DEVELOPMENT AND USE OF A GIS DATABASE FOR THE EVALUATION OF UNCOATED WEATHERING STEEL HIGHWAY BRIDGE PERFORMANCE

by

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A thesis submitted to the Faculty of the University of Delaware in partial fulfillment of the requirements for the degree of Master of Civil Engineering

Spring 2014

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HIGHWAY BRIDGE PERFORMANCE

by

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TABLE OF CONTENTS

LIST OF TABLES ix
LIST OF FIGURES xii
ABSTRACT xiv

Chapter

1 INTRODUCTION 1

1.1 Motivation 1
1.2 Objectives, Scope, and Thesis Organization 2

2 GIS DATABASE OF UNCOATED WEATHERING STEEL BRIDGES 4

2.1 Building the GIS Database 4

2.1.1 Data Types 5

2.1.1.1 National Bridge Inventory Data 6

2.1.1.1.1 Identifying UWS Bridges 7
2.1.1.1.2 Accessing Raw NBI Data 7
2.1.1.1.3 Formatting NBI Files for Importing into GIS 8
2.1.1.1.4 Identifying and Synthesizing NBI Data of Interest 9

2.1.1.1.4.1 Record Type (Item 5A) 9
2.1.1.1.4.2 Latitude and Longitude (Item 16 and 17) 10
2.1.1.1.4.3 Year Built and Year Reconstructed (Item 27 and Item 106) 11
2.1.1.1.4.4 ADT Under the Structure (Items 5A and 29) 12
2.1.1.1.4.5 Service Under the Bridge (Item 42B) 13

2.1.1.1.4.6 Vertical Under-Clearance (Item 54B) and Navigational Vertical Clearance (Item 39) . 14
2.1.1.1.4.7 Minimum Lateral Under-Clearance on Right/Left (Item 55 and 56) 15
2.1.1.1.4.8 Superstructure Rating (Item 59)..... 16

2.1.1.2 Chemical Concentration Data..... 17
2.1.1.3 Climatic Data..... 18

2.1.1.3.1 Snowfall..... 18
2.1.1.3.2 Humidity..... 20
2.1.1.3.3 Time of Wetness..... 23
2.1.1.3.4 Other Unused Data 24

2.1.1.3.4.1 Temperature..... 26
2.1.1.3.4.2 Fog and Precipitation..... 28

2.1.1.4 Geographic Data: Distance to Coast..... 31

2.1.1.4.1 Extracted Vector Shoreline (EVS) 32
2.1.1.4.2 Electronic Navigational Chart (ENC) 32

2.1.2 Associating NBI and Environmental Data 36

2.1.2.1 Coordinate Systems- WGS 1984 and NAD 1983 HARN..... 37
2.1.2.2 GIS Data Types- Geospatial Data 38
2.1.2.3 GIS Data Association Methods 39

2.1.2.3.1 Project Management Tool 40
2.1.2.3.2 Spatial Join Tool..... 40
2.1.2.3.3 Buffer Tool 41
2.1.2.3.4 Near Tool..... 42

2.2 Use of GIS Database to Form Clusters/ Compile Local Statistics 43

2.2.1 State Boundary Analysis 43

2.2.1.1 New York 44
2.2.1.2 Louisiana 44

2.2.2 Radius from a Reference Point Analysis 46

3 SELECTION OF BRIDGES FOR STUDY 49

3.1 Methodology 49

3.1.1 Reference Bridges 50

3.1.1.1 State-Recommended Reference Bridges 51

3.1.1.1.1 Survey of Bridge Owners 51
3.1.1.1.2 Other Considerations 54

3.1.1.2 Filtering by Parameters of Interest 55

3.1.1.2.1 Geographical Considerations 56
3.1.1.2.2 Performance Considerations 56

3.1.2 Proximate Bridges 57
3.1.3 Cluster Bridges 57

3.1.3.1 Statistical Analysis 57
3.1.3.2 Bridge Categorization Based on Parametric Combinations 59
3.1.3.3 Selected Categories from Parametric Combinations 62
3.1.3.4 Selecting Specific Cluster Bridges 63

3.1.4 Field Bridges 65

3.2 Examples 66

3.2.1 Phase II 67

3.2.1.1 Good Deicing (New York) 67

3.2.1.1.1 Reference Bridge Selection 72
3.2.1.1.2 Proximate Bridge Selection 73
3.2.1.1.3 Cluster Bridge Selection 74
3.2.1.1.4 Field Bridge Selection 79

3.2.1.2 Inferior Deicing (Maryland) 81

3.2.1.2.1 Reference Bridge Selection 82
3.2.1.2.2 Proximate Bridge Selection 84
3.2.1.2.3 Cluster Bridge Selection 86

3.2.1.2.4 Field Bridge Selection 89

3.2.1.3 Good Coastal (Texas) 92

3.2.1.3.1 Proximate Bridge Selection 92
3.2.1.3.2 Cluster Bridge Selection 95
3.2.1.3.3 Reference and Field Bridge Selection 100

3.2.2 Phase III 104

3.2.2.1 Inferior-Performing Clusters 104
3.2.2.2 Good Clusters 105
3.2.2.3 Colorado 109

3.2.2.3.1 Reference Bridge 109
3.2.2.3.2 Proximate and Cluster Bridges 110
3.2.2.3.3 Field Bridges 110

4 DESK STUDY OF UWS CLUSTERS 113

4.1 Methodology 113

4.1.1 Inspection Report Data 114

4.1.1.1 Commonly Recognized (CoRe) Structure Elements 114
4.1.1.2 Condition States 116
4.1.1.3 Smart Flags 117

4.1.2 Analysis of Inspection Report Information 117

4.1.2.1 Statistics 117
4.1.2.2 Qualitative Descriptions 118
4.1.2.3 Photographs 119

4.1.3 Cluster Data Comparisons 119

4.2 Phase II Examples 120

4.2.1 New York 120
4.2.2 Maryland 124
4.2.3 Texas 126
4.2.4 Louisiana 126

4.3 Phase III Work in Progress - Colorado 130

5 CONCLUSIONS 132

5.1 Summary 132
5.2 Conclusions 133
5.3 Future Work 134

REFERENCES 136

Appendices

A CAUS Humidity Maps 140
B UWS Survey 146
C Proximate Bridges for Potential Phase III State-Recommended Inferior Performing Bridges 148
D Proximate Bridges for Potential Phase III Good Performing Clusters 197
E Permission Letters 206

LIST OF TABLES

Table 2.1: Excerpt of New York Bridge GIS Data 45

Table 2.2: Excerpt of Louisiana Bridge GIS Data 47

Table 2.3: Excerpt from Maryland Bridge GIS Data 48

Table 3.1: UWS Bridges with Overall Performance Issues 53

Table 3.2: Parameter Classification for Deicing Clusters 58

Table 3.3: Parameter Classification for Coastal Clusters 59

Table 3.4: Parametric Combinations for Phase II Deicing Clusters 60

Table 3.5: Parametric Combinations for Phase II Coastal Cluster 62

Table 3.6: Targeted Parametric Combinations for Deicing Clusters 64

Table 3.7: Targeted Parametric Combinations for Coastal Clusters 64

Table 3.8: Superstructure Condition Rating as a Function of Age for UWS Bridges in Agencies experiencing Appreciable Snowfall (for population 1-49 years) 69

Table 3.9: Good Deicing Candidates Resulting from Parameter Filtering Method 73

Table 3.10: Proximate Bridges in Parametric Categories of Interest, New York 75

Table 3.11: Cluster Bridges, New York 80

Table 3.12: Potential Reference Bridges Comparison, Maryland 83

Table 3.13: Proximate Bridges in Parametric Categories of Interest, Maryland 85

Table 3.14 : Cluster Bridges, Maryland 90

Table 3.15: Proximate Bridges in Parametric Categories of Interest, Texas 94

Table 3.16: Matrix of Bridges, Texas 98

Table 3.17: Cluster Bridges, Texas 101

Table 3.18: Proximate/Cluster Bridges, Colorado 111

Table 4.1: CoRe Elements Considered in Desk Study 115

Table 4.2: Excerpt of Condition State Data in Typical Inspection Report 118

Table 4.3: Inspection Report Summary, New York 125

Table 4.4: Conversation of New York Condition Rating to Ratio in CoRe Element Condition States 126

Table 4.5: Inspection Reports Summary, Maryland 127

Table 4.6: Inspection Reports Summary, Texas 128

Table 4.7: Inspection Reports Summary, Louisiana 129

Table 4.8: Inspection Report Summary, Colorado 131

Table C.1: Summary of State Recommended Inferior Performing Bridge Clusters 149

Table C.2: Alabama Cluster based on 12321 and 12322, Proximate Bridges 150

Table C.3: Colorado Cluster based on F-11-AO, F-11-AP, and F-11-AT, Proximate Bridges 151

Table C.4: Connecticut Cluster based on 3830, Proximate Bridges 152

Table C.5: Iowa Cluster based on 41331, Proximate Bridges 156

Table C.6: Maine Cluster based on 1004, Proximate Bridges 159

Table C.7: Maine Cluster based on 2928, Proximate Bridges 163

Table C.8: Massachusetts Cluster based on A18001AE8DOTNBI, Proximate Bridges 164

Table C.9: Massachusetts Cluster based on B230213T5DOTNBI), Proximate Bridges 171

Table C.10: Michigan Cluster based on 8097, Proximate Bridges 174

Table C.11: Michigan Cluster based on 4586, Proximate Bridges 184

Table C.12: Minnesota Cluster based on 62861, Proximate Bridges..... 185

Table C.13: Pennsylvania Cluster based on 25435, Proximate Bridges 188

Table C.14: Pennsylvania Cluster based on 10473, Proximate Bridges 190

Table C.15: Rhode Island Cluster based on 170, Proximate Bridges 195

Table C.16: Washington Cluster based on 0011490A0000000, Proximate Bridges..... 196

Table C.17: Wyoming Cluster based on CCC, Proximate Bridges 196

Table D.1: Summary of Good Clusters for Phase III 197

Table D.2: Hampton Roads Cluster, Proximate Bridges..... 198

Table D.3: North Carolina Cluster, Proximate Bridges 199

Table D.4: Arkansas Cluster, Proximate Bridges..... 200

Table D.5: Seattle Cluster, Proximate Bridges..... 203

Table D.6: Bread Basket Cluster based on SD99, Proximate Bridges..... 204

Table D.7: Bread Basket Cluster based on NE99, Proximate Bridge 205

Table D.8: Chicago Cluster, Proximate Bridges 205

LIST OF FIGURES

Figure 2.1: Chemical Concentration Stations 18
Figure 2.2: Mean Total Snowfall Stations 19
Figure 2.3: NOAA Humidity Stations 22
Figure 2.4.: CAUS January Humidity 23
Figure 2.5: TOW Stations 24
Figure 2.6: Mean Daily Average Temperature Stations 26
Figure 2.7: Mean Daily Maximum Temperature Stations 27
Figure 2.8: Mean Daily Minimum Temperature Stations 27
Figure 2.9: Mean Number of Days with Temperature below 32°F Stations 28
Figure 2.10: Mean Number of Days with Heavy Fog Stations 29
Figure 2.11: Mean Number of Days with Measureable Precipitation Stations 30
Figure 2.12: Mean Total Precipitation Stations 30
Figure 2.13: Mean Wind Speed Stations 31
Figure 2.14: EVS Shoreline (NOAA, 2013) 33
Figure 2.15: EVS Shoreline, Continental US 34
Figure 2.16: ENC Shoreline, Continental US 35
Figure 2.17: EVS Shoreline, near Houston, TX 35
Figure 2.18: ENC Shoreline, near Houston, TX 36
Figure 2.19: Illustration of point to line measurement (ESRI, 2012) 43
Figure 3.1: U.S. Annual Total Snowfall (NOAA, 2002) 68

Figure 3.2: Average Superstructure Condition Rating vs. Average Age for Agencies Receiving Appreciable Snowfall 70

Figure 3.3: Superstructure Condition Rating versus Age, New York 81

Figure 3.4: Superstructure Condition Rating versus Age, Maryland 91

Figure 3.5: Possible Proximate Bridges, Texas 93

Figure 3.6: Superstructure Condition Rating vs. Age, Texas 102

Figure 3.7: US Nitrate ion wet deposition, 2010 (NADP, 2012) 108

Figure A.1: CAUS February Humidity 140

Figure A.2: CAUS March Humidity 140

Figure A.3: CAUS April Humidity 141

Figure A.4: CAUS May Humidity 141

Figure A.5: CAUS June Humidity 142

Figure A.6: CAUS July Humidity 142

Figure A.7: CAUS August Humidity 143

Figure A.8: CAUS September Humidity 143

Figure A.9: CAUS October Humidity 144

Figure A.10: CAUS November Humidity 144

Figure A.11: CAUS December Humidity 145

Figure A.12: CAUS Annual Humidity 145

ABSTRACT

Uncoated weathering steel (UWS) has been used in the United States for highway bridge construction since 1964. Thus there is now a significant population of these bridges that have been in service for an extended period of time and it is desirable to evaluate their long-term performance. In furtherance of this goal, first a national UWS inventory was created by compiling quantitative data from the National Bridge Inventory (NBI) for the UWS bridges and associating environmental variables that may affect UWS performance (including atmospheric chemical concentrations, climate characteristics, and geographical parameters) to each bridge location using geographic information systems (GIS). This database describing the environmental conditions and corresponding performance of nearly 10,000 bridges allows for a comprehensive and quantitative description of the UWS bridge population. The next phase of research involved selecting a subset of bridges from this national inventory for further consideration for more detailed evaluation, including field evaluations. To accomplish this, a statistically driven process was created and implemented to form a matrix of bridges that contains single-parameter variations of potentially influential environmental variables, where the environments of interest focused on coastal locations and overpasses over heavily-salted, high volume roadways. The third component of this research was to develop a process for analyzing the performance of the selected bridges, based on compiling data from the owner's inspection reports. Those reports along with information in the national UWS inventory can ultimately be used to inform conclusions regarding the performance of UWS bridges.

Chapter 1

INTRODUCTION

1.1 Motivation

Uncoated weathering steel (UWS) is often considered to be a desirable material choice for highway bridge construction because of its environmental advantages, durability, low maintenance requirements, and cost effectiveness. UWS has been used for bridge construction in the United States (US) since 1964. However, its early performance received mixed results throughout the US, where certain environmental conditions caused unfavorable UWS performance. In 1989, the Federal Highway Administration (FHWA) issued a Technical Advisory (TA) 5140.22 to provide specific guidelines and recommendations to bridge owners on situations where and how UWS should not be used. However, the TA also stated, "Further work is needed to quantify and understand the performance of uncoated weathering steel in a variety of circumstances and conditions".

Since the publication of this TA, many state transportation agencies have conducted their own research and testing on UWS bridges, including but not limited to Idaho, Texas, Iowa, and West Virginia. Those findings were state specific and a more comprehensive review is needed to understand how to improve UWS performance on a national level. Therefore, in order to better understand the performance of UWS throughout the US, research through the Long Term Bridge Performance Program (LTBPP) and Federal Highway Administration (FHWA) has been commissioned with the goal of revising the 1989 TA with quantified data.

1.2 Objectives, Scope, and Thesis Organization

The objective of the larger research project encompassed by the results presented herein is to examine and assess the performance of UWS bridges in various situations and regions using a comprehensive and statistically driven process that will provide quantifiable results. In furtherance of this goal, the research that is the subject of this thesis began with creating a national UWS inventory containing both information about the bridges as well as the climate in which each bridge is located. This is described in Chapter 2 and was accomplished with the cooperation of representatives from 46 state transportation agencies throughout the US, who identified all known UWS bridges within their jurisdictions. After the UWS bridge inventory was compiled using the National Bridge Inventory (NBI) and Microsoft Access, GIS was used to associate climatic, environmental, and geographical data to each bridge. Chapter 2 provides background on the bridge attributes as well as chemical, environmental, and geographical parameters of interest that were included in the national UWS inventory. Chapter 2 also describes the use of GIS to create "bridge clusters", which are bridges in geographic proximity to one another and were used in subsequent phases of this work.

The second primary goal of the research serving as the subject of this thesis was to use the national UWS inventory to select bridges of interest for further evaluation using a statistically driven process, which is described in Chapter 3. This first involved creating a methodology for categorizing bridges based on parameters known to be influential to UWS performance, selecting categories of bridges of greatest interest, and selecting specific bridges within those categories that could be generally applied in a consistent manner throughout the US. This methodology was then employed to select approximately 100 specific bridges (out of the nearly 10,000

in the national UWS inventory) for further evaluation and a subset of 13 of these 100 bridges for in-depth field inspections. These bridges were selected to focus on the two key issues to which bridge owners have most frequently attributed poor UWS performance in prior work (McConnell et al. 2012): coastal locations and overpasses over heavily salted roadways. The selected bridges then encompass wide gradations in performance despite being located in similar environments and allow for the evaluation of assessing variable performance as a result of slightly altered environments.

The third component of the subject research was to develop a process for analyzing the performance of the selected bridges. Specifically, Chapter 4 describes how performance characteristics of the selected bridges were compiled using the owner's inspection reports. Those reports along with information in the national UWS inventory that was created can be used to inform conclusions regarding the performance of UWS bridges.

Chapter 5 discusses the conclusion of this research. This chapter also provides recommendations for future work.

Chapter 2

GIS DATABASE OF UNCOATED WEATHERING STEEL BRIDGES

A key component of this work was creating a national GIS database of uncoated weathering steel bridges. This was of interest in order to associate various geographic and climate variables with each bridge site and to facilitate grouping bridges by geography in later stages of this work. This chapter will discuss how the UWS bridge GIS database was compiled, organized, and utilized. This database includes various National Bridge Inventory (NBI), climate, atmospheric chemical concentration, and geographic data types; the significance of each of these data types to this project will also be explained. In addition, an explanation of how these variables were associated to each bridge site through the GIS software using various different tools is included. This section will also describe the use of GIS to create bridge clusters that will be used in subsequent phases of this work.

2.1 Building the GIS Database

In order to create the UWS database, the relevant data types to be included in the database first needed to be identified and then specific values for these data types imported into GIS. These considerations and methods are explained in the following subsection, Section 2.1.1. Next a methodology for associating the climate, chemical concentration, and geographic data to each bridge site was determined and implemented. This process is described in Section 2.1.2.

