in type I (different element types with the same types of defects).

**2) Defects do not exist in the decision tree.**

a. NCDOT confirmed to ignore “Damage” defects on all elements currently.
b. NCDOT confirmed to ignore “Deterioration” on Element 333 (Other Bridge Rail).
c. For element 521 (Concrete Protective Coating) assigned to parent element 234 (Reinforced Concrete Pier Cap), if it’s in CS 3 or 4, trigger “Epoxy Coating” or “DO NOTHING”. For element 521 (Concrete Protective Coating) assigned to parent element 109 (Prestressed Concrete Open Girder/Beam), if it’s in CS 3 or 4, trigger “Epoxy Coating Girder Ends” or “DO NOTHING”.

## APPENDIX H Miscellaneous Cost Estimation Parameters

| Bridge Number | Interstate Route | Overlay Type | Bridge Number | Interstate Route | Overlay Type |
|---|---|---|---|---|---|
| 030003 | 0 | 1 | 590452 | 1 | 0 |
| 030004 | 0 | 1 | 590459 | 0 | 1 |
| 030006 | 0 | 1 | 590460 | 0 | 1 |
| 030010 | 0 | 1 | 590463 | 0 | 1 |
| 030012 | 0 | 1 | 590475 | 0 | 1 |
| 030013 | 0 | 1 | 590478 | 1 | 0 |
| 030022 | 0 | 1 | 590479 | 1 | 0 |
| 030024 | 0 | 1 | 590480 | 0 | 1 |
| 030027 | 0 | 1 | 590481 | 0 | 1 |
| 030028 | 0 | 1 | 590487 | 1 | 0 |
| 030032 | 0 | 1 | 590488 | 1 | 0 |
| 030033 | 0 | 1 | 590489 | 0 | 1 |
| 030036 | 0 | 1 | 590507 | 1 | 0 |
| 030049 | 0 | 1 | 590508 | 1 | 0 |
| 030050 | 0 | 1 | 590509 | 1 | 0 |
| 030051 | 0 | 1 | 590510 | 1 | 0 |
| 030054 | 0 | 1 | 590513 | 0 | 1 |
| 030056 | 0 | 1 | 590515 | 0 | 1 |
| 030057 | 0 | 1 | 590516 | 0 | 1 |
| 030058 | 0 | 1 | 590517 | 0 | 1 |
| 030060 | 0 | 1 | 590522 | 1 | 0 |
| 030064 | 0 | 1 | 590532 | 1 | 0 |
| 030065 | 0 | 1 | 590539 | 0 | 1 |
| 030066 | 0 | 1 | 590540 | 0 | 1 |
| 030067 | 0 | 1 | 590541 | 0 | 1 |
| 030071 | 0 | 1 | 590544 | 1 | 0 |
| 030072 | 0 | 1 | 590559 | 0 | 1 |
| 030073 | 0 | 1 | 590597 | 0 | 1 |
| 030074 | 0 | 1 | 590599 | 0 | 1 |
| 030076 | 0 | 1 | 590600 | 0 | 1 |
| 030078 | 0 | 1 | 590601 | 1 | 0 |
| 030081 | 0 | 1 | 590602 | 0 | 1 |
| 030100 | 0 | 1 | 590603 | 1 | 0 |
| 030126 | 0 | 1 | 590604 | 1 | 0 |
| 030150 | 0 | 1 | 590605 | 1 | 0 |
| 030151 | 0 | 1 | 590606 | 1 | 0 |
| 030159 | 0 | 1 | 590607 | 1 | 0 |
| 030172 | 0 | 1 | 590619 | 0 | 1 |
| 030173 | 0 | 1 | 590638 | 1 | 0 |
| 030179 | 0 | 1 | 590639 | 1 | 0 |
| 030184 | 0 | 1 | 590649 | 0 | 1 |
| 030193 | 0 | 1 | 590653 | 0 | 1 |
| 030199 | 0 | 1 | 590657 | 1 | 0 |
| 030201 | 0 | 1 | 590658 | 1 | 0 |
| 030207 | 0 | 1 | 590659 | 1 | 0 |
| 030209 | 0 | 1 | 590660 | 1 | 0 |
| 030210 | 0 | 1 | 590662 | 1 | 0 |
| 030244 | 0 | 1 | 590663 | 1 | 0 |
| 030251 | 0 | 1 | 590664 | 1 | 0 |

| | | | | | |
|---|---|---|---|---|---|
| 030258 | 0 | 1 | 590667 | 0 | 1 |
| 030267 | 0 | 1 | 590668 | 0 | 1 |
| 030292 | 0 | 1 | 590669 | 0 | 1 |
| 030300 | 0 | 1 | 590670 | 1 | 0 |
| 030301 | 0 | 1 | 590676 | 0 | 1 |
| 030308 | 0 | 1 | 590680 | 0 | 1 |
| 030314 | 0 | 1 | 590681 | 0 | 1 |
| 120006 | 0 | 1 | 590695 | 0 | 1 |
| 120007 | 0 | 1 | 590714 | 0 | 1 |
| 120009 | 0 | 1 | 590740 | 0 | 1 |
| 120013 | 0 | 1 | 590742 | 0 | 1 |
| 120016 | 0 | 1 | 590743 | 1 | 0 |
| 120017 | 0 | 1 | 590744 | 1 | 0 |
| 120020 | 0 | 1 | 590746 | 0 | 1 |
| 120021 | 0 | 1 | 590747 | 1 | 0 |
| 120022 | 0 | 1 | 590748 | 0 | 1 |
| 120023 | 0 | 1 | 590802 | 1 | 0 |
| 120027 | 0 | 1 | 590803 | 1 | 0 |
| 120034 | 0 | 1 | 590805 | 1 | 0 |
| 120035 | 0 | 1 | 590809 | 0 | 1 |
| 120042 | 0 | 1 | 590811 | 0 | 1 |
| 120060 | 0 | 1 | 590814 | 0 | 1 |
| 120075 | 0 | 1 | 590818 | 1 | 0 |
| 120081 | 0 | 1 | 590821 | 0 | 1 |
| 120082 | 0 | 1 | 590822 | 0 | 1 |
| 120083 | 0 | 1 | 590824 | 0 | 1 |
| 120096 | 0 | 1 | 590826 | 0 | 1 |
| 120100 | 0 | 1 | 590841 | 0 | 1 |
| 120104 | 0 | 1 | 590847 | 0 | 1 |
| 120107 | 0 | 1 | 590852 | 0 | 1 |
| 120114 | 0 | 1 | 590921 | 0 | 1 |
| 120117 | 0 | 1 | 590922 | 1 | 0 |
| 120118 | 0 | 1 | 590923 | 1 | 0 |
| 120121 | 0 | 1 | 590925 | 0 | 1 |
| 120127 | 0 | 1 | 590929 | 1 | 0 |
| 120133 | 0 | 1 | 590938 | 0 | 1 |
| 120141 | 0 | 1 | 590939 | 1 | 0 |
| 120148 | 0 | 1 | 590940 | 1 | 0 |
| 120155 | 0 | 1 | 590945 | 0 | 1 |
| 120172 | 0 | 1 | 590949 | 1 | 0 |
| 120178 | 0 | 1 | 590950 | 1 | 0 |
| 120179 | 0 | 1 | 590953 | 1 | 0 |
| 120193 | 0 | 1 | 590954 | 1 | 0 |
| 120267 | 0 | 1 | 590957 | 1 | 0 |
| 120336 | 0 | 1 | 590960 | 1 | 0 |
| 120337 | 0 | 1 | 590961 | 1 | 0 |
| 120341 | 0 | 1 | 590962 | 0 | 1 |
| 120348 | 0 | 1 | 590963 | 1 | 0 |
| 120357 | 0 | 1 | 590964 | 1 | 0 |
| 120386 | 0 | 1 | 590965 | 1 | 0 |
| 120397 | 0 | 1 | 590966 | 1 | 0 |
| 590003 | 0 | 1 | 590967 | 1 | 0 |
| 590004 | 0 | 1 | 590968 | 1 | 0 |

| | | | | | |
|---|---|---|---|---|---|
| 590017 | 0 | 1 | 590969 | 1 | 0 |
| 590019 | 0 | 1 | 590974 | 1 | 0 |
| 590023 | 0 | 1 | 590981 | 0 | 1 |
| 590025 | 0 | 1 | 590983 | 0 | 1 |
| 590027 | 0 | 1 | 590986 | 1 | 0 |
| 590028 | 0 | 1 | 590987 | 1 | 0 |
| 590035 | 1 | 0 | 590988 | 0 | 1 |
| 590047 | 1 | 0 | 590994 | 1 | 0 |
| 590052 | 0 | 1 | 591002 | 0 | 1 |
| 590053 | 0 | 1 | 591020 | 0 | 1 |
| 590055 | 0 | 1 | 591225 | 1 | 0 |
| 590066 | 0 | 1 | 591228 | 1 | 0 |
| 590067 | 0 | 1 | 591258 | 0 | 1 |
| 590071 | 1 | 0 | 591261 | 1 | 0 |
| 590078 | 1 | 0 | 591263 | 1 | 0 |
| 590079 | 0 | 1 | 591304 | 1 | 0 |
| 590084 | 0 | 1 | 591305 | 1 | 0 |
| 590085 | 0 | 1 | 591306 | 0 | 1 |
| 590089 | 0 | 1 | 591319 | 1 | 0 |
| 590093 | 0 | 1 | 591328 | 1 | 0 |
| 590101 | 0 | 1 | 591399 | 1 | 0 |
| 590112 | 0 | 1 | 591400 | 1 | 0 |
| 590113 | 1 | 0 | 591401 | 1 | 0 |
| 590115 | 1 | 0 | 830007 | 0 | 1 |
| 590118 | 1 | 0 | 830009 | 0 | 1 |
| 590120 | 0 | 1 | 830010 | 0 | 1 |
| 590121 | 0 | 1 | 830015 | 0 | 1 |
| 590122 | 0 | 1 | 830016 | 0 | 1 |
| 590126 | 0 | 1 | 830018 | 0 | 1 |
| 590129 | 0 | 1 | 830020 | 0 | 1 |
| 590132 | 0 | 1 | 830021 | 0 | 1 |
| 590135 | 0 | 1 | 830023 | 0 | 1 |
| 590136 | 0 | 1 | 830025 | 0 | 1 |
| 590137 | 0 | 1 | 830026 | 0 | 1 |
| 590138 | 0 | 1 | 830028 | 0 | 1 |
| 590145 | 0 | 1 | 830031 | 0 | 1 |
| 590146 | 0 | 1 | 830033 | 0 | 1 |
| 590148 | 0 | 1 | 830037 | 0 | 1 |
| 590150 | 0 | 1 | 830039 | 0 | 1 |
| 590156 | 0 | 1 | 830040 | 0 | 1 |
| 590161 | 0 | 1 | 830046 | 0 | 1 |
| 590163 | 0 | 1 | 830047 | 0 | 1 |
| 590167 | 0 | 1 | 830048 | 0 | 1 |
| 590169 | 0 | 1 | 830049 | 0 | 1 |
| 590173 | 0 | 1 | 830050 | 0 | 1 |
| 590175 | 0 | 1 | 830052 | 0 | 1 |
| 590176 | 0 | 1 | 830061 | 0 | 1 |
| 590179 | 0 | 1 | 830063 | 0 | 1 |
| 590182 | 0 | 1 | 830079 | 0 | 1 |
| 590187 | 0 | 1 | 830099 | 0 | 1 |
| 590188 | 0 | 1 | 830101 | 0 | 1 |
| 590193 | 0 | 1 | 830105 | 0 | 1 |
| 590201 | 0 | 1 | 830116 | 0 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| 590202 | 0 | 1 | 830134 | 0 | 1 |
| 590203 | 1 | 0 | 830171 | 0 | 1 |
| 590204 | 1 | 0 | 830183 | 0 | 1 |
| 590205 | 0 | 1 | 830208 | 0 | 1 |
| 590207 | 1 | 0 | 830209 | 0 | 1 |
| 590212 | 0 | 1 | 830213 | 0 | 1 |
| 590213 | 1 | 0 | 830258 | 0 | 1 |
| 590215 | 1 | 0 | 830267 | 0 | 1 |
| 590216 | 0 | 1 | 830280 | 0 | 1 |
| 590221 | 1 | 0 | 830282 | 0 | 1 |
| 590222 | 1 | 0 | 830299 | 0 | 1 |
| 590223 | 0 | 1 | 830300 | 0 | 1 |
| 590227 | 1 | 0 | 830301 | 0 | 1 |
| 590230 | 1 | 0 | 830302 | 0 | 1 |
| 590231 | 1 | 0 | 830303 | 0 | 1 |
| 590239 | 0 | 1 | 890003 | 0 | 1 |
| 590241 | 1 | 0 | 890008 | 0 | 1 |
| 590243 | 1 | 0 | 890009 | 0 | 1 |
| 590245 | 0 | 1 | 890010 | 0 | 1 |
| 590249 | 0 | 1 | 890019 | 0 | 1 |
| 590257 | 0 | 1 | 890022 | 0 | 1 |
| 590266 | 0 | 1 | 890023 | 0 | 1 |
| 590281 | 1 | 0 | 890024 | 0 | 1 |
| 590282 | 1 | 0 | 890026 | 0 | 1 |
| 590283 | 1 | 0 | 890032 | 0 | 1 |
| 590285 | 0 | 1 | 890033 | 0 | 1 |
| 590294 | 0 | 1 | 890038 | 0 | 1 |
| 590296 | 1 | 0 | 890043 | 0 | 1 |
| 590297 | 1 | 0 | 890045 | 0 | 1 |
| 590302 | 1 | 0 | 890049 | 0 | 1 |
| 590303 | 1 | 0 | 890057 | 0 | 1 |
| 590304 | 0 | 1 | 890058 | 0 | 1 |
| 590308 | 1 | 0 | 890059 | 0 | 1 |
| 590309 | 0 | 1 | 890065 | 0 | 1 |
| 590311 | 0 | 1 | 890068 | 0 | 1 |
| 590312 | 0 | 1 | 890073 | 0 | 1 |
| 590315 | 1 | 0 | 890075 | 0 | 1 |
| 590316 | 1 | 0 | 890076 | 0 | 1 |
| 590317 | 0 | 1 | 890078 | 0 | 1 |
| 590318 | 0 | 1 | 890079 | 0 | 1 |
| 590322 | 1 | 0 | 890085 | 0 | 1 |
| 590323 | 0 | 1 | 890086 | 0 | 1 |
| 590327 | 1 | 0 | 890089 | 0 | 1 |
| 590328 | 1 | 0 | 890100 | 0 | 1 |
| 590332 | 1 | 0 | 890102 | 0 | 1 |
| 590335 | 0 | 1 | 890104 | 0 | 1 |
| 590337 | 1 | 0 | 890147 | 0 | 1 |
| 590338 | 0 | 1 | 890166 | 0 | 1 |
| 590339 | 1 | 0 | 890170 | 0 | 1 |
| 590341 | 0 | 1 | 890179 | 0 | 1 |
| 590342 | 0 | 1 | 890185 | 0 | 1 |
| 590345 | 0 | 1 | 890194 | 0 | 1 |
| 590349 | 0 | 1 | 890206 | 0 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| 590350 | 0 | 1 | 890209 | 0 | 1 |
| 590352 | 1 | 0 | 890223 | 0 | 1 |
| 590354 | 0 | 1 | 890271 | 0 | 1 |
| 590355 | 0 | 1 | 890362 | 0 | 1 |
| 590356 | 0 | 1 | 890477 | 0 | 1 |
| 590357 | 0 | 1 | 890483 | 0 | 1 |
| 590361 | 0 | 1 | 890491 | 0 | 1 |
| 590362 | 0 | 1 | 890492 | 0 | 1 |
| 590363 | 0 | 1 | 890501 | 0 | 1 |
| 590403 | 0 | 1 | 890518 | 0 | 1 |
| 590404 | 0 | 1 | 890530 | 0 | 1 |
| 590450 | 1 | 0 | 890550 | 0 | 1 |
| 590451 | 0 | 1 | 890551 | 0 | 1 |

## APPENDIX I  Bridge Element Unit

| Element Name | Element Number | Unit |
|---|---|---|
| Assembly Joint with Seal | 303 | Feet |
| Assembly Joint without Seal | 305 | Feet |
| Compression Joint Seal | 302 | Feet |
| Concrete Protective Coating | 521 | Square Feet |
| Concrete Protective Coating | 521 | Square Feet |
| Disc Bearing | 315 | Each |
| Elastomeric Bearing | 310 | Each |
| Enclosed/Concealed Bearings | 312 | Each |
| Fixed Bearing | 313 | Each |
| Metal Bridge Railing | 330 | Feet |
| Movable Bearing | 311 | Each |
| Open Expansion Joint | 304 | Feet |
| Other Bearings | 316 | Each |
| Other Bridge Railing | 333 | Feet |
| Pot Bearing | 314 | Each |
| Pourable Joint Seal | 301 | Feet |
| Prestressed Concrete Closed Web/Box Girder | 104 | Feet |
| Prestressed Concrete Open Girder/Beam | 109 | Feet |
| Prestressed Concrete Top Flange | 15 | Square Feet |
| Reinforced Concrete Arch | 144 | Feet |
| Reinforced Concrete Bridge Railing | 331 | Feet |
| Reinforced Concrete Closed Web/Box Girder | 105 | Feet |
| Reinforced Concrete Deck | 12 | Square Feet |
| Reinforced Concrete Open Girder/Beam | 110 | Feet |
| Reinforced Concrete Slabs | 38 | Square Feet |
| Reinforced Concrete Top Flange | 16 | Square Feet |
| Steel Deck Corrugated/Orthotropic/Etc. | 30 | Square Feet |
| Steel Floor Beam | 152 | Feet |
| Steel Open Girder/Beam | 107 | Feet |
| Steel Stringer | 113 | Feet |
| Concrete Protective Coating | 521 | Square Feet |
| Concrete Protective Coating | 521 | Square Feet |
| Masonry Abutments | 217 | Feet |
| Other Abutments | 218 | Feet |
| Other Pile | 229 | Each |
| Prestressed Concrete Column | 204 | Each |
| Prestressed Concrete Pier Cap | 233 | Feet |
| Prestressed Concrete Pile | 226 | Each |
| Reinforced Concrete Abutment | 215 | Feet |
| Reinforced Concrete Column | 205 | Feet |
| Reinforced Concrete Pier Cap | 234 | Feet |
| Reinforced Concrete Pier Wall | 210 | Feet |

| | | |
|---|---|---|
| Reinforced Concrete Pile | 227 | Each |
| Reinforced Concrete Pile Cap/Footing | 220 | Feet |
| Steel Abutment | 219 | Feet |
| Steel Column | 202 | Each |
| Steel Pier Cap | 231 | Feet |
| Steel Pile | 225 | Each |
| Timber Abutment | 216 | Feet |
| Timber Column | 206 | Each |
| Timber Pile | 228 | Each |

## APPENDIX J Meeting Minutes_November 15, 2023

**Project No.:** **RP 2023-05**
**Title:** **Prioritizing NCDOT Bridge Preservation Projects Using Bridge Element Inspection Data**
**Meeting:** **Meeting Minutes—Progress Report for Cost Estimation Model and Cost-benefit Tradeoff Model**
**Location:** **1000 Birch Ridge Dr. Raleigh, NC 27610**
**DOT CCA Structures Conference Room Col. B4**
**Date:** **November 15, 2023**
**Time:** **9:00 a.m.–11:00 a.m.**

**Meeting Attendees**

| Steering and Implementation Committee | Research and Development | Research Team |
|---|---|---|
| Nicholas Pierce | | Min Liu |
| Asa Godfrey | | Chase Nicholas |
| Samuel Megahed | | Chuanni He |
| Timothy Sherrill | | |

**1) Research methodology for GIS bridge criticality evaluation.**

a. The AADT Data from NCDOT traffic management unit is at the route/network segment level not the bridge level. The coordinates of the bridges are insufficient to obtain the bridge AADT. A bridge characteristics-based approach is developed to obtain bridge traffic volume for bridges without AADT data.
b. The methodology can be extended to accommodate bridge traffic data from other Divisions or updated traffic data.

**2) R-Shiny application for activity triggering model and cost estimation model:**

a. SMU suggested changing the default overlay type based on its EAC for specific bridges.
b. The customization options for overlay type can include (Epoxy, PPC, LMC, HMWM, and Silane)
c. SMU suggests that the summary tab should reflect the bridge prioritization result with a specific preservation activity list and cost estimation per bridge. The research team agreed on the design and will include the module once the bridge criticality data are derived and the cost estimation model is validated.
d. SMU will provide another dataset indicating interstate bridges. The research team will remove the interstate selection option from the APP.
e. For interstate bridges, the default overlay type can be selected between PPC/LMC, but the program should still list the Epoxy Overlay as an option for customization.
f. SUM suggests adding "Welding, Bolted, and Cut-out" activity types for "Steel Beam Repair" activity. The extended service life for these types is the same. The unit cost can be found in the "SMU Activities Pay Items.xlsx" file (Cut-out: $6,685.37 per LF; Bolted: $3,168 per LF; Welding: $1,631.16 per LF). No unit conversion is needed for this activity.

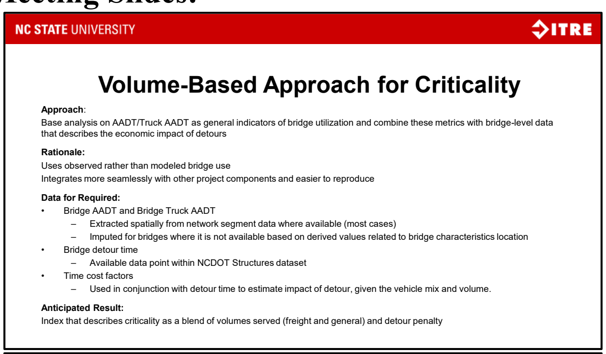
g. For the “Steel Beam Repair” activity, the APP should provide customization for users to select between the three types (Welding, Bolted, and Cut-out). This function should be the same as the Overlay activity (default by lowest annuity but provide customization options).
h. The “Overlay” activity should not overwrite “Concrete for Deck Repair” activity.
i. “Overlay”, “Silane”, and “HMWM” should be considered at the bridge level. And the majority activity will overwrite the others. However, the users should still be able to customize between overlay/silane afterward.

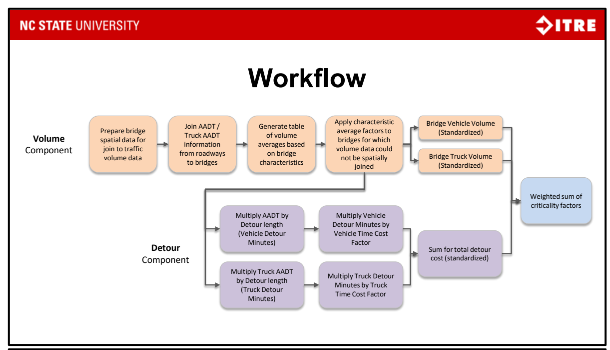
| Action Items | |
|---|---|
| 1 | SMU will update the unit cost for “Epoxy Overlay”. |
| 2 | SMU will check and revise the overwriting rules and send it to the research team. |
| 3 | The research team will send the APP update logs to the research team. |
| 4 | The research team will revise the APP based on suggestions provided in this meeting. |

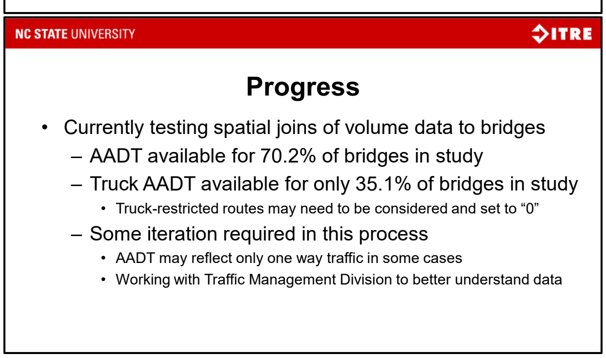
**Follow up:**

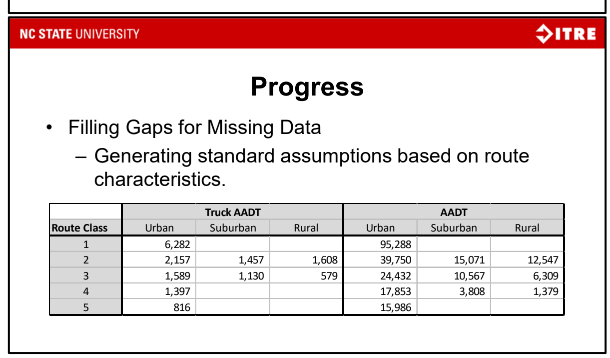
1. SMU has provided an updated “Division10_Elements.xlsx” dataset indicating interstate bridges.
2. The research team has sent the slides for the GIS module to SMU.