2.1.1 Data Types

For this phase of research, two types of bridge clusters (which are explained in detail in Section 3.1) were explored, bridges subjected to deicing agents and coastal bridges. The specific variables that were included in the database were specifically chosen accordingly while also considering other variables that have found to potentially correlate to UWS performance (e.g., fog, sulfur oxides). These variables are classified as either primary variables or secondary variables. A primary parameter is defined as a variable that previous research and experience suggests may have a significant influence on overall performance of UWS bridges and was thus taken into direct consideration when choosing specific bridges for further evaluation. A secondary parameter is defined as a variable that is either thought to affect UWS performance to a lesser extent or its influence on UWS performance is uncertain. These parameters were incorporated into the database in order to take these variables into consideration in this research when feasible to include additional variables and so that this information would be known if desired in future research.

The GIS database thus consisted of four different types of data: NBI, atmospheric chemical concentration, climatic, and geographical data. Each of these data types and the corresponding manner in which specific values were obtained for each is described in the following sub-sections. In summary, NBI information of greatest interest was latitude and longitude, crossing type, ADT under the structure, vertical and lateral under-clearances, age, and superstructure condition rating, although the full NBI records for each bridge are included in the database. Chemical concentration data included atmospheric concentrations of Cl^-, NO_3^-, and SO_4^{-2}. The climatic data was comprised of snowfall, humidity, time of wetness, temperature, fog, precipitation, and wind data. The geographical data examined was distance to the

coast. After completing the required GIS analysis, each bridge in the UWS database was described by NBI, chemical concentration, climatic, and geographical data specific to its unique location.

The full rational for identifying each of these parameters as primary and secondary variables in the two different cluster types is also explained in the following sections. In summary, primary variables for the deicing cluster included crossing type, ADT under the structure, snowfall, humidity, vertical and lateral under-clearances, and age. Humidity, distance to the coast, Cl^- concentration, and age were the primary variables for the coastal clusters. The remaining variables were secondary parameters for both cluster types. The primary and secondary parameter data from each cluster was critical to later conducting a statistical analysis that aided in selecting specific bridges for further evaluation.

2.1.1.1 National Bridge Inventory Data

The NBI provides information (physical attributes, location, etc.) on all state and federal bridges in the United States and was used to gather necessary data for the UWS database. Details of the multiple steps necessary to extract the data of interest into the UWS database are first explained below. This includes identifying the bridges of interest, accessing the raw NBI data, and synthesizing this information in a useful way. Details on each of the items of interest in the NBI are also provided below. In summary, these were record type (which indicates whether the route on or under the bridge is being described), latitude, longitude, year built and reconstructed, ADT, service under the bridge, vertical under-clearance, navigational vertical clearance, minimum lateral under-clearance on right/left, and superstructure rating.

2.1.1.1.1 Identifying UWS Bridges

As a part of this research project, a survey (which is further discussed in Section 3.1.1.1.1) was sent to each Long Term Bridge Performance Program (LTBPP, Friedland et. al 2007) state coordinator (including all 50 states, Puerto Rico, and the District of Columbia) requesting information about the overall performance and perception of UWS bridges within their agency. Simultaneously, a listing of all known UWS bridges within each agency was requested. The states were asked to provide the structure/bridge identification number of each UWS bridge within its agency and most provided additional details about the bridges as well, which aided in data verification.

However, many agencies did not have easily searchable records indicating which bridges are UWS. For many, it required "human intel" or a method of deduction to determine the UWS bridges. For example, multiple agencies conveyed that the first-hand knowledge of inspectors in district agencies was used to compile the list of their UWS bridges. Alternatively, one agency conveyed that they record paint type, so the combination of no paint type and steel was inferred to be a UWS bridge. The data is thus potentially vulnerable to some inaccuracies or omissions as a result. For example, some of the state inventories that were received contained bridges that were ultimately found to be painted steel and bridges that were built before UWS bridges were introduced in 1964 (Albrecht and Naeemi 1984).

2.1.1.1.2 Accessing Raw NBI Data

FHWA has NBI records dating back to 1992 available, but for the purposes of this project, only the 2011 and 2012 records were used. The project initially began when the 2011 bridge records were the most recent records available. Once the 2012 records became available, all data was updated to reflect the most current information.

These were extracted from the FHWA website: (http://www.fhwa.dot.gov/bridge/nbi/scii.cfm).

2.1.1.1.3 Formatting NBI Files for Importing into GIS

The NBI records in delimited format (an option available on the FHWA website) were imported as tables into Microsoft Access 2010 using the "text file" option under the "external data" submenu. Separate text files exist for each state in the NBI and after a state NBI text file was imported to Microsoft Access as a table, the UWS bridge structure numbers (identified by each state coordinator) were also saved as a separate table. The purpose of using Microsoft Access was to utilize its querying capabilities to extract the UWS bridges from the larger populations. To accomplish this, a relationship was first established between the state NBI table and the UWS bridge structure numbers table by using the "relationships" option under "database tools" submenu. The state NBI bridge structure numbers and the UWS bridge structure numbers were then linked creating a one-to-one relationship between the two tables. The "Simple Query" selection from the "Query Wizard" option under the "Create" submenu was used to filter and extract the UWS NBI records from the state NBI records into a new table. In this extraction process, the inventory routes that went under the structure were also included.

The filtered and extracted UWS bridge NBI records for each state were next exported to Microsoft Excel using the table to excel option under the external data submenu. Microsoft Excel has the capability to sort using different levels and save its files in a GIS compatible format, .csv. Microsoft Access was not capable of saving tables in the .csv format and thus Microsoft Excel was used for this next necessary

step. At the end of this process, each state that provided an inventory of UWS bridges had a Microsoft Access table and a .csv file from Microsoft Excel.

2.1.1.1.4 Identifying and Synthesizing NBI Data of Interest

From over one hundred items in the NBI, the specific items that were most likely to affect overall UWS bridge performance were identified. These items and their relevance to UWS performance is explained below in the order that they appear in the NBI records. The item numbers that appear in parentheses after each heading refer to the NBI item numbers using the official Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges (1995), abbreviated as the NBI Coding Guide in the discussion that follows. In some cases, some synthesis of the raw NBI data was necessary in order to efficiently report and consider these items of interest. These considerations are also explained below.

2.1.1.1.4.1 Record Type (Item 5A)

Each bridge in the NBI has an identification number and all the NBI data associated with that bridge is known as the "NBI record(s)" for that particular bridge. All bridges have at least one record that contains the majority of the information about the bridge and the route that the bridge carries. There are one or more additional records for a structure corresponding to one or more route(s) the bridge may cross. An entry of "1" as the record type (Item 5A) indicates the primary record, containing the details of the structure and the route carried by the structure. Additional records describe the routes going under the structures and are referred to secondary records or under records. A "2" specifies a single route going under the structure and information about this route is contained in this record. Additional routes being

crossed by the structure are labeled with alpha characters beginning with "A" and continuing through "Z" as needed. Only information that is relevant to the inventory route is contained in the secondary records (FHWA 1995).

Record type column (5A) was used to determine whether the NBI record was the primary record or a secondary record for the GIS database. The majority of the needed information was contained in the primary records but (as will be detailed below), the ADT information in the secondary records were also critical pieces of information used in the UWS database and in selecting specific bridges for further evaluation (as described in Section 3.2).

2.1.1.1.4.2 Latitude and Longitude (Item 16 and 17)

The latitude and longitude from Items 16 and 17 give the geographic coordinates of the bridge location in degrees, minutes, and seconds and were used in the GIS analysis to accurately map the bridges and ultimately associate them with the geography-dependent variables. The latitude and longitude values from the NBI records were converted to decimal degrees and plotted in GIS using the WGS 1984 coordinate .The bridge coordinates are referenced at the beginning of the bridge in the direction of the route or another location that is comparable with each agency's linear referencing system (LRS, see FHWA 1995).

Occasionally, a bridge would have latitude and longitude values that did not coincide with the actual bridge location. These errors were detected by plotting the bridge latitude and longitude on Google Earth (2013). If the bridge points were not within state boundaries then the latitude and longitude were reviewed. Two different methods were used to find the coordinate discrepancies once the bridges were plotted. The first method visually examined the inventory of a specific agency relative to its

state boundaries; if the bridges of a specific agency were not located within the state boundaries, it was concluded that the bridge latitude and longitude coordinates for the state were incorrect. The second method focused on the "features intersected" and "facility carried" entries from the NBI records; if these entries did not coincide with what the bridge was carrying and interesting on Google Earth, it was concluded that the latitude and longitude values were incorrect. Therefore, those latitude and longitude values were manually changed using http://itouchmap.com/latlong.html to correct the inconsistencies. This website was used to obtain the latitude and longitude based on the intersection of the route carried and feature intersected.

2.1.1.1.4.3 Year Built and Year Reconstructed (Item 27 and Item 106)

Age is an important consideration for all UWS bridges since there is a direct relationship between age and structural deterioration. Because the age of interest is the age of the UWS components rather than the age of the structure as a whole, the year built (Item 27) and year reconstructed (Item 106) entries in the NBI were considered. Since it is impossible to know whether the UWS components of these structures were built during the initial construction or the reconstruction, the more recent of these two dates was used in statistical analyses of the resulting UWS database. This is both conservative (i.e., would over-estimate the decrease in superstructure rating that occurs over time if this assumption is incorrect) and most consistent with actual practice, i.e., girders are often replaced during a reconstruction. The age of the structure was then calculated relative to 2013 (the current date at the time of this writing). Often, when specific bridges of interest were identified, the exact age of the UWS components was determined through additional correspondence

with the owners in these cases, but it was not feasible to obtain this information for every structure in the UWS database.

After compiling the database, it was observed that a small number of bridges were included that have year built and year reconstructed (where applicable) values prior to the date when UWS is first known to have been used in highway bridges (i.e., 1964, Albrecht and Naeemi 1984). The UWS used during the 1940s and 1950s had a steel that was alloyed with different amounts of copper, phosphorus, chromium, nickel, and silicon than the 1964 UWS. Thus, its patina formation properties were different than "modern" UWS (AISC 1993). Consequently, bridges constructed or reconstructed prior to 1964 were excluded from all subsequent data analysis but retained in the overall database for future reference.

2.1.1.1.4.4 ADT Under the Structure (Items 5A and 29)

The average daily traffic (ADT) underneath the structure was a primary parameter for the deicing agents cluster. The volume of traffic, including cars and trucks, under the bridges has been shown to affect the condition of the UWS girders in several prior research studies. This is because salt-spray collects on the girders from the cars and trucks traveling under the bridges, adding a corrosive solution layer to the superstructure (AISI 1982). As the ADT under the structure increases, so does the potential for this corrosive solution in climates where snowfall regularly occurs. For example, studies done in Michigan showed larger volumes of traffic increased the amount of salt applied and amount of salt spray contamination (Culp and Tinklenberg 1980). Additionally, two bridges from a 1993 AISI study in Michigan with heavy traffic and heavy salt exposure were examined. The bridges were first inspected in 1981 and then again in 1994. In 1981 the bridges' "lower sheltered surfaces" had

flaky/laminar rust but no section-loss; however, when these bridges were reevaluated in 1994 severe corrosion was visible over the entire bridge (AISI 1995). It was concluded that the heavy traffic increased the amount of salt-spray and corrosion (AISI 1995). Extended periods of heavy deicing salts exposure have also been stated as causing the initial corrosion rate to continue and prevent proper patina formation (WJE 2013). A separate (and seemingly lesser) effect of ADT is that traffic releases pollutants, including SO_4^{-2}, which also create a corrosive environment (Albrecht and Naeemi 1984).

The ADT underneath the structure was obtained by summing the ADT values in Item 29 for the record types identified with a "2" or "A" through "Z" alpha character in Item 5A. Thus, this sum represents the volume of traffic on the inventory routes under the structure. Occasionally, a bridge crossing a highway, according to Item 42B described below, did not report an ADT beneath the structure. In this situation, the ADT was left blank.

2.1.1.1.4.5 Service Under the Bridge (Item 42B)

The type of service under the structure was used to classify the crossing, a primary parameter, under the bridge for the deicing cluster. This is of interest because the type of crossing may affect the atmospheric chemical concentrations and humidity. For example, a highway crossing may experience salt-spray from traffic beneath the structure and waterway crossings in marine environments are more susceptible to chloride exposure. Item 42B lists the following services: (0) other, (1) highway, with or without pedestrian, (2) railroad, (3) pedestrian + bicycle, (4) highway + railroad, (5) waterway, (6) highway + waterway, (7) railroad + waterway, (8) highway + railroad + waterway, and (9) relief for waterway (FHWA 1995). Cases 1, 2, 4, 5, 6, 7, and 8

(highways, railroads, waterways, and/or the combinations) were the classifications of interest in this work since these are the most common situations.

2.1.1.1.4.6 Vertical Under-Clearance (Item 54B) and Navigational Vertical Clearance (Item 39)

The vertical under-clearance was a primary parameter for the deicing clusters. Lower clearances increase the potential for deicing agents (typically salts) on the routes below the structure to be transferred to the structural elements of the bridge due to the salts becoming mixed with liquids on the roadway and then becoming displaced by traffic on the routes under the bridge. The salt-spray deposited on the girders can create a corrosive environment, which may be more severe for the lower clearances (AISI 1982). Alternatively, bridges with low water crossings over bodies of water are vulnerable to extended periods of wetness due to flooding or "condensation of water vapor" (FHWA 1989). Coastal bridges' exposures to atmospheric chlorides, which lead to corrosive settings, (Albrecht and Naeemi 1984) are also likely to increase as vertical under clearance decreases. Thus, clearance over roadways and bodies of water are relevant variables affecting UWS performance.

Highways and railroads have vertical under-clearance values in item 54B. According to the NBI Coding Guide, the vertical under-clearance is taken from the travel lanes on the roadway for highway bridges (FHWA 1995). If the bridge crosses a railroad then the railroad tracks to the superstructure's underside are measured to the nearest hundredth of a meter as the vertical under-clearance. If the under-clearance is greater than 30 meters, then a value of 99.99 can be entered by the inspector. The most critical value (lower value) is logged if a railroad and highway are under the structure.

If the crossing type is not a highway or railroad, then a value of 0 is recorded (FHWA 1995). This value of 0 is the common entry for bridges over waterways .

Item 39 also examines vertical under-clearance for bridges that cross waterways. Specifically, this item refers to vertical navigational clearances over waterways. According to the NBI Coding Guide, the minimum clearance in Item 39 is to be measured above a datum ("indicated on a navigational permit issued by a control agency") that is measured the nearest hundredth of a meter (FHWA 1995). Upon reviewing the NBI records, it was observed that neither a vertical under-clearance nor navigational vertical clearance was provided for the majority of bridges that crossed waterways. Therefore, the vertical clearance over bodies of water cannot be determined for most bridges. Inquiries with selected state coordinators to attempt to determine other possible means for determining this data led to the conclusion that there is not a way to determine this information from existing records within these representative agencies.

2.1.1.1.4.7 Minimum Lateral Under-Clearance on Right/Left (Item 55 and 56)

The minimum lateral under-clearance was a primary parameter for the deicing cluster based on the fact that it contributes to the so-called tunnel effect, defined by FHWA (1989) as a "combination of narrow depressed roadway sections between vertical retaining walls, narrow shoulders, minimum vertical clearances and deep abutments adjacent to the shoulders". The above mentioned conditions prevent the air currents from dissipating the "salt spray" generated by deicing salts on underpasses, which was previously discussed above. The lesser the lateral under-clearance, the greater the corrosive affect the salt-spray and chemical concentrations is likely to be on the structural members.

According to the NBI Coding Guide (FWHA, 1995) the minimum lateral under-clearance to the right and left is measured from the centerline of the respective right/left side track of a railroad and the respective right/left edge of the roadway (excluding the shoulder) for highways to the nearest substructure unit, rigid barrier, or toe of slope. The clearance should be measured from the right/left edge of the "through" roadway since ramps, accelerating or turning lanes are not considered. If a railroad and highway are beneath the structure, the lessor of the two measurements is recorded. If the under-clearance is greater than 30 meters, then a value of 99.99 is noted. A value of 0, indicating not applicable, is recorded if the crossing is other than a highway or railroad (FHWA, 1995).

For the purposes of this project, the minimum of the left and right lateral under-clearance values were used in subsequent data analysis as this is the more critical situation. However, if either the left or right clearance value was a 0, indicating not applicable, then the remaining value was used.

2.1.1.1.4.8 Superstructure Rating (Item 59)

The superstructure rating is an integer value from 1 to 9 (or an "N" for culverts, FHWA 1995) that is meant to describe the overall physical condition of the superstructure members (girders, cross frames, bearings, paint, joints, etc. as applicable for each structure). The value is influenced by multiple bridge characteristics including visual signs of over-stressed members such as plastic deformations or fatigue cracks, damage resulting from vehicular impacts, missing bolts in structural connections, and corrosion. The latter of these is one of the more common, but obviously not the only, causes of decreasing superstructure condition ratings. Thus, these ratings can provide general information on possible UWS

performance. However, it should be noted that upon review of detailed data from several agencies, it was observed that the very low superstructure condition ratings (values of 1 to 3) associated with some UWS bridges are not a result of UWS or corrosion-related issues.

2.1.1.2 Chemical Concentration Data

Atmospheric chemical concentrations of Cl^-, NO_3^-, and SO_4^{-2} were considered. These concentrations can be naturally-occurring or man-made, being present in precipitation, most deicing agents, and automobile/industrial discharge and then becoming deposited on UWS surfaces. In addition, coastal regions are known to have salt-laden air that results in higher levels of chloride exposure, which has been attributed to unfavorable corrosion conditions (FHWA 1989). Nitrates will cause osmotic blistering if not removed from the steel surface during surface preparations (Appleman 1987). Furthermore, it has been shown that sulfates and chlorides unfavorably affect the protective oxide coating formation on weathering steel in various situations (Albrecht and Naeemi 1984). These chemical concentrations were considered secondary variables.

Yearly data sets for Cl^-, NO_3^-, and SO_4^{-2} concentrations, measured in mg/L of precipitation, are available online by the National Atmospheric Deposition Program at http://nadp.isws.illinois.edu/ntn/annualmapsbyyear.aspx through the National Trends Network. There are 199 monitoring sites, located throughout the US, that measure these chemical concentrations. The stations' latitudes and longitudes are in the WGS 1984 coordinate system and this location data was later used in GIS to associate chemical concentration values to each bridge based on its location data (see Section 2.1.2).

The stations are equipped with an automated precipitation chemistry collector and a gage. Site operators collect samples weekly on Tuesdays and weigh the sample to determine its volume. The monitoring stations are located "away from point sources of population" such as metropolitan cities and urban areas where pollution levels are typically highest (NADP 2012). The locations of these stations are shown in Figure 2.1.

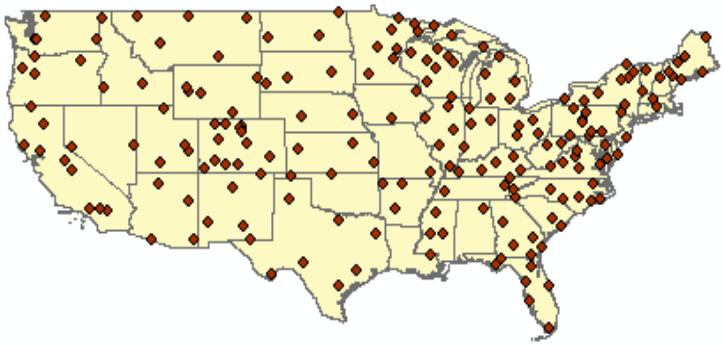

Figure 2.1: Chemical Concentration Stations

2.1.1.3 Climatic Data

The climatic data, gathered from a variety of sources, was used in GIS to assign snowfall, humidity, and time of wetness data to each bridge. These are discussed in the sections below.

2.1.1.3.1 Snowfall

Snowfall was a primary parameter for the deicing cluster since the amount of snowfall in a region affected the quantity of deicing salts used on the roadways under the bridge and thus the volume of deicing salts depositing on the UWS and other components of bridges. A study was conducted by the Ministry of Transportation in

Ontario within a region that received large amounts of snowfall and therefore greater exposure to deicing salts. Their analysis indicated the heavily corroded regions had greater amounts of chloride within the corrosion products than regions away from the corroded areas (Coomarasamy et al 2008).

Data from the Climate Atlas of the United States provided different snowfall data sets. The annual snowfall (inches) from the "Mean Total Snowfall" provided data from 3,735 stations throughout the United States (NOAA 2002). There were alternative data sets available such as mean number of days with measurable snowfall exceeding various values (i.e., 0.1", 1", 5", and 10"), mean number of days with measurable snow depth, and mean maximum daily snowfall. The stations for the selected data set had latitudes and longitudes referenced to the WGS 1984 coordinate system. This location data was later used in GIS to associate annual snowfall values to each bridge based on its location data, as will be described in Section 2.1.2.

These stations in the "Mean Total Snowfall" set were numerous throughout much of the continental US. However, there are fewer stations in states such as Nevada, Utah, New Mexico, and Idaho as seen in Figure 2.2.

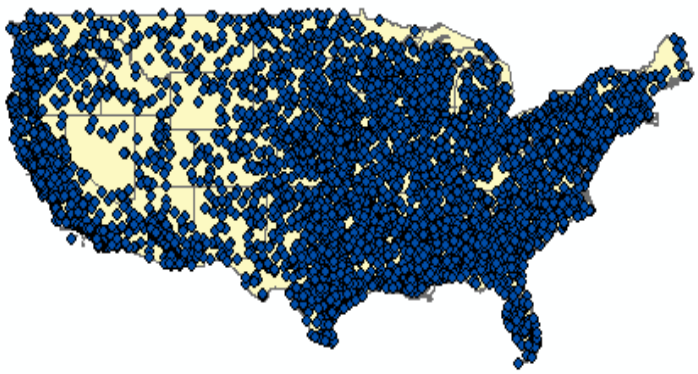

Figure 2.2: Mean Total Snowfall Stations

2.1.1.3.2 Humidity

Humidity was a primary parameter for the deicing and coastal clusters since it has been attributed to poor performance of weathering steel. Albrecht and Naeemi (1984) reported: (1) bridges in California and Alaska with high humidity and extended periods of wetness were heavily corroded, and (2) bridges located along the Gulf of Mexico coast in Louisiana with high humidity had problems forming the protective oxide coating. Humidity is also related to the time of wetness and its effects on weathering discussed in Section 2.1.1.3.3.

There were two data sets available for relative humidity. The first was from the National Oceanic and Atmospheric Administration and it will be referred to as the NOAA humidity data set (NOAA 2008). The relative humidity was reported as an average percentage in the morning and afternoon, monthly and annually. The humidity values were averaged daily, monthly and then yearly for morning and afternoon over the years of available data. The 265 stations had records for varying amount of years (NOAA 2008). The locations of the stations was dispersed unevenly with more stations along the west and east coastal states and fewer stations in the Central USA.

The second data set came from the Climate Atlas of the United States (NOAA 2002). This data set will be referred to as the CAUS humidity data set. The average relative humidity was given as a value within a range (typically of 10% relative humidity) for each station monthly and annually. For instance, if the average relative humidity over a particular month at a particular station was 70% then it would fall within “Category G”, which indicates an average relative humidity between 66 and 75%. The humidity values were averaged first daily, then monthly, and finally yearly. There is approximately 30 years of data and on average 1,525 stations for each monthly data set. The January dataset contained the greatest number of stations

(2,436) and the April dataset was based on the fewest number of stations (1,178) (NOAA 2002).

An important advantage of this dataset is that the high volume of station information has been used to create GIS contours that connect the latitudes and longitudes of stations with relative humidity values that fall within a specified range (such as "Category G", representing an average humidity for a month or year, depending on whether it is a monthly or annual dataset, between 65 and 75%). Those stations are connected by vectors creating polygons, or "contours", which distinguishes the small pockets of high humidity from the larger contours of lower humidity. Thus, there is a high probability that the humidity information that could be associated with the bridges would be correct, although expressed as value within a relatively broad range of values.

In contrast, the NOAA data did not provide contours and thus judgment would be required by the research team to determine how to best associate a specific bridge with the station data (e.g., choose closest station or interpolate between multiple stations with various geographical relationships to the point of interest). Since this step has already been done by climate experts in the CAUS data set, this was the dataset ultimately used to classify the humidity at specific bridges. A comparison of the location information of the two datasets is shown in Figures 2.3 and 2.4 where Figure 2.4. displays the CAUS humidity for January and the remaining months can be seen in Appendix A. Figure 2.3 shows the stations where humidity data exists in the NOAA dataset.

To combat the fact that the relative humidity is bracketed over a rather broad range in the selected dataset, the monthly data was used to describe the humidity at

each bridge. For example, a bridge site may be described as being in Category H in January, Category G in February and March, and Category F for the remaining 9 months of the year. The months in each category were counted and concatenated to create humidity labels such as 9F, 2G, 1H for the example scenario. Thus, even though precise values for humidity are not given in this dataset, by including the monthly data, there is typically a variation in humidity over the 100 mile distance from one boundary of a typical cluster to the other.

The stations for the CAUS humidity data set had latitudes and longitudes that were shaped into contours referenced to the WGS 1984 coordinate system. This location data was later used in GIS to associate relative humidity values to each bridge based on its location data, as will be described in Section 2.1.2.

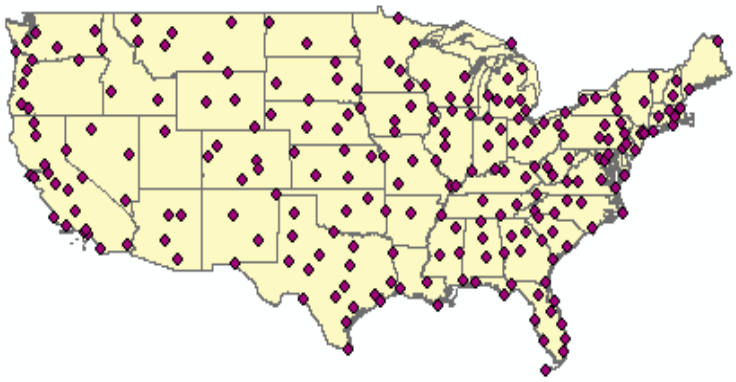

Figure 2.3: NOAA Humidity Stations

Figure 2.4.: CAUS January Humidity

2.1.1.3.3 Time of Wetness

The time of wetness (TOW) was a parameter of interest for the deicing and coastal clusters since it is known to influence corrosion (National Association of Corrosion Engineers, NACE, 2010). NACE states, "[t]he TOW refers to the period of time during which the atmospheric conditions are favorable for the formation of a surface layer of moisture on a metal or alloy", which is a key chemical mechanism for corrosion to occur. The "favorable conditions" are defined as the time period where the relative humidity is above 80 percent and the temperature is above 32°F (0°C) (NACE 2010). The TOW data, reported in hours per year, was compiled by Dr. Steve B. Chase from the University of Virginia from a variety of different sources (Chase, Personal Communication 2012). Chase analyzed and documented the results for 1020 stations throughout the United States. However, it was observed that within specific localized regions of interest, (i.e., "clusters" which will be discussed in Section 3.1) the TOW data had little variation, making it difficult to apply for the purpose of

classifying differences within a population. Thus, TOW is considered as a secondary variable in this work.

The stations for the TOW data set had latitudes and longitudes referenced to the WGS 1984 coordinate system. This location data was later used in GIS to associate TOW values to each bridge based on its location data as described in Section 2.1.2. These stations are distributed unevenly with an abundance of stations along the east and west coast, Iowa, and Minnesota. The remainder of the United States has uniformly dispersed stations as seen in Figure 2.5.

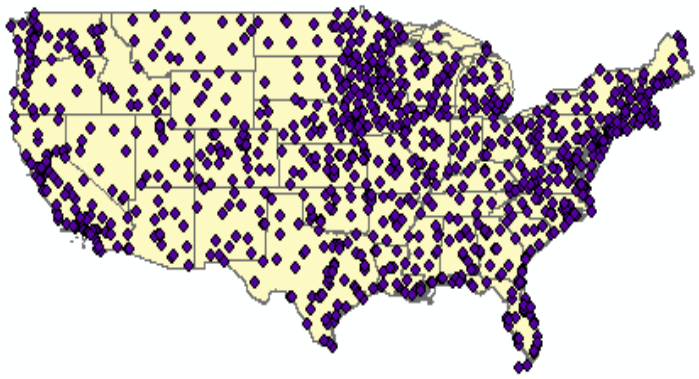

Figure 2.5: TOW Stations

2.1.1.3.4 Other Unused Data

In addition to the primary and secondary data used in the GIS analysis, a few additional data sets from the Climate Atlas of the United States (National Oceanic and Atmospheric Administration 2002) were included into the GIS analysis. These are believed to be of lessor importance than the primary and secondary variables discussed above but were included in the event that they may be useful in future work. These data sets relate to temperature, fog, precipitation, and wind. The stations for the data sets mentioned in the subsequent sections have latitudes and longitudes

referenced to the WGS 1984 coordinate system. This location data was later used in GIS to associate the various temperatures, fog, precipitation, and wind values to each bridge based on its location data as will be described in subsequent sections.

The above mentioned data sets from the Climate Atlas of the United States had "mean monthly values" and a "mean annual value". To determine the mean monthly values, first the average value throughout each day was calculated to give a daily average. Then the average value for each month was calculated by averaging these daily averages. These values were known as the "monthly means." Each month had a "monthly mean" for a period of 30 years. The "mean monthly value" was then calculated for each month by averaging the 30 "monthly means". For example, the "mean monthly value" for January was calculated by averaging all of the January "monthly means" for the 30 year period. Calculating the "mean annual value" was a similar process. A "yearly mean" was calculated for each year for a 30 year period by averaging the 12 "monthly means" for each year. The "mean annual value" was calculated by averaging the "yearly means" over the 30 year period (NOAA 2002). This 30-year averaging process is consistent for all data sets discussed below that originate from the Climate Atlas of the United States unless stated otherwise.

If the data set was an average of the number of days a certain condition existed a slightly different method was followed. The "monthly means" were the number of days within the month that a certain condition was met. For example, three days in a month could have a temperature below 32°F. The "mean monthly values" were calculated for each month by averaging the 30 "monthly means." The process for obtaining the "mean annual value" was the same as before. The "yearly means" were

calculated by averaging the “monthly means” for a year. The “mean annual value” was the average of the 30 “yearly means” (NOAA 2002).

2.1.1.3.4.1 Temperature

The data sets related to temperature include: (1) Mean Daily Average Temperature, (2) Mean Daily Maximum Temperature, (3) Mean Daily Minimum Temperature, and (4) Mean Number of Days with Temperature below 32°F. The average, minimum, and maximum temperatures assist in identifying regions that are “wet” for TOW (since one of the criteria for a region to be considered “wet” for TOW is temperatures above 32°F (0°C), NACE 2010) and regions experiencing freeze-thaw cycles.

The 4,613 stations providing records for the above mentioned temperature data sets were distributed uniformly through the United States, with subtle variations for the stations in each data set in the western US, as seen in Figure 2.6, 2.7, 2.8 and 2.9. The temperatures were reported to the tenths of a degree Fahrenheit.

Figure 2.6: Mean Daily Average Temperature Stations

Figure 2.7: Mean Daily Maximum Temperature Stations

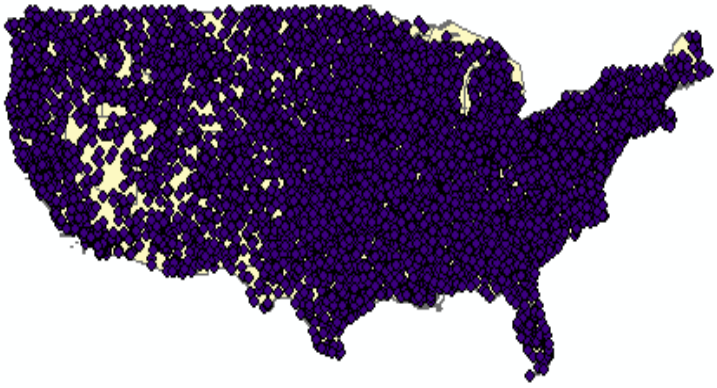

Figure 2.8: Mean Daily Minimum Temperature Stations

Figure 2.9: Mean Number of Days with Temperature below 32°F Stations

To calculate the number of days the temperature was below freezing (the last temperature data set mentioned above) the lowest daily observed temperature for each 24-hour period was recorded. If this temperature was below or equal to 32° F it counted as a day. The days were summed for each month (NOAA 2002). Then procedure described in Section 2.1.1.3.4 was used to get the "mean monthly values" and "mean annual values" for each off the data sets described.

2.1.1.3.4.2 Fog and Precipitation

Albrecht and Naeemi (1984) found that bridges with extensive corrosion were in regions of heavy precipitation, high humidity and frequent fog. These factors created "wet" and "moist" environments typical to high TOW, previously discussed in Section 2.1.1.3.3. Thus, the following climate data was also included in the GIS database: (1) The Mean Number of Days with Heavy Fog, (2) The Mean Number of Days with Measurable Precipitation, and (3) Mean Total Precipitation.

The Mean Number of Days with Heavy Fog data set had records from 351 stations dispersed throughout the United States with more stations along coastlines

and in the eastern half of the US as seen in Figure 2.10. According to the Climate Atlas of the United States, a day with heavy fog is defined as, "…reducing visibility to 0.25 mile or less" on at least one occurrence during the 24-hr time period. These days for each month are then summed and averaged over the 30-year time period (NOAA 2002).

Figure 2.10: Mean Number of Days with Heavy Fog Stations

The Mean Number of Days with Measureable Precipitation data set had measurements from 7,799 stations, thoroughly sampling the continental US with the exception of Nevada and Utah as seen in Figure 2.11. If there was 0.01" or greater of precipitation in a 24-hour period, this is counted as 1 day (NOAA 2002). Then procedure described in Section 2.1.1.3.4 was used to get the "mean monthly values" and "mean annual values" for each off the data sets described.

The Mean Total Precipitation data set provided data from 6,323 stations, thoroughly sampling the continental US, but with fewer stations in Nevada, New

Mexico, and Utah as seen in Figure 2.12. The precipitation was reported to the hundredths of an inch.

Figure 2.11: Mean Number of Days with Measureable Precipitation Stations

Figure 2.12: Mean Total Precipitation Stations

The final data set is The Mean Wind Speed. Wind is a component in the wet-dry cycles necessary for patina formation by drying the weathering steel surface after precipitation and/or dew (McDad et al 2000). Wind is also a component in the "tunnel effect" discussed in Section 2.1.1.1.4. The wind can further increase the amount of deicing agent "spray" depositing on the bridge structure (Ocel, personal communication 2013). The Mean Wind Speed data set includes data obtained from 204 stations. These stations were dispersed throughout the United States with more stations in the eastern half of the country, and particularly along the northern Atlantic Coast, as seen Figure 2.13. The data is expressed in miles per hour by first averaging as the mean of all "1-minute wind speed" observations in a 24-hour period to obtain daily wind speeds (NOAA 2002).

Figure 2.13: Mean Wind Speed Stations

2.1.1.4 Geographic Data: Distance to Coast

Distance to the coastline was a primary parameter of interest for coastal clusters. This is based on results from previous studies where, for example, Louisiana bridges within the proximity of the coastline reported corrosion problems due to

airborne salts (Raman and Naszrazadani 1989). Similarly, the Texas DOT cited larger flakes on the interior surfaces of coastal bridges compared to other bridges they inspected in their study of 40 UWS bridge inspections (McDad et al. 2000).

Two “digital vector shoreline” data sets are available from NOAA’s Office of Coast Survey (OCS) Shorelines, Extracted Vector Shoreline (EVS) and Electronic Navigational Chart (ENC). Both of these shoreline data sets (NOAA OCS 2012) were evaluated as a means for defining the coastline in the GIS analysis such that distance to the coast from each relevant bridge could be calculated by the GIS program. These datasets are described in more detail below.