**Meeting Slides:**




| | Truck AADT | | | AADT | | |
|---|---|---|---|---|---|---|
| Route Class | Urban | Suburban | Rural | Urban | Suburban | Rural |
| 1 | 6,282 | | | 95,288 | | |
| 2 | 2,157 | 1,457 | 1,608 | 39,750 | 15,071 | 12,547 |
| 3 | 1,589 | 1,130 | 579 | 24,432 | 10,567 | 6,309 |
| 4 | 1,397 | | | 17,853 | 3,808 | 1,379 |
| 5 | 816 | | | 15,986 | | |

NC STATE UNIVERSITY ITRE

# Time Cost Factors

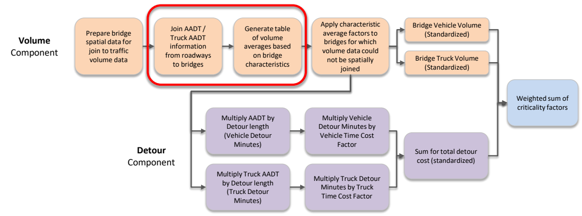
**Source:** Benefit Cost Analysis Guidance for Discretionary Grant Programs (USDOT)

*Table A-3: Value of Travel Time Savings*

| Recommended Monetized Value(s) | | References and Notes |
|---|---|---|
| **Recommended Hourly Values of Travel Time Savings (2021 $ per person-hour)** | | *Revised Departmental Guidance on Valuation of Travel Time in Economic Analysis (2016)* https://www.transportation.gov/office-policy/transportation-policy/revised-departmental-guidance-valuation-travel-time-economic |
| **Category** | **Hourly Value** | |
| General Travel Time | | |
| Personal[1] | $17.00 | |
| Business[2] | $31.90 | |
| All Purposes[3] | $18.80 | |
| Walking, Cycling, Waiting, Standing, and Transfer Time[4] | $34.00 | |
| Commercial Vehicle Operators[5] | | |
| Truck Drivers | $32.40 | |
| Bus Drivers | $35.00 | |
| Transit Rail Operators | $58.40 | |
| Locomotive Engineers | $57.40 | |

NC STATE UNIVERSITY ITRE

# Workflow



## APPENDIX K Development Guidelines for Shiny Application

The research team developed a user-friendly bridge preservation planning app named the Bridge Guidance Planner (BGP) using the Shiny package in R. The BGP app is designed to generate bridge preservation plan reports based on bridge inspection data. The BGP app is deployed to the cloud via shinyapps.io, allowing users to conveniently access the BGP app through a web browser. This appendix is the developer documentation for the BGP app, detailing the development process.

### 1. Development Environment

R is a programming language for statistical computing and data analysis. Shiny is an R package used to create user-friendly interactive applications. RStudio is an integrated development environment (IDE) designed for R. Shinyapps.io is a hosting service provided by RStudio specifically for deploying and hosting applications developed with Shiny.

In addition to the Shiny package, the BGP app utilizes other R packages for data analysis and visualization. Table A14 lists the development environment for BGP, including the R packages and their versions.

Table A14 Development Environment and Packages for BGP App

| Tool | | Version |
|---|---|---|
| R | | 4.3.0 |
| RStudio | | 2023.3.1.446 |
| R packages | shiny | 1.7.4.1 |
| | markdown | 1.7 |
| | rmarkdown | 2.23 |
| | DT | 0.28 |
| | ggplot2 | 3.4.2 |
| | ggThemeAssist | 0.1.5 |
| | priceR | 0.1.67 |
| | shinyjs | 2.1.0 |
| | scales | 1.2.1 |
| | writexl | 1.4.2 |
| | plotly | 4.10.4 |
| | dplyr | 1.1.2 |
| | tidyverse | 2.0.0 |
| | imputeTS | 3.3 |
| | readxl | 1.4.3 |
| | stringr | 1.5.0 |
| | ddpcr | 1.15.1 |
| | labelled | 2.12.0 |

### 2. App File Structure

The BGP app is stored in a folder named “Rshiny”. The file structure of the Rshiny folder is shown in Figure A1. Below is a list of all the folders and files in the Rshiny directory.

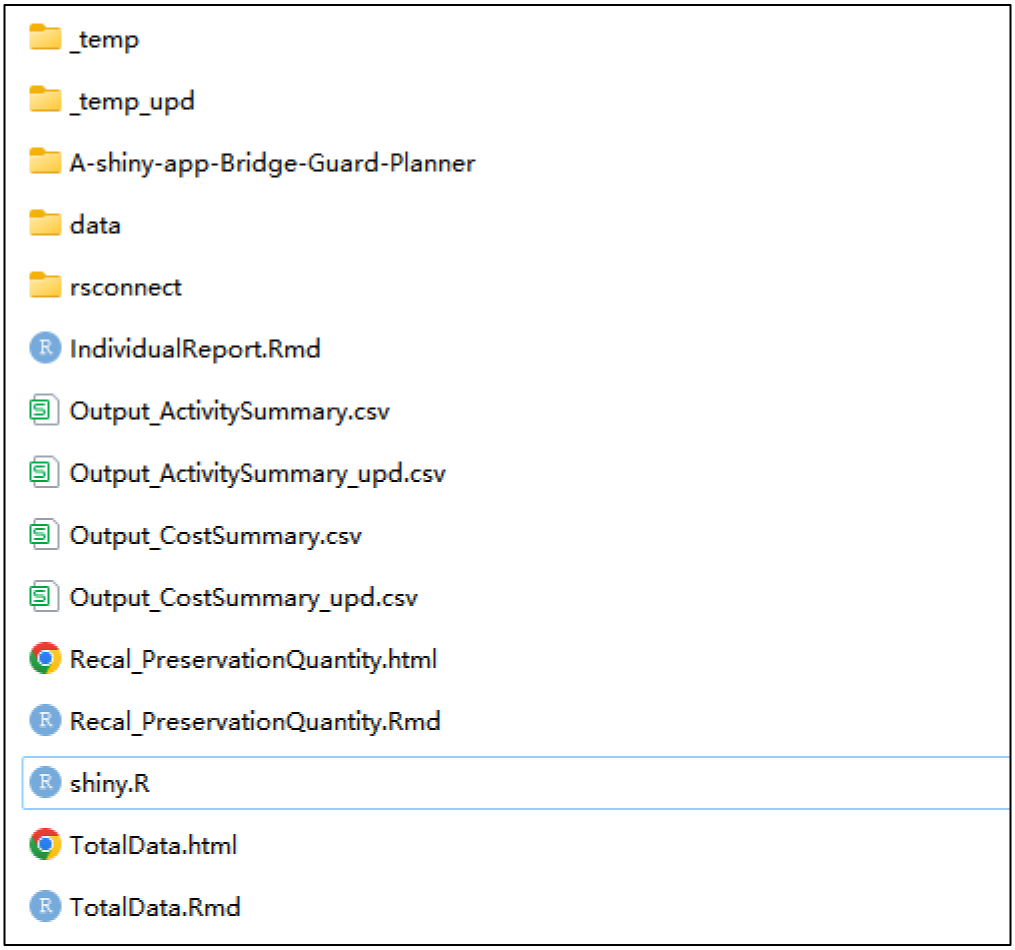


Figure A1 File Structure of the BGP App Directory

*2.1 Folder Descriptions:*

- **_temp/**: Temporary folder used to store .RData cache files for the initial cost calculation results for each bridge.
- **_temp_upd/**: Temporary folder used to store .RData cache files for the recalculated cost results of each bridge.
- **A-shiny-app-Bridge-Guard-Planner/**: Stores the application's Git configuration files.
- **data/**: Core data folder, containing all essential data related to bridge preservation. The definitions of the data in this folder are detailed in Chapters 3, Chapters 4, and Chapters 5 of the main text.
- **rsconnect/**: RStudio Connect folder, automatically generated when deploying the BGP app to the cloud via shinyapps.io.

*2.2 File Descriptions:*

- **shiny.R**: The main code file for the BGP app, controlling both the UI and the server.
- **TotalData.Rmd**: An R Markdown file responsible for triggering bridge preservation activities and calculating bridge preservation costs. The specific algorithms are detailed in Chapters 4 and Chapters 5.

- **IndividualReport.Rmd**: An R Markdown file used to generate individual bridge preservation reports in HTML format.
- **Recal_PreservationQuantity.Rmd**: An R Markdown file used to recalculate bridge preservation activities and costs based on the user-defined preservation application scope. The definition of the preservation application scope is detailed in Section 3.1.
- **Output_ActivitySummary.csv**: An output CSV file that summarizes the number of preservation activities for each bridge. The activity counts in this CSV file are based on the default parameters.
- **Output_ActivitySummary_upd.csv**: An output CSV file that summarizes the results of the initial calculation of all bridge preservation costs. The activity counts in this CSV file are based on the parameters modified by the user.
- **Output_CostSummary.csv**: An output CSV file that summarizes the results of the initial calculation of all bridge preservation costs. It includes data on the number of preservation activities required for each bridge, preservation costs, EAC, service life, and so on.
- **Output_CostSummary_upd.csv**: An output CSV file that summarizes the recalculated results of all bridge preservation costs after the user has modified the parameters. It includes data on the number of preservation activities required for each bridge, preservation costs, EAC, service life, and so on.
- **TotalData.html**: A file generated from TotalData.Rmd.
- **Recal_PreservationQuantity.html**: A file generated from Recal_PreservationQuantity.Rmd.

## 3. App Module Introduction

In the development of a Shiny application, the UI and server are two core components. The UI is responsible for defining the application's appearance and layout, displaying user input controls, and presenting the program's output. The server handles the inputs, executes data processing, generates outputs, and sends the results to the UI for display. The UI and server work together to build the functional modules. As shown in Figure A2, the structure of the BGP app comprises five major functional modules. The following sections will introduce them individually.

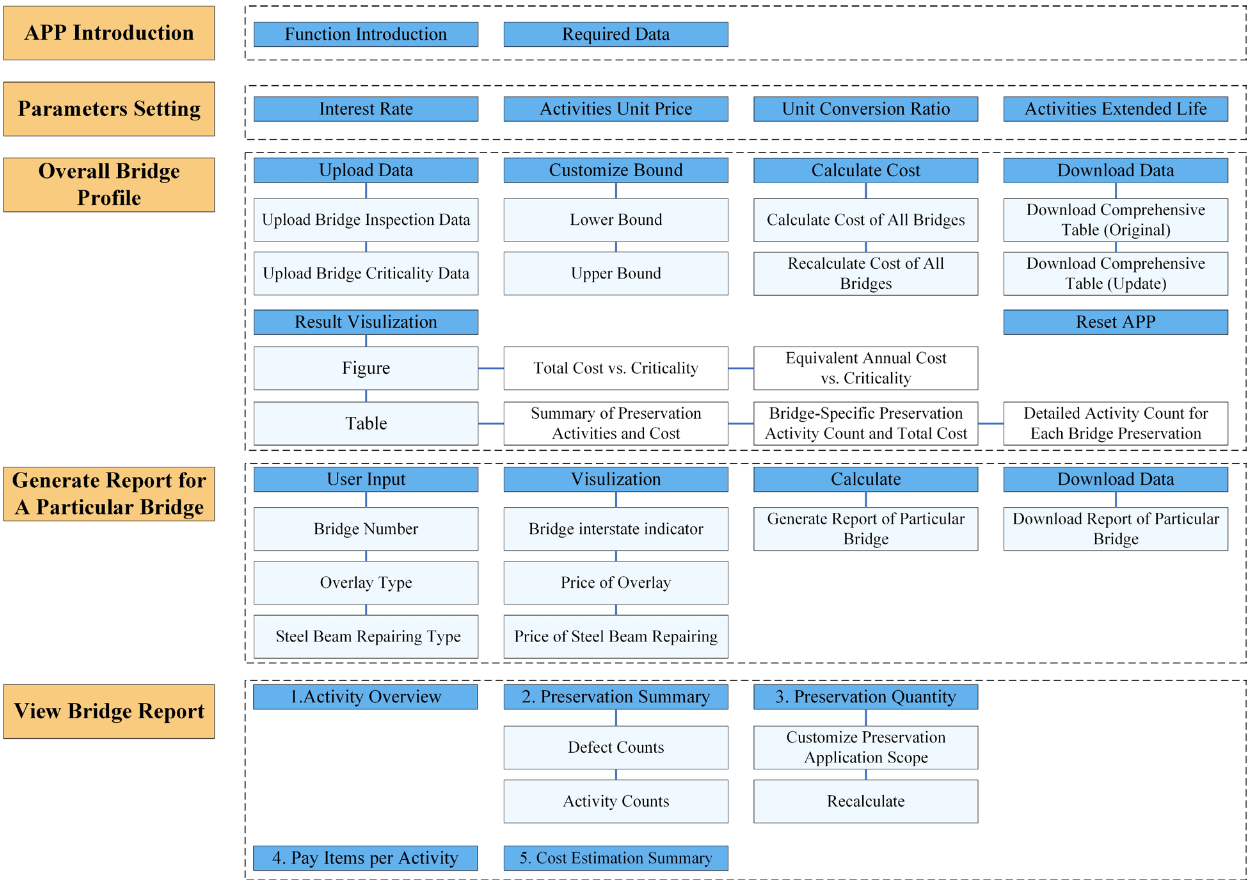


Figure A2 The BGP App Structure

### *3.1 App Introduction*

Figure A3 displays the UI page of the BGP app's introduction. This UI simply introduces the app's functions and the required data.

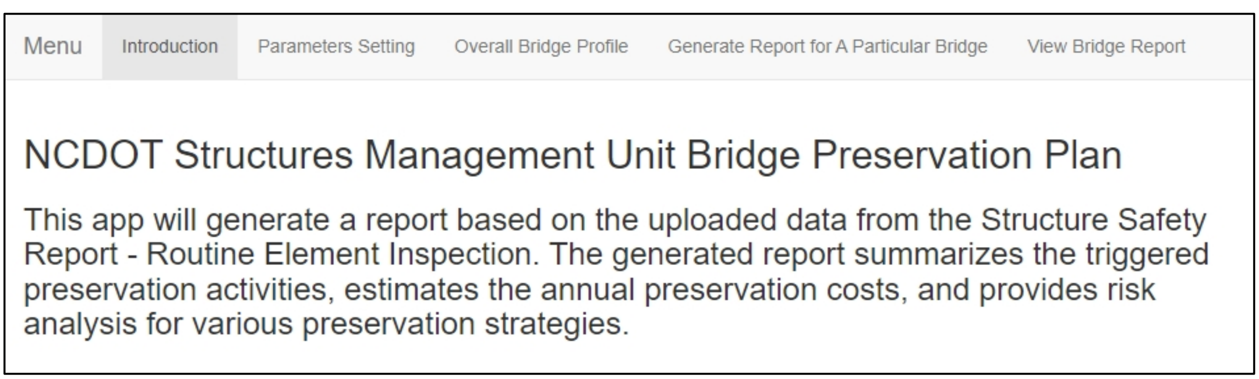


Figure A3 UI-Introduction of BGP App

### *3.2 Parameters setting*

As shown in Figure A2, under the Parameters Setting functional module, four types of parameters can be customized by the user: interest rate, activities unit price, unit conversion ratio, and activities extended life. Figure A4 displays the UI interface for setting the interest rate and activities unit price. The default value for the interest rate is set at 3%. Users can customize the interest rate in the input box, which is stored in the variable "IR" in numeric format. The activities unit price, unit conversion ratio, and activities extended life are formatted as data frames. Descriptions of these three datasets are provided in Section 3.2.

In the server, the data processing pipeline for these three datasets is similar. Using activities unit price as an example, the default values are obtained by reading the file "Step 0_Unit_Price.csv" in the "data/" folder. After reading the data, the activities unit price is stored in the variable "price_default_react" and presented in the UI. The server listens for modifications to the activity unit price table in the UI. If the user modifies the table parameters, the modified activities unit price is stored in the variable "price_react". When the user clicks the "Restore Price Defaults" button in the lower left corner (see Figure A4), the value of "price_default_react" overwrites "price_react", restoring the activities unit price to its default values.

The default values for the unit conversion ratio are stored in the variable "unit_match_default_react", and the modified table is stored in the variable "unit_match_react". The default values for activities extended life are stored in the variable "extended_life_default_react", and the modified table is stored in the variable "extended_life_react".

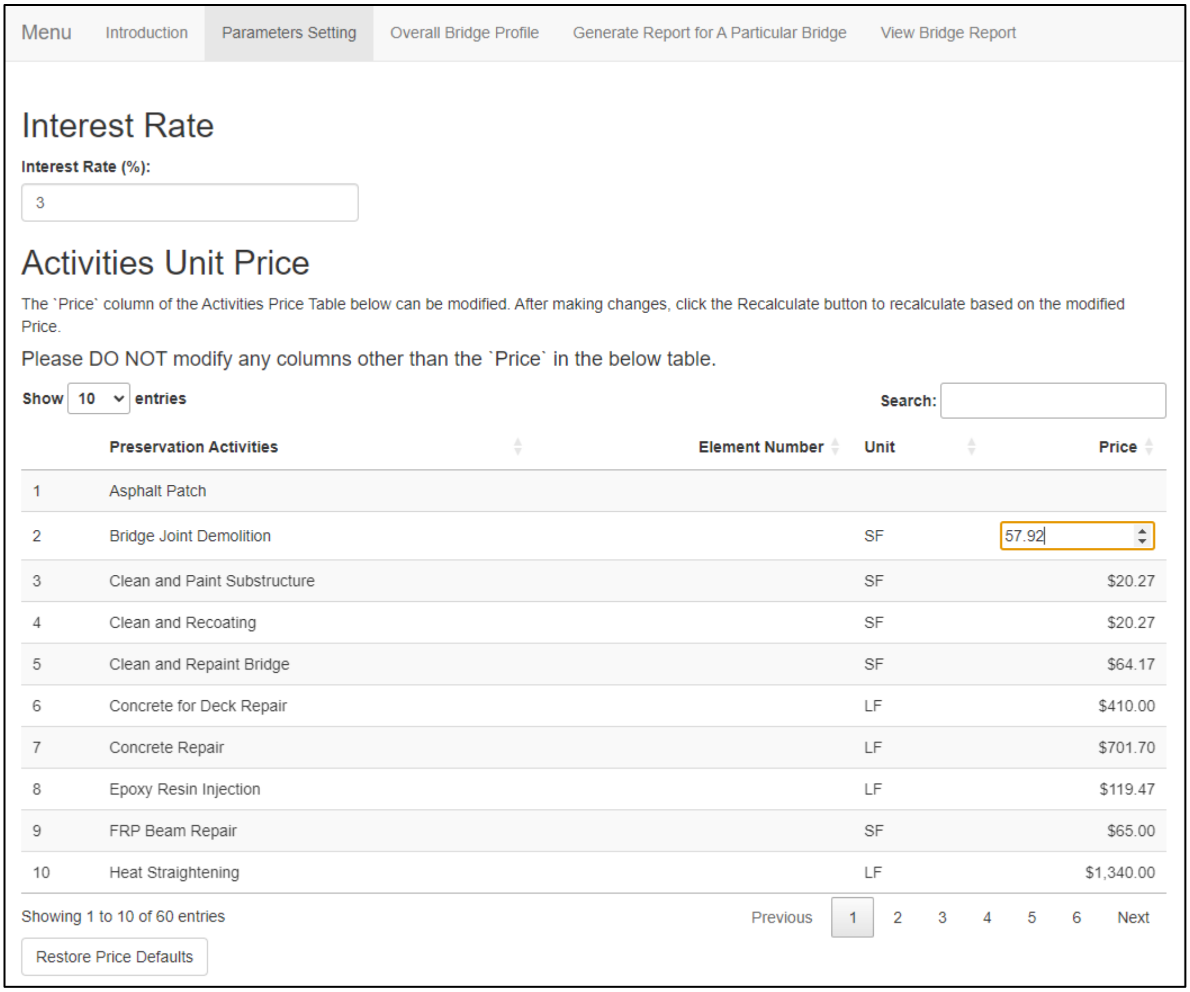


Figure A4 UI-Parameter Settings (Interest Rate and Activities Unit Price)

### *3.3 Overall Bridge Profile*

As shown in Figure A2, the Overall Bridge Profile has six subfunctional modules: Upload Data, Customize Bounds, Calculate Cost, Result Visualization, Download Data, and Reset App. An introduction to each functional module and their interactions follows.

#### 3.3.1 Upload Data

Upload Data obtains the necessary data for calculating bridge costs. As shown in Figure A5, users need to upload three datasets on this page: superstructure inspection data, substructure inspection data, and bridge criticality data. Descriptions of these datasets can be found in Section 3.1. The uploaded superstructure and substructure inspection data are stored in the variables “new_super” and “new_sub”, respectively. The uploaded bridge criticality data are stored in the variable “result_crit”.

#### 3.3.2 Customize Bound

The lower bound and upper bound determine the grouping criteria for the bridges. As shown in Figure A5, the default values for the lower bound and upper bound are set to $10,000 and

$500,000, respectively. The user inputs for the lower bound and upper bound in the UI are stored in the variables "lower_bound" and "upper_bound", respectively.

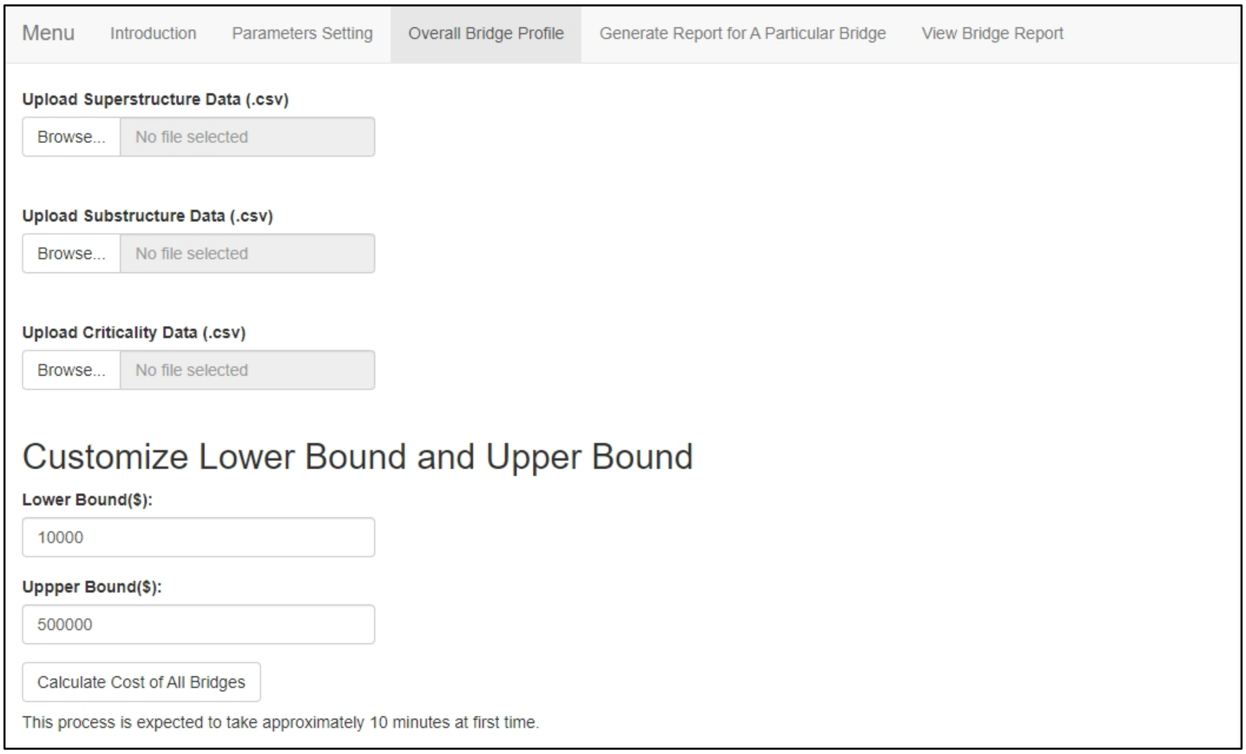


Figure A5 UI-Upload Data and Customize Bound

### 3.3.3 Calculate Cost

Figure A6 illustrates the framework for calculating bridge preservation costs. When the user clicks the "Calculate Cost of All Bridges" button, the server gets the required datasets from functional modules Parameters Setting and Upload Data. Additionally, it reads the Miscellaneous Cost Estimation Parameters from data/Step 0_Params.csv. Details of this dataset can be found in Section 5.1.

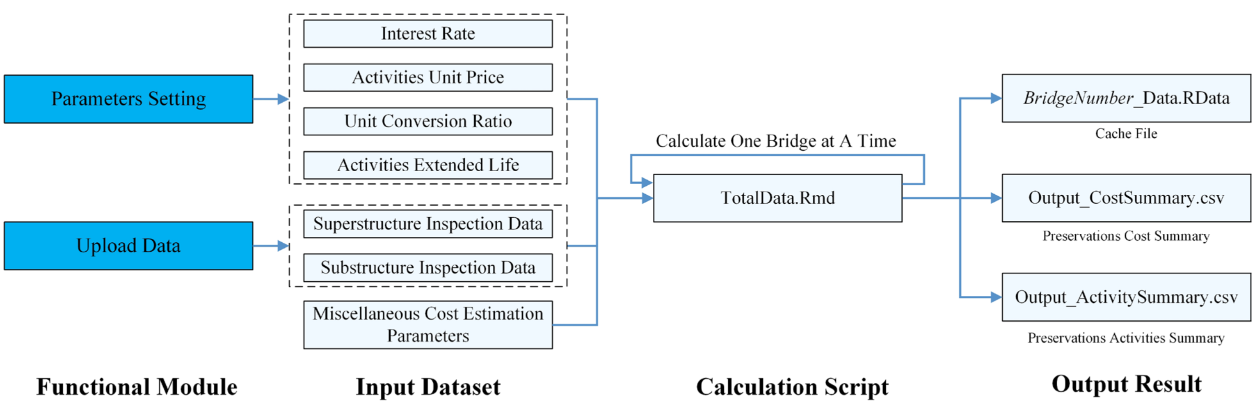


Figure A6 Framework for Calculating Bridge Preservation Costs

These datasets are input for the calculation script TotalData.Rmd. TotalData.Rmd is a script used for triggering bridge preservation activities and estimating costs. The triggers for bridge preservation activities are discussed in Chapter 4, and cost estimation is detailed in Chapter 5. Each run of TotalData.Rmd calculates the required preservation activities and costs for one bridge.