2.1.1.4.1 Extracted Vector Shoreline (EVS)

EVS represents the shoreline by outlining the “land plate” (shown in the tan color in Figure 2.14) and excluding the “marsh areas” (shown in blue in Figure 2.14). While no clear definition of land versus marsh could be obtained from the source, it is stated that the data is not “tidally referenced” (NOAA OCS 2012). Other details on the methodology used to create this dataset are also available from NOAA OCS (2012). The EVS is not maintained and does not represent the most current nautical charts (NOAA OCS 2012).

2.1.1.4.2 Electronic Navigational Chart (ENC)

The ENC shoreline was created from charted information and original "source" information. According to NOAA OCS Shorelines (2012), “The ENC shoreline is collected for navigational waters and accurately depicts the tidally influenced shoreline including “waterways” and “tidal creeks”. It also includes other information relevant to navigation, such as obstructions and channel limits (NOAA OCS 2012).

Figure 2.14: EVS Shoreline (NOAA, 2013)

This shoreline was constructed using various information from the U.S. Army Corps of Engineers surveys, drawings, and permits; U.S. Coast Guard Local Notices to Mariners; National Imagery and Mapping Agency Notices to Mariners; NOAA hydrographic surveys; and the region of interest's largest scale paper chart (NOAA OCS 2012) to create an accurate shoreline. The data was extracted from ENC GIS Direct (NOAA OCS 2012). According to NOAA OCS, this "interactive portal" was created by "…transforming Approach and Harbor, Coastal, General, Overview, NOAA ENC version 2 cells to ESRI's shape file format using Safe Software's Feature Manipulation Engine" (NOAA OCS 2012). The ENC shoreline is maintained and updated regularly to represent the most current coastline information.

Ultimately, the ENC shoreline data was chosen since it is maintained and updated regularly, whereas the EVS shoreline is not maintained or representative of the current nautical charts (NOAA OCS 2012). NOAA OSC also stated that ENC is the,"…newest and most powerful electronic charting product (NOAA OCS 2012)."

The two shorelines are compared in Figure 2.15 (displaying an EVS shoreline) and Figure 2.16 (depicting an ENC shoreline) for the continental US. At a local level, Figure 2.17 displays an EVS shoreline and Figure 2.18 depicts an ENC shoreline along the Gulf Coast near Houston, TX. From this comparison it is seen that the selected ENC data set calculates distance to the coast to be farther from the bridges of interest (shown by black dots in the Figures 2.17 and 2.18) since the EVS displays more rivers, streams, etc. This was determined to be desirable since it was assumed that the chloride levels (the primary reason for evaluating distance to the coast) in the vicinity of these smaller bodies of water with presumably lower chloride concentrations would be less than that near the coast as defined by the ENC dataset.

Figure 2.15: EVS Shoreline, Continental US

Figure 2.16: ENC Shoreline, Continental US

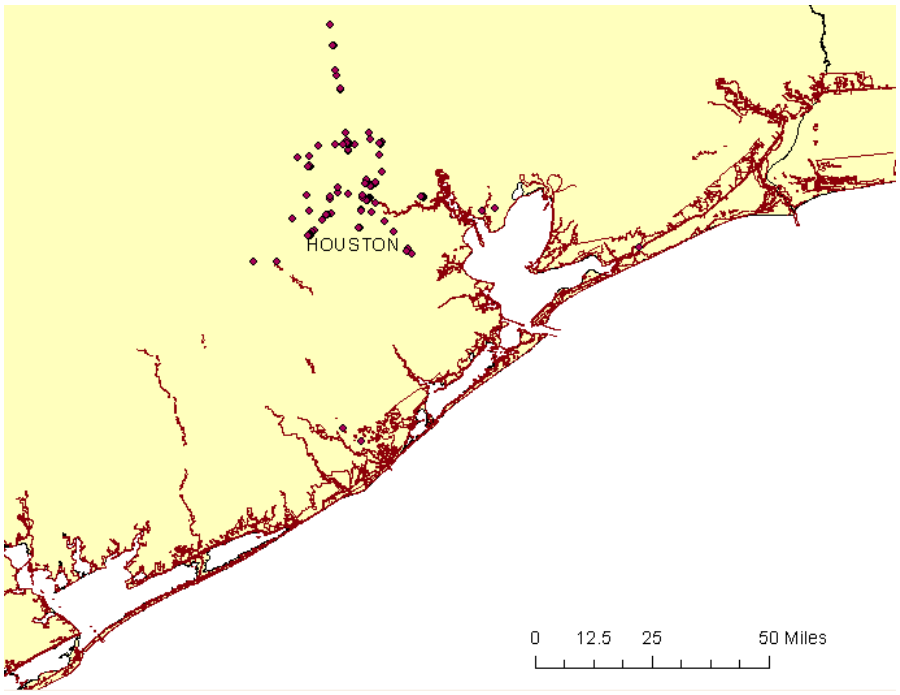

Figure 2.17: EVS Shoreline, near Houston, TX

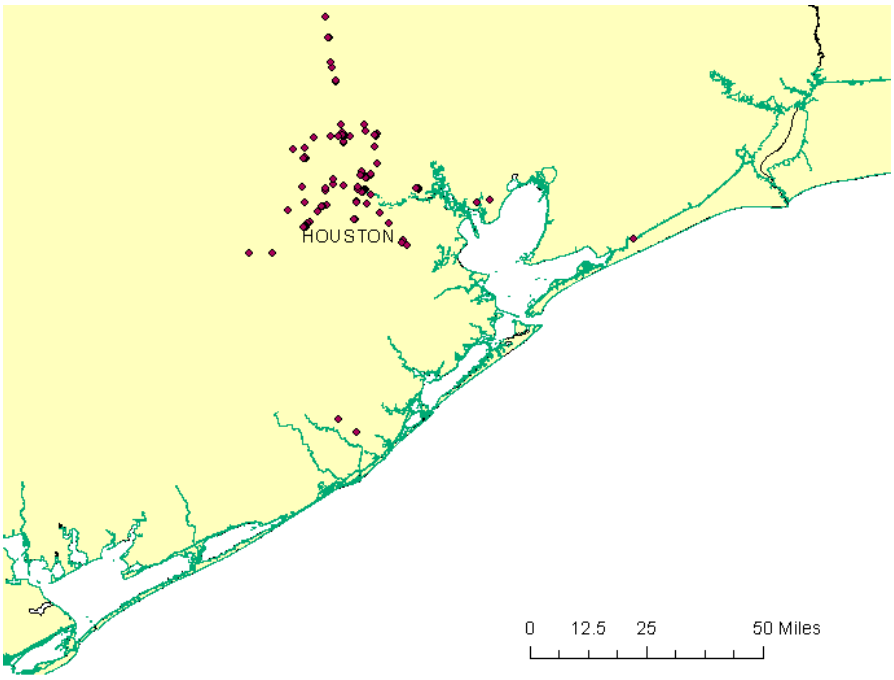

Figure 2.18: ENC Shoreline, near Houston, TX

2.1.2 Associating NBI and Environmental Data

Once the .csv files containing the NBI parameters of interest for each USW bridge were created (see Section 2.1.1.1.3), they were then imported into GIS through a series of steps. First, each state .csv was transformed into a shape file. A shape file is a format that contains information such as location, shape, and attributes of geographic features. Shape files contain a feature class (Mearns, personal communication, 2013). A feature class (homogeneous collections of common features, each having the same spatial representation, such as points, lines, or polygons) is based off latitude, longitude, (creating a point) and a reference coordinate system (ESRI 2012). Each state .csv file was placed in a folder that was accessible to the GIS library. The state of interest was selected from the GIS catalog window and the "create feature class option" was chosen from the submenu. Then the "From XY Table" function was

utilized to create a feature class based longitude and latitude values, which were placed in the appropriate x and y columns. Latitude and longitude values correspond to the WGS 1984 coordinate system and it was chosen as the reference system under the "edit" option in the "From XY Table" window. However, this coordinate system is not accurate for the spatial join, buffer, and near analysis. The potential problems associated with this are described in Section 2.1.2.3. Each state feature class was then converted into its specific state plane of the 1983 NAD HARN coordinate system using the project tool described in Section 2.1.2.3.1. Subsequent sections below will describe how GIS was used to associate each bridge to the environmental data reviewed above. Key concepts needed to successfully execute the analysis include an understanding of the coordinate systems, GIS data types, and the analysis tools used in GIS, each of which are also described below.

2.1.2.1 Coordinate Systems- WGS 1984 and NAD 1983 HARN

The bridge and environmental station latitude and longitude values referenced the World Geodetic System (WGS) 1984 datum. According to ESRI (2012), a datum, "…defines the position of the spheroid [ellipsoid] relative to the center of the earth. It is also a reference frame for measuring locations on the surface of the earth. The WGS 1984 reference frame breaks the earth into 15x15 degree graticule cells (grid of intersecting lines, specifically latitude and longitude lines in this case) embodying a sphere and distorts distances. The error increases the further the element (points, polygons, lines) is away from the equator. This coordinate system maintains the shape and direction of data (lines, polygons, boundaries, etc.) but distorts distance and area measurements. This datum should not be used to perform linear operations, such as distance measurements (Mearns, 2013). Since it was required to find the minimum

distance between a given bridge and the available stations where various types of environmental data was measured to determine the closest station (described in more detail below in Section 2.1.2.3.2), a solution is to "project" (see Sec 2.1.2.3.1) the WGS 1984 coordinate system into a different reference frame for more accurate results. Mearns (2013) suggested using the North American Datum (NAD) 1983 Higher Accuracy Reference Network (HARN) datum for this purpose. WGS 1984 and NAD 1983 HARN coordinates are about one to two meters apart creating distance and area discrepancies (ESRI 2012). While this is not a significant discrepancy for the objectives of this research, the higher accuracy NAD 1983 HARN coordinate system was employed given its higher level of accuracy.

NAD 1983 HARN is based on earth and satellite observations using the Geodetic Reference System (GRS) 1980 spheroid (ESRI 2012). A network of adjustment and control points were introduced to constrain the system back to the geocentric origin, the earth's center of mass (NGS 2013). These points were modified and recalculated to a higher level of accuracy for the NAD 1983 HARN coordinate system relative to the NAD 1983. A majority of the states had one or multiple NAD 1983 HARN state plane coordinate systems and each state plane had a high degree of accuracy within its boundaries. In addition, the control points in the NAD 1983 HARN datum also allow for accurate distance calculation used for the Buffer and Near tools (refer to Section 2.1.2.3.3 and 2.1.2.3.4).

2.1.2.2 GIS Data Types- Geospatial Data

The chemical, climatic, and geographic data was in the geospatial GIS format in the shape file. According to the Environmental Protection Agency (EPA) geospatial data is, "…information that identifies the geographic location and

characteristics of natural or constructed features and boundaries on the earth, typically represented by points, lines, polygons, and/or complex geographic features" (EPA 2012). The datasets mentioned above were represented by points, lines, polygons, etc. and this section will describe examples of these features.

Geospatial data can reference latitudes and longitudes in a coordinate system to determine locations. Each bridge or environmental station is plotted as a single point (Mearns 2013). Thus, data is only known with certainty at these points and GIS tools, described in Section 2.1.2.3, are needed to associate data to different points. In addition, geospatial data also comes in various formats, such as shape, geodatabase, tif, etc., that is already compatible with GIS. These various file types can have polygon or line data embedded within their code that connects the various latitude and longitude points together. For example, when the contours of the CAUS humidity data sets were mapped, the geospatial file referenced multiple points and/or lines to create the contours (Mearns 2013). In this way, a value at any possible point is given.

2.1.2.3 GIS Data Association Methods

Four different tools were used in the GIS analysis to associate the chemical, climatic, and geographical shape files with each UWS bridge in each state inventory. These are the Project Management, Spatial Join, Buffer, and Near Tools, which are described below. As mentioned earlier in Section 2.1.2, each state that provided a UWS inventory had a separate shape file to be converted into its specific state plane of the 1983 NAD HARN coordinate system, which provided more accuracy. GIS could then precisely associate chemical, climatic, and geographical data to each bridge using the tools described below.

2.1.2.3.1 Project Management Tool

As previously mentioned in Section 2.1.2.1, Mearns (2013) recommended projecting the WGS 1984 coordinate system to the NAD 1983 HARN datum to minimize distance and area distortions. Thus, all geospatial data in each feature class was converted in this manner using the Project Management Tool.

The Project Management Tool transforms the coordinate system of the input feature class to a new output feature class with a newly defined coordinate system. The required information to use this tool is the input coordinate system and output coordinate system. The coordinates from the old coordinate system are then recalculated to equivalent values in the new projected system (ESRI 2012). In this case, WGS 1984 coordinates were recalculated in terms of NAD 1983 HARN coordinates for all data sets not already expressed in this coordinate system.

2.1.2.3.2 Spatial Join Tool

The Spatial Join Tool was used to associate data from the chemical and climatic feature classes to each bridge inventory feature class. Each chemical, environmental, and geographical feature class was joined to the state feature class individually resulting in a progressively larger state feature file each time a new feature class was joined. This was accomplished using the latitudes and longitudes for each bridge and each station providing chemical and climatic data. The latitude and longitude of the bridges and stations results in a spatial relationship between the bridge and environmental feature classes. The Spatial Join Tool has two class feature inputs, known as the "Target Feature" and "Join Feature". According to the ESRI (2012) the Spatial Join Tool, "Joins attributes from one feature class to another based on the spatial relationship. The target feature and the joined attributes from the join features

are written to the output feature class". In this work the "Target Feature" was the file containing the list of UWS bridges and the "Join Features" were the various chemical and climatic data sets. The output class feature contained the environmental data associated to the bridge sites.

The "Match Option" determined the condition used to match station information to each bridge location. For geospatial data that involved points, the "Closest" option matched the closest station and associated the data at this station with each bridge site. For geospatial data that consisted of lines or polygons, the "Intersect" option matched the contour data overlapping with each bridge site to the respective bridge site (ESRI 2012).

2.1.2.3.3 Buffer Tool

The buffer tool was used to create a specified radius (50 miles, generally) around reference bridges (see Section 3.1) to create bridge clusters. According to the ESRI (2012) the buffer tool "…creates buffer polygons around input feature [classes] to a specified distance. For best results, the buffer option should be performed in a projected coordinate system that minimizes distortion for that particular input dataset." Since the data sets were in datum projected coordinate system (NAD 1984 HARN, see Section 2.1.2.1), GIS automatically created a Geodesic buffer (ESRI 2012). A Geodesic buffer is a type of buffer that accounts for the spheroid shape of the earth and measures the distances on a globe instead of a Cartesian place (ESRI 2012), thus improving accuracy. Distortions were also avoided when buffering by using a feature class that has a geographic coordinate system (a datum such as NAD 1983 HARN) and specifying a "Buffer Distance" in linear units (ESRI 2012).

The radius distance is specified in the "Buffer Distance" field in miles. When a datum coordinate system and linear units are used as inputs, the buffer tool will generate true a Geodesic buffer that accurately represent distances (ESRI 2012). A circle of the identified radius would circumscribe the reference bridge and the bridges within the radius could then be identified and extracted by using the circle from the "select by shape" function. All the records within the specified radius are now highlighted in the attributes table (a table with information about the features that are joined or related through the various GIS tools) and can be copied to Excel (ESRI 2012).

2.1.2.3.4 Near Tool

The near tool was used for coastal bridges to determine their distances to the coastline. The ESRI (2012) describes the near tool as "…determining the distances from each feature in the input features to the nearest feature in the near features." In order to get accurate measurements in linear units, the geographic coordinate system was projected using the Project Management Tool. The input features and near features can be point, multipoint, line, or polygon (ESRI 2012). In the present cases, the input features were the bridges as points with known latitude and longitude and the near feature was the ENC shoreline data, which consists of lines. Figure 2.19 illustrates how GIS measures distance from a point to a line (ESRI 2012). The closest point from the near feature's line or polygon is used to measure the distance to the input feature.

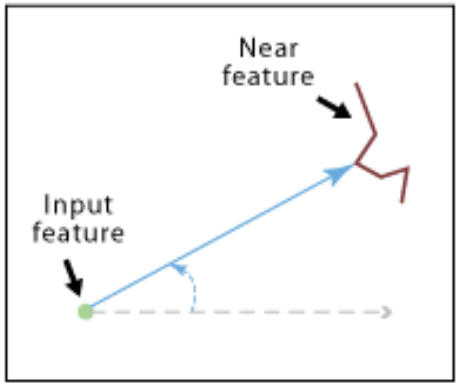

Figure 2.19: Illustration of point to line measurement (ESRI, 2012)

2.2 Use of GIS Database to Form Clusters/ Compile Local Statistics

Various types of analysis can be performed using the information and techniques described in Section 2.1. Ultimately this analysis was performed with all variables discussed for all bridges. This was carried out one state at a time to ensure the correct HARN 1983 NAD state plane coordinate system was used and then this data was merged into one database. Examples of this type of state-level analysis, where specific variables of interest are highlighted in order to limit the data to a reasonable scope, are shown below in Section 2.2.1. Section 2.2.2 illustrates a second use of the GIS database, to determine the bridges within a specified radius of a reference bridge. Chapter 3 will then detail the use of this data to select bridges of interest for further evaluation in subsequent phases of this research.

2.2.1 State Boundary Analysis

Two types of analysis of the UWS GIS database were performed in this work. The type of analysis depended on whether specific bridges of interest were identified by the states. The first was tailored for the bridge population in a given state. This type

of analysis was for states that did not recommended UWS bridges. The second analysis was specific to a cluster of bridges within a specified radius. This type analysis was performed if particular bridges were identified by the states. Both types of analysis are described in the subsequent sections.

2.2.1.1 New York

Due to its location, the primary parameters of interest for New York requiring GIS analysis were snowfall and humidity. Secondary parameters were chemical concentrations and TOW. Snowfall, CAUS humidity, and TOW were paired with the state feature class using the spatial join tool. As previously described in Section 2.1.2.3.2, the chemical and environmental stations, which were points, were linked to bridges using the geographically "closest" match option. The CAUS humidity feature class, comprised of polygons, was joined to the bridges used the "intersect" linking option. All of the bridges within the state boundary were selected on the attribute table (a table with information about the features that are joined or related through the various GIS tools) and exported to an excel sheet (ESRI 2012). An excerpt is shown in Table 2.1, where it can be seen that the data includes NBI, climatic, and chemical concentration information.