In addition to the datasets mentioned above, the script TotalData.Rmd also requires several bridge-level parameters for each calculation:

- **Number**: Bridge number.
- **InterState**: Indicates whether the bridge is an interstate. A value of 1 means the bridge is an interstate, while 0 means it is non-interstate.
- **OverlayType**: The type of overlay preservation activity. If the bridge is interstate, the script selects the activity with the lowest unit price from Overlay (PPC) and Overlay (LMC). If the bridge is non-interstate, it selects the activity with the lowest unit price from Overlay (Epoxy), Overlay (PPC), and Overlay (LMC).
- **SteelBeamRepairType**: Indicates the type of steel beam repair activity. There are three candidates: Steel Beam Repair (Bolted), Steel Beam Repair (Cut-out), and Steel Beam Repair (Welding). The server selects the activity with the lowest unit price from these three as the applied steel beam repair type.
- **Recalculate**: Indicates whether it is the initial calculation or a recalculation, which affects the output path of the calculation results. A value of 1 represents recalculation, and 0 represents the initial calculation.

The server uses a for loop to call TotalData.Rmd multiple times until all bridges are processed. The cache file generated by each bridge calculation is stored in the “temp/” directory with the filename format “BridgeNumber_Data.RData”. For example, after calculating bridge 030003, TotalData.Rmd will generate a cache file named “030003_Data.RData” in the “temp/” directory. This file contains detailed records of the results generated during each calculation step for bridge 030003. The calculated cost estimations are recorded in “Output_CostSummary.csv”, while the triggered preservation activities are recorded in “Output_ActivitySummary.csv”. The results for each bridge are stored as one row in the CSV file.

The calculation of bridge preservation costs is divided into two submodules: Initial Calculation and Recalculation. The recalculation process is similar to the initial calculation process, with the main difference being the output path for the results.

Cache files generated by recalculations are saved in the “temp_upd/” directory. The calculated cost estimations are recorded in “Output_CostSummary_upd.csv”, while the triggered preservation activities are recorded in “Output_ActivitySummary_upd.csv”. The research team separates the initial calculation results from the recalculation results instead of overwriting them. This approach allows users to easily download and compare the two sets of results.
Cache files generated by recalculations are saved in the “temp_upd” directory. The calculated cost estimations are recorded in “Output_CostSummary_upd.csv”, while the triggered preservation activities are recorded in “Output_ActivitySummary_upd.csv”. The research team separates the initial calculation results from the recalculation results instead of overwriting them. This approach allows users to easily download and compare the two sets of results.

### 3.3.4 Calculation Result Visualization

Figure A7 shows the framework for visualizing the calculation results. The calculation results, and data uploaded by the user, provide the required data for the result visualization module. By joining the calculated total bridge costs with the user-uploaded bridge criticality data using the bridge number, a dataset containing both bridge preservation costs and criticality is obtained. This dataset is stored in the variable "df_cost_sum".

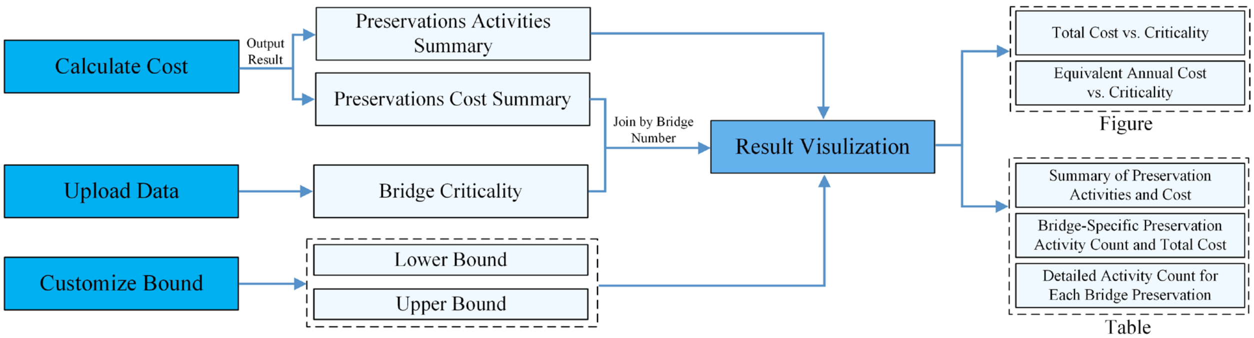



Figure A7 Calculation Result Visualization Framework

Figure A8 shows the five charts in the result visualization module. Figure A8(a) shows a scatter plot of bridge total cost vs. bridge criticality. When the user hovers the mouse over a point in the scatter plot, the UI will display detailed information for the bridge. To create this scatter plot, bridges are grouped based on their total preservation cost and priority. The steps to create this scatter plot are as follows:

- 1. Bridges with total costs less than the lower bound and greater than the upper bound are singled out.
- 2. The remaining bridges (with total costs between the lower and upper bounds) are used to calculate their respective cost-benefit ratio based on criticality and total cost.
- 3. These bridges are then sorted by their cost-benefit ratio to obtain a priority ranking.
- 4. Based on their priority ranking, bridges are categorized into four groups: critical priority, high priority, medium priority, and low priority. The specific algorithms for steps 1–4 are detailed in Chapter 7.
- 5. Merge information such as bridge number, county, AADT, criticality, total activity, total cost, and priority ranking. This merged information will be displayed as a tooltip when the user hovers the cursor over a point in the scatter plot.
- 6. Use R package Plotly to create an interactive scatter plot, with total preservation cost on the $x$ axis, criticality on the $y$ axis, and different colors representing different priority groups.

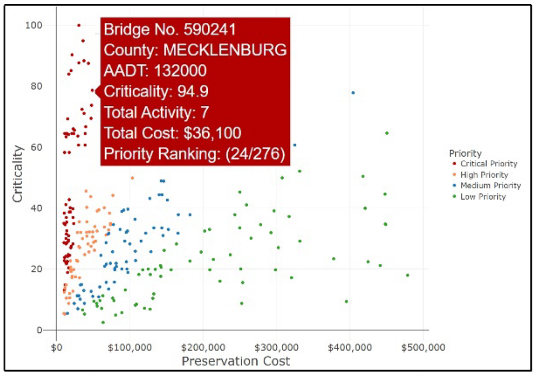
Figure A8(b) is a scatter plot showing bridge EAC vs. bridge criticality. The steps to create Figure A8(b) are similar to those for Figure A8(a). In the first step, bridges are singled out based on total cost. The only difference is that in the second step, the cost-benefit ratio is calculated using criticality and EAC. The purpose of creating these two plots is to provide users with a comparison of bridge preservation priorities from different perspectives.

Figure A8(c), Figure A8(d), and Figure A8(e) are three tables displaying the calculation results.

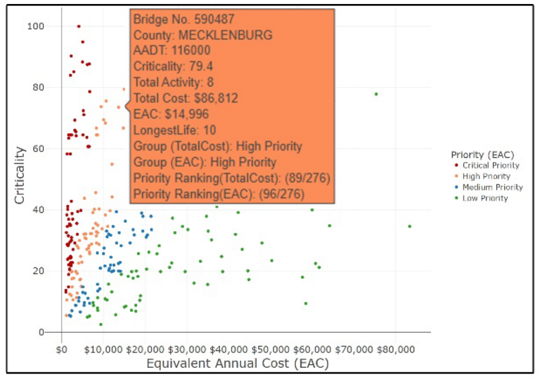
Figure A8(c) shows statistical information on the number of preservation activities and the total preservation cost for all bridges. Below are the descriptions of each column in Figure A8(c):

- **TotalActivitySuper**: The number of preservation activities required for the superstructure.
- **TotalActivitySub**: The number of preservation activities required for the substructure.
- **TotalActivity**: The total number of preservation activities required for the entire bridge.
- **TotalCost**: The total preservation cost for the bridge.

By calculating the minimum, 1st quartile, median, mean, 3rd quartile, and maximum for these four parameters, the dataset for Figure A8(c) is obtained. Figure A8(d) displays the table for the "df_cost_sum" variable, which contains both the bridge preservation cost results and criticality. As shown in Figure A8(d), a dropdown menu is provided at the top of the table. Users can select from eight groups: Critical Priority, High Priority, Medium Priority, Low Priority, Greater than Upper Bound, Less than Lower Bound, No Need for Preservation, and All. The table in Figure A8(d) will update according to the selection in the dropdown menu. This helps users quickly find bridges in different groups. Figure A8(e) shows the preservation activities summary, corresponding to the file "Output_ActivitySummary.csv".




(a) Total Cost vs. Criticality




(b) Equivalent Annual Cost vs. Criticality

Table 1: Summary of Bridge Preservation Activities and Cost Statistics

Show 10 entries Search:

| | TotalActivitySuper | TotalActivitySub | TotalActivity | TotalCost |
|---|---|---|---|---|
| Minimum | 0 | 0 | 0 | $0 |
| 1st Quartile | 2 | 1 | 4 | $6,318 |
| Median | 4 | 3 | 7 | $28,308 |
| Mean | 6.2 | 4.3 | 10.4 | $150,866 |
| 3rd Quartile | 8 | 6 | 14 | $99,322 |
| Maximum | 137 | 42 | 171 | $7,271,125 |

Showing 1 to 6 of 6 entries Previous 1 Next

(c) Summary of Preservation Activities and Cost

Table 2: Bridge Preservation Activity Count and Total Cost

Choose A Bridge Group

All

Show 10 entries Search:

| Number | County | AADT | TotalActivitySuper | TotalActivitySub | TotalActivity | TotalCost | Criticality | Group |
|---|---|---|---|---|---|---|---|---|
| 030003 | ANSON | 18500 | 21 | 15 | 36 | $201,888 | 32.5 | Low Priority |
| 030004 | ANSON | 18500 | 5 | 2 | 7 | $55,190 | 32.5 | High Priority |
| 030006 | ANSON | 3600 | 3 | 3 | 6 | $14,952 | 18.9 | Critical Priority |
| 030010 | ANSON | 2700 | 2 | 0 | 2 | $3,765 | 15.11 | < Lower Bound |
| 030012 | ANSON | 1500 | 4 | 2 | 6 | $2,643 | 14.41 | < Lower Bound |
| 030013 | ANSON | 800 | 1 | 0 | 1 | $164 | 7.96 | < Lower Bound |
| 030022 | ANSON | 2200 | 0 | 0 | 0 | $0 | 14.64 | No Need for Preservation |
| 030024 | ANSON | 3000 | 7 | 3 | 10 | $6,564 | 13.42 | < Lower Bound |
| 030027 | ANSON | 1600 | 5 | 2 | 7 | $78,855 | 15.71 | Medium Priority |
| 030028 | ANSON | 550 | 14 | 4 | 18 | $127,580 | 6.86 | Low Priority |

Showing 1 to 10 of 442 entries Previous 1 2 3 4 5 … 45 Next

(d) Bridge-Specific Preservation Activity Count and Total Cost

Table 3: Detailed Activity Count for Each Bridge Preservation

Show 10 entries Search:

| Number | Shotcrete Repair | Replace Section of Concrete Barrier | Concrete Repair | Silane | Replace missing or broken fasteners | Replace Timber Superstructure Element | Clean and Paint Substructure | Repair Steel Substructure Element | Replace Steel Substructure Element | Steel Crack Arrest | Temporary Shoring | Scour Countermeasures | Concrete for Deck Repair | Overlay (Epoxy) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 030003 | 13 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| 030004 | 2 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030006 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030010 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030012 | 2 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030013 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030022 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030024 | 2 | 0 | 2 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030027 | 3 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030028 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

Showing 1 to 10 of 442 entries Previous 1 2 3 4 5 … 45 Next

(e) Detailed Activity Count for Each Bridge Preservation

Figure A8 isualization of All Bridge Calculation Result

### 3.3.5 Download Calculation Result

As shown in Figure A9, the UI provides two buttons to download XLSX tables. The XLSX table consists of three sheets, corresponding to Figure A8(c), Figure A8(d), and Figure A8(e) described above. The “Original Table” button produces a table containing calculation results based on the initial calculations. The “Update Table” button produces a table containing results generated after the user modifies parameters and clicks the “recalculate cost of all bridges” button.

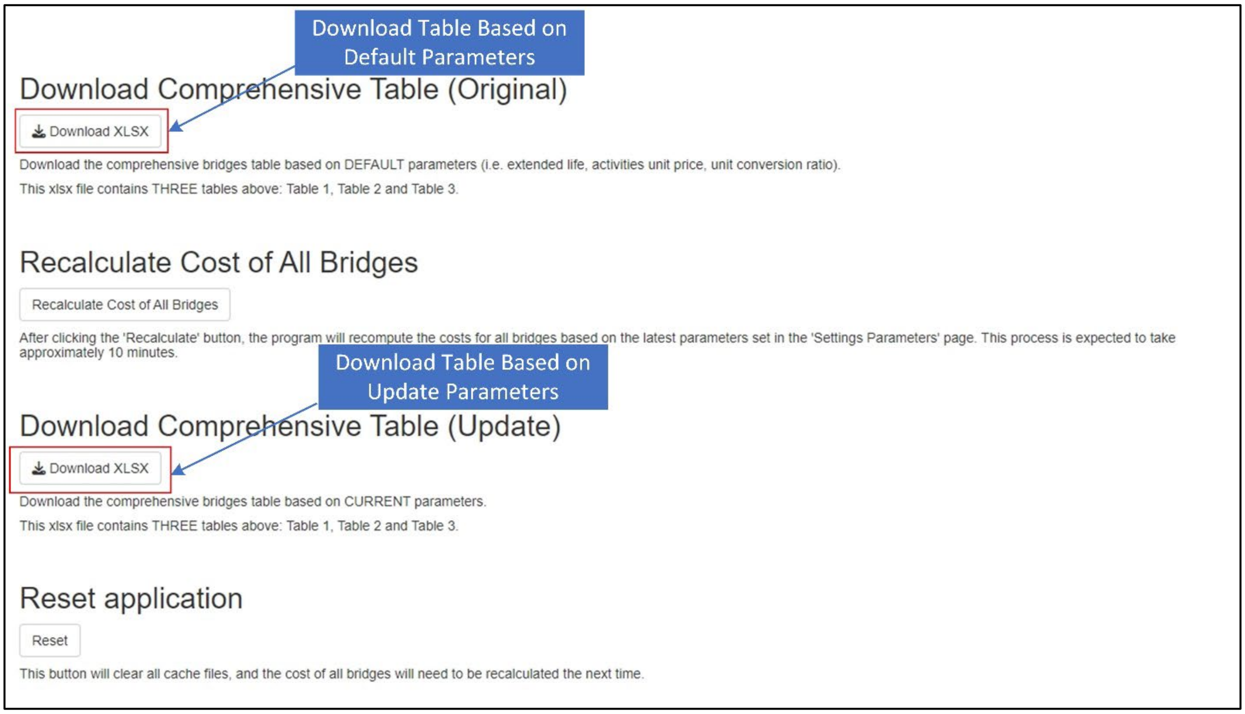



Figure A9 UI-Download Comprehensive Results Table

### 3.3.6 Reset BGP App

As shown in Figure A10, a reset button is located at the bottom of the Overall Bridge Profile page. When the reset button is clicked, the server will clear all cache files in the “temp/” and “temp_upd/” folders. Additionally, all data in the four CSV files that record the calculation results (“Output_CostSummary.csv”,“Output_ActivitySummary.csv”, “Output_CostSummary_upd.csv”, “Output_ActivitySummary_upd.csv”) will be cleared except for the header row.

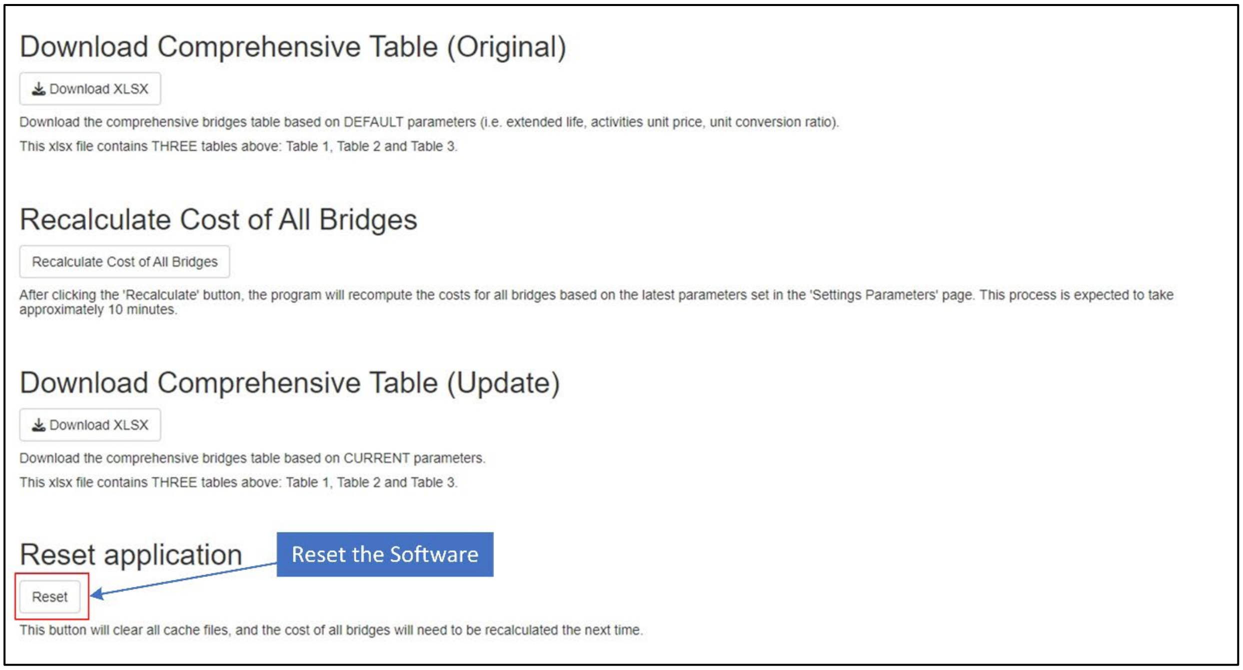



Figure A10 UI-Reset the BGP App

<u>4. Generate Report for a Particular Bridge</u>

Figure A11 shows the framework for generating a report for a particular bridge. Generating a report for a particular bridge requires two types of input. The first type includes data from the Parameters Setting module, such as interest rate and activities unit price. The second type includes inputs from the user on this page.

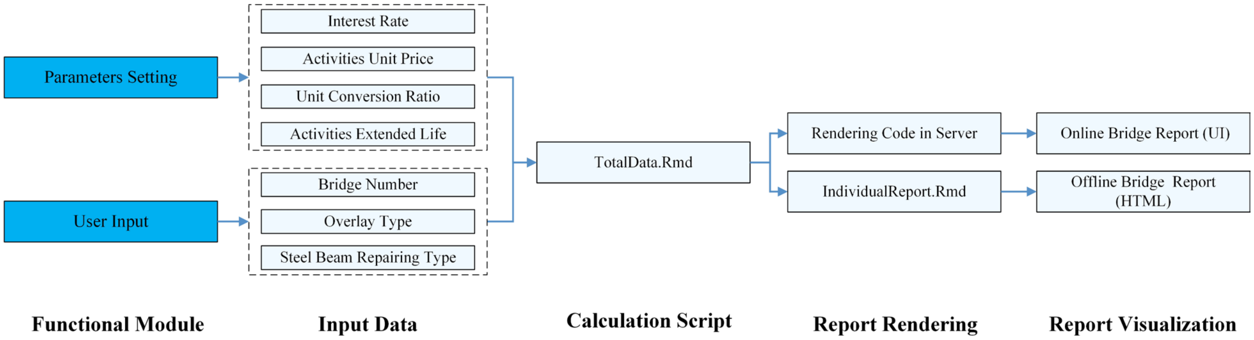



Figure A11 Generate Bridge Report Framework

*4.1 Input Data*

Figure A12 displays the UI interface for generating a report for a particular bridge. This UI interface includes three input fields, allowing users to customize the bridge number, overlay type, and steel beam repair type. Each input field is accompanied by the corresponding data display.

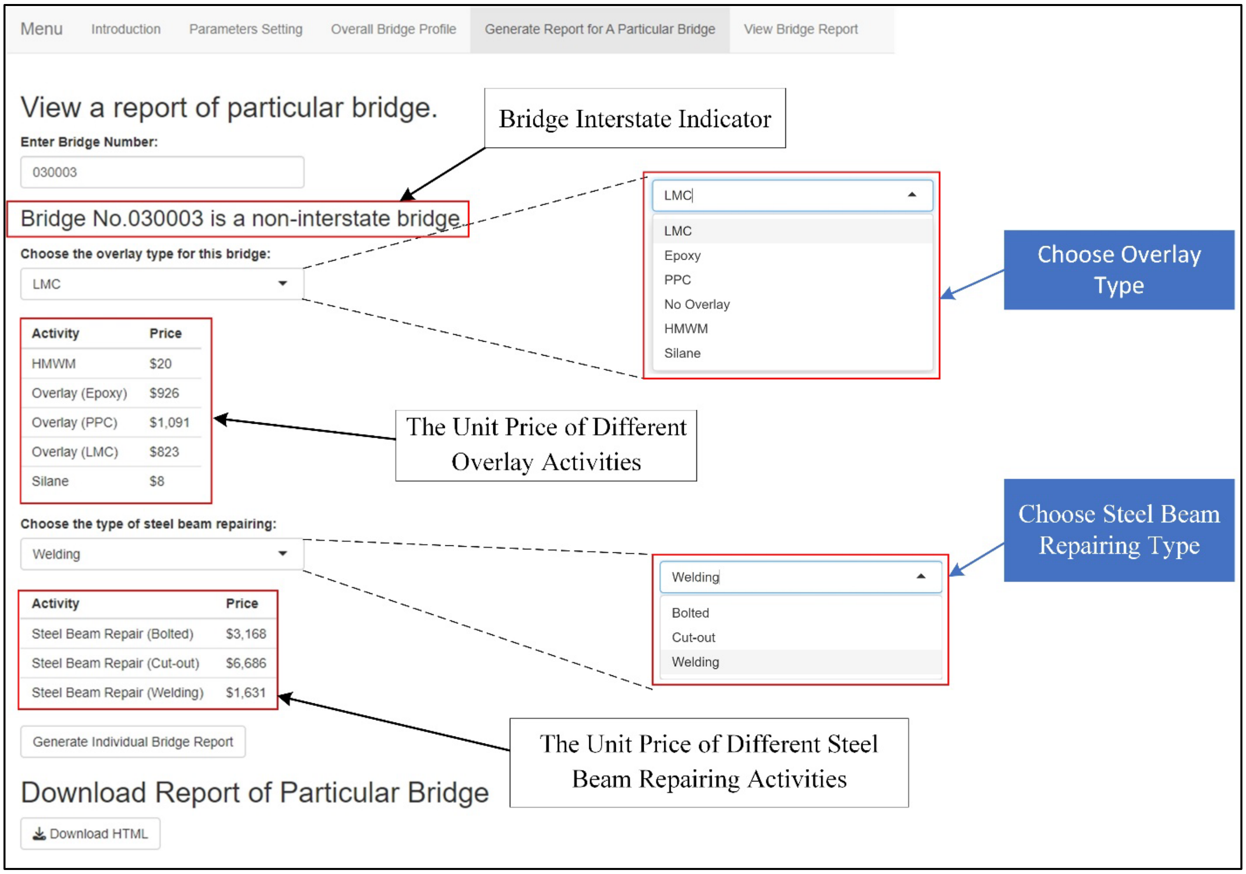



Figure A12 UI-Generate Report for a Particular Bridge

4.1.1 Enter Bridge Number

The calculation script TotalData.Rmd generates the corresponding bridge preservation report based on the entered bridge number. Below the bridge number input field is a bridge interstate indicator, which reflects the interstate status of the entered bridge. The server reads the bridge number from the input field and matches it with the "Interstate" column in the Miscellaneous Cost Estimation Parameters dataset.

Figure A13 shows the pseudocode for the server to determine the interstate status of the entered bridge. Based on the matching results, the UI will prompt the user with the interstate type of the entered bridge.

**Algorithm A1**: determine interstate type of input bridge
**Inputs**: bridge interstate data from miscellaneous cost estimation parameters, bridge number input from UI
**Outputs**: bridge type message for UI

Read in *bridge interstate data*
Read in *input bridge number*

Initialize *output message* variable for the UI

if *input bridge number* exists in *bridge interstate data*:
    Get *Interstate value* corresponding to the *input bridge number* from miscellaneous cost estimation parameters

```
    if Interstate value is 1:
      Set output message to "Bridge No. [input bridge number] is an interstate bridge."

    else if Interstate value is 0:
      Set output message to "Bridge No. [input bridge number] is a non-interstate bridge."

  else:
    Set output message to "The input bridge No. [input bridge number] is not in the database, please re-enter."

  Display output message in the UI
```

Figure A13 Algorithm for Determining Bridge Interstate Type

4.1.2 Choose Overlay Type

As shown in Figure A12, there are six overlay options: LMC, Epoxy, PPC, No Overlay, HMWM, and Silane. The server will automatically set the default value based on the entered bridge number and the unit price of overlay activities. If an interstate bridge number is entered, the app will select the activity with the lowest unit price from Overlay (PPC) and Overlay (LMC) as the default value. For a non-interstate bridge number, the app will select the activity with the lowest unit price from Overlay (Epoxy), Overlay (PPC), and Overlay (LMC) as the default value. The other three overlay type options, No Overlay, HMWM, and Silane, are available for user customization.

The overlay type setting functions at the bridge level. Once the overlay type is set to a specific type, the overlay activities for the entire bridge will be set to that type. Below the overlay type selection box is a table displaying the unit prices for various overlay activities. The prices in this table are linked to the variable "price_react" from the Parameters Setting module. When the user modifies the activities unit price, the unit prices for overlay activities in this table will automatically update. The price display table for steel beam repairing has the same setup.

4.1.3 Choose Steel Beam Repairing Type

As shown in Figure A12, there are three options for steel beam repairing: Bolted, Cut-out, and Welding. The input field will select the activity with the lowest price among the three steel beam repairing options as the default value. Like the overlay type setting, the steel beam repairing setting functions at the bridge level, meaning that the entire bridge will follow the specified steel beam repairing type.

### *4.2 Bridge Report Calculation*

When the user clicks the "Generate Report" button, the server will input the data from the Parameters Setting module and the user inputs into the calculation script TotalData.Rmd. After completion of the calculations, TotalData.Rmd will generate a list of preservation activities and their associated costs for the bridge.

The calculated list of preservation activities and costs will replace the corresponding rows in "Output_ActivitySummary_upd.csv" and "Output_CostSummary_upd.csv". For example, if the user generates a report for bridge 030004 on this page, the activity list and costs generated by TotalData.Rmd will replace the row for bridge 030004 in "Output_ActivitySummary_upd.csv" and "Output_CostSummary_upd.csv". This ensures that the results calculated with customized parameters are reflected in the summary results.

*4.3 Report Rendering*

The calculation results obtained from TotalData.Rmd are used to generate two forms of reports with the same content: an online bridge report and an offline HTML report. The online bridge report is rendered by the server's code and displayed directly in the UI. The offline HTML report is generated by IndividualReport.Rmd to create an HTML format report, which can be downloaded by the user for offline viewing.

When the user clicks "Generate Individual Bridge Report", the server will render the online bridge report and display it on the View Bridge Report page. The HTML report will be rendered and generated when the user clicks "Download HTML". The content of the report will be described in APPENDIX L, Section 2.5.

5. View Bridge Report

The content presented in the online bridge report is the same as that in the offline bridge report. The content of the report is described in Appendix L, Section 2.5. In the UI, in addition to viewing the bridge report, users can also customize the application scope of preservation activities for each element on the Required Preservation Quantity page. The definition of the activities application scope can be seen in Section 5.1. Figure A14 shows the UI for viewing the required preservation quantity in the online bridge report, which includes a table and a recalculate button.

The table columns "Level2Quantity", "Level3Quantity", and "Level4Quantity" represent the quantity of preservation activities required for each CS level. The "PreserveUntil" indicates the activities application scope. "MainQty" represents the actual quantity of preservation activities needed. The default value for the application scope of all bridge activities is set to 2. Therefore, initially, the required preservation quantity for an element equals the sum of all preservation activities quantities for CS levels 2, 3, and 4.

The server listens for changes in the "PreserveUntil" column of the table and will automatically update the "MainQty" column. For example, in the first row of the table in Figure A14, span 1's reinforced concrete deck requires the preservation activity HMWM. The activity application scope is set to 2. The quantities of preservation needed for levels 2, 3, and 4 are 1005, 1, and 0, respectively. Therefore, the corresponding preservation quantity is 1006 (1005+1+0). If the user changes the application scope to 3, the corresponding preservation quantity in the table will automatically update to 1 (1+0). Since changes in the preservation quantity will affect the bridge's preservation costs, users need to click the "Recalculate Based on Updated Preservation Scope" button at the bottom left to obtain the updated preservation cost based on the new activity application scope. After clicking, Recal_PreservationQuantity.Rmd will be called to recalculate the result in the report that depends on the preservation quantity. Once the recalculation is complete, the server will update the data in the Pay Items per Activity and Cost Estimation Summary sections to match the user's modified activity application scope.

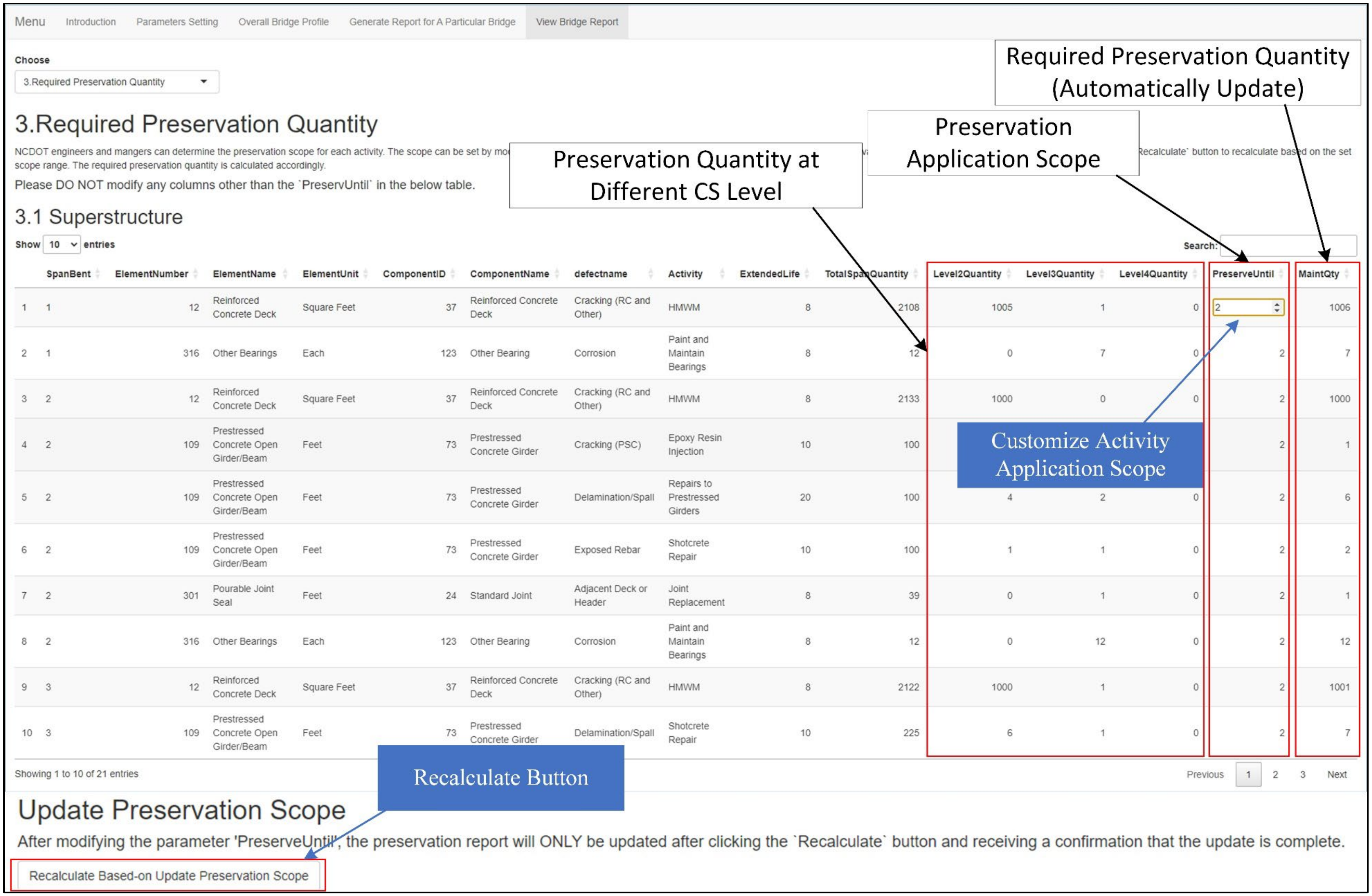



Figure A14 UI-Customize Preservation Application Scope

## APPENDIX L Shiny Application User Instruction

The research team developed a user-friendly bridge preservation planning app named BGP using the Shiny package in R. The BGP app is designed to generate bridge preservation plan reports based on bridge inspection data. Users can upload the bridge inspection data to quickly calculate the required preservation activities and costs for bridges. The BGP allows users to customize various parameters related to bridge preservation (e.g., activities unit prices, extended life), creating flexible bridge preservation plan reports. The generated reports can provide engineers with guidance and serve as a reference for bridge preservation practices. Appendix L will introduce the app's features and provide a user guide.

### 1. Function Introduction

The BGP app has the following three main functions:

- **Calculate the total cost for all bridges**

The BGP app can quickly calculate the preservation costs for all bridges based on their inspection data. The calculated results will be presented in a table as shown in Figure A15. This table provides detailed information on the number of preservation activities required, preservation costs, criticality, and other relevant data for each bridge.

Table 2: Bridge-Specific Preservation Activity Count and Total Cost

Choose A Bridge Group

All

Show 10 entries

Search:

| Number | County | AADT | TotalActivitySuper | TotalActivitySub | TotalActivity | TotalCost | Criticality | Group |
|---|---|---|---|---|---|---|---|---|
| 030003 | ANSON | 18500 | 21 | 15 | 36 | $201,888 | 32.5 | Low Priority |
| 030004 | ANSON | 18500 | 5 | 2 | 7 | $55,190 | 32.5 | High Priority |
| 030006 | ANSON | 3600 | 3 | 3 | 6 | $14,952 | 18.9 | Critical Priority |
| 030010 | ANSON | 2700 | 2 | 0 | 2 | $3,765 | 15.11 | < Lower Bound |
| 030012 | ANSON | 1500 | 4 | 2 | 6 | $2,643 | 14.41 | < Lower Bound |
| 030013 | ANSON | 800 | 1 | 0 | 1 | $164 | 7.96 | < Lower Bound |
| 030022 | ANSON | 2200 | 0 | 0 | 0 | $0 | 14.64 | No Need for Preservation |
| 030024 | ANSON | 3000 | 7 | 3 | 10 | $6,564 | 13.42 | < Lower Bound |
| 030027 | ANSON | 1600 | 5 | 2 | 7 | $78,855 | 15.71 | Medium Priority |
| 030028 | ANSON | 550 | 14 | 4 | 18 | $127,580 | 6.86 | Low Priority |

Showing 1 to 10 of 442 entries Previous 1 2 3 4 5 … 45 Next

Figure A15 Bridge Total Preservation Cost

- **Visualize the relationship between bridge criticality and preservation cost**

The BGP app can create scatter plots that illustrate the relationship between bridge criticality and preservation cost. As shown in Figure A16, the plot displays the relationship between bridge criticality and total preservation cost for hundreds of bridges in North Carolina's Division 10.

Bridges are categorized into various priority levels based on the ratio of criticality to preservation cost. This scatter plot enables users to quickly identify bridges with high preservation priority.

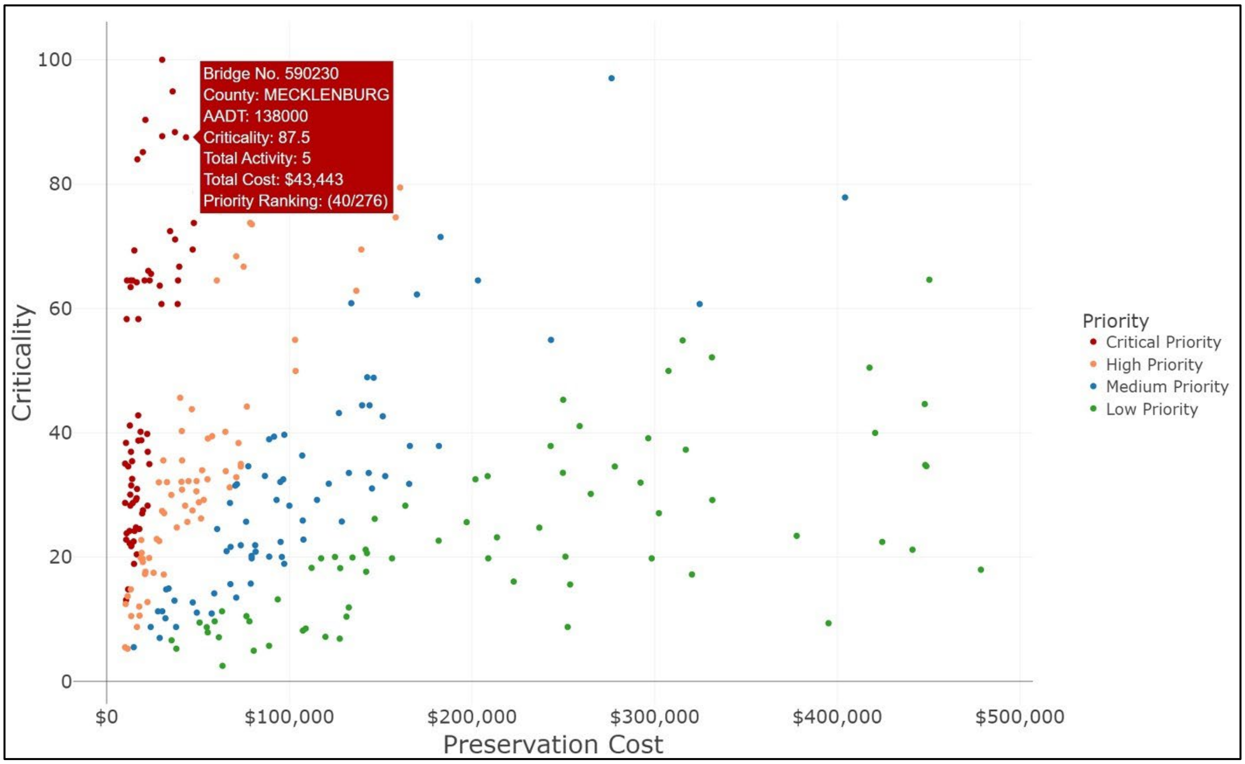


Figure A16 Bridge Criticality vs Total Preservation Cost

- **Generate bridge preservation plan reports.**

The BGP app can generate a detailed preservation plan report for a specific bridge. This report provides comprehensive information on the bridge elements that require preservation, the required preservation activities, and the costs of each activity. As shown in Figure A17, the BGP app generates a bar chart for bridge "030003" that breaks down the total preservation cost by activity.

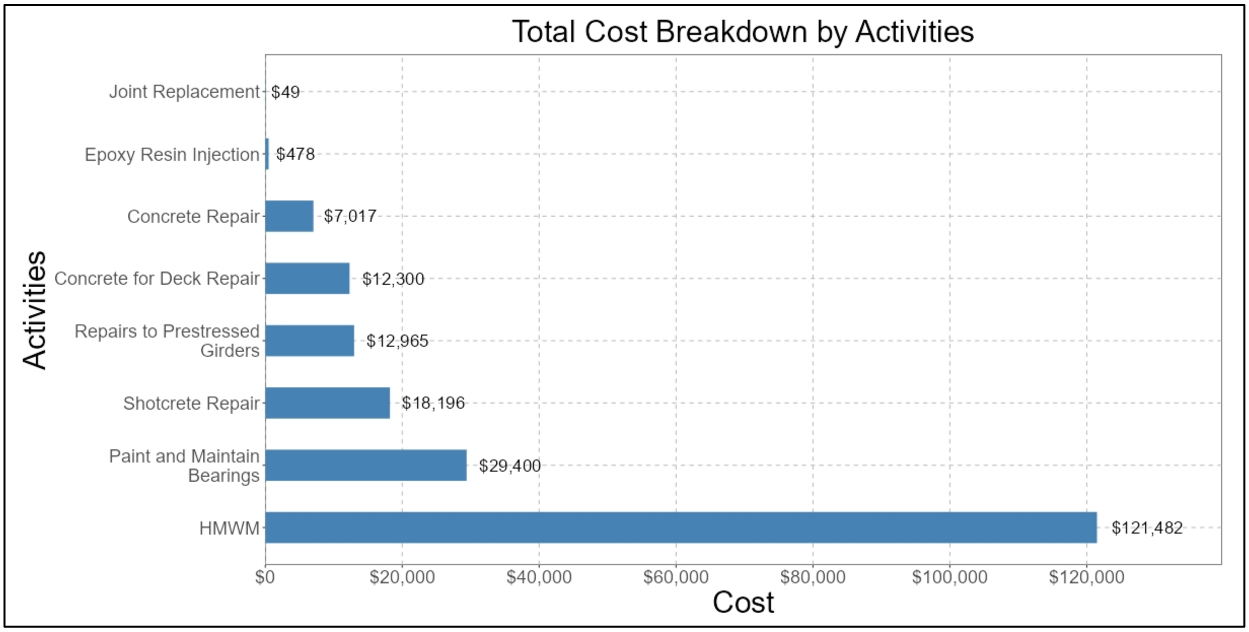


Figure A17 Cost Summary of Bridge 030003

## 2. App User Manual

There are two ways to launch this app: via RStudio and via a web browser. The two methods differ only in the startup process, with no differences in functionality or interface. Below is a user guide for launching the BGP app in a web browser.

### *2.1. Launching the Shiny App*

First, open the BGP app in your browser by navigating to the following URL: **https://ncdotrp2023-05.shinyapps.io/rshiny/**

Upon opening the BGP app in your browser, you will see the user interface as shown in Figure A18. At the top of the interface is the navigation bar. The app is divided into five pages:

- Introduction
- Parameters Setting
- Overall Bridge Profile
- Generate Report for a Particular Bridge
- View Bridge Report

By clicking on the options in the navigation bar, you can access the corresponding pages. The Introduction page provides an overview of the app's basic functions.

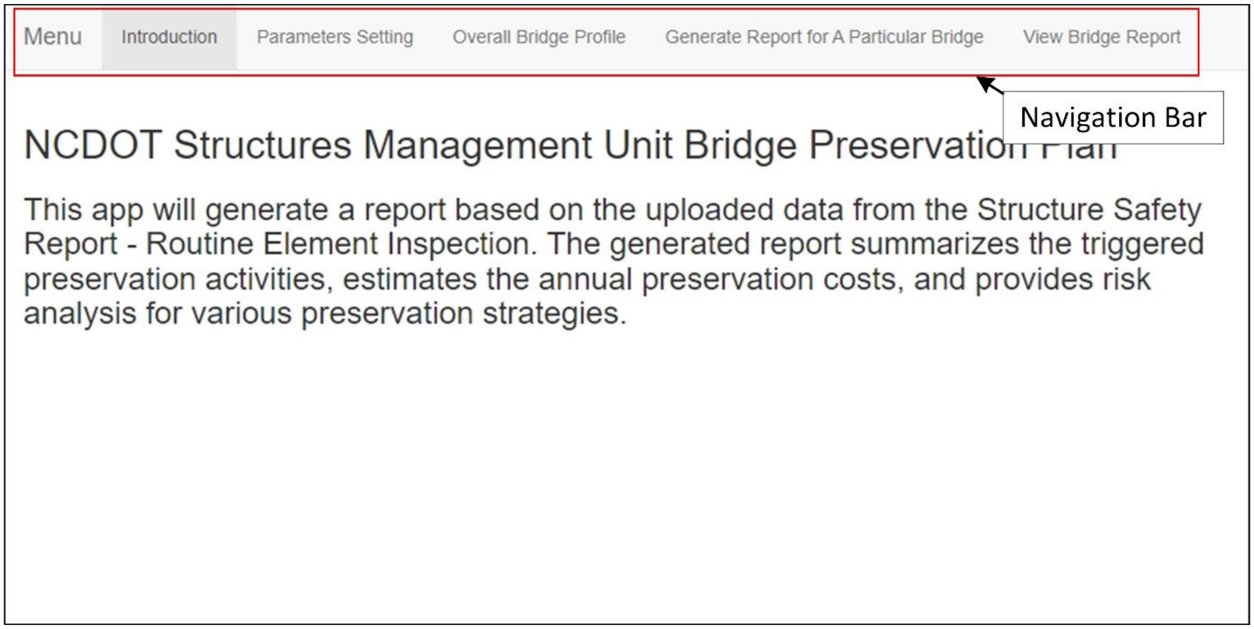



Figure A18 BGP App Introduction Page

*2.2 Parameters Setting*

On the “Parameters Setting” page, you can customize four types of parameters necessary for the bridge preservation plan: interest, activities unit price, unit conversion ratio, and activities extended life. The functions of these parameters have been described in the dataset section. The definitions and functions of these parameters are found in Chapter 3.

2.2.1 Interest Setting

As shown in Figure A19, the interest rate can be set by entering the corresponding number in the red box. It is important to note that the unit for the interest rate is “%”. For example, to set the interest rate to 3%, you should enter “3” in the input box, not “0.03”. The default value for the interest rate is set at 3%.

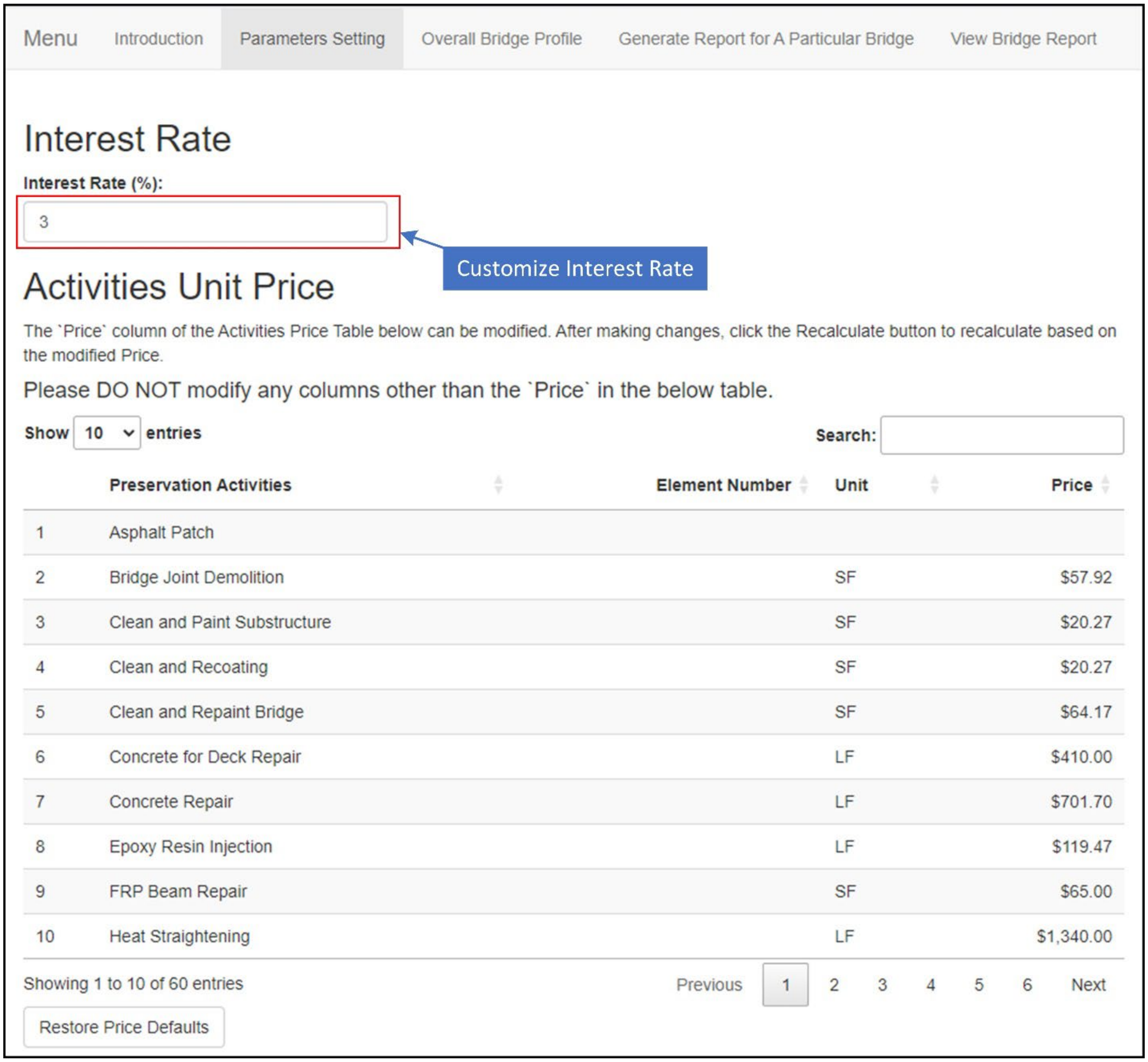



Figure A19 Parameters Setting: Interest Rate

2.2.2 Activities Unit Price Setting

The BGP app enables the calculation of the bridge preservation activities unit price, with default values sourced from the "Step 0_Unit_Price.csv" file. Figure A20 provides a guide on how to customize the unit prices. Users can customize the unit price by clicking on the elements in the "Price" column and entering the desired value in the input box. For example, to customize the price of the "Joint Replacement" activity for element 305, as shown in Figure A20, click on the "Price" cell in the row corresponding to "Joint Replacement" and "305", then enter the desired value.

Clicking the "Restore Price Defaults" button in the lower left corner restores the prices to their default values, which are sourced from "Step 0_Unit_Price.csv". The operations for modifying parameters and restoring default values for the Unit Conversion Ratio and Activities Extended

Life tables are the same. It is important to note that users should not modify any columns other than the “Price” column, as this may cause the program to return an error. For user convenience, the table in the BGP app includes Search, Sort, and Pagination features:

- **Search**: A search box is located at the top right of the table. Entering text in the search box will filter the corresponding rows.
- **Sort**: The column headers have two triangles on the right side. Clicking on the triangles will sort the table by that column.
- **Pagination**: Clicking the numbers at the bottom right of the table allows for page navigation.