2.2.1.2 Louisiana

Due to the Louisiana climate, the primary parameters of interest for this state were humidity and distance to the coast. Secondary parameters were chemical concentrations and TOW. The CAUS humidity, chemical concentrations, and TOW were associated with each bridge in the same manner as described in the New York example, which was described in Section 2.2.1.1. However, the distance to the coast

Table 2.1: Excerpt of New York Bridge GIS Data

		PRIMARY VARIABLES					SECONDARY VARIABLES				DEPENDENT VARIABLES	
STRUCTURE ID	CROSSING TYPE	ADT UNDER STRUCTURE	VERTICAL UNDER-CLEARANCE (m)	MINIMUM LATERAL UNDER-CLEARANCE	SNOW FALL (in)	RELATIVE HUMIDITY (%)	TOW (hours/year)	Cl (mg/L)	NO3 (mg/L)	SO4 (mg/L)	AGE (years)	SUPER STRUCTURE RATING
		Value	Value	Value	Value	Value	Value	Value	Value	Value	Value	Value
A1	Highway	21600	4.44	3.0	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	26	8
A2	Highway+Waterway	15198	4.45	4.1	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	31	8
A3	Highway+Waterway	15198	4.37	3.7	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	31	8
A4	Highway	22015	4.42	5.0	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	29	8
A5	Highway	22015	4.39	5.0	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	29	8
A6	Highway	8500	4.44	4.3	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	29	8
A7	Highway	15150	5.1	2.0	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	30	7
A8	Highway	15150	5.3	2.0	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	30	7
A9	Highway	33156	5	2.0	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	30	7
A10	Highway	70941	5.15	3.0	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	30	8
A11	Highway	8500	4.55	4.3	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	29	8
A12	Highway	6400	4.44	3.0	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	29	8
A13	Highway	400	4.42	3.0	92.2	0F, 11G, 1H	2894	0.073	0.879	1.150	22	9
A14	Highway	6400	4.45	3.4	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	29	8
A15	Highway	5775	4.37	6.7	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	29	8
A16	Highway	5869	4.41	7.3	90.1	2F, 10G, 0H	2630	0.049	0.732	0.932	24	8
A17	Highway+Waterway		4.52	2.4	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	29	7
A18	Highway	400	4.55	2.0	92.2	0F, 11G, 1H	2894	0.073	0.879	1.150	22	9
A19	Highway+Waterway		5.02	3.0	60.4	0F, 11G, 1H	2937	0.049	0.732	0.932	42	6
A20	Highway	3850	4.6	3.2	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	30	8
A21	Highway	3850	4.64	3.7	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	30	8
A22	Highway	5775	4.55	6.7	92.2	0F, 11G, 1H	2630	0.073	0.879	1.150	29	8
A23	Highway+Waterway		17.75	9.0	153.6	1F, 10G, 1H	2630	0.073	0.879	1.150	22	8
A24	Railroad		6.24		93.0	0F, 10G, 2H	2937	0.049	0.732	0.932	37	6
A25	Railroad		6.14		92.2	0F, 10G, 2H	2630	0.073	0.879	1.150	32	7
A26	Railroad		5.99		92.2	0F, 10G, 2H	2630	0.073	0.879	1.150	32	6
A27	Railroad		6.4		92.2	0F, 10G, 2H	2630	0.073	0.879	1.150	35	8
A28	Railroad				93.3	4F, 8G, 0H	2630	0.049	0.732	0.932	23	8
A29	Railroad		6.62		60.4	1F, 10G, 1H	2630	0.049	0.732	0.932	29	7
A30	Railroad		6.62		90.1	2F, 10G, 0H	2937	0.049	0.732	0.932	22	8
A31	Railroad		6.22		93.3	4F, 8G, 0H	2630	0.049	0.732	0.932	22	8
A32	Waterway		4		92.2	0F, 11G, 1H	2894	0.073	0.879	1.150	47	6
A33	Waterway		2		92.2	0F, 11G, 1H	2894	0.073	0.879	1.150	31	8
A34	Waterway		4		86.6	1F, 10G, 1H	2894	0.073	0.879	1.150	28	8
A35	Highway+Waterway	1860	4.37	1.8	92.2	0F, 11G, 1H	2894	0.073	0.879	1.150	25	8
A36	Highway+Waterway		4.44	3.0	60.4	0F, 11G, 1H	2937	0.049	0.732	0.932	42	6
A37	Highway+Railroad		6.48	0.8	92.2	0F, 10G, 2H	2630	0.073	0.879	1.150	31	8
A38	Highway+Railroad	4300	6.45	3.1	92.2	0F, 10G, 2H	2630	0.073	0.879	1.150	26	8
A39	Waterway				153.6	4F, 8G, 0H	2630	0.073	0.879	1.150	25	5
A40	Waterway				138.5	2F, 10G, 0H	2707	0.073	0.879	1.150	33	9

was analyzed using the near tool, described in Section 2.1.2.3.4. The state feature class was joined to the ENC feature class and the distance to the coast was output in feet, which was later converted to miles. All of the bridges within the state were then linked with corresponding environmental variables and exported to an excel sheet. An excerpt of this output is shown for selected bridges in Table 2.2, where it can be seen that the data includes NBI, climatic, chemical concentration, and geographic information.

2.2.2 Radius from a Reference Point Analysis

As will be detailed in Section 3.1.1.2.1, it was frequently of interest to compile data for sets of bridges based on their proximity to a reference point, which consisted of a bridge of interest. Proximity was defined based on prescribing a radius of a specified distance circumscribing the point of interest. Prior to this step, the analysis proceeds as the same manner as described in Section 2.1.2, then the bridge of interest was selected by the attribute function using the bridge ID option. As an example, an excerpt of data based on a 50 mile radius around Maryland Bridge C27, is shown in Table 2.3. Then the buffer tool, as previously described in Section 2.1.2.3.3 was used to select the bridges within the specified radius. All the records within the specified radius become highlighted in the attributes table and were then exported to Excel by copying and pasting. It can be seen in Table 2.3 that this analysis has the capability to cross state boundaries, with the bridges within a 50 mile radius of this reference bridge falling within the state boundaries of Maryland as well as Virginia and West Virginia.

Table 2.2: Excerpt of Louisiana Bridge GIS Data

		PRIMARY VARIABLES		SECONDARY VARIABLES				DEPENDENT VARIABLES	
STRUCTURE ID	CROSSING TYPE	DISTANCE TO COAST (miles)	RELATIVE HUMIDITY (%)	TOW (hours/year)	Cl (mg/L)	NO3 (mg/L)	SO4 (mg/L)	AGE (years)	SUPER STRUCTURE RATING
		Value	Value	Value	Value	Value	Value	Value	Value
B1	Waterway	0.1	1G, 10H, 1I	4418	0.372	0.572	0.663	38	7
B2	Highway + Water + Railroad	0.0	7G, 5H, 0I	3988	0.372	0.572	0.663	38	7
B3	Waterway	0.2	7G, 5H, 0I	4418	0.372	0.572	0.663	32	5
B4	Waterway	0.3	7G, 5H, 0I	4268	0.372	0.572	0.663	30	7
B5	Highway	0.3	7G, 5H, 0I	4268	0.372	0.572	0.663	33	7
B6	Highway + Water	0.4	7G, 5H, 0I	4418	0.372	0.572	0.663	28	6
B7	Highway + Railroad	0.5	7G, 5H, 0I	4268	0.372	0.572	0.663	30	6
B8	Highway + Railroad	0.6	7G, 5H, 0I	4268	0.372	0.572	0.663	34	7
B9	Highway + Railroad	0.7	7G, 5H, 0I	4268	0.372	0.572	0.663	34	6
B10	Waterway	0.1	9G, 3H, 0I	3988	0.372	0.572	0.663	37	4
B11	Waterway	0.1	9G, 3H, 0I	3988	0.372	0.572	0.663	30	6
B12	Highway	0.1	9G, 3H, 0I	3443	0.372	0.572	0.663	36	7
B13	Waterway	0.3	9G, 3H, 0I	3988	0.372	0.572	0.663	33	7
B14	Waterway	0.6	10G, 2H, 0I	3850	0.372	0.572	0.663	37	6
B15	Waterway	2.7	9G, 3H, 0I	4202	0.372	0.572	0.663	36	7
B16	Waterway	3.2	9G, 3H, 0I	4202	0.372	0.572	0.663	36	7
B17	Waterway	2.0	9G, 3H, 0I	3850	0.372	0.572	0.663	37	6
B18	Waterway	13.5	9G, 3H, 0I	4380	0.372	0.572	0.663	34	7
B19	Highway + Railroad	0.8	7G, 5H, 0I	4268	0.372	0.572	0.663	34	7
B20	Highway	2.4	9G, 3H, 0I	4268	0.372	0.572	0.663	27	6
B21	Waterway	11.1	9G, 3H, 0I	3988	0.372	0.572	0.663	37	7
B22	Waterway	89.8	10G, 2H, 0I	3810	0.222	0.572	0.663	37	7
B23	Waterway	89.8	10G, 2H, 0I	3810	0.222	0.572	0.663	33	8
B24	Waterway	17.5	12G, 0H, 0I	3526	0.372	0.572	0.663	34	7
B25	Highway	4.1	10G, 2H, 0I	3526	0.372	0.572	0.663	37	7
B26	Waterway	15.3	10G, 2H, 0I	4380	0.372	0.572	0.663	26	7
B27	Waterway	70.5	12G, 0H, 0I	3835	0.372	0.572	0.663	35	8
B28	Waterway	63.7	12G, 0H, 0I	3810	0.372	0.572	0.663	35	8

Table 2.3: Excerpt from Maryland Bridge GIS Data

			PRIMARY VARIABLES					SECONDARY VARIABLES						DEPENDENT VARIABLES	
STRUCTURE ID	STATE	CROSSING TYPE	ADT UNDER STRUCTURE	VERTICAL UNDER-CLEARANCE (m)	MINIMUM LATERAL UNDER-CLEARANCE (m)	SNOWFALL (in)	RELATIVE HUMIDITY (%)	TOW (hours/year)	SNOWFALL (inches)	Cl (mg/L)	NO3 (mg/L)	SO4 (mg/L)	AGE (years)	SUPER STRUCTURE RATING
			Value	Highway (Column 54B)	Value	Value?	Value	Value	Value	Value	Value	Value	Value	Value
C1	VA	Highway	237529	4.97	3.4	23.4	3F, 3G, 0H	3113	23.4	0.217	0.768	0.851	26	7
C2	MD	Highway	53480	5	3	23.5	3F, 3G, 0H	2786	23.5	0.296	0.619	0.671	25	7
C3	MD	Highway	36798	5	3	18.7	3F, 3G, 0H	3113	18.7	0.217	0.768	0.851	22	6
C4	VA	Highway	167635	4.92	2.0	18.2	2F, 8G, 2H	2786	18.2	0.296	0.619	0.671	32	6
C5	VA	Highway	84550	4.49	4.3	21.8	3F, 3G, 0H	2786	21.8	0.217	0.768	0.851	49	6
C6	MD	Highway	272854	5	1	18.7	3F, 3G, 0H	3113	18.7	0.217	0.768	0.851	22	7
C7	MD	Highway	253738	4	3	18.7	3F, 3G, 0H	3113	18.7	0.217	0.768	0.851	22	7
C9	MD	Highway	33710	5	4	21.9	4F, 8G, 0H	2319	21.9	0.296	0.619	0.671	25	7
C10	MD	Highway	33710	5	4	21.9	4F, 8G, 0H	2319	21.9	0.296	0.619	0.671	25	7
C11	MD	Highway	33710	5	4	21.9	4F, 8G, 0H	2319	21.9	0.296	0.619	0.671	23	7
C12	MD	Highway	69020	5	6	27.8	3F, 3G, 0H	2518	27.8	0.217	0.768	0.851	39	6
C13	MD	Highway	67380	5	6	27.8	3F, 3G, 0H	2518	27.8	0.217	0.768	0.851	39	6
C14	MD	Highway	65550	4	7	27.8	3F, 3G, 0H	2319	27.8	0.217	0.768	0.851	39	6
C15	MD	Highway	65550	5	7	27.8	3F, 3G, 0H	2319	27.8	0.217	0.768	0.851	39	5
C16	MD	Highway	71700	5	7	22.4	3F, 3G, 0H	2319	22.4	0.217	0.768	0.851	37	6
C17	MD	Highway	183230	5	6.1	15.7	3F, 3G, 0H	2786	15.7	0.296	0.619	0.671	41	6
C18	MD	Highway	78741	5	10.4	18.7	3F, 3G, 0H	3113	18.7	0.217	0.768	0.851	22	7
C19	MD	Highway	68623	5	7	27.8	4F, 8G, 0H	2518	27.8	0.217	0.768	0.851	28	7
C20	MD	Highway	53922	5	7	27.8	4F, 8G, 0H	2518	27.8	0.217	0.768	0.851	27	7
C21	MD	Highway	189237	5	8	25.3	4F, 8G, 0H	2319	25.3	0.217	0.768	0.851	29	7
C22	MD	Highway	68761	5	8	25.3	4F, 8G, 0H	2319	25.3	0.217	0.768	0.851	27	7
C23	MD	Highway	55810	5	8	25.3	4F, 8G, 0H	2319	25.3	0.217	0.768	0.851	27	7
C24	MD	Highway	55810	5	8	25.3	4F, 8G, 0H	2319	25.3	0.217	0.768	0.851	27	7
C25	MD	Highway	53922	5	7	27.8	4F, 8G, 0H	2518	27.8	0.217	0.768	0.851	27	7
C26	MD	Highway	91300	5	7	20.4	4F, 8G, 0H	2319	20.4	0.296	0.619	0.671	25	7
C27	MD	Highway	71700	5	7	22.4	4F, 8G, 0H	2319	22.4	0.217	0.768	0.851	39	6
C28	MD	Highway	88600	5	7.9	21.9	5F, 7G, 0H	2319	21.9	0.296	0.619	0.671	22	7
C29	MD	Highway	66903	5	6.4	22.4	4F, 8G, 0H	2319	22.4	0.296	0.619	0.671	32	7
C30	MD	Highway	66903	5	6.4	22.4	4F, 8G, 0H	2319	22.4	0.296	0.619	0.671	32	7
C31	MD	Highway	91300	5	7	20.4	4F, 8G, 0H	2319	20.4	0.296	0.619	0.671	25	7
C32	MD	Highway	85270	4	7	22.4	5F, 7G, 0H	2319	22.4	0.217	0.768	0.851	39	6
C33	MD	Highway	81712	5	9	22.4	4F, 8G, 0H	2319	22.4	0.296	0.619	0.671	31	7
C34	MD	highway	81712	5	9	22.4	4F, 8G, 0H	2319	22.4	0.296	0.619	0.671	31	7
C35	MD	highway	113590	5	6	20.4	4F, 8G, 0H	2727	20.4	0.296	0.619	0.671	23	7
C36	VA	Highway	89620	5.66	2.0	18.2	2F, 8G, 2H	2786	18.2	0.296	0.619	0.671	30	5
C37	VA	Highway	218945	5.71	2.0	18.2	2F, 8G, 2H	2786	18.2	0.296	0.619	0.671	30	7
C38	VA	highway	181082	5.18	2.0	18.2	2F, 8G, 2H	2786	18.2	0.296	0.619	0.671	30	7
C39	VA	highway	180422	5.15	0.9	18.2	2F, 8G, 2H	2786	18.2	0.296	0.619	0.671	30	7
C40	VA	highway	266439	5.25	1.0	21.8	3F, 3G, 0H	3347	21.8	0.217	0.768	0.851	27	6

Chapter 3

SELECTION OF BRIDGES FOR STUDY

After the GIS database was compiled and organized, as described in Chapter 2, it was used to aid in selecting appropriate bridges for further evaluation. The methodology for this process is first described below in Section 3.1, which is largely based on information received from the LTBPP state coordinators as well as statistical analysis of various parameters within the GIS UWS database. Then, Section 3.2 illustrates the application of this methodology to select specific bridges. Chapter 4 will then describe the preliminary evaluations carried out on these bridges in order to begin to inform updates to the TA 5140.22 (FHWA 1989), a primary goal of the larger project to which this research contributes.

3.1 Methodology

There are four different classifications of bridges considered in this work. In decreasing order of the level of detail in which these four types of bridges are evaluated, these are: (1) reference bridges, (2) field bridges, (3) cluster bridges, and (4) proximate bridges. A reference bridge is defined as a bridge with the most detailed field evaluation. Field bridges are other bridges subjected to field evaluation, but on a more limited scale. Cluster bridges are bridges that are evaluated based on inspection reports. Proximate bridges are other bridges located within a specific distance of the other bridge types and having an age within a defined range of interest. The methodology for choosing each of these types of bridges is described in this section.

Two different reference bridge types were examined: “inferior” performing and “good” performing. An “inferior” cluster is a cluster based on a reference bridge that was identified by an owner as exhibiting poor UWS performance relative to other UWS bridges within the same agency. In contrast, a “good” cluster is identified based on various screening measures that indicated it was performing well despite being in an environment where below-average performance was expected.

The general methodology is the same for both cluster types, but some differences exist for some good clusters. In the majority of cases, the sequence of selecting bridges for each of the four bridge types is as follows, and is the order in which the details on the methodology are given below. The reference bridges are typically the known starting point, identified based on information from bridge owners and / or statistical evaluation of data in the UWS database (described in Chapter 2). Then proximate bridges are identified using GIS and age criteria (described in Section 2.1.1.1.4). Next cluster bridges are selected as a subset of the proximate bridges based on a rigorous statistical process described herein. Once the cluster bridges were identified, inspection reports from each of these structures were requested from their owners and the UWS condition of each of these structures was reviewed relative to the statistical classification of the influential parameters of the structure to select field bridges. In contrast, in some good clusters, a particular geographic region of interest was first identified , which meant that proximate bridges were the first to be identified and then bridges of interest to populate the other three categories were selected.