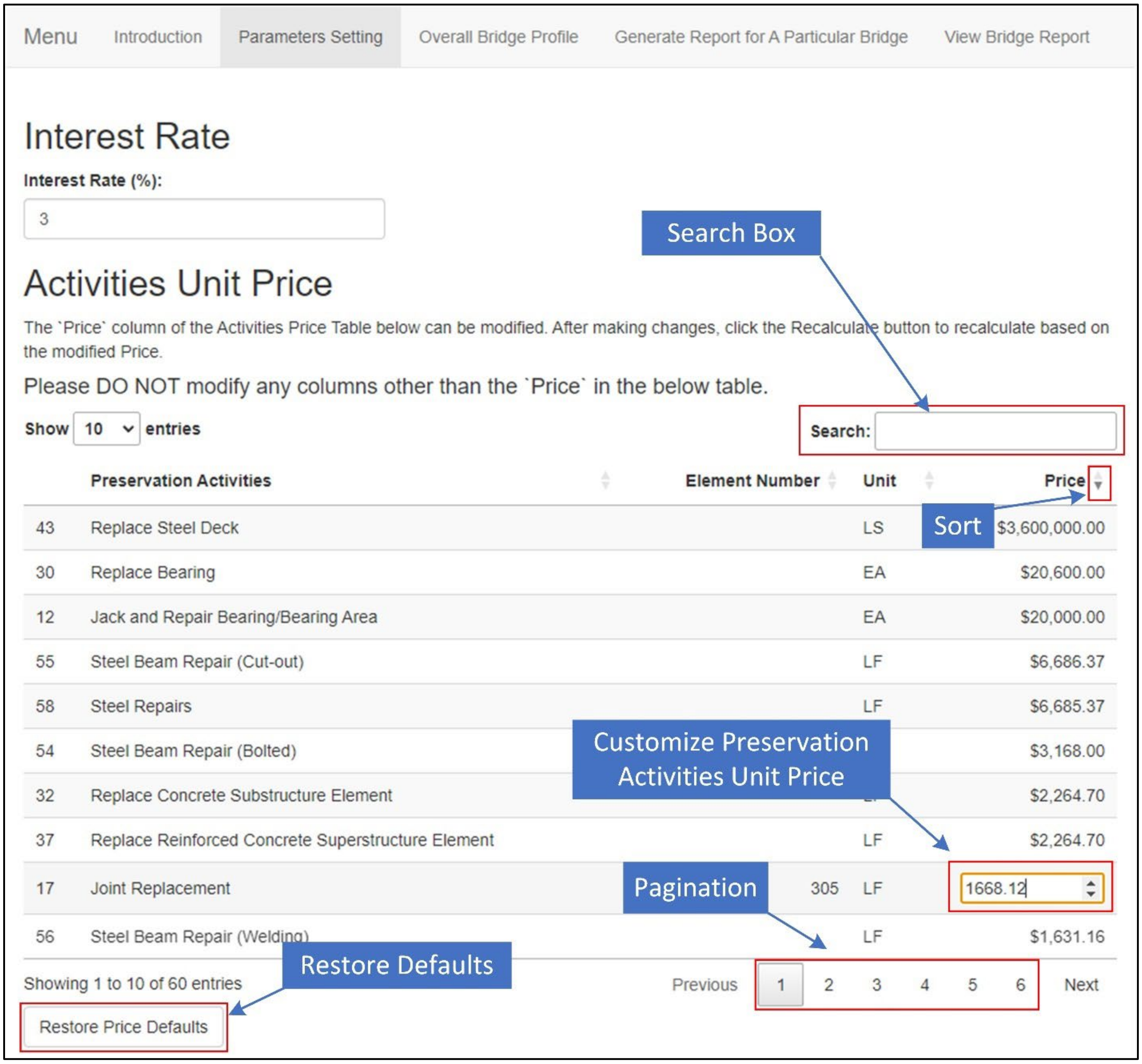



Figure A20 Parameters Setting: Activities Unit Price

The process of customizing the unit conversion ratio and activities extended life is similar to customizing the unit price, so their instructions are not repeated here.

*2.3 Generate Overall Bridge Profile*

On the Overall Bridge Profile page, users can calculate the preservation costs for all bridges to gain a quick overview of them.

2.3.1 Steps to Generate Overall Bridge Profile

As shown in Figure A21, generating the overall bridge profile can be divided into four steps.

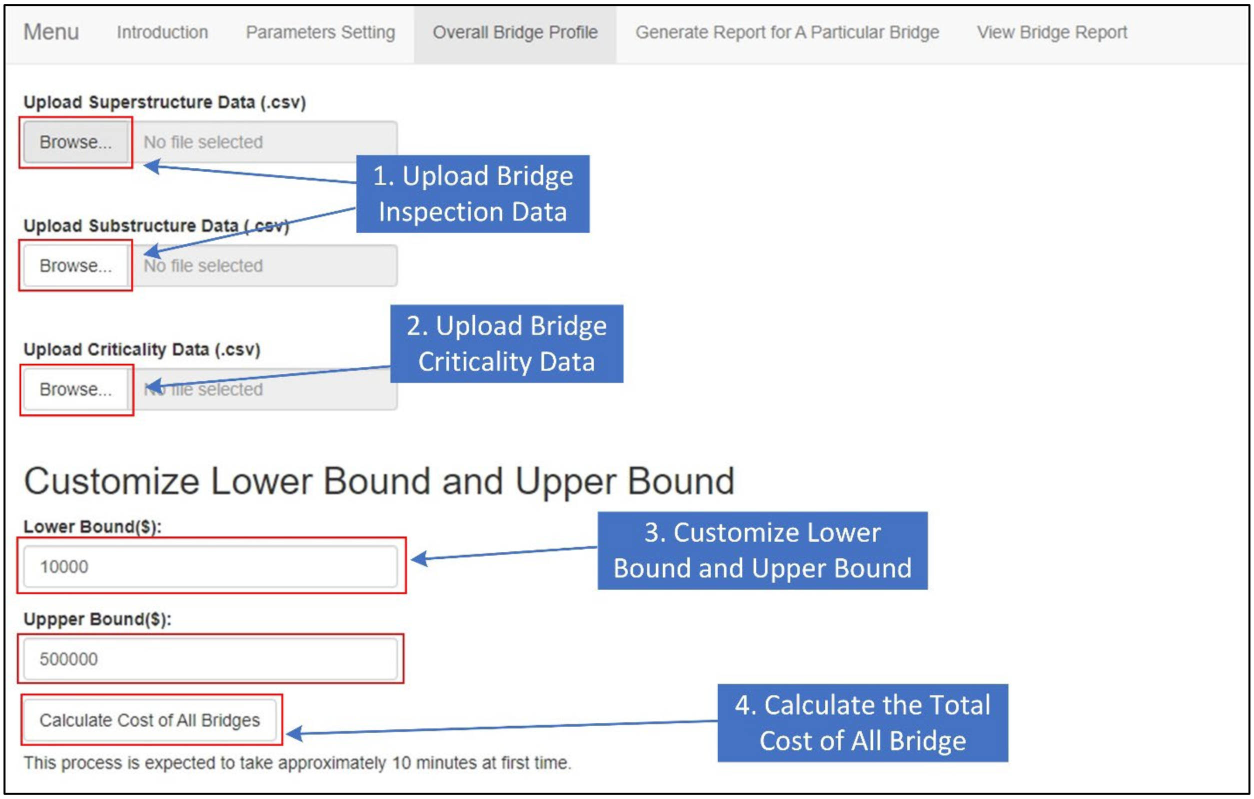



Figure A21 Steps to Generate Overall Bridge Profile

- **Step 1: Upload Bridge Inspection Data**

Users need to upload bridge superstructure and bridge substructure inspection data. These two datasets were obtained from the NCDOT bridge database. Their detailed introduction is found in Chapter 3.

- **Step 2: Upload Bridge Criticality Data**

The criticality data form a dataset detailing the importance of each bridge, as discussed in Chapter 6. As shown in Figure A21, to upload data, users can simply click the "Browse" button and upload the corresponding datasets. The uploaded data must be in CSV format.

For calculating the preservation costs of the 442 bridges in District 10 of North Carolina, the required datasets are:

1. **Bridge superstructure inspection data**: "Step 0_new_super.csv"
2. **Bridge substructure inspection data**: "Step 0_new_sub.csv"
3. **Bridge criticality data**: "bridgeCritOut_Scale.csv"

These three files are submitted with the BGP app and are stored in the "data/" folder within the BGP app directory.

- **Step 3: Customize Lower Bound and Upper Bound**

The lower bound and upper bound are parameters related to bridge grouping. In the BGP app, the default values for the lower bound and upper bound are $10,000 and $500,000, respectively. For example, with these default values, after the calculation, all bridges with a total preservation cost of less than $10,000 or greater than $500,000 were singled out. Subsequently, bridges with a total cost between $10,000 and $500,000 were divided into four groups (critical priority, high priority, medium priority, and low priority) based on the ratio of criticality to total preservation cost (i.e., preservation priority). This algorithm can be found in Chapter 7. Users can customize these two parameters in the input boxes.

- **Step 4: Click "Calculate Cost of All Bridges"**

After clicking the "Calculate Cost of All Bridges" button, the BGP app begins calculating the total preservation cost for all bridges. It is important to note that this initial calculation takes approximately 10 minutes. As shown in Figure A22, during the calculation process, a progress bar will appear in the bottom right corner of the interface, indicating which bridge the BGP app is currently calculating. If the calculation process is interrupted, the app will resume from the point where it was interrupted the next time it runs. This effectively prevents the need to restart from the beginning due to unexpected interruptions. It is important to note that if the app has already calculated the total cost for all bridges once before, clicking "Calculate Cost of All Bridges" will immediately complete and display the results without any wait time.

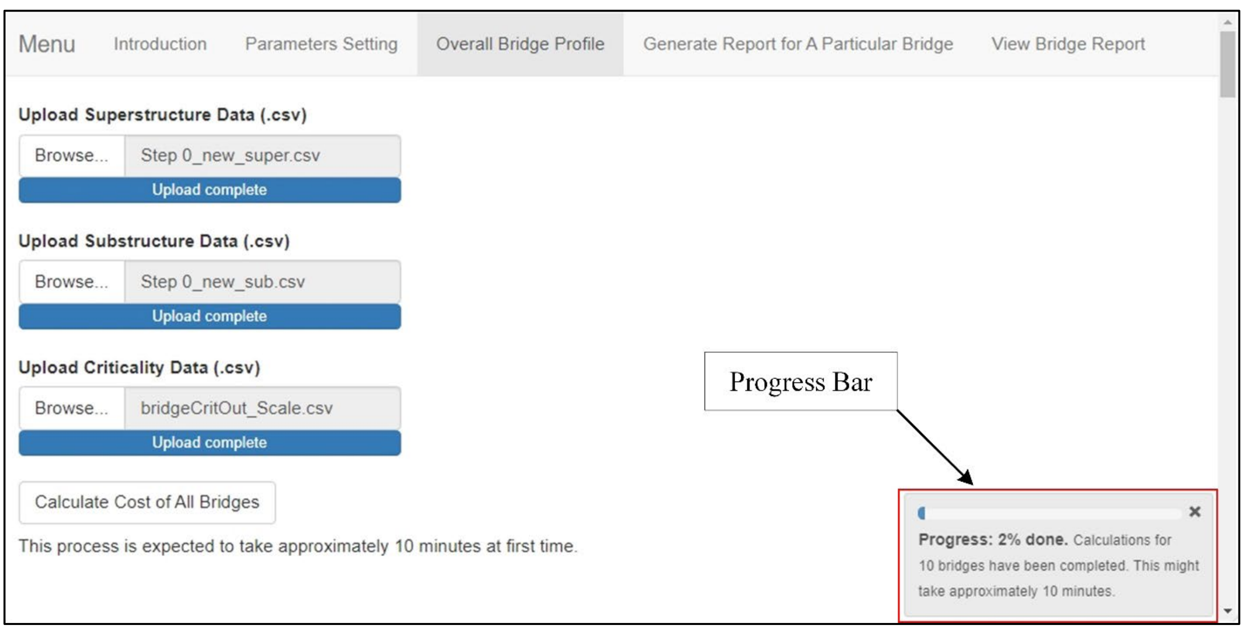



Figure A22 Progress Indicator for Calculating the Total Cost of All Bridges

### 2.3.2 Visualization of Calculation Results

After the calculation is completed, the app will display two scatter plots and three tables to visualize the results.

- **Scatter Plot 1: Preservation Total Cost vs. Criticality**

Figure A23 shows the first scatter plot generated by the BGP app: Total Cost vs. Criticality. The title at the top of Figure A23 displays the lower and upper bounds for the bridges, which are set to the default values of $10,000 and $500,000. This scatter plot illustrates the relationship between the preservation total cost and criticality of the bridges. The *x* axis represents the preservation total cost, and the *y* axis represents the criticality. Bridges with total costs between the lower and upper bounds are categorized into four prioritization levels: critical priority, high priority, medium priority, and low priority. The algorithm for calculating the preservation prioritization can be found in Chapter 7.

Each point on the scatter plot represents a bridge. Users can hover the mouse cursor over a point to view detailed information about the bridge, including the bridge number, county, AADT, criticality, total activities, total cost, and priority ranking. By clicking the camera icon in the toolbar at the top right of the scatter plot, users can download the scatter plot.

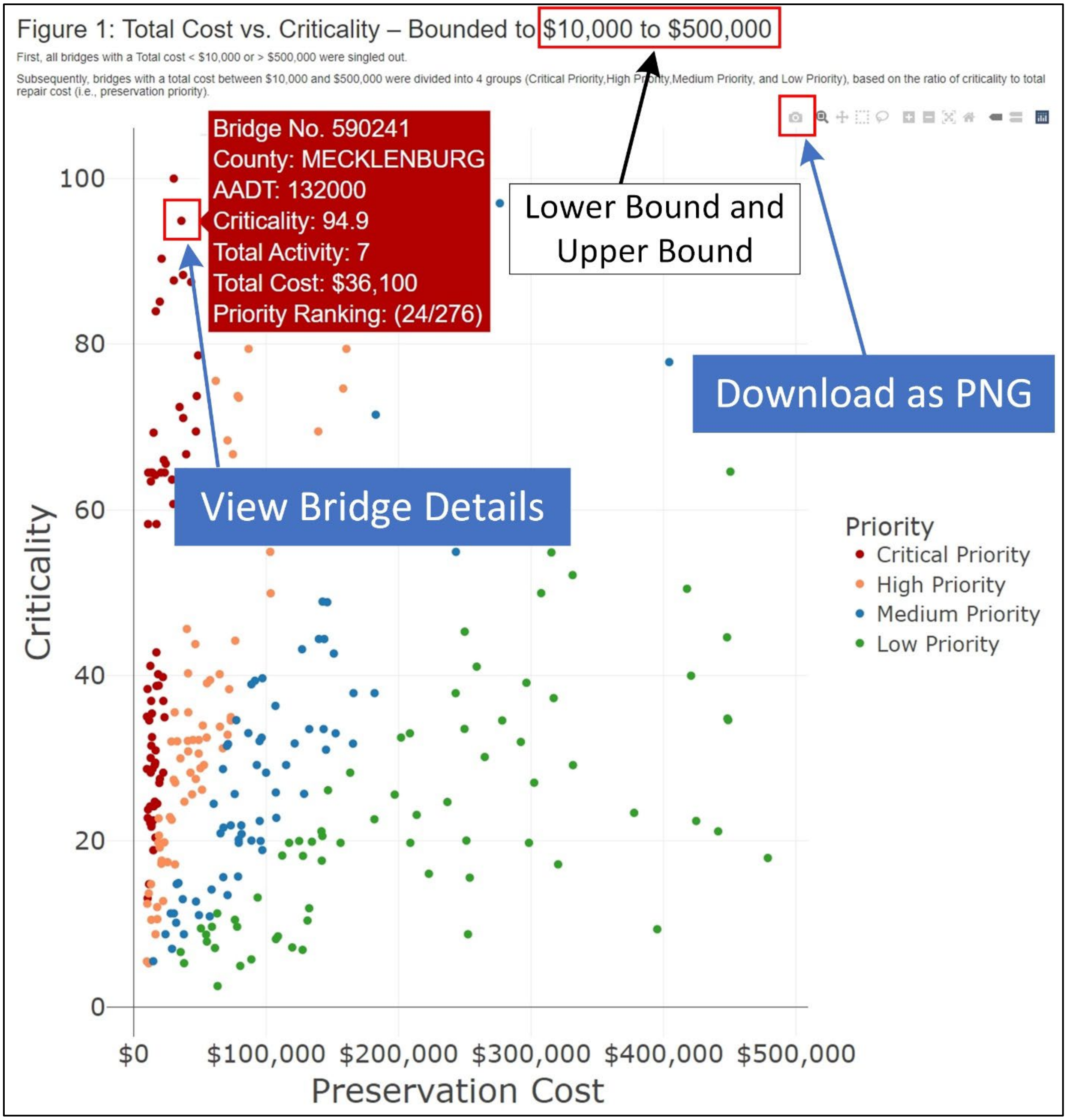



Figure A23 Scatter Plot of Total Cost vs. Criticality

- **Scatter Plot 2: Preservation EAC vs. Criticality**

Figure A24 shows the second scatter plot generated by the BGP app. This scatter plot illustrates the relationship between the EAC and criticality of the bridges. The *x* axis represents the EAC, and the *y* axis represents criticality. The algorithm for calculating the bridge preservation EAC is detailed in Section 5.5.

Similar to Scatter Plot 1, this plot only includes bridges with total costs between the lower and upper bounds. However, the priority ranking of the bridges in Scatter Plot 2 is calculated based on EAC. The specific algorithm can be found in Chapter 7. Users can hover the mouse cursor over a point to view detailed information about the bridge. This includes the bridge number, county, AADT, criticality, total activities, total cost, priority ranking, EAC, longest life, group (EAC), and priority ranking (EAC).

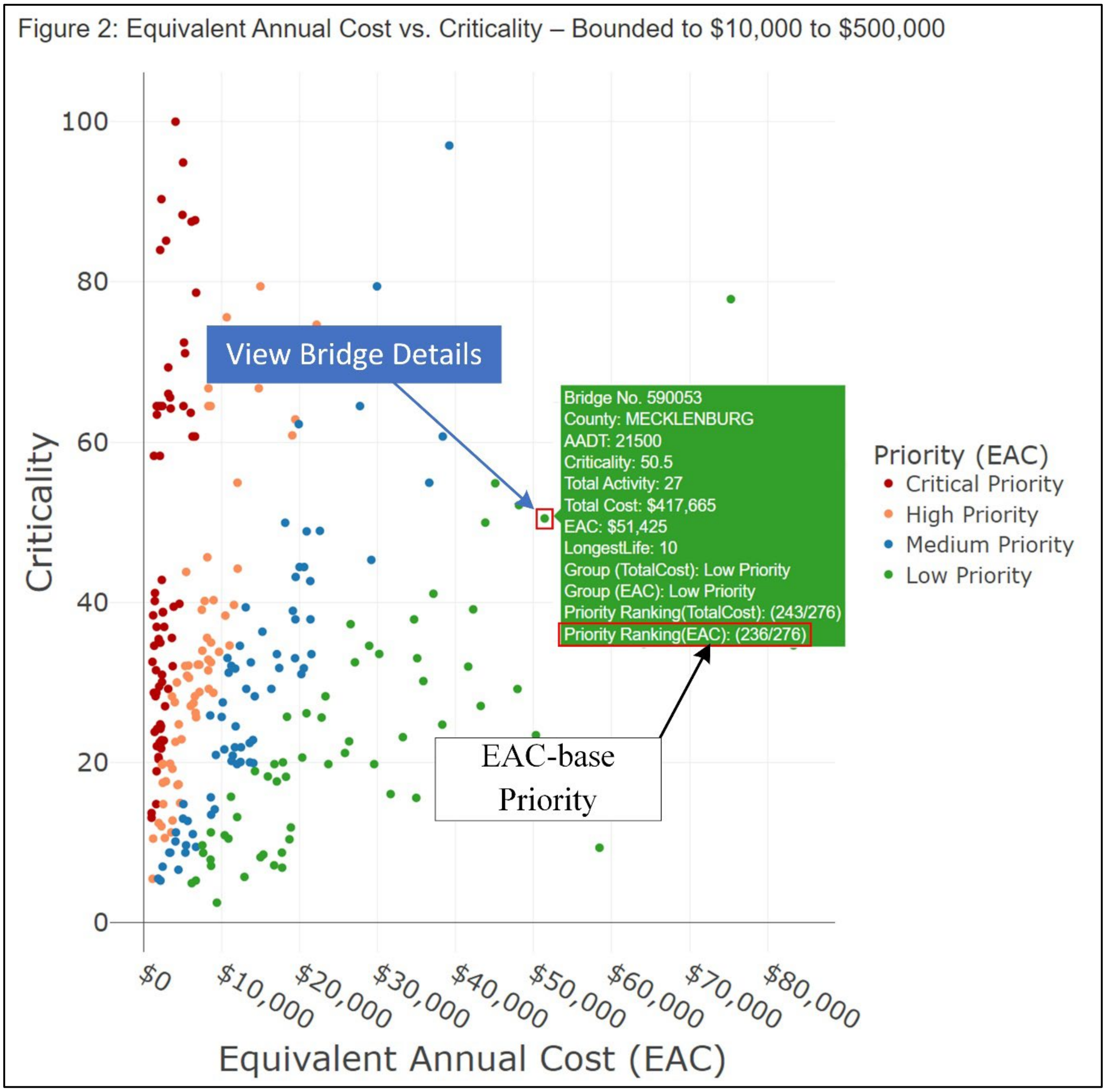



Figure A24 Scatter Plot of Preservation EAC vs. Criticality

- **Summary of Bridge Preservation Activities and Cost Statistics**

The table in Figure A25 displays statistical features for all bridges regarding activities and costs. The row names on the far left of the table represent six statistical features: minimum, first quartile, median, mean, third quartile, and maximum. The table contains four columns. The first three columns relate to the number of preservation activities for the superstructure, substructure, and the entire bridge. The fourth column represents the total preservation cost for the bridge. This table provides users with a quick overview of all the bridges. For example, the table shows that among the 442 bridges uploaded from North Carolina's Division 10, the maximum total preservation cost is $7,271,125, while the mean cost is $150,866.

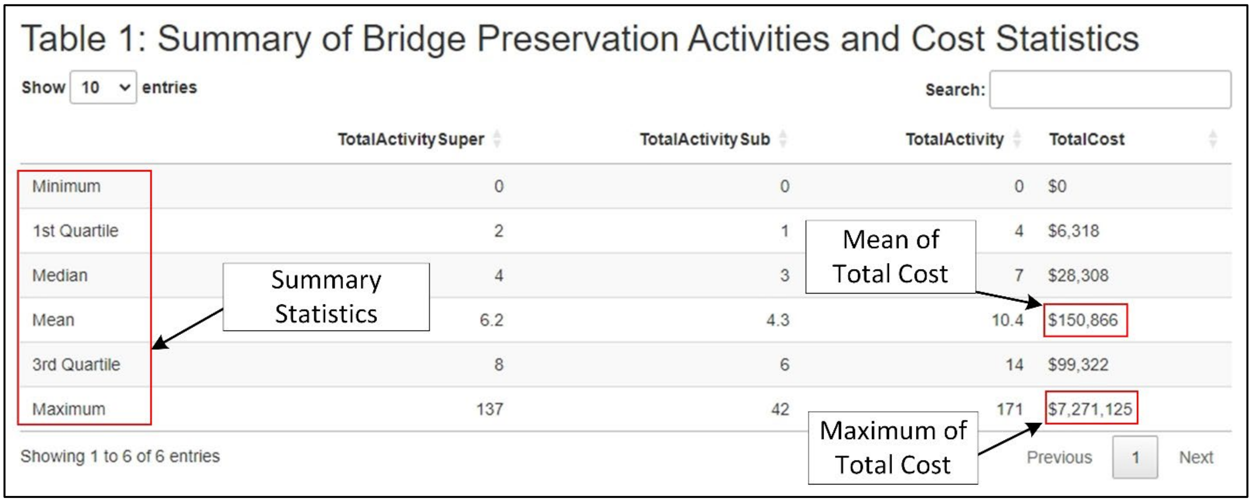


Table 1: Summary of Bridge Preservation Activities and Cost Statistics

Show 10 entries Search:

| | TotalActivity Super | TotalActivity Sub | TotalActivity | TotalCost |
|---|---|---|---|---|
| Minimum | 0 | 0 | 0 | $0 |
| 1st Quartile | 2 | 1 | 4 | $6,318 |
| Median | 4 | 3 | 7 | $28,308 |
| Mean | 6.2 | 4.3 | 10.4 | $150,866 |
| 3rd Quartile | 8 | 6 | 14 | $99,322 |
| Maximum | 137 | 42 | 171 | $7,271,125 |

Showing 1 to 6 of 6 entries Previous 1 Next



Figure A25 Summary Table of Bridge Preservation Activities and Cost Statistics

- **Bridge Preservation Activity Count and Total Cost**

The table in Figure A26 displays various information about the bridges. Specifically, it includes the bridge number, county, AADT, number of preservation activities, total preservation cost, criticality, and group. Users can filter the bridges displayed in the table by selecting one of eight options from the "Choose a Bridge Group" dropdown menu: ALL, Critical Priority, High Priority, Medium Priority, Low Priority, Greater than Upper Bound, Less than Lower Bound, and No Need for Preservation.