3.1.1 Reference Bridges

The selection of reference bridges was based on either a bridge identified by owners as one exhibiting poor UWS performance relative to other UWS bridges

within the same agency (i.e., are "state-recommended", as described in Section 3.1.1.1) or by filtering parameters of interest from the UWS database (which is described in Section 3.1.1.2). These methods are described in the following subsections. Generally the parametric evaluations were used to identify good reference bridges and the state recommendations were used to identify inferior reference bridges; however, in some cases parametric evaluations were used to also identify inferior reference bridge candidates when a general issue was raised by an owner without identifying a suitable corresponding reference bridge. The specific process used for each cluster considered in this work is later described in Section 3.2.

3.1.1.1 State-Recommended Reference Bridges

The state- recommended reference bridges were obtained from the state coordinators who responded to a UWS specific survey. The content and results of this survey will be discussed in the subsequent section.

3.1.1.1.1 Survey of Bridge Owners

The first step in determining state-recommended was to survey all LTBPP State coordinators, representing all 50 states, the District of Columbia and Puerto Rico. The full version of the survey can be seen in Appendix B and has been thoroughly discussed by McConnell et al (2012).

Of particular interest to the present discussion are Questions 3 and 4, which asked the respondents to identify any bridges with overall performance issues and provide a discussion of the condition and environment in which these bridges were located in order to inform potential causes of inferior performance. The responses to these questions were placed into one of the four categories: (1) none of the UWS

bridges within the agency have overall performance issues; (2) one or more bridges have inferior performance due to problematic details or maintenance issues such as having a timber deck or leaking joints; (3) one or more specific UWS bridges have an overall performance issue; or (4) there are overall performance issues related to UWS, but no specific bridges are mentioned (McConnell et al 2012).

Sixteen agencies provided specific bridges with overall performance issues related to UWS. A summary of the information provided by these agencies is listed in Table 3.1. Here it can be seen that the majority of these agencies noted that the environment in which these bridges are located is typically associated with use of deicing agents, a coastal environment, or both. Specifically, these agencies were often located in the north-eastern United States and the reported bridges often cross highways where there is regular use of deicing agents in the winter months. Agencies along the northern Gulf coast and northern Atlantic coast were those to note inferior performing bridges in coastal environments. The other states that reported problems with specific UWS bridges were Washington and Wyoming Indiana and Ohio also reported that some bridges within their jurisdiction suffer from inferior performance, but did not provide a listing of specific bridges and their associated environments (McConnell et al 2012).

The details given by the 16 agencies with specific bridges with overall performance issues lead to the creation of key categories of six interest. Alabama, Louisiana, and Mississippi fall into the "Coastal Category". The second, "Deicing Agent", category includes Colorado, Iowa, Maryland, Maine, Michigan, Minnesota, New York, and Wisconsin, which noted deicing salts being a likely factor affecting the performance of their UWS bridges with inferior performance. The third category is a

Table 3.1: UWS Bridges with Overall Performance Issues

Potential Cause of Inferior Performance	States		Number of Bridges
Coastal Location	2	AL, LA	3
Deicing Agents	8	CO, IA, MD, ME, MI, MN, NY, WI	17
Combination of Coastal Location and Deicing Agents	3	CT, MA, RI	5
Low-Water Crossing	1	PA	3
Site-Specific Effect	1	WY	1
Unknown	1	WA	1
TBD	2	IN, OH	TBD

combination of deicing agent use and coastal location. Rhode Island, Connecticut, and Massachusetts fall into this combination category. Pennsylvania's worst three bridges in terms of overall performance were all low-water crossings and thus were placed in a separate category. The bridge in Wyoming, located "over a hot spring that continually envelopes the bridge in stream which condensates on the girders", falls into the "Unique Environment Category" due to this unusual situation. Washington reported a structure located in elevated mountainous terrain where deicing agents are not used. Therefore, it was placed into the "Unknown Effect Category" since the cause of inferior overall performance is less clear in this situation (McConnell et al 2012).

It became clear after reviewing, organizing, and compiling the surveys that there were three dominate categories: deicing agents, coastal, and deicing agents + coastal. It was then decided to focus on the deicing agent and coastal categories in the present Phase II research, and address the combined category in future work. Bridges falling into other categories are deemed to be of lesser importance to achieving the

overall objective of informing general design and maintenance guidelines on a national basis. In summary, the list of bridges generated by the Phase I survey and given in Table 3.1 form the starting point for reference bridges in the inferior performance clusters. These bridges were then categorized and the most commonly-occurring issues (effects of deicing agents and coastal locations) were prioritized for evaluation in the present work. Additional considerations to further evaluate reference bridge candidates are discussed in the Section 3.1.1.1.2 below.

3.1.1.1.2 Other Considerations

After the state-recommended reference bridge candidates were identified by the survey of the state coordinators, the inspection reports for these reference bridge candidates were requested from the corresponding agencies. These were then reviewed to ensure that the condition of the selected reference bridge candidate was consistent overall inferior performance and screened to ensure that the bridge did not have any extraordinary unique details which would make translating the performance of the subject bridge to forming general conclusions on UWS performance difficult.

In instances where an agency recommended more than one reference bridge candidate, an effort was made to identify the best candidate within that agency. One criteria used in this process was to consider the number of potential proximate bridges within each reference bridge candidate based on a fixed radius (generally 50 miles) around the reference bridge candidates was also taken into consideration. A minimum of 10 bridges within the specified radius was established as a minimum threshold for a reference bridge candidate to be viable for further consideration. A second criteria was the relative performance of the reference bridge candidates within a given agency, with a strong inclination towards selecting the bridge with the overall worst UWS

performance. This was considered relative to the severity of the environment of the bridge based on the values of the influential parameters for that category type (e.g., deicing or coastal), which will be discussed in greater detail in Section 3.1.3.3. An example of selecting a state-recommended reference bridge (specifically, an inferior performing deicing category reference bridge in Maryland) is described in Section 3.2.1.2.

3.1.1.2 Filtering by Parameters of Interest

To determine good reference bridge candidates, a statistical evaluation of influential parameters in the UWS database was conducted to determine the bridges in the most severe environments and then the condition of these bridges were evaluated to determine those in the best condition despite being in a severe environment. This same concept was applied to also identify inferior performing bridges in some cases when an agency reported a specific problem (poor performance of coastal bridges in Louisiana), but could not readily identify a suitable reference bridge candidate that would adequately represent the general population of UWS bridges. However, in this case, bridges with the worst performance were sought.

To carry out this process, the database queries were first constrained to a geographical region of interest. This process is described in Section 3.1.1.2.1 and identified all bridges within the geography of interest, from which a candidate could later be identified. This then allowed the associated quantities of the influential variables in the UWS GIS database to be determined so that typical conditions and performance within that region could be quantified and good or inferior outliers could be identified, depending on the specific type of bridge desired. This process is described in Section 3.1.1.2.2.

3.1.1.2.1 Geographical Considerations

When the reference bridges did not originate from the direct suggestion of a state-coordinator, they were selected based on the desire to represent a specific geography-related variable. For example, good deicing and good coastal reference bridges were desired as well as an inferior performing coastal reference bridge. Thus, some preliminary decisions to constrain the geography of interest were necessary, e.g., bridges within 50 miles of the coastline or bridges where snowfall exceeds a particular threshold. Once these decisions were made for each cluster, specific examples of which are detailed in Section 3.2, the bridges satisfying the geographical constraints were identified in the UWS GIS database and exported to Microsoft Excel (2010) to facilitate the next step of the process, described below in Section 3.1.2.

3.1.1.2.2 Performance Considerations

The next step in identifying reference bridge candidates based on UWS GIS database values was to analyze the parametric values of the influential variables, which were a function of the cluster type, and identify outliers. For example, for the deicing clusters, ADT on underpasses, amount of annual snowfall, age of the structure, and its condition were key considerations. Thus, when a good deicing reference bridge candidate was desired, combinations of high ADT on underpasses, high snowfall, high age, and high superstructure condition ratings were used to identify preliminary candidates. An additional technique was to graph the superstructure condition rating versus age to facilitate identifying bridges that were at the extremes in terms of high age and high superstructure condition rating. Bridges built after 1964 and older than the age of 20 were examined (further discussed in Section 2. 1.1.1.4).

The specific parametric criteria and process used to identify each specific reference bridge where these techniques were used is subsequently described in Section 3.2.

3.1.2 Proximate Bridges

Following the selection of a reference bridge, proximate bridges are identified. These are identified by selecting the coordinates of the reference bridge as the center of a circle of a prescribed radius (typically 50 miles) in GIS. The GIS techniques previously described in Section 2.2.2 are then used to identify all the bridges within the circle thus circumscribed. This list was then filtered to remove bridges that were: (1) built, or reconstructed when applicable, prior to 1964 and (2) younger than 20 years old, as described in Section 2.1.1.1.4.

3.1.3 Cluster Bridges

The cluster bridges were selected as a subset of the proximate bridges based on a rigorous statistical evaluation of the key influential parameters (discussed in Section 2.1.1), which include bridge characteristics from NBI records (crossing type, vertical and lateral under-clearances, ADT under the structure, etc.), chemical concentrations, climatic variables, and geographical attributes unique to each bridge. The subsequent sections describe the statistical analyses performed, the process of using this analysis to categorize bridges, the rationale for choosing categories of interest, and then the rationale for choosing specific cluster bridges within the established categories of interest.

3.1.3.1 Statistical Analysis

For each of the proximate bridges within a cluster, values for each of the primary, secondary, and dependent parameters (listed in Tables 3.2 and 3.3) are

organized in a Microsoft Excel (2010) worksheet. Statistical analysis of the proximate bridge population is then performed to determine the mean, standard deviation, maximum value, minimum value, and median of the parameters. The value of each primary and secondary parameter of each bridge is then categorized as "high" or "low" based on its relationship to the median; if the value is greater than the median it is "high", while a value less than or equal to the median is considered "low." The median plus or minus one standard deviation was also computed and used to identify bridges as "very high" or "very low" to reveal bridges with more extreme parametric values so that these issues could be considered when making final cluster bridge selections. Using the median value as the division between "high" and "low" would ideally lead to half of half of the bridges being categorized as "high" and the other half as "low" for each parameter of interest. This was not the case though if a large proportion of the population had a parametric value equal to the median value.

Table 3.2: Parameter Classification for Deicing Clusters

Parameters	Primary	Secondary	Condition Attributes
Crossing Type	✓		
ADT	✓		
Vertical Under-Clearance	✓		
Lateral Under-Clearance	✓		
Relative Humidity	✓		
Snowfall	✓		
Time of Wetness		✓	
Cl^-		✓	
NO^{3-}		✓	
SO_2^{4-}		✓	
Age			✓
Superstructure Rating			✓

Table 3.3: Parameter Classification for Coastal Clusters

Parameters	Primary	Secondary	Condition Attributes
Distance to the Coast	✓		
Relative Humidity	✓		
Cl^-	✓		
Crossing Type		✓	
Time of Wetness		✓	
NO^{3-}		✓	
SO_2^{4-}		✓	
Age			✓
Superstructure Rating			✓

3.1.3.2 Bridge Categorization Based on Parametric Combinations

The different possible combinations of "high" and "low" for each of the parameters resulted in various possible parametric combinations, as shown in Table 3.4 for the deicing cluster and 3.5 for the coastal cluster. The parametric combinations involved varying each of the primary parameters one parameter at a time, with the exception of age and superstructure condition rating, which are classified as condition attributes rather than independent variables. Since waterway crossings were not a primary interest in the deicing clusters, bridges that only cross waterways are classified as category "W". Age was not taken into consideration in the parametric combinations because it was decided that the research objectives to evaluate performance as a result of differing conditions could be best met by keeping the age as high and consistent as possible within each cluster while allowing the other parameters to vary. A higher age allowed for performance over a greater time span, which serves as both a worst-case scenario and is most likely to lead to detecting any differences in performance in differing environments.

Table 3.4: Parametric Combinations for Phase II Deicing Clusters

Combination	Crossing	ADT of Crossing	Vertical Under-clearance	Lateral Under-clearance	Humidity	Annual Snowfall
1	Highway	High	Low	Low	High	High
2	Highway	High	Low	Low	High	Low
3	Highway	High	Low	Low	Low	High
4	Highway	High	Low	Low	Low	Low
5	Highway	High	Low	High	High	High
6	Highway	High	Low	High	High	Low
7	Highway	High	Low	High	Low	High
8	Highway	High	Low	High	Low	Low
9	Highway	High	High	Low	High	High
10	Highway	High	High	Low	High	Low
11	Highway	High	High	Low	Low	High
12	Highway	High	High	Low	Low	Low
13	Highway	High	High	High	High	High
14	Highway	High	High	High	High	Low
15	Highway	High	High	High	Low	High
16	Highway	High	High	High	Low	Low
17	Highway	Low	Low	Low	High	High
18	Highway	Low	Low	Low	High	Low
19	Highway	Low	Low	Low	Low	High
20	Highway	Low	Low	Low	Low	Low
21	Highway	Low	Low	High	High	High
22	Highway	Low	Low	High	High	Low
23	Highway	Low	Low	High	Low	High
24	Highway	Low	Low	High	Low	Low
25	Highway	Low	High	Low	High	High
26	Highway	Low	High	Low	High	Low
27	Highway	Low	High	Low	Low	High
28	Highway	Low	High	Low	Low	Low
29	Highway	Low	High	High	High	High
30	Highway	Low	High	High	High	Low
31	Highway	Low	High	High	Low	High
32	Highway	Low	High	High	Low	Low
33	Rail	NA	Low	not priority	High	not relevant
34	Rail	NA	Low	not priority	Low	not relevant
35	Rail	NA	High	not priority	High	not relevant
36	Rail	NA	High	not priority	Low	not relevant

Applying this process to the deicing cluster, Table 3.4 shows that there are 32 parametric combinations possible for independently varying the five primary variables for highway crossings. Because several of the parameters are not of primary interest for rail crossings, which do not have salted roadways beneath them as for highway bridges, there are an additional 4 parametric combinations for rail crossing. Water crossings were eliminated from detailed consideration, in consultation with the project manager, after it was revealed that there was insufficient information available to document clearances over water on a typical basis and that without this information there was little interest in further evaluating water crossings at the present time. Thus, all water crossings are placed into Category W. Other crossing types are too rare to be of primary consideration in this work. Thus, the total number of parametric combinations considered for the deicing cluster is 36 and the total number of categories is 37 including the water category.

There are two primary variables (excluding age) for the coastal category of bridges. The Cl^- concentration data is fairly course, this leads to all of the bridges within the relatively closely-defined coastal clusters that have been evaluated to date having the same Cl^- concentration. Thus, this parameter was removed from further consideration in the parametric categories and evaluated as a secondary variable. As a result, 4 parametric combinations are possible for the coastal clusters (see Table 3.5).

Each of the proximate bridges in the coastal and deicing clusters are categorized to a parametric combination unique to its "high" and "low" parametric values. For example, a bridge in a deicing cluster with high ADT, low vertical under-clearance, high lateral under-clearance, low humidity, and high annual snowfall would

Table 3.5: Parametric Combinations for Phase II Coastal Cluster

Combination	Distance to Coast	Humidity
1	Low	High
2	Low	Low
3	High	Low
4	High	High

be placed in Category 7 (see Table 3.4). Bridges that crossed more than one attribute were preliminarily categorized based on both crossing types and a final categorization was made after the parametric combinations of interest were identified, as described below in Section 3.1.3.3.

3.1.3.3 Selected Categories from Parametric Combinations

After the proximate bridges within a cluster are categorized by their parametric combinations, a subset of these is selected to comprise the cluster bridges. Specifically, the targeted parametric combinations are selected by establishing a baseline parametric combination (typically either the worst-case scenario defined below and / or the category corresponding to the reference bridge) and then varying each of the primary variables one at a time to establish the other parametric combinations of greatest interest. For example, for the deicing category, the worst-case scenario having the most severe parametric categories of each parameter is Combination 1 (see Table 3.4). Thus, if a reference bridge was in this category, then the remaining highway crossing combinations of interest would be 2, 3, 5, 9, and 17, which would independently vary snowfall, humidity, lateral under-clearance, vertical under-clearance and ADT, respectively. Combination 32 is also included where possible as an opposite extreme.

Tables 3.6 and 3.7 list the targeted parametric combinations based on the baseline category being the worst-case scenario (Combination 1) for both clusters. Ideally, this process will allow cluster bridges with specific parametric combinations to be compared to the baseline category in order to reveal how the varied parameter affects the UWS performance.

3.1.3.4 Selecting Specific Cluster Bridges

Once all bridges have been categorized and the categories of interest identified, specific bridges within those categories are then selected as the cluster bridges. In order to assess repeatability in any findings that are observed, a minimum of two bridges in each category is selected when possible, or a minimum of two bridges from closely-related categories are typically used otherwise. For the coastal category, which has fewer categories, an effort is made to include at least three bridges in each category of interest.

In cases where more bridges are assigned to a category of interest than are reasonable to include in the intended cluster size of 10 to 20 bridges, an effort is made select bridges that are as similar to the reference bridge as possible, with only the parametric value that is intended to be varied by the category under consideration being varied. In other words, the goal is for not only the "high" or "low" designation kept constant except for one variable, but the specific values within those categories to also remain as constant as possible. For example, if the reference bridge has an ADT of 70,000 and an annual snowfall of 23 inches, when cluster bridges with different humidity values are sought, bridges that have similar values of ADT and snowfall are prioritized.

Table 3.6: Targeted Parametric Combinations for Deicing Clusters

Combination	Crossing	ADT of Crossing	Vertical Under-clearance	Lateral Under-clearance	Humidity	Annual Snowfall	Notes
1	Highway	High	Low	Low	High	High	Worst-case scenario
2	Highway	High	Low	Low	High	Low	Vary snowfall
3	Highway	High	Low	Low	Low	High	Vary humidity
5	Highway	High	Low	High	High	High	Vary lateral under-clearance
9	Highway	High	High	Low	High	High	Vary vertical under-clearance
17	Highway	Low	Low	Low	High	High	Vary ADTT
32	Highway	Low	High	High	Low	Low	Best-case scenario for highway
33	Rail	NA	Low	not priority	High	not relevant	Worst-case rail
35	Rail	NA	High	not priority	High	not relevant	vary under-clearance

Table 3.7: Targeted Parametric Combinations for Coastal Clusters

Combination	Distance to Coast	Humidity	Notes
1	Low	High	Worst Case
2	Low	Low	Vary Humidity
4	High	High	Vary Distance

Additionally, for the parameter being varied, preference is also given to cluster bridge candidates where the parameter has a value at a high or low extreme, in the hopes that this will better reveal influences of these parameters. For example, if the purpose of a given selected parametric combination is to have low snowfall and there are bridges in that category with annual snowfall values of 8, 12, and 13 inches, the bridge with the 8 in. annual snowfall will be selected assuming this also has equivalent similarity to the reference bridge based on the other parametric values as described above.

A final consideration in selecting specific cluster bridges is the superstructure condition rating. Since this is treated as a dependent variable, no effort is generally made to select bridges with a specific superstructure condition rating. However, if multiple bridges populate the same parametric combination category, then the average superstructure condition rating of the bridges within that category is evaluated and an effort is thus made to choose cluster bridges that are representative of this average when selecting cluster bridges to represent that parametric combination category.

This statistical and decision making process led to a list of typically 10 to 20 cluster bridges. The inspection reports for each of these cluster bridges were then requested and reviewed to complete the next steps of this research, including the selection of field bridges, which is described below in Section 3.1.4.

3.1.4 Field Bridges

Field bridges (additional bridges subjected to field work, at a more modest scale relative to the reference bridge) were selected after receiving the inspection reports on all cluster bridges. These reports were carefully evaluated, with particular focus on tabulating condition state information of CoRe elements (FHWA 2006,

which will be described in Section 4.1.1.1) and key words relating to UWS issues or corrosion as well as considering all photographs of UWS performance that were provided. Addition details on the information compiled as a result of this process can be found in Chapter 4.

Two of these bridges were then selected as field bridges, one generally representing the best condition bridge within the cluster and the other representing the worst condition bridge within the cluster. Here, best and worst are assessed based largely on the percentages of the girders and other UWS elements in various condition states, which is considered relative to age and severity of the parametric category. For example if two bridges have all of the superstructure in Condition State 1 (the best condition) but one bridge has more snowfall than another and all other parameters are equal, then it would be said that the bridge with greater snowfall was "best". In identifying the "worst" cluster bridge, information from the inspection reports was assessed to determine if advanced condition states were the result of leaking joints or other known problematic details and these bridges were eliminated from consideration as field bridges. Examples within Section 3.2.1 will fully explain any additional rationale needed to select the specific bridges used in this work to date. .

3.2 Examples

This research study was divided into Phase II and Phase III. Phase II involves four clusters, containing all possible combinations of deicing versus coastal clusters and good versus inferior-performing clusters. This is the phase of work that was the current primary effort and the selection of the specific bridges selected for evaluation in Phase II is detailed below in Section 3.2.1.

Phase III will involve additional samples of these cluster types as well as other cluster types. Preliminary efforts on selecting bridges for evaluation in Phase III will be described in Section 3.2.2.

3.2.1 Phase II

Considering that the scope of the present work was to evaluate four UWS clusters, a decision on which type of clusters would be evaluated was necessary. Given there was an interest in evaluating both good and inferior clusters and the coastal and deicing categories, this led to choosing one cluster representing each of the four possible combinations of these categories. The rationale behind choosing the reference, proximate, cluster, and field bridges for three of these clusters completed at the time of this writing will be discussed in the subsequent sections.

3.2.1.1 Good Deicing (New York)

The first step in forming the good deicing cluster was to identify a good-performing bridge with advanced age in a region where high annual snowfall occurs. In addition, because a primary interest in this work, based on the survey responses discussed in Section 3.1.1 was performance of UWS bridges that serve as highway overpasses over salted roadways, a bridge serving as a highway overpass and crossing a facility with a high ADT was also of paramount importance.

As a preliminary step in this effort, the superstructure condition ratings versus age (calculated as described in Section 3.1.1.2.2) were considered for UWS bridges within each state where appreciable annual snowfall exists (based on Figure 3.1) and for which the UWS inventory was available. Specifically, the agencies considered were: Maryland, Virginia, West Virginia, Maine, New Hampshire, Vermont,

Pennsylvania, New York, Michigan, Wisconsin, Minnesota, Iowa, Montana, Illinois, Arkansas, Colorado, Wyoming, Missouri, and Idaho. For each state-level population, the average age and average superstructure condition rating were then calculated and tabulated. Superstructure condition rating versus age was also plotted for each bridge in these state-level datasets and used to calculate a linear trend-line approximating the superstructure condition rating versus age for that population. These results are summarized by Table 3.8, which was compiled in an effort to reveal the agencies with the average best performance, such that specific bridges meeting the desired objectives within those agencies could be sought.

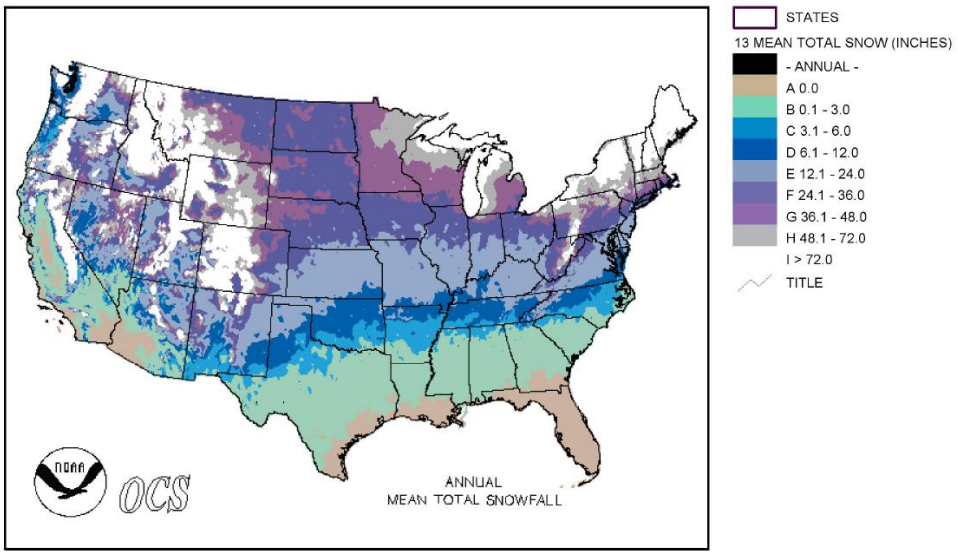

Figure 3.1: U.S. Annual Total Snowfall (NOAA, 2002)

Table 3.8: Superstructure Condition Rating as a Function of Age for UWS Bridges in Agencies experiencing Appreciable Snowfall (for population 1-49 years)

	Average Age	Average Rating	Trend line Equation Rating = f(Age)
Maryland	27.2	6.8	y = -0.0405x + 7.8965
Virginia	18.9	7.0	y = -0.0569x + 8.1117
West Virginia	9.8	8.0	y = -0.0657x + 8.6035
Maine	**21.3**	**7.8**	y = -0.0382x + 8.5857
New Hampshire	**22.1**	**7.8**	y = -0.0378x + 8.6465
Vermont	**23.8**	**7.8**	y = -0.0047x + 7.9021
New York	**19.2**	**7.8**	y = -0.0518x + 8.8227
Pennsylvania	21.5	7.0	y = -0.0532x + 8.1748
Michigan	31.3	6.5	y = 0.0003x + 6.531
Wisconsin	32.1	7.0	y = -0.0153x + 7.4507
Minnesota	32.1	7.1	y = -0.0358x + 8.221
Iowa	10.7	8.0	y = -0.0412x + 8.4493
Montana	15.6	7.2	y = -0.0264x + 7.6047
Illinois	24.0	6.9	y = -0.0647x + 8.4505
Arkansas	16.3	7.7	y = -0.0406x + 8.3776
Colorado	22.4	6.8	y = -0.0716x + 8.3966
Wyoming	19.4	6.0	y = -0.0019x + 6.0219
Missouri	17.8	7.8	y = -0.0717x + 9.0922
Idaho	17.2	7.4	y = -0.0542x + 8.2888

These average superstructure condition ratings vs. average age for each agency were then plotted, as shown in Figure 3.2. Based on the criteria that agencies appearing the greatest distance above the trend line (seen in Figure 3.2) have the best average performance, Vermont, New Hampshire, Maine, and New York, in that order, were identified as being the best candidates for agencies containing potential good deicing clusters. These states were sequentially evaluated to identify potential good deicing reference bridges within these populations (and appear in bold in Table 3.8).

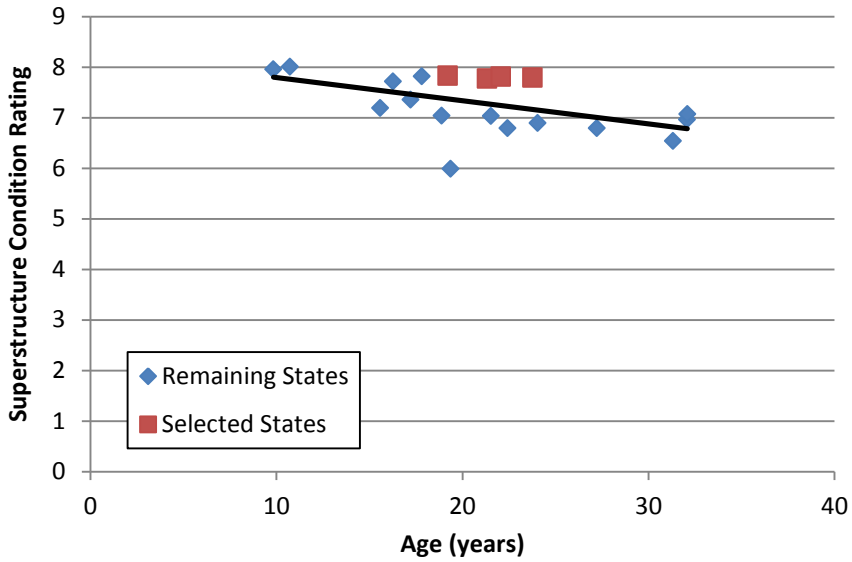

Figure 3.2: Average Superstructure Condition Rating vs. Average Age for Agencies Receiving Appreciable Snowfall

This evaluation consisted of compiling the parametric values of the influential parameters (as previously described in Section 3.1.3.1) and then categorizing the bridges within each identified state agency using the deicing parametric combinations shown in Table 3.4. Bridges that were classified as having both a "high" snowfall and a "high" ADT were sought. This evaluation showed that neither Maine nor Vermont had any bridges occupying such categories. New Hampshire bridges matching the desired parametric grouping were revealed to have painted weathering steel upon receipt of the corresponding inspection reports. Ultimately, New York was revealed to have two bridges that fit the desired criteria of high snowfall and high ADT under the structure coupled with very good performance as quantified by a superstructure condition rating of an 8 or above at over 20 years of age. Therefore, New York was chosen as the agency to represent a "good" cluster for the deicing agent category and

the selection of specific reference, proximate, cluster, and field bridges proceeded as described below.

In parallel with this work, an alternative process of searching for good performing outliers was executed. Specifically, the NBI data from the remaining states listed in Table 3.8, with the exception of Maryland and Virginia because bridges from these states were represented in the inferior-performing deicing cluster (Minnesota, Michigan, Arkansas, Colorado, Idaho, West Virginia, Pennsylvania, Wisconsin, Iowa, Montana, Illinois, Wyoming, and Missouri) were filtered to search for bridges that were outliers with respect to good performance despite severe deicing conditions. Specifically, the parameters used to filter the bridges were: age (between 49-20 years old, old enough that bridge had been in service through many winters but young enough that modern UWS was possibly used); very good or excellent superstructure condition rating (8 or above); high ADT under the structure such that the roadway would likely be treated with deicing agents during severe weather (over 50,000); and sufficient annual snowfall to make it likely that multiple treatments of deicing agents would be applied per year (over 20”). These quantifications were based on assessing the typical values of these parameters in the UWS database and then attempting to set relatively high thresholds such that a small number of bridges would result.

As a result, there were 12 bridges fitting these criteria, which are listed in Table 3.9. As can be seen in this table, the majority of these are in Michigan and requests for follow-up information on these bridges were unsuccessful. Given Michigan’s history with UWS bridges, it is suspected that these bridges have been painted or had other remedial efforts performed. Inquiries into the details of the two

bridges from Colorado were also made and it was determined that these bridges do meet the criteria for good performing deicing reference bridges.

At this stage, a comparison between the New York and Colorado candidates was made and it was determined that the New York candidates would become the focus of Phase II due to the more similar climates of Maryland and New York versus Maryland and Colorado since a decision had been made at this point to use a Maryland bridge as the inferior-performing deicing reference bridge (as will be further explained in Section 3.2.1.2. The process for selecting specific reference, proximate, cluster, and field bridges in New York is explained in Sections 3.2.1.2.1 through 3.2.1.2.4, immediately below. The Colorado bridges serve as the basis for a potential cluster for consideration in Phase III and are thus discussed in Section 3.2.2.3.

3.2.1.1.1 Reference Bridge Selection

The analysis described in Section 3.2.1.1 revealed that New York had two bridges that fit the desired criteria of high snowfall and high ADT under the structure. Age and superstructure condition rating were additional considerations in selecting these two bridges for further consideration, where both of these structures had similar ages of 32 and 30 and superstructure condition ratings of 8 in the 2011 NBI that was being used at that time. The first one was located near Rochester and the other near Buffalo and these bridges will be referenced accordingly in the in the discussion that follows.

Inspection reports for both of these bridges were requested and received. Upon review of these, it was observed that the superstructure condition rating of the Rochester bridge had decreased to 7 after the most-recent inspection of this structure. Other notes in the inspection reports also suggested that the Buffalo bridge had

Table 3.9: Good Deicing Candidates Resulting from Parameter Filtering Method

STATE	SUPERSTRUCTURE CONDITION RATING	ADT UNDER THE STRUCTURE	AGE (years)	SNOWFALL (inches)
CO	8	84000	31	62.6
CO	8	62500	31	62.6
ID	8	57000	24	21.3
MI	8	199900	41	26.8
MI	8	199900	41	26.8
MI	8	176060	42	26.8
MI	8	163508	42	30.8
MI	8	157192	41	26.8
MI	8	154300	34	33.3
MI	8	107776	41	30.8
MI	8	104464	39	41.7
MI	8	93220	42	30.8

superior condition to the Rochester bridge. Thus, the Buffalo Bridge (A10) was selected as the reference bridge for the Phase II good deicing agent cluster.

It is interesting to note however that, despite previously-reported problems with Rochester area bridges (McMahon and McFadden 2014), this Rochester bridge significantly out-performs others in the national population when considering the severity of the environment in which it is located. The Rochester bridge has an ADT of 122,170 on the underpass and an annual snowfall of 93 inches, suggesting that it is subjected to well above average applications of deicing agents, yet is still rating as having a “good” superstructure after 32 years of service.

3.2.1.1.2 Proximate Bridge Selection

A GIS point of reference analysis (described in Section 2.2.2) was conducted on the Buffalo reference bridge with a radius of 50 miles. The results are then filtered to exclude bridges newer than 20 years old and older than 49 years old, for reasons

previously explained in Section 2.1.1.1.1. An excerpt of the resulting list of bridges is displayed in Table 3.10, with the proximate bridges sorted by their appropriate parametric combination categories, bridge labels, and crossing types, in that order. The data is divided into three sections: primary variables, secondary variables, and condition attributes. These groupings contain the numerical value of each parameter for each bridge and their high ("H") or low ("L") categorization based on the statistical analysis discussed in Section 3.1.3.1. The specific primary variables, secondary variables, and condition attributes for the deicing cluster are discussed in Section 3.1.3.1.a. The statistics for the cluster can be found at the bottom of the table, which includes the median values used to determine the "high" and "low" and parametric classifications. Because there are a total of 89 proximate bridges within the cluster, only representative bridges in categories of interest or that will ultimately be included in the cluster for other reasons, (as discussed in Section 3.2.1.1.3) are listed in the table for conciseness.