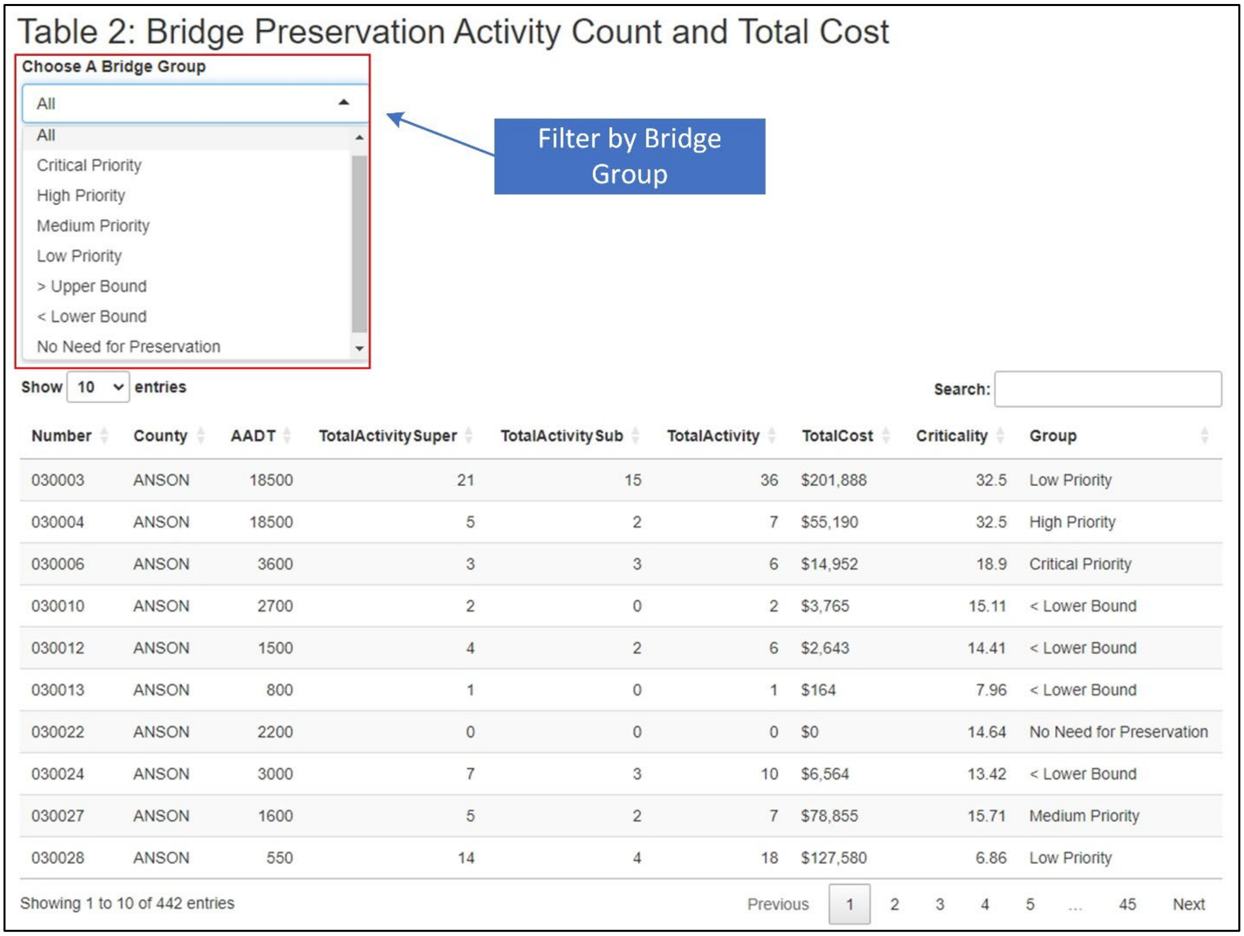


Table 2: Bridge Preservation Activity Count and Total Cost

Choose A Bridge Group

All

All
Critical Priority
High Priority
Medium Priority
Low Priority
> Upper Bound
< Lower Bound
No Need for Preservation

Filter by Bridge Group

Show 10 entries Search:

| Number | County | AADT | TotalActivitySuper | TotalActivitySub | TotalActivity | TotalCost | Criticality | Group |
|---|---|---|---|---|---|---|---|---|
| 030003 | ANSON | 18500 | 21 | 15 | 36 | $201,888 | 32.5 | Low Priority |
| 030004 | ANSON | 18500 | 5 | 2 | 7 | $55,190 | 32.5 | High Priority |
| 030006 | ANSON | 3600 | 3 | 3 | 6 | $14,952 | 18.9 | Critical Priority |
| 030010 | ANSON | 2700 | 2 | 0 | 2 | $3,765 | 15.11 | < Lower Bound |
| 030012 | ANSON | 1500 | 4 | 2 | 6 | $2,643 | 14.41 | < Lower Bound |
| 030013 | ANSON | 800 | 1 | 0 | 1 | $164 | 7.96 | < Lower Bound |
| 030022 | ANSON | 2200 | 0 | 0 | 0 | $0 | 14.64 | No Need for Preservation |
| 030024 | ANSON | 3000 | 7 | 3 | 10 | $6,564 | 13.42 | < Lower Bound |
| 030027 | ANSON | 1600 | 5 | 2 | 7 | $78,855 | 15.71 | Medium Priority |
| 030028 | ANSON | 550 | 14 | 4 | 18 | $127,580 | 6.86 | Low Priority |

Showing 1 to 10 of 442 entries Previous 1 2 3 4 5 … 45 Next

Figure A26 Bridge Preservation Activity Count and Total Cost

- **Bridge Preservation Activity Count and Total Cost**

The table in Figure A27 displays the specific number of preservation activities required for 442 bridges. The first column lists the bridge numbers, while the remaining columns show the number of each preservation activity. For example, by looking at the first row, you can see the number of preservation activities needed for bridge 030003. By sliding the scrollbar at the bottom of the table, users can view additional preservation activities.

Table 3: Detailed Activity Count for Each Bridge Preservation

Show 10 entries          Search:

| Number | Shotcrete Repair | Replace Section of Concrete Barrier | Concrete Repair | Silane | Replace missing or broken fasteners | Replace Timber Superstructure Element | Clean and Paint Substructure | Repair Steel Substructure Element | Replace Steel Substructure Element | Steel Crack Arrest | Temporary Shoring |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 030003 | 13 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030004 | 2 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030006 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030010 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030012 | 2 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030013 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030022 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030024 | 2 | [illegible] | [illegible] | [illegible] | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030027 | 3 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030028 | [illegible] | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

See more activities by using the slider

Showing 1 to 10 of 442 entries          Previous 1 2 3 4 5 … 45 Next

Figure A27 Detailed Activity Count for Each Bridge Preservation

As shown in Figure A28, a “Download XLSX” button is provided below the table. Users can click this button to download the three tables mentioned above. The XLSX file contains three sheets corresponding to the three tables. It is important to note that the calculation results in the downloaded tables are based on the default parameters (i.e., interest rate, activities unit price, extended life, conversion ratio). If the default parameters are changed, the results will need to be recalculated, as demonstrated in Section 2.3.3.

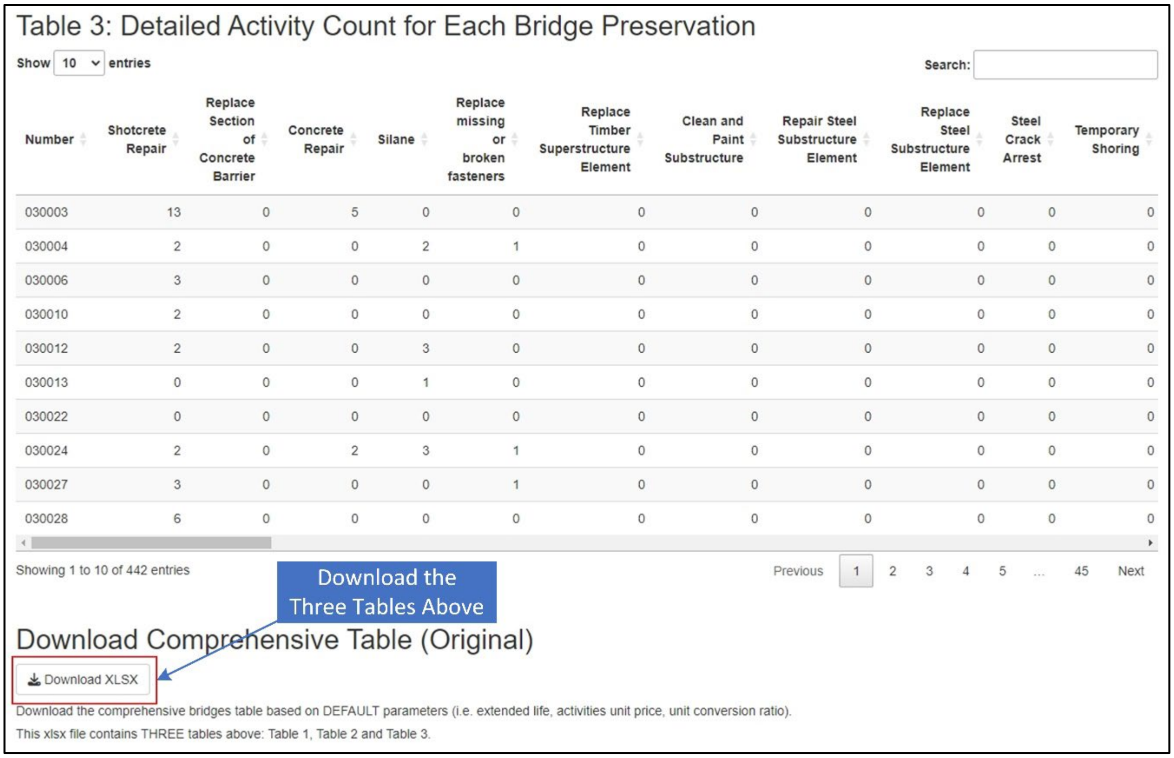


Table 3: Detailed Activity Count for Each Bridge Preservation

| Number | Shotcrete Repair | Replace Section of Concrete Barrier | Concrete Repair | Silane | Replace missing or broken fasteners | Replace Timber Superstructure Element | Clean and Paint Substructure | Repair Steel Substructure Element | Replace Steel Substructure Element | Steel Crack Arrest | Temporary Shoring |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 030003 | 13 | 0 | 5 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030004 | 2 | 0 | 0 | 2 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030006 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030010 | 2 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030012 | 2 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030013 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030022 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030024 | 2 | 0 | 2 | 3 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030027 | 3 | 0 | 0 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 030028 | 6 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |



Figure A28 Download Comprehensive Table (Original)

2.3.3 Recalculate Based on Updated Parameters

If the user modifies any parameters on the Parameters Setting page (e.g., activities unit price), the calculation results need to be recalculated before they are displayed. As shown in Figure A29, when the user clicks the “Recalculate Cost of All Bridges” button, the BGP app will perform recalculations based on the updated parameters. The recalculation process is similar to the initial calculation and takes approximately 10 minutes. Once the recalculations are complete, the figures and content on the Overall Bridge Profile page will be updated. Users can then click the “Download XLSX” button under the Download Comprehensive Table (Update) section to download the updated tables.

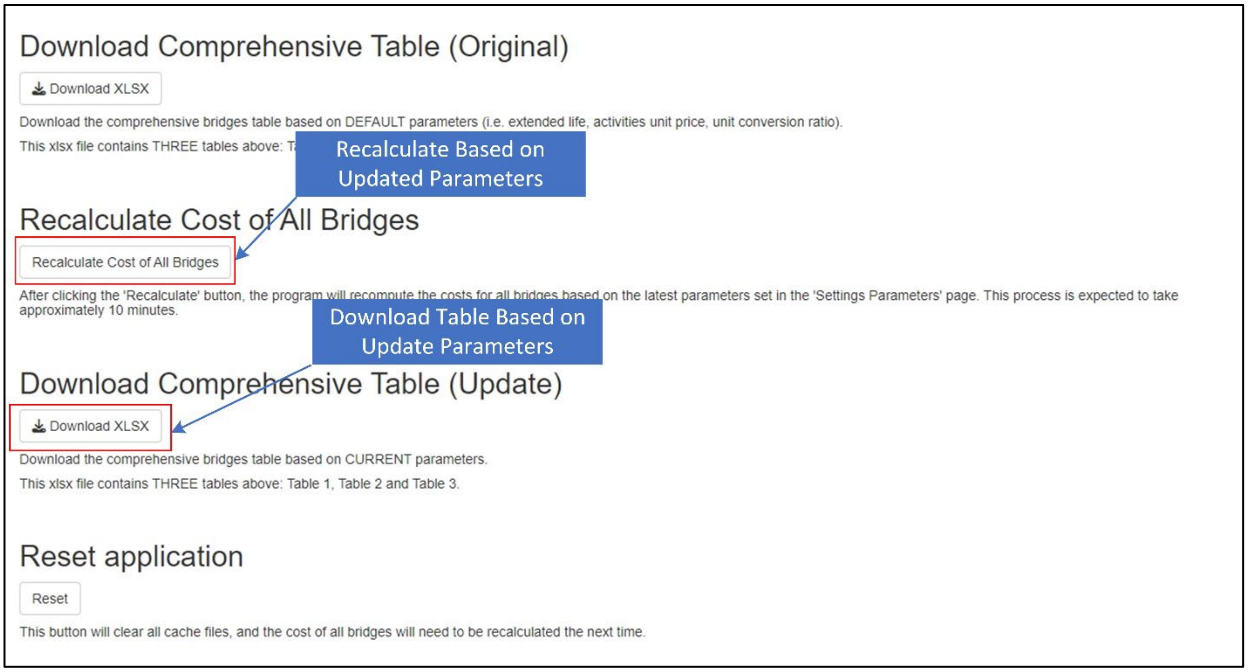



Figure A29 Recalculate and Download Updated Table

2.3.4 Reset

As shown in Figure A30, a reset button is located at the bottom of the overall bridge profile page. Clicking this button will clear all cache files in the BGP app. All previously calculated results will be erased. After resetting, the user needs to recalculate all bridges to view the overall bridge profile.

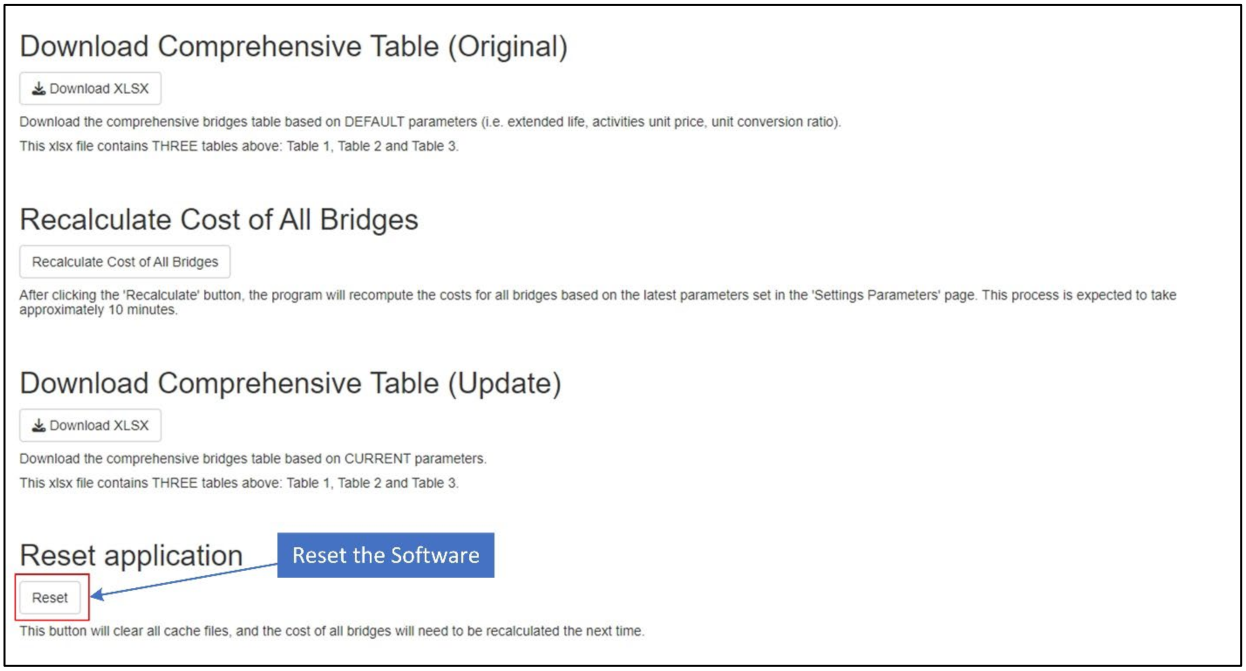



Figure A30 Reset the BGP App

*2.4 Generate Report for A Particular Bridge*

Figure A31 shows the layout and features of the Generate Report for a Particular Bridge page. On this page, users can enter the bridge number of interest in the input box to generate a preservation plan report for that specific bridge. Below the input box is a bridge interstate indicator that informs the user of the interstate type of the entered bridge number. If the entered bridge number is not in the database, a message will prompt with "The input bridge is not in the database, please re-enter." If an interstate bridge number is entered, the app will select the activity with the lowest unit price from Overlay (PPC) and Overlay (LMC) as the default value. If a non-interstate bridge number is entered, the app will select the activity with the lowest unit price from Overlay (Epoxy), Overlay (PPC), and Overlay (LMC) as the default value.

Users can also customize the types of overlay and steel beam repair activities. The overlay type options are LMC, Epoxy, PPC, HMWM, Silane, and No Overlay. Once an overlay type is selected, the entire bridge's overlay activities are set to that option. Similarly, the steel beam repairing options are Bolted, Cut-out, and Welding. Below the selection boxes are two tables displaying the unit prices for these preservation activities.

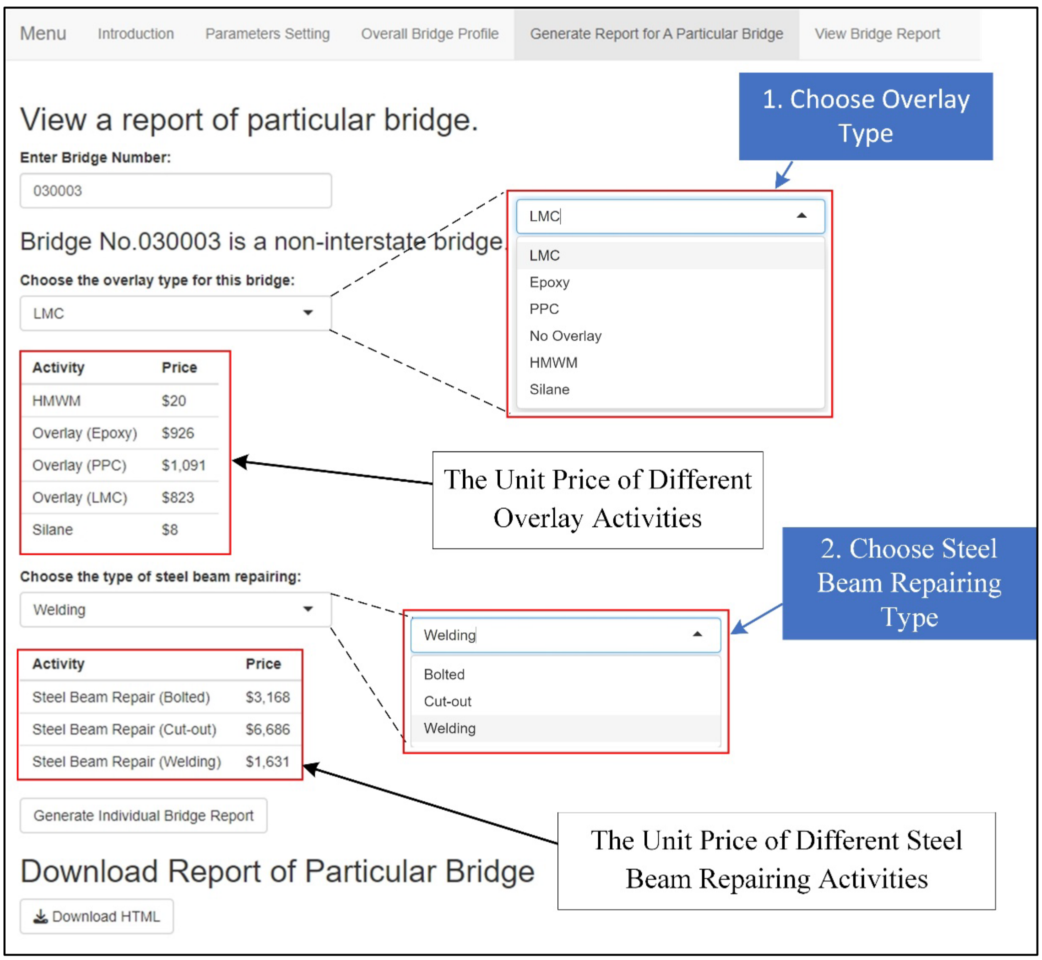



Figure A31 Customize Overlay Type and Steel Beam Repairing Type

After entering the bridge number and defining the parameters, as shown in Figure A32, click the "Generate Individual Bridge Report" button to generate a report for the entered bridge. After a few seconds, a notification will appear in the bottom right corner of the BGP app, indicating that the calculation is complete. If the user modifies any parameters in the Parameters Setting or Generate Individual Bridge Report sections, they need to click the "Generate Individual Bridge Report" button again and wait for the calculation to be completed to generate an updated report.

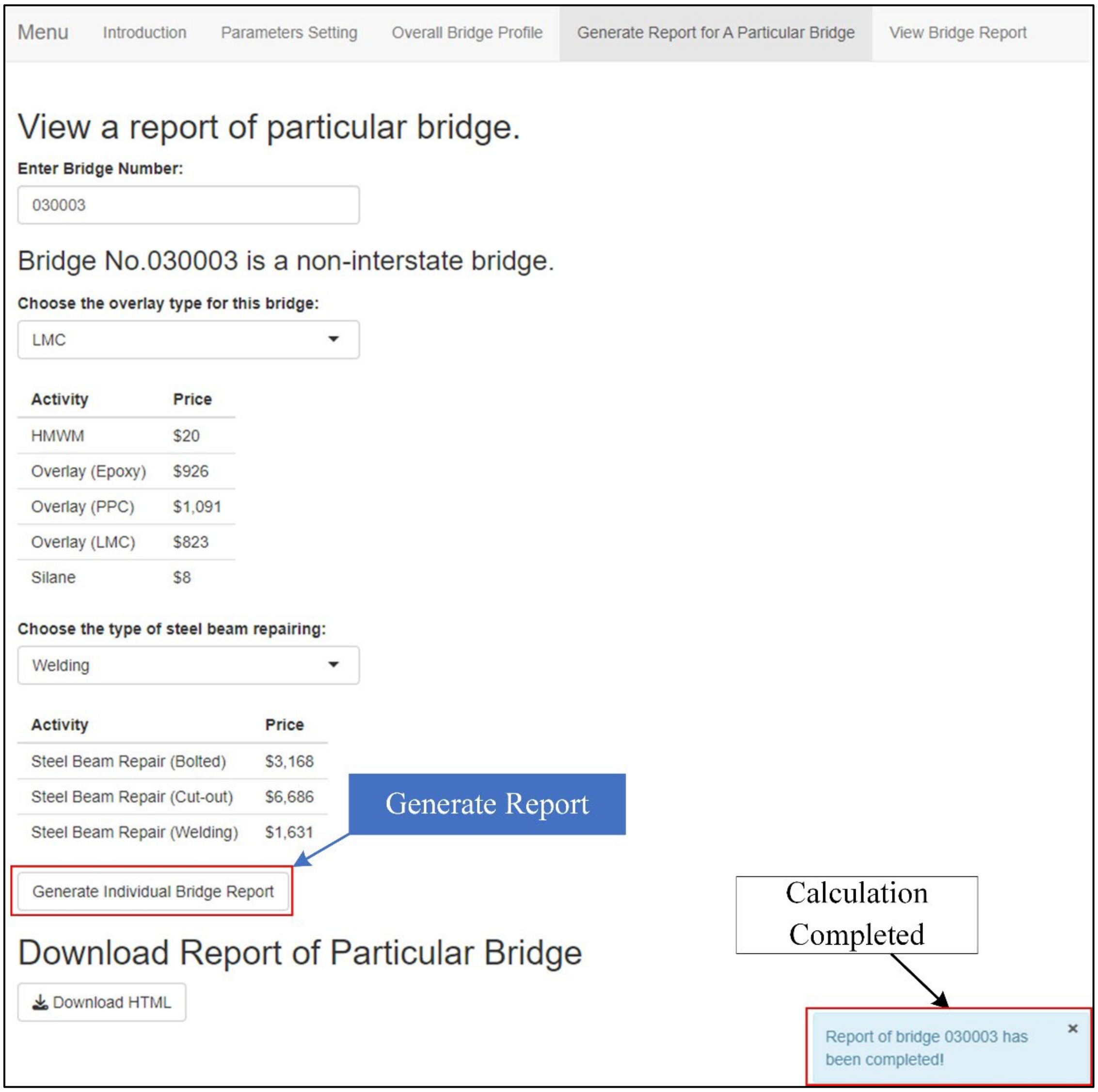


Figure A32 Generate Individual Bridge Preservation Report

As shown in Figure A33, there are two ways to view the generated report: online and offline. The offline report is in HTML format. The report can be viewed online on the View Bridge Report page. There is no difference between the reports viewed in these two ways. The following example illustrates how to view the generated bridge preservation report online.

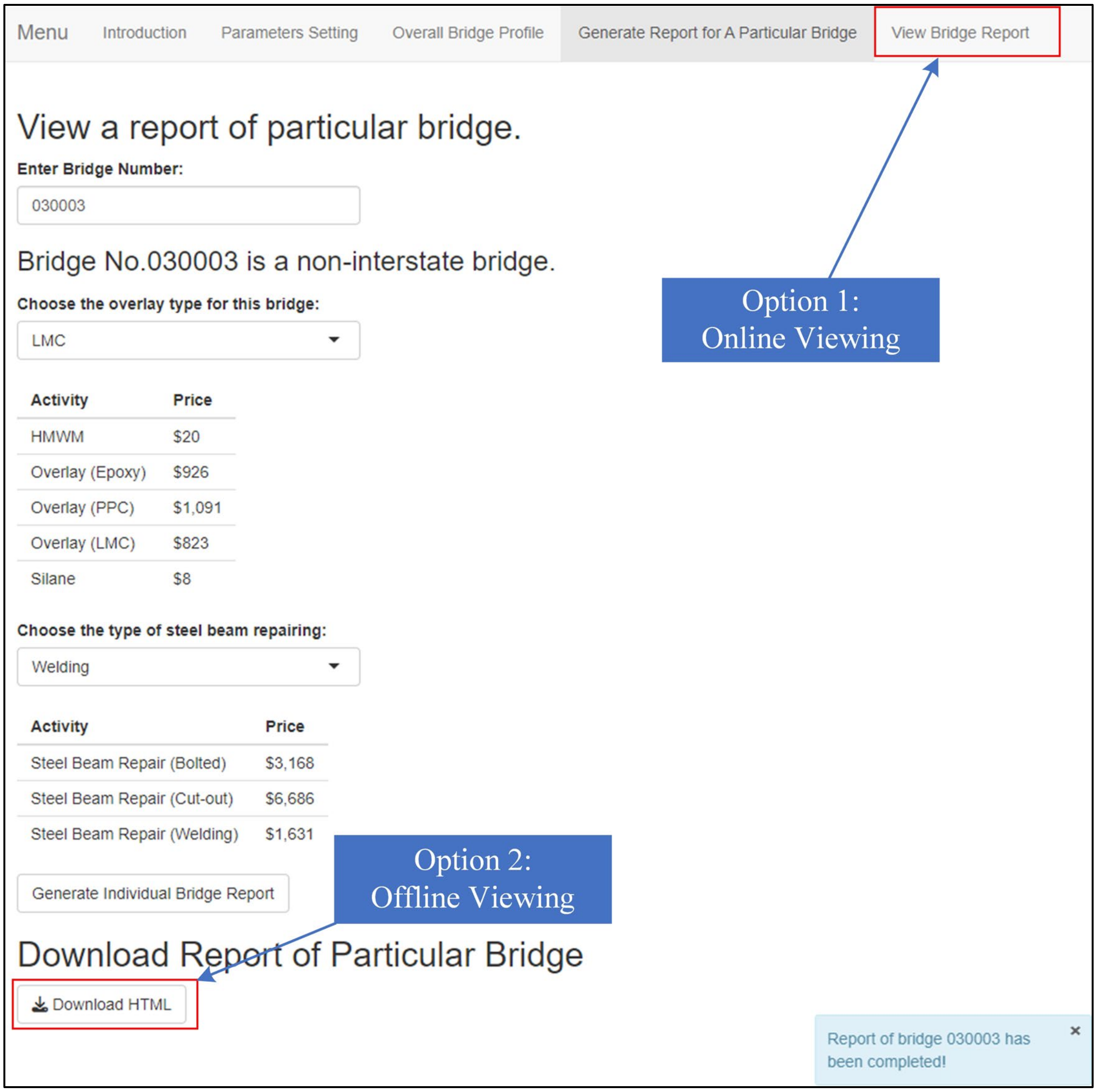



Figure A33 Two Ways to View Bridge Preservation Reports

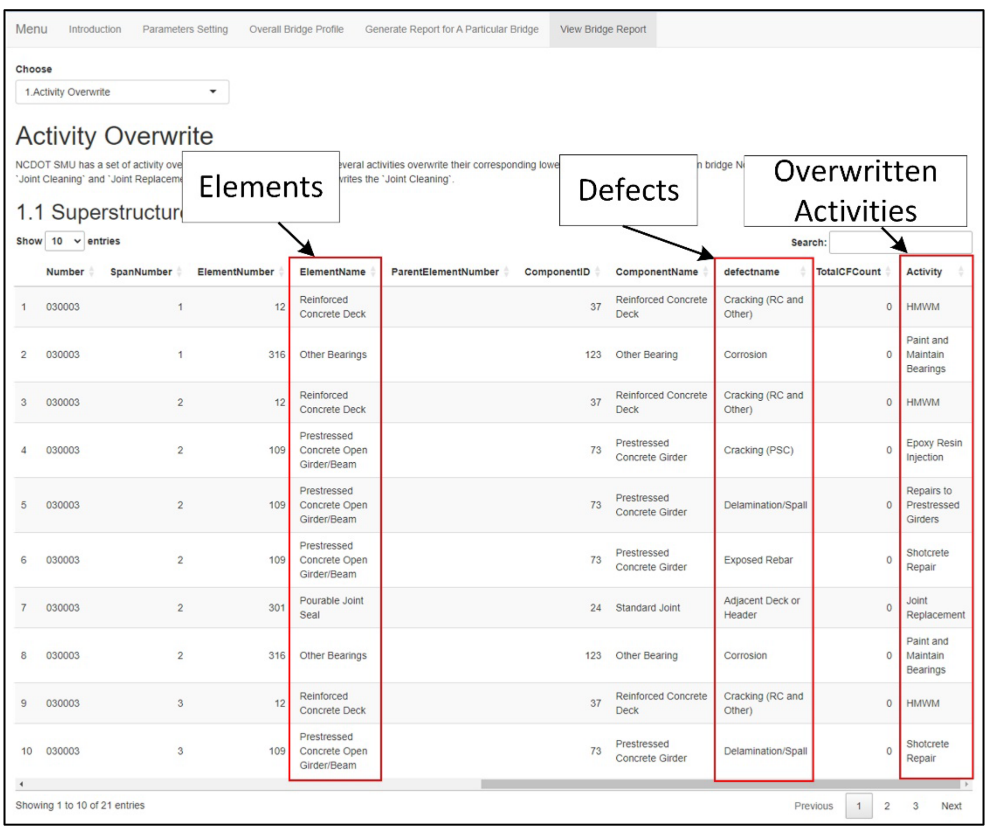
*2.5 View Bridge Report*

As shown in Figure A34, the generated bridge report consists of five sections. Users can view each section by selecting different options from the dropdown menu. Below is an example of the preservation report of bridge 030003.


Figure A34 Choosing Different Sections of the Report

2.5.1 Activity Overwrite

The Activity Overwrite page contains two tables displaying the preservation activities for the superstructure and substructure of the bridge after overwriting. The algorithms for triggering and overwriting preservation activities are detailed in Chapter 4. Figure A35 and Figure A36 show the UI displaying the preservation activities for the superstructure and substructure of bridge 030003, respectively. These tables provide detailed records of the defects on each element of the bridge and the necessary preservation activities after overwriting.




| | Number | SpanNumber | ElementNumber | ElementName | ParentElementNumber | ComponentID | ComponentName | defectname | TotalCFCount | Activity |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 030003 | 1 | 12 | Reinforced Concrete Deck | | 37 | Reinforced Concrete Deck | Cracking (RC and Other) | 0 | HMWM |
| 2 | 030003 | 1 | 316 | Other Bearings | | 123 | Other Bearing | Corrosion | 0 | Paint and Maintain Bearings |
| 3 | 030003 | 2 | 12 | Reinforced Concrete Deck | | 37 | Reinforced Concrete Deck | Cracking (RC and Other) | 0 | HMWM |
| 4 | 030003 | 2 | 109 | Prestressed Concrete Open Girder/Beam | | 73 | Prestressed Concrete Girder | Cracking (PSC) | 0 | Epoxy Resin Injection |
| 5 | 030003 | 2 | 109 | Prestressed Concrete Open Girder/Beam | | 73 | Prestressed Concrete Girder | Delamination/Spall | 0 | Repairs to Prestressed Girders |
| 6 | 030003 | 2 | 109 | Prestressed Concrete Open Girder/Beam | | 73 | Prestressed Concrete Girder | Exposed Rebar | 0 | Shotcrete Repair |
| 7 | 030003 | 2 | 301 | Pourable Joint Seal | | 24 | Standard Joint | Adjacent Deck or Header | 0 | Joint Replacement |
| 8 | 030003 | 2 | 316 | Other Bearings | | 123 | Other Bearing | Corrosion | 0 | Paint and Maintain Bearings |
| 9 | 030003 | 3 | 12 | Reinforced Concrete Deck | | 37 | Reinforced Concrete Deck | Cracking (RC and Other) | 0 | HMWM |
| 10 | 030003 | 3 | 109 | Prestressed Concrete Open Girder/Beam | | 73 | Prestressed Concrete Girder | Delamination/Spall | 0 | Shotcrete Repair |

Figure A35 Superstructure Overwritten Activity Table for Bridge 030003


1.2 Substructure

Show 10 entries

Search:

| | Number | bentname | ElementNumber | ElementName | ParentElementNumber | ComponentID | ComponentName | defectname | TotalCFCount | Activity |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 030003 | Bent 1 | 234 | Reinforced Concrete Pier Cap | | 66 | Reinforced Concrete Pier Cap | Cracking (RC and Other) | 0 | Epoxy Resin Injection |
| 2 | 030003 | Bent 2 | 205 | Reinforced Concrete Column | | 47 | Reinforced Concrete Column | Delamination/Spall | | Shotcrete Repair |
| 3 | 030003 | Bent 2 | 205 | Reinforced Concrete Column | | 47 | Reinforced Concrete Column | Exposed Rebar | | Shotcrete Repair |
| 4 | 030003 | Bent 2 | 234 | Reinforced Concrete Pier Cap | | 66 | Reinforced Concrete Pier Cap | Exposed Rebar | 0 | Concrete Repair |
| 5 | 030003 | Bent 3 | 205 | Reinforced Concrete Column | | 47 | Reinforced Concrete Column | Delamination/Spall | | Shotcrete Repair |
| 6 | 030003 | Bent 3 | 205 | Reinforced Concrete Column | | 47 | Reinforced Concrete Column | Exposed Rebar | | Shotcrete Repair |
| 7 | 030003 | Bent 3 | 234 | Reinforced Concrete Pier Cap | | 66 | Reinforced Concrete Pier Cap | Delamination/Spall | 0 | Concrete Repair |
| 8 | 030003 | Bent 4 | 205 | Reinforced Concrete Column | | 47 | Reinforced Concrete Column | Delamination/Spall | 0 | Shotcrete Repair |
| 9 | 030003 | Bent 4 | 205 | Reinforced Concrete Column | | 47 | Reinforced Concrete Column | Exposed Rebar | 0 | Shotcrete Repair |
| 10 | 030003 | Bent 4 | 234 | Reinforced Concrete Pier Cap | | 66 | Reinforced Concrete Pier Cap | Delamination/Spall | 0 | Concrete Repair |

Showing 1 to 10 of 15 entries

Previous 1 2 Next

Figure A36 Substructure Overwritten Activity Table for Bridge 030003

### 2.5.2 Bridge Preservation Summary

The Bridge Preservation Summary page includes four bar charts summarizing the defects and preservation activities for the bridge's superstructure and substructure.

Figure A37 shows the counts of defects and the required preservation activities for the superstructure of bridge 030003. The bar charts are arranged in ascending order of counts from top to bottom. These bar charts help users quickly understand the defects of the bridge and the number of required preservation activities. Figure A38 displays the counts of defects and the required preservation activities for the substructure.

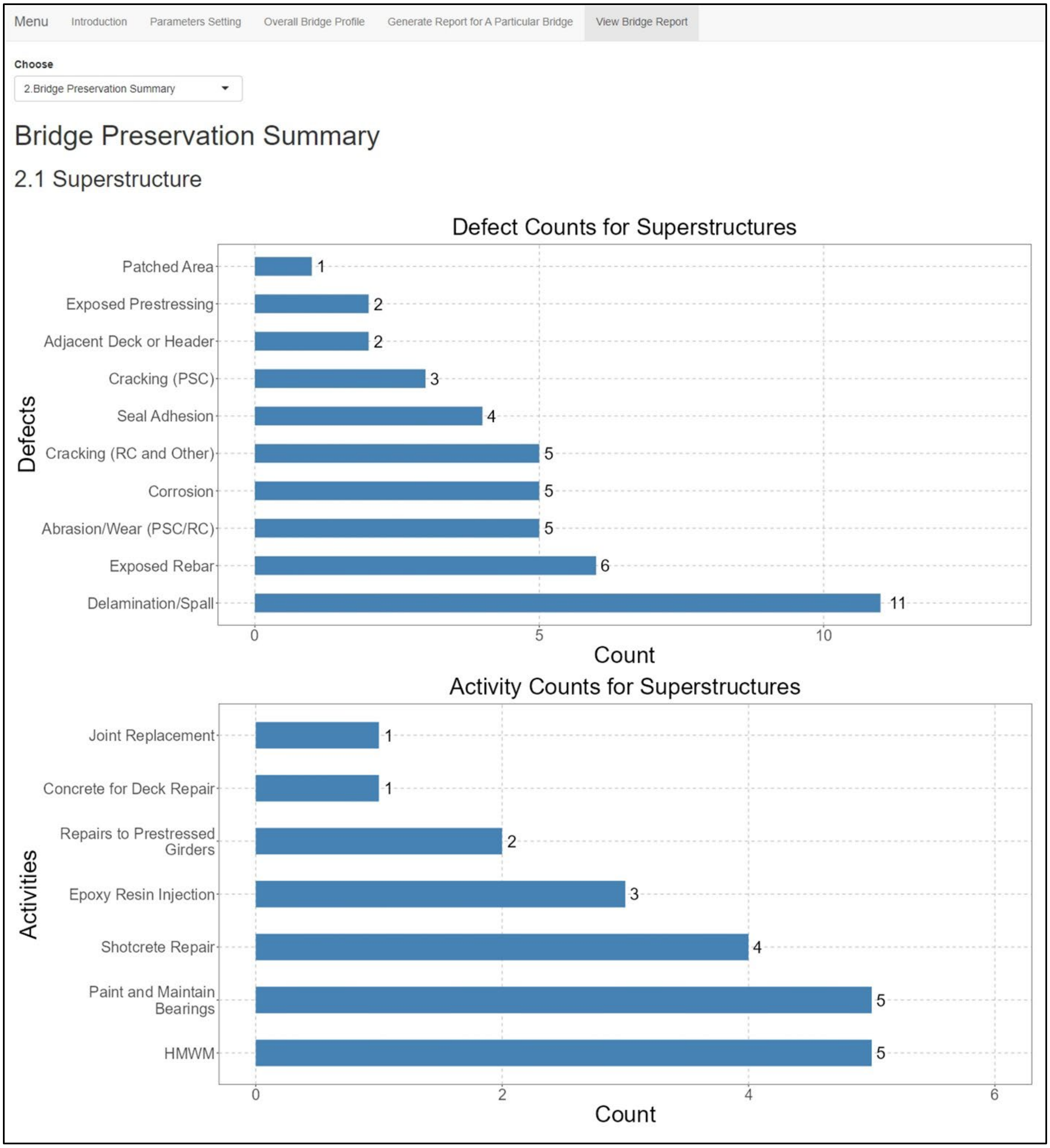



Figure A37 Superstructure Defects and Preservation Activity Counts for Bridge 030003

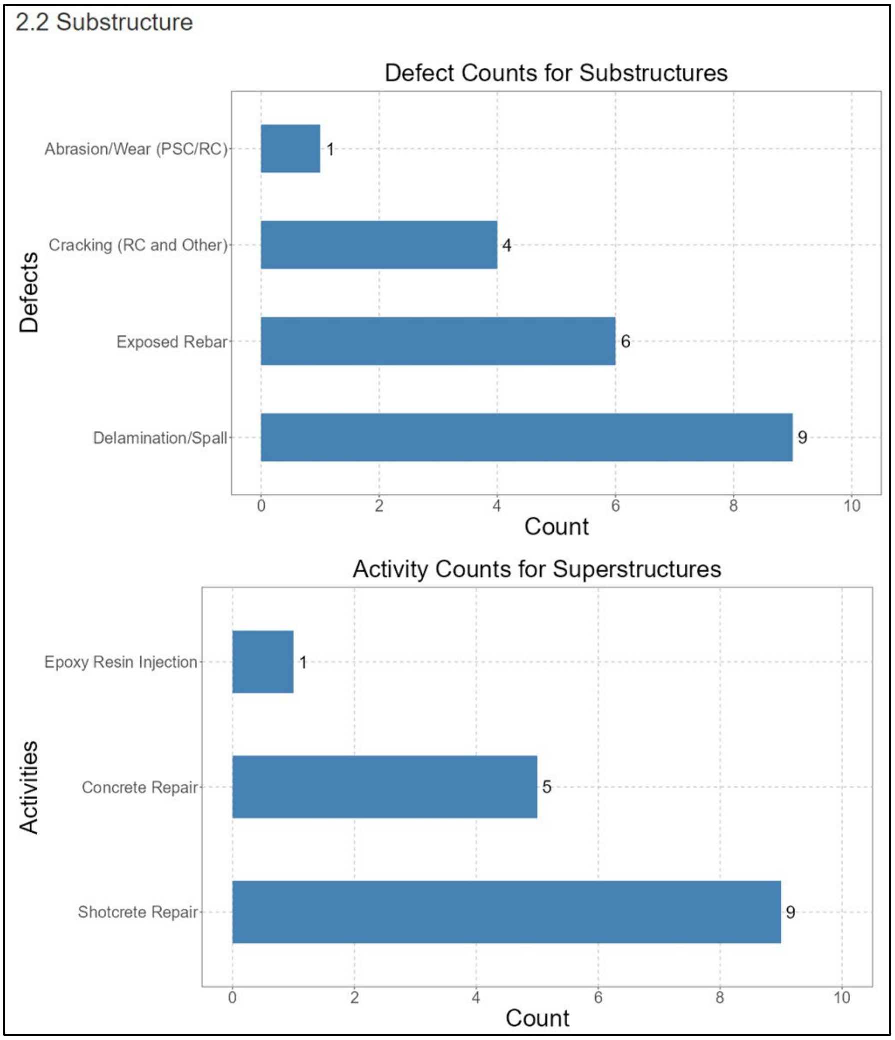



Figure A38 Substructure Defects and Preservation Activity Counts for Bridge 030003

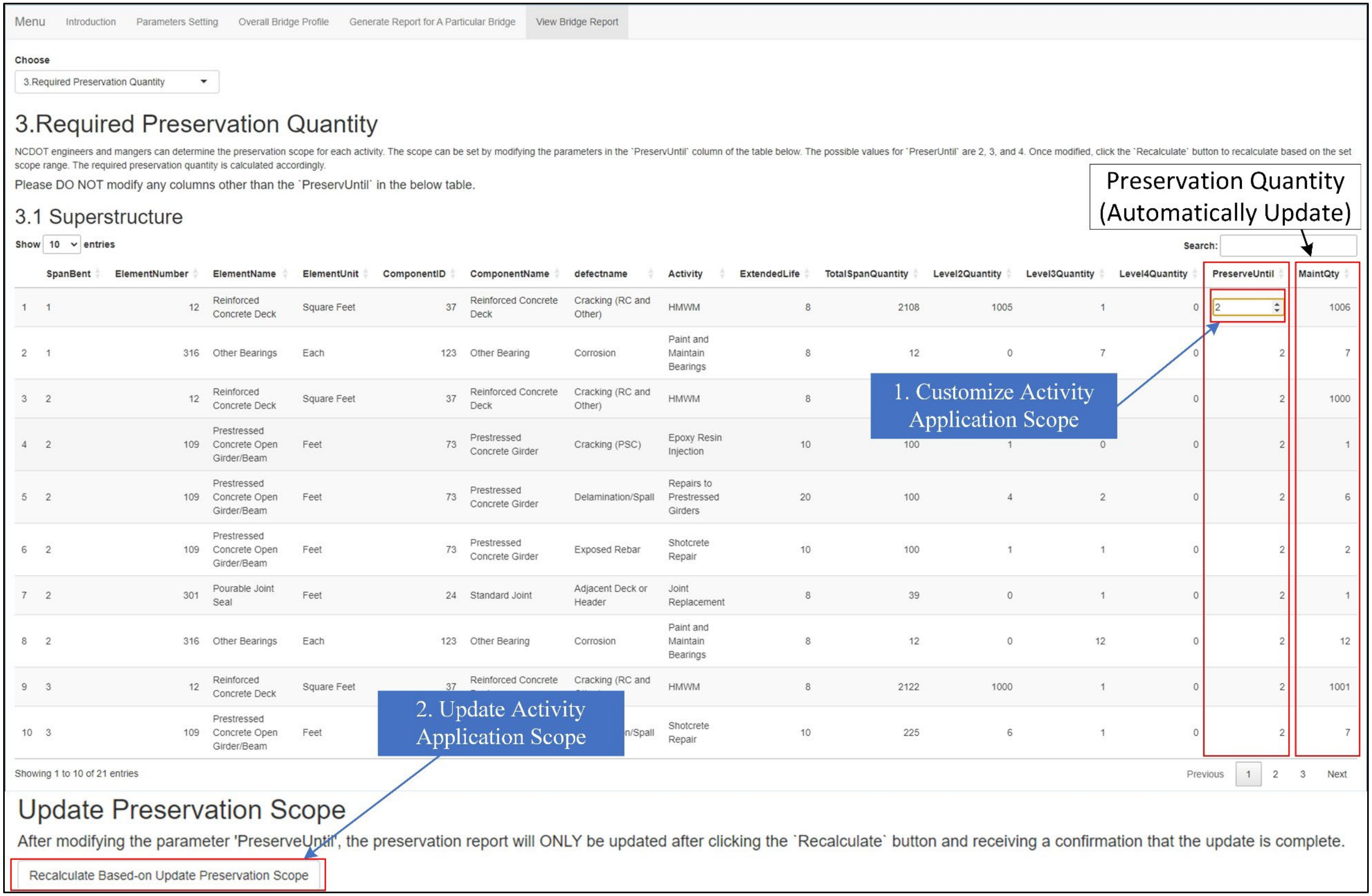
2.5.3 Required Preservation Quantity

The Required Preservation Quantity page includes two tables, displaying the required preservation activities quantity for each element on the superstructure and substructure. Figure A39 shows the activity application scope and preservation quantity for the superstructure of bridge 030003. The activity application scope determines which CS level of an element requires a specific preservation activity. It is a key factor in calculating the preservation quantity. For example, if the activity scope is set to CS 2, as shown in the first row of Figure A39, the HMWM activity will apply to defects at or above CS 2 (i.e., CS 2, CS 3, and CS 4). The total preservation quantity (1006) is the sum of the quantities for CS 2 (1005), CS 3 (1), and CS 4 (0). The definition of activity application scope can be found in Section 5.1.1, and the definition of preservation quantity is detailed in Section 5.3.

In this table, all activity application scopes are set to the default value of 2. Users can customize the activity application scope by modifying the values in the "PreserveUntil" column. The activity application scope has three options: 2, 3, and 4. After modifying the activity application scope, the preservation quantity in the table will automatically update. For example, in the first row of the table in Figure A39, span 1's reinforced concrete deck requires HMWM. The activity application scope is set to 2, corresponding to a preservation quantity of 1006. If the user changes the application scope to 3, the corresponding preservation quantity in the table will automatically update to 1.

The preservation quantity affects the bridge preservation costs. If users need to obtain the preservation costs based on the updated activity application scope, they must click the "Recalculate Based on Updated Preservation Scope" button at the bottom left. After clicking, the BGP app will regenerate the report based on the updated activity application scope.

.



Menu | Introduction | Parameters Setting | Overall Bridge Profile | Generate Report for A Particular Bridge | View Bridge Report

**Choose**

3.Required Preservation Quantity

## 3.Required Preservation Quantity

NCDOT engineers and mangers can determine the preservation scope for each activity. The scope can be set by modifying the parameters in the `PreservUntil` column of the table below. The possible values for `PreserUntil` are 2, 3, and 4. Once modified, click the `Recalculate` button to recalculate based on the set scope range. The required preservation quantity is calculated accordingly.

Please DO NOT modify any columns other than the `PreservUntil` in the below table.

### 3.1 Superstructure

Show 10 entries Search:

| | SpanBent | ElementNumber | ElementName | ElementUnit | ComponentID | ComponentName | defectname | Activity | ExtendedLife | TotalSpanQuantity | Level2Quantity | Level3Quantity | Level4Quantity | PreserveUntil | MaintQty |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 12 | Reinforced Concrete Deck | Square Feet | 37 | Reinforced Concrete Deck | Cracking (RC and Other) | HMWM | 8 | 2108 | 1005 | 1 | 0 | 2 | 1006 |
| 2 | 1 | 316 | Other Bearings | Each | 123 | Other Bearing | Corrosion | Paint and Maintain Bearings | 8 | 12 | 0 | 7 | 0 | 2 | 7 |
| 3 | 2 | 12 | Reinforced Concrete Deck | Square Feet | 37 | Reinforced Concrete Deck | Cracking (RC and Other) | HMWM | 8 | [illegible] | [illegible] | [illegible] | 0 | 2 | 1000 |
| 4 | 2 | 109 | Prestressed Concrete Open Girder/Beam | Feet | 73 | Prestressed Concrete Girder | Cracking (PSC) | Epoxy Resin Injection | 10 | 100 | 1 | 0 | 0 | 2 | 1 |
| 5 | 2 | 109 | Prestressed Concrete Open Girder/Beam | Feet | 73 | Prestressed Concrete Girder | Delamination/Spall | Repairs to Prestressed Girders | 20 | 100 | 4 | 2 | 0 | 2 | 6 |
| 6 | 2 | 109 | Prestressed Concrete Open Girder/Beam | Feet | 73 | Prestressed Concrete Girder | Exposed Rebar | Shotcrete Repair | 10 | 100 | 1 | 1 | 0 | 2 | 2 |
| 7 | 2 | 301 | Pourable Joint Seal | Feet | 24 | Standard Joint | Adjacent Deck or Header | Joint Replacement | 8 | 39 | 0 | 1 | 0 | 2 | 1 |
| 8 | 2 | 316 | Other Bearings | Each | 123 | Other Bearing | Corrosion | Paint and Maintain Bearings | 8 | 12 | 0 | 12 | 0 | 2 | 12 |
| 9 | 3 | 12 | Reinforced Concrete Deck | Square Feet | 37 | Reinforced Concrete [illegible] | Cracking (RC and [illegible] | HMWM | 8 | 2122 | 1000 | 1 | 0 | 2 | 1001 |
| 10 | 3 | 109 | Prestressed Concrete Open Girder/Beam | Feet | [illegible] | [illegible] | [illegible]n/Spall | Shotcrete Repair | 10 | 225 | 6 | 1 | 0 | 2 | 7 |

Showing 1 to 10 of 21 entries Previous 1 2 3 Next

## Update Preservation Scope

After modifying the parameter 'PreserveUntil', the preservation report will ONLY be updated after clicking the `Recalculate` button and receiving a confirmation that the update is complete.

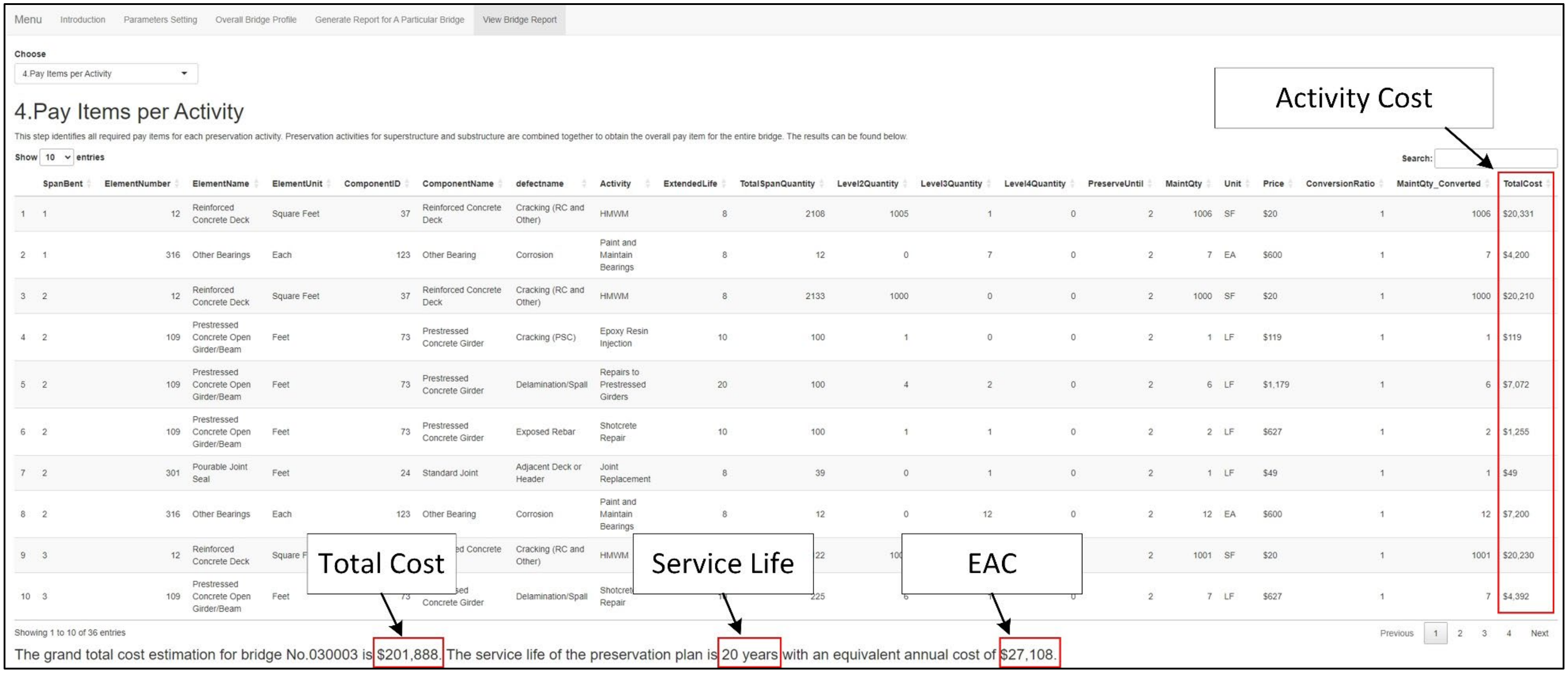
Recalculate Based-on Update Preservation Scope



Figure A39 Bridge 030003 Superstructure Required Preservation Quantity and Customization

### 2.5.4 Pay Items per Activity

The Pay Items per Activity page displays information related to bridge preservation costs. Figure A40 shows the pay items per activity list for bridge 030003. The rightmost column of the table lists the costs of various preservation activities for the elements of the bridge. At the bottom of the table, a summary is provided, which includes the total cost, service life, and EAC of the bridge. The algorithms for these calculations can be found in Chapter 5.




| | SpanBent | ElementNumber | ElementName | ElementUnit | ComponentID | ComponentName | defectname | Activity | ExtendedLife | TotalSpanQuantity | Level2Quantity | Level3Quantity | Level4Quantity | PreserveUntil | MaintQty | Unit | Price | ConversionRatio | MaintQty_Converted | TotalCost |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 12 | Reinforced Concrete Deck | Square Feet | 37 | Reinforced Concrete Deck | Cracking (RC and Other) | HMWM | 8 | 2108 | 1005 | 1 | 0 | 2 | 1006 | SF | $20 | 1 | 1006 | $20,331 |
| 2 | 1 | 316 | Other Bearings | Each | 123 | Other Bearing | Corrosion | Paint and Maintain Bearings | 8 | 12 | 0 | 7 | 0 | 2 | 7 | EA | $600 | 1 | 7 | $4,200 |
| 3 | 2 | 12 | Reinforced Concrete Deck | Square Feet | 37 | Reinforced Concrete Deck | Cracking (RC and Other) | HMWM | 8 | 2133 | 1000 | 0 | 0 | 2 | 1000 | SF | $20 | 1 | 1000 | $20,210 |
| 4 | 2 | 109 | Prestressed Concrete Open Girder/Beam | Feet | 73 | Prestressed Concrete Girder | Cracking (PSC) | Epoxy Resin Injection | 10 | 100 | 1 | 0 | 0 | 2 | 1 | LF | $119 | 1 | 1 | $119 |
| 5 | 2 | 109 | Prestressed Concrete Open Girder/Beam | Feet | 73 | Prestressed Concrete Girder | Delamination/Spall | Repairs to Prestressed Girders | 20 | 100 | 4 | 2 | 0 | 2 | 6 | LF | $1,179 | 1 | 6 | $7,072 |
| 6 | 2 | 109 | Prestressed Concrete Open Girder/Beam | Feet | 73 | Prestressed Concrete Girder | Exposed Rebar | Shotcrete Repair | 10 | 100 | 1 | 1 | 0 | 2 | 2 | LF | $627 | 1 | 2 | $1,255 |
| 7 | 2 | 301 | Pourable Joint Seal | Feet | 24 | Standard Joint | Adjacent Deck or Header | Joint Replacement | 8 | 39 | 0 | 1 | 0 | 2 | 1 | LF | $49 | 1 | 1 | $49 |
| 8 | 2 | 316 | Other Bearings | Each | 123 | Other Bearing | Corrosion | Paint and Maintain Bearings | 8 | 12 | 0 | 12 | 0 | 2 | 12 | EA | $600 | 1 | 12 | $7,200 |
| 9 | 3 | 12 | Reinforced Concrete Deck | Square F | [illegible] | ...ed Concrete | Cracking (RC and Other) | HMWM | [illegible] | 22 | 10 | [illegible] | [illegible] | 2 | 1001 | SF | $20 | 1 | 1001 | $20,230 |
| 10 | 3 | 109 | Prestressed Concrete Open Girder/Beam | Feet | 73 | ...sed Concrete Girder | Delamination/Spall | Shotcret Repair | 1 | 225 | 6 | 1 | 0 | 2 | 7 | LF | $627 | 1 | 7 | $4,392 |

Figure A40 Pay Items per Activity List and Conclusion for Bridge 030003

2.5.5 Cost Estimation Summary

The Cost Estimation Summary includes two tables that categorize and summarize the total cost by preservation activity and element. Figure A41 shows the cost estimation summary for bridge 030003. The costs are displayed in ascending order from top to bottom.

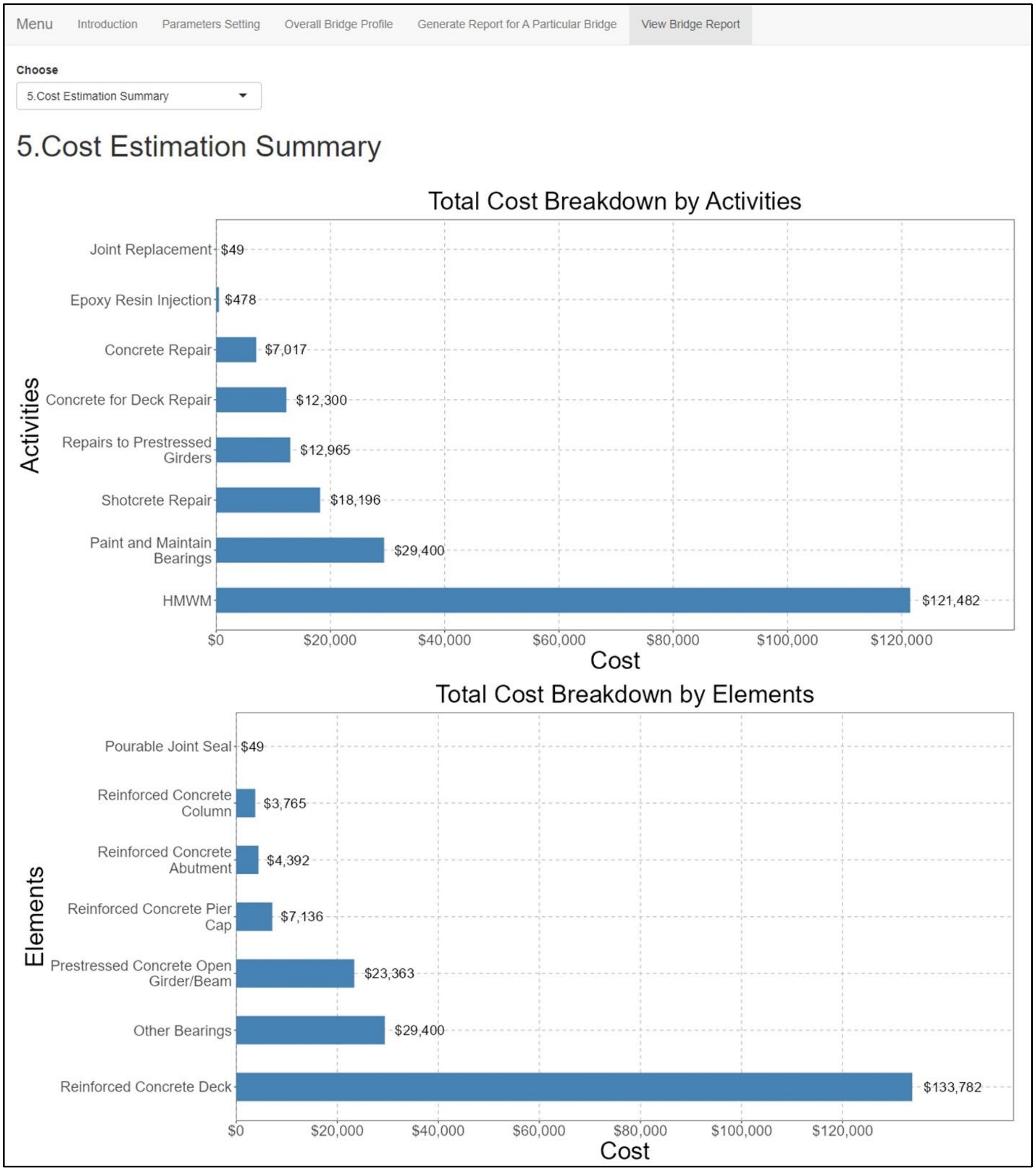



Figure A41 Cost Estimation Summary for Bridge 030003

## REFERENCES


AASHTO (American Association of State Highway and Transportation Officials). 2007. *Maintenance Manual for Roadways and Bridges*. Washington, DC: American Association of State Highway and Transportation Officials.

AASHTO (American Association of State Highway and Transportation Officials). 2010a. *AASHTON LRFD Bridge Deisgn Specifications (Fifth Edition)*. Washington D.C: American Association of State Highway and Transportation Officials.

AASHTO (American Association of State Highway and Transportation Officials). 2010b. *AASHTO Bridge Element Inspection Guide Manual*.

AASHTO (American Association of State Highway and Transportation Officials). 2019. *Manual for Bridge Element Inspection*. AASHTO (American Association of State Highway and Transportation Officials).

ADOT (Arizona Department of Transportation). 2016. *Bridge group bridge preservation program*. Arizona Department of Transportation.

AKDOT (Alaska Department of Transportation). 2017. *Bridge Inspection Program*.

ALDOT (Alabama Department of Transportation). 2017. *Bridge inspection manual*.

ARDOT (Arkansas Department of Transportation). 2020. *Bridge Inspection Manual*.

ARTBA (American Road and Transportation Builders Association). 2023a. "Bridge Report." Accessed September 7, 2023. https://artbabridgereport.org/state/map.

ARTBA (American Road and Transportation Builders Association). 2023b. *Bridge Report*.

ASCE (American Society of Civil Engineers). 2021. *Bridge Infrastructure Report Card*. Reston, VA.

Brown, M., and A. Ahmad. 2006. *Virginia's Planned Preventive Maintenance Initiative*.

Cady, P. D. 1994. *Sealers for Portland cement concrete highway facilities*.

Caltrans (California Department of Transportation). 2014. *Chapter H - Bridges*.

Cavalline, T. L., M. J. Whelan, B. Q. Tempest, R. Goyal, and J. D. Ramsey. 2015. *Determination of Bridge Deterioration Models and Bridge User Costs for the NCDOT Bridge Management System*.

CDOT (Colorado Department of Transportation). 2015. *Region 1 major structure asset management list*. Colorado Department of Transportation.

Contreras-Nieto, C., Y. Shan, P. Lewis, and J. A. Hartell. 2019. "Bridge maintenance prioritization using analytic hierarchy process and fusion tables." *Autom. Constr.*, 101 (November 2018): 99–110. Elsevier. https://doi.org/10.1016/j.autcon.2019.01.016.

CTDOT (Connecticut Department of Transportation). 2011. *Items for Inclusion in the Connecticut Department of Transportation's Bridge Preventive Maintenance Program*.

DelDOT (Delaware Department of Transportation). 2012. *Road system bridges*. Delware Department of Transportation.

Esri. 2022. "What is GIS?" https://www.esri.com/en-us/what-is-gis/overview#

FDOT (Florida Department of Transportation). 2018. *Bridge Maintenance Course Series - Reference Manual*.

FHWA (Federal Highway Administration). 1995. *Recording and coding guide for the structure inventory and appraisal of the nation's bridges*. Washington DC.

FHWA (Federal Highway Administration). 2011. *Bridge Preservation Guide*.

FHWA (Federal Highway Administration). 2013. *Bridge management practices in Idaho, Michigan and Virginia*. U.S. Department of Transportation Federal Highway Administration.

FHWA (Federal Highway Administration). 2014. *Specification for the national bridge inventory bridge elements*.
FHWA (Federal Highway Administration). 2016. *Synthesis of National and International Methodologies Used for Bridge Health Indices Magnetic Flux Leakage Inspection of perstressed concrete View project Bridges View project*.
FHWA (Federal Highway Administration). 2018. *Bridge Preservation Guide Maintaining a Resilient Infrastructure to Preserve Mobility Quality Assurance Statement*. Washington, DC.
FHWA (Federal Highway Administration). 2019. "Connection Details for PBES."
GDOT (Georgia Department of Transportation). 2013. *Bridge Structures Maintenance Program*.
Hafezzadeh, R., F. Autelitano, and F. Giuliani. 2021. "Asphalt-based cold patches for repairing road potholes – An overview." *Constr. Build. Mater.*, 306: 124870. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2021.124870.
Harries, K. A., J. Kasan, and J. Aktas. 2009. *Repair methods for prestressed girder bridges.* Pennsylvania. Dept. of Transportation.
HDOT (Hawaii Department of Transportation). 2017. *Bridge Inspection Manual*.
Hearn, G. 2020. *Proposed AASHTO Guides for Bridge Preservation Actions*. Washington DC.
Hopwood II, T., S. Palle, B. Meade, R. Younce, D. Wells, and C. Goff. 2018. *Spot Painting to Extend Highway Bridge Coating Life: Volume 1: Guidance*.
IADOT (Iowa Department of Transportation). 2014. *Bridge Element Inspection Guide*.
IDOT (Illinois Department of Transportation). 2019. *Bridge preservation guide*. Illinois Department of Transportation.
INDOT (Indiana Department of Transportation). 2010. *Indiana Historic Bridge Inventory*.
INDOT (Indiana Department of Transportation). 2013. *CHAPTER 412 Bridge Preservation*.
ITD (Idaho Department of Transportation). 2022. *Operations Manual*.
Khaleghi, B. 2014. *Washington State Bridge Preservation and Asset Management*. Washington State Department of Transportation.
KSDOT (Kansas Department of Transportation). 2022. *Kansas Local Bridge Improvement Program Program Guidelines 2024*.
LaDOTD (Louisiana Department of Transportation). 2020. *Bridge Inspection Manual*.
Lin, W., and T. Yoda. 2017. "Steel Bridges." *Bridg. Eng.*, 111–136. https://doi.org/10.1016/b978-0-12-804432-2.00007-4.
Liu, H., D. Wu, and J. Zhao. 2018. *Towards an Open-Source Web GIS-based Bridge Management System using Advanced Geo-Spatial Data Visualization and Integration Technologies*. Norman, Oklahoma.
Lu, P. 2018. *Iowa DOT Bridge Preservation Manual*.
MassDOT (Massachusetts Department of Transportation). 2019. *Bridge Inspection Handbook*.
MDDOT (Maryland Department of Transportation). 2012. *Bridge Management System*.
MDOT (Michigan Department of Transportation). 2005. *Bridge Capital Scheduled Maintenance Manual*.
MDT (Montana Department of Transportation). 2002. *MDT Maintenance Environmental Best Management Practices*.
MDT (Montana Department of Transportation). 2019. *Transportation asset management plan*. Montana Department of Transportation.
MEDOT (Maine Department of Transportation). 2011. *Bridge Preservation Guide*.
MnDOT (Minnesota Department of Transportation). 2016. *Bridge Inspection Field Manual*.

MnDOT (Minnesota Department of Transportation). 2019. *Bridge Preservation Resources for Local Agencies*.
Moon, F. L., J. Laning, D. S. Lowdermilk, S. Chase, J. Hooks, and A. E. Aktan. 2009. "A pragmatic risk-based approach to prioritizing bridges." *Nondestruct. Charact. Compos. Mater. Aerosp. Eng. Civ. Infrastructure, Homel. Secur.* San Diego, CA.
MSDOT (Mississippi Department of Transportation). 2012. *Bridge Safety Inspection Policy and Procedure Manual*.
NCDOT (North Carolina Department of Transportation). 2019a. *North Carolina Department of Transportation Transportation Asset Management Plan 2019 Final Report*.
NCDOT (North Carolina Department of Transportation). 2019b. "Prioritization 6.0 Scoring Criteria, Weights, and Normalization for All Modes (with Criteria Definitions)."
NCDOT (North Carolina Department of Transportation). 2020a. "Evolution of Bridge Technology."
NCDOT (North Carolina Department of Transportation). 2020b. "Steel Stringer/Multi Beam Bridges."
NCDOT (North Carolina Department of Transportation). 2020c. "Timber Stringer Bridges."
NCDOT (North Carolina Department of Transportation). 2024a. "North Carolina Bridge Information." Accessed June 10, 2024. https://www.ncdot.gov/initiatives-policies/Transportation/bridges/Pages/default.aspx.
NCDOT (North Carolina Department of Transportation). 2024b. "2023 NCDOT Annual Performance Report." Accessed June 10, 2024. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.ncdot.gov/about-us/our-mission/Documents/2023-interactive-annual-report.pdf.
NDDOT (North Dakota Department of Transportation). 2021. *Bridge Preservation for Local Agencies*.
NEDOT (Nebraska Department of Transportation). 2010. *Bridge Inspection Program*.
NHDOT (New Hampshire Department of Transportation). 2015. *NHDOT Bridge Strategy - Definitions*.
NHDOT (New Hampshire Department of Transportation). 2019. *NHDOT GIS Data Catalog Map Metadata*.
Nicholas, D. C., T. Dudley, W. Head, S. Bert, N. D. Norboge, G. List, and D. Findley. 2022. "Identifying and prioritizing bridges critical to commerce: A case study of weight-restricted bridges in North Carolina." *Int. J. Transp. Sci. Technol.*, 11 (3): 455–467. Tongji University and Tongji University Press. https://doi.org/10.1016/j.ijtst.2021.06.001.
NJDOT (New Jersey Department of Transportation). 2014. *Bridge Element Inspection Manual*.
NVDOT (Nevada Department of Transportation). 2021. *2021 Nevada State Preservation Report*.
NYSDOT (New York Department of Transportation). 2008a. *Fundamentals of Bridge Maintenance and Inspection*.
NYSDOT (New York Department of Transportation). 2008b. *Section 6 Bridge Railing Railing and Barrier Design for New and Replacement Bridges Service Levels Railing / Barrier Design Alternatives*.
NYSDOT (New York Department of Transportation). 2017. *Bridge Inspection Manual*.
OHDOT (Ohio Department of Transportation). 2010. *Ohio Historic Bridge Maintenance & Preservation Guidance*.
OHDOT (Ohio Department of Transportation). 2022. *Roadway Infrastructure Maintenance Responsibility Manual*.

ORDOT (Oregon Department of Transportation). 2021a. *2019-2021 Legislatively Adopted Program Budget*.
ORDOT (Oregon Department of Transportation). 2021b. *Bridge Condition Report & Tunnel Data*.
PennDOT (Pennsylvania Department of Transportation). 2012. *Bridge Maintenance Manual*.
PennDOT (Pennsylvania Department of Transportation). 2022. *Bridge Safety Inspection Manual*.
RIDOT (Rhode Island Department of Transportation). 2016. *Bridge Inspection Manual*.
SCDOT (South Carolina Department of Transportation). 2020. *Bridge Inspection Guidance Document*.
Shanafelt, G. 0., and W. B. Horn. 1980. *Damage Evaluation and Repair Methods for Prestressed Concrete Bridge Members*. Washington DC.
She, T. H., G. Aouad, and M. Sarshar. 1999. "A geographic information system (GIS)-based bridge management system." *Comput. Civ. Infrastruct. Eng.*, 14 (6): 417–427. https://doi.org/10.1111/0885-9507.00160.
TDOT (Tennessee Department of Transportation). 2019. *Transportation Asset Management Plan*.
Thompson, T. S. 2006. *South Dakota Department of Transportation Bridge Management System Implementation*.
TxDOT (Texas Department of Transportation). 2005. *Maintenance Operations Manual*.
TxDOT (Texas Department of Transportation). 2022. *Bridge Inspection Manual*.
UDOT (Utah Department of Transportation). 2017. *Bridge Management Manual*.
United States Department of Transportation (USDOT). 2016. *The Value of Travel Time Savings: Departmental Guidance for Conducting Economic Evaluations Revision 2 (2016 Update)*.
VDOT (Virginia Department of Transportation). 2022. *Bridge Inspection Definitions*.
VTrans (Vermont Department of Transportation). 2020. *Bridge Preservation and Preventive Maintenance 2020 Program*.
Washer, G., M. Hammed, and H. Brown. 2017. *Bridge Maintenance Program for the City of Columbia, Missouri*.
Whelan, M., T. Cavalline, K. Lane, and F. Street. 2019. *Guidelines for Prioritization of Bridge Replacement , Rehabilitation , and Preservation Projects*.
WIDOT (Wisconsin Department of Transportation). 2016. *Bridge Preservation Policy Guide*.
WVDOT (West Virginia Department of Transportation). 2012. *GIS Enhancement Project & Project Prioritization Process presented*.
WYDOT (Wyoming Department of Transportation). 2018. *Chapter 4 Bridge Program Drawings*.
Żemajtis, J., and R. E. Weyers. 1996. "Concrete bridge service life extension using sealers in chloride-laden environments." *Transp. Res. Rec.*, 1561 (1): 1–5. SAGE Publications Sage CA: Los Angeles, CA.