3.2.1.1.3 Cluster Bridge Selection

After identifying the proximate bridges, the statistical analysis of the cluster was performed. As previously described in Section 3.1.3.1, this primarily consists of determining the median value of each of the influential variables for a deicing cluster and then classifying each bridge as having a high or low value with respect to each of these parameters. Each of the proximate bridges was then categorized using the process previously described in Section 3.1.3.2. The next step was to identify the categories of interest. Because the reference bridge was categorized as Category 10,

Table 3.10: Proximate Bridges in Parametric Categories of Interest, New York

			PRIMARY VARIABLES														SECONDARY VARIABLES								CONDITION ATTRIBUTES			
CATEGORY	STRUCTURE ID	CROSSING TYPE	ADT UNDER STRUCTURE		VERTICAL UNDER-CLEARANCE (m)		MINIMUM LATERAL UNDER-CLEARANCE (m)		RELATIVE HUMIDITY (%)		SNOWFALL (in)		TOW (hours/year)		Cl (mg/L)		NO3 (mg/L)		SO4 (mg/L)		AGE (years)		SUPER STRUCTURE RATING	
			Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L
10	A7	Highway	15150	H	5.1	L	2.0	L	0F, 11G, 1H	H	92.2	L	2630	L	0.073	L	0.879	L	1.150	L	30	H	7	L
10	A8	Highway	15150	H	5.3	H	2.0	L	0F, 11G, 1H	H	92.2	L	2630	L	0.073	L	0.879	L	1.150	L	30	H	7	L
10	A9	Highway	33156	H	5	H	2.0	L	0F, 11G, 1H	H	92.2	L	2630	L	0.073	L	0.879	L	1.150	L	30	H	7	L
10	**A10**	**Highway**	**70341**	**H**	**5.15**	**H**	**3.0**	**L**	**0F, 11G, 1H**	**H**	**92.2**	**L**	**2630**	**L**	**0.073**	**L**	**0.879**	**L**	**1.150**	**L**	**30**	**H**	**8**	**L**
14	A11	Highway	8500	H	4.55	H	4.3	H	0F, 11G, 1H	H	92.2	L	2630	L	0.073	L	0.879	L	1.150	L	29	L	8	L
18	A12	Highway	6400	L	4.44	L	3.0	L	0F, 11G, 1H	H	92.2	L	2630	L	0.073	L	0.879	L	1.150	L	29	L	8	L
18	A13	Highway	400	L	4.42	L	3.0	L	0F, 11G, 1H	H	92.2	L	2894	H	0.073	L	0.879	L	1.150	L	22	L	9	H
22	A14	Highway	6400	L	4.45	L	3.4	H	0F, 11G, 1H	H	92.2	L	2630	L	0.073	L	0.879	L	1.150	L	29	L	8	L
22	A15	Highway	5775	L	4.37	L	6.7	H	0F, 11G, 1H	H	92.2	L	2630	L	0.073	L	0.879	L	1.150	L	29	L	8	L
24	A16	Highway	5863	L	4.41	L	7.3	H	2F, 10G, 0H	L	90.1	L	2630	L	0.049	L	0.732	L	0.932	L	24	L	8	L
26	A17	Highway+Waterway			4.52	H	2.4	L	0F, 11G, 1H	H	92.2	L	2630	L	0.073	L	0.879	L	1.150	L	29	L	7	L
26	A18	Highway	400	L	4.55	H	2.0	L	0F, 11G, 1H	H	92.2	L	2894	H	0.073	L	0.879	L	1.150	L	22	L	9	H
26	A19	Highway+Waterway			5.02	H	3.0	L	0F, 11G, 1H	H	60.4	L	2937	H	0.049	L	0.732	L	0.932	L	42	H	6	L
30	A20	Highway	3850	L	4.6	H	3.2	H	0F, 11G, 1H	H	92.2	L	2630	L	0.073	L	0.879	L	1.150	L	30	H	8	L
30	A21	Highway	3850	L	4.64	H	3.7	H	0F, 11G, 1H	H	92.2	L	2630	L	0.073	L	0.879	L	1.150	L	30	H	8	L
30	A22	Highway	5775	L	4.55	H	6.7	H	0F, 11G, 1H	H	92.2	L	2630	L	0.073	L	0.879	L	1.150	L	29	L	8	L
31	A23	Highway+Waterway			17.75	H	9.0	H	1F, 10G, 1H	L	153.6	H	2630	L	0.073	L	0.879	L	1.150	L	22	L	8	L
33	A24	Railroad			6.24	H			0F, 10G, 2H	H	93.0	H	2937	H	0.049	L	0.732	L	0.932	L	37	H	6	L
33	A25	Railroad			6.14	H			0F, 10G, 2H	H	92.2	L	2630	L	0.073	L	0.879	L	1.150	L	32	H	7	L
33	A26	Railroad			5.99	H			0F, 10G, 2H	H	92.2	L	2630	L	0.073	L	0.879	L	1.150	L	32	H	6	L
33	A27	Railroad			6.4	H			0F, 10G, 2H	H	92.2	L	2630	L	0.073	L	0.879	L	1.150	L	35	H	8	L
34	A28	Railroad				L			4F, 8G, 0H	L	93.3	H	2630	L	0.049	L	0.732	L	0.932	L	23	L	8	L
36	A29	Railroad			6.62	H			1F, 10G, 1H	L	60.4	L	2630	L	0.049	L	0.732	L	0.932	L	29	L	7	L
36	A30	Railroad			6.62	H			2F, 10G, 0H	L	90.1	L	2937	H	0.049	L	0.732	L	0.932	L	22	L	8	L
36	A31	Railroad			6.22	H			4F, 8G, 0H	L	93.3	H	2630	L	0.049	L	0.732	L	0.932	L	22	L	8	L
37	A32	Waterway			4	L			0F, 11G, 1H	H	92.2	L	2894	H	0.073	L	0.879	L	1.150	L	47	H	6	L
37	A33	Waterway			2	L			0F, 11G, 1H	H	92.2	L	2894	H	0.073	L	0.879	L	1.150	L	31	H	8	L
38	A34	Waterway			4	L			1F, 10G, 1H	L	86.6	L	2894	H	0.073	L	0.879	L	1.150	L	28	L	8	L
18,38	A35	Highway+Waterway	1860	L	4.37	L	1.8	L	0F, 11G, 1H	H	92.2	L	2894	H	0.073	L	0.879	L	1.150	L	25	L	8	L
18,39	A36	Highway+Waterway			4.44	L	3.0	L	0F, 11G, 1H	H	60.4	L	2937	H	0.049	L	0.732	L	0.932	L	42	H	6	L
26,35	A37	Highway+Railroad			6.48	H	0.8	L	0F, 10G, 2H	H	92.2	L	2630	L	0.073	L	0.879	L	1.150	L	31	H	8	L
30,35	A38	Highway+Railroad	4300	L	6.45	H	3.1	H	0F, 10G, 2H	H	92.2	L	2630	L	0.073	L	0.879	L	1.150	L	26	L	8	L
W	A39	Waterway		L					4F, 8G, 0H	L	153.6	H	2630	L	0.073	L	0.879	L	1.150	L	25	L	5	L
W	A40	Waterway		L					2F, 10G, 0H	L	138.5	H	2707	H	0.073	L	0.879	L	1.150	L	33	H	9	H
	MEAN		13286		5		4		3.3F, 8.2G, 0.5H		104		2682		0.067		0.843		1.036		28.7		7.8	
	STANDARD DEV		15407		2		2		2.0F, 1.5G, 1.0H		28		107		0.010		0.064		0.095		6.0		0.8	
Statistics	MAX		70341		18		9		0F, 11G, 1H		154		2937		0.073		0.879		1.150		47.0		9.0	
	MIN		400		4		1		4F, 8G, 0H		60		2630		0.049		0.732		0.932		20.0		5.0	
	MEDIAN		7450		5		3		1F, 11G, 0H		92.2		2630		0.073		0.879		1.150		29.0		8.0	

the remaining categories of primary interest are those that result in varying only one primary parameter at a time, i.e., Categories 2, 9, 12, 14, 26, and 35. Category 33 represents varying the vertical under-clearance of the rail crossing. Additionally, Categories 1 and 32 represent the worst- and best-case scenarios with respect to severity of environment and would ideally be included, but no bridges populate these categories and thus these categories were not included.

However, Table 3.10 shows that many of these categories are not populated with any bridges or only one bridge, while a minimum of two bridges is desired to confirm any trends that may be revealed. As a result, the following substitutions were made. The resulting list of cluster bridges is summarized in Table 3.11.

- Category 2, vary vertical under-clearance: The one existing Category 2 bridge (A1) is used. In place of a second Category 2 bridge, the Category 6 bridge (which differs from Category 2 in only the lateral under-clearance being high instead of low) with the lowest lateral under-clearance is selected, which is Bridge A3.
- Category 9, vary snowfall: Since no bridges were categorized as Category 9, the best available options were Bridges A19 and A37, (which were originally classified as Categories 18 and 26, respectively). There are only three bridges with snowfall values different from the reference bridge within the cluster and the selected two bridges are the only pair of bridges available that have a similar amount of annual snowfall as one another (60.4 in.) to enable potential repeatability in the findings while also being different from the reference bridge.

- Category 10, baseline category: Bridge A9 was selected as a second Category 10, in addition to the reference bridge, as it was the bridge with parametric values most similar to the reference bridge. This will enable an assessment of whether there are other factors contributing to differences in performance of these two structures.
- Category 12, vary humidity: Since no bridges populate Category 12, Bridges A16 and A23 were the best options available that are as similar as possible to the reference bridge except for having lower humidity values. These bridges were originally classified into Categories 24 and 31, respectively.
- Category 14, vary lateral under-clearance: The one bridge classified as Category 14 (A11) is used. In addition, Bridge A5 (originally classified as Category 6 and having an ADT of 22,000) is used as a second bridge with high lateral under-clearance because this bridge also helps bridge the gap between the large difference in ADT values between the reference bridge (71,000) and Bridge A11 (8,500), despite both being classified as having high ADT.
- Category 26, vary ADT: While three Category 26 bridges exist, none of these were selected to represent this category. One of the three, Bridge A19, was deemed as the best option available for evaluating variable snowfall, so will be used in the cluster for that purpose. A second option, Bridge A17, was eliminated since the ADT for this structure, while presumably "low", is unknown. While the remaining Category 26 bridge was a potential option, ultimately two Category 30 bridges

(A20 and A21) were deemed to best represent possible variations in ADT as the lateral under-clearance of these bridges was more similar to the reference bridge than the remaining Category 26 bridge (A18).

- Category 33, vary lateral under-clearance of railroad crossing: Four bridges exist in Category 33. The two of these with the lowest vertical under-clearance (A25 and A26) were selected for inclusion in the cluster as these two bridges also had parametric values similar or equal to those of the reference bridge for the remaining influential variables.
- Category 35, vary crossing type to railroad: Two Category 35 bridges (A37 and A38) exist and were used to populate this category in the cluster.

Other bridges were also included in the cluster because there superstructure condition rating was much higher or lower than expected relative to the structure's age. One of these is Bridge A40, which is the oldest bridge (with an age of 33 years at the time of this writing) with a superstructure condition rating of 9. The second is Bridge A27, which of the two oldest bridges (at 35 years at the time of this writing) having a rating of 8, A27 is the one located in the more humid environment. Conversely, Bridge A39 is included because it is the sole bridge in this population with a superstructure condition rating of 5 or lower despite having an age of only 25 years at the time of this writing.

Lastly, while it had been decided to remove low water crossings as an area of focus for this research due to the lack of a means to readily determine which bridges fit this criteria. Bridge A33 was a rare example where a navigation clearance is

recorded and this value is listed in the NBI as being only 2 m., fitting the definition of a low water clearance. Thus bridge was also included in the cluster.

Once these bridges were selected, the condition versus age of these cluster bridges was plotted relative to the same data for the proximate bridges to ensure that the cluster bridges adequately represent the condition of the larger population of which they are a part. This comparison is shown in Figure 3.3, where it is demonstrated through the trend lines shown here that this is the case.

3.2.1.1.4 Field Bridge Selection

The inspection reports for all of the cluster bridges listed in Table 3.11 were requested, received, and then reviewed to identify the best- and worst-performing bridges to serve as the field bridges, as previously discussed in Section 3.1.4. A summary of the inspection reports for all cluster bridges will be discussed in Section 4.2.1. This shows that Bridge A3 did not have any UWS related issues noted in the inspection report while also having parametric values more than severe than the median for most primary variables, equal to the median for snowfall, and only less severe than the median for lateral under-clearance. This bridge was thus selected as the best performing UWS bridge within this cluster. The worst-performing bridge is Bridge A9, the girders of which are noted as having delaminations approximately 1/16 to 1/8" thick.

Table 3.11: Cluster Bridges, New York

			PRIMARY VARIABLES																SECONDARY VARIABLES								CONDITION ATTRIBUTES			
CATEGORY	STRUCTURE ID	CROSSING TYPE	ADT UNDER STRUCTURE		VERTICAL UNDER-CLEARANCE (m)		MINIMUM LATERAL UNDER-CLEARANCE (m)		RELATIVE HUMIDITY (%)		SNOWFALL (in)		TOW (hours/year)		Cl (mg/L)		NO3 (mg/L)		SO4 (mg/L)		AGE (years)		SUPER STRUCTURE RATING	
			Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L
2	A1	Highway	21600	H	4.44	L	3.0	L	0F, 11G, 1H	H	32.2	L	2630	L	0.073	L	0.879	L	1.150	L	26	L	8	L
6	A3	Highway+Waterway	15198	H	4.37	L	3.7	H	0F, 11G, 1H	H	32.2	L	2630	L	0.073	L	0.879	L	1.150	L	31	H	8	L
6	A5	Highway	22015	H	4.39	L	5.0	H	0F, 11G, 1H	H	32.2	L	2630	L	0.073	L	0.879	L	1.150	L	29	L	8	L
10	A9	Highway	33156	H	5	H	2.0	L	0F, 11G, 1H	H	32.2	L	2630	L	0.073	L	0.879	L	1.150	L	30	H	7	L
10	**A10**	**Highway**	**70941**	H	**5.15**	H	**3.0**	L	**0F, 11G, 1H**	H	**32.2**	L	**2630**	L	**0.073**	L	**0.879**	L	**1.150**	L	**30**	H	**8**	L
14	A11	Highway	8500	H	4.55	H	4.3	H	0F, 11G, 1H	H	32.2	L	2630	L	0.073	L	0.879	L	1.150	L	29	L	8	L
24	A16	Highway	5869	L	4.41	L	7.3	H	2F, 10G, 0H	L	30.1	L	2630	L	0.049	L	0.732	L	0.932	L	24	L	8	L
26	A19	Highway+Waterway			5.02	H	3.0	L	0F, 11G, 1H	H	60.4	L	2937	H	0.049	L	0.732	L	0.932	L	42	H	6	L
30	A20	Highway	3850	L	4.6	H	3.2	H	0F, 11G, 1H	H	32.2	L	2630	L	0.073	L	0.879	L	1.150	L	30	H	8	L
30	A21	Highway	3850	L	4.64	H	3.7	H	0F, 11G, 1H	H	32.2	L	2630	L	0.073	L	0.879	L	1.150	L	30	H	8	L
31	A23	Highway+Waterway			17.75	H	9.0	H	1F, 10G, 1H	L	153.6	H	2630	L	0.073	L	0.879	L	1.150	L	22	L	8	L
33	A25	Railroad			6.14	H			0F, 10G, 2H	H	32.2	L	2630	L	0.073	L	0.879	L	1.150	L	32	H	7	L
33	A26	Railroad			5.99	H			0F, 10G, 2H	H	32.2	L	2630	L	0.073	L	0.879	L	1.150	L	32	H	6	L
33	A27	Railroad			6.4	H			0F, 10G, 2H	H	32.2	L	2630	L	0.073	L	0.879	L	1.150	L	35	H	8	L
37	A33	Waterway			2	L			0F, 11G, 1H	H	32.2	L	2894	H	0.073	L	0.879	L	1.150	L	31	H	8	L
18,39	A36	Highway+Waterway			4.44	L	3.0	L	0F, 11G, 1H	H	60.4	L	2937	H	0.049	L	0.732	L	0.932	L	42	H	6	L
26,35	A37	Highway+Railroad			6.48	H	0.8	L	0F, 10G, 2H	H	32.2	L	2630	L	0.073	L	0.879	L	1.150	L	31	H	8	L
30,35	A38	Highway+Railroad	4300	L	6.45	H	3.1	H	0F, 10G, 2H	H	32.2	L	2630	L	0.073	L	0.879	L	1.150	L	26	L	8	L
W	A39	Waterway		L					4F, 8G, 0H	L	153.6	H	2630	L	0.073	L	0.879	L	1.150	L	25	L	5	L
W	A40	Waterway		L					2F, 10G, 0H	L	138.5	H	2707	H	0.073	L	0.879	L	1.150	L	33	H	9	H
	MEAN		13286		5		4		3.3F, 8.2G, 0.5H		104		2682		0.067		0.843		1.096		28.6		7.8	
	STANDARD DEV		15407		2		2		2.0F, 1.5G, 1.0H		28		107		0.010		0.064		0.095		6.1		0.8	
Statistics	MAX		70941		18		9		0F, 11G, 1H		154		2937		0.073		0.879		1.150		47.0		9.0	
	MIN		400		4		1		4F, 8G, 0H		60		2630		0.049		0.732		0.932		17.0		5.0	
	MEDIAN		7450		5		3		1F, 11G, 0H		32.2		2630		0.073		0.879		1.150		29.0		8.0	

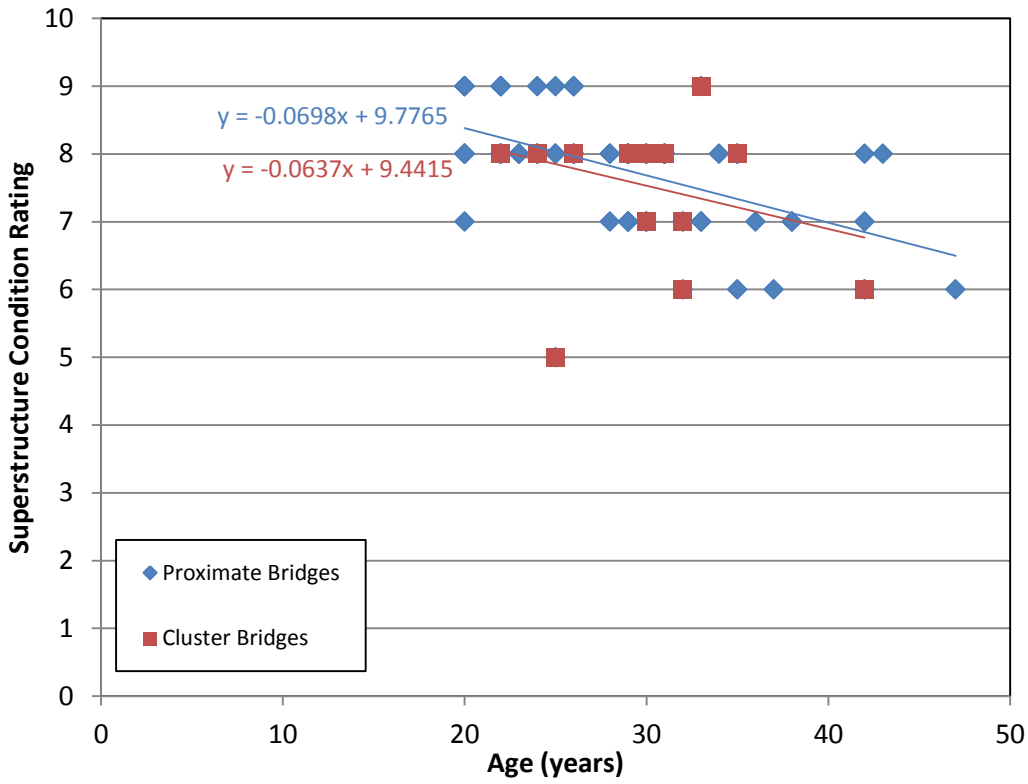

Figure 3.3: Superstructure Condition Rating versus Age, New York

3.2.1.2 Inferior Deicing (Maryland)

The inferior-performing deicing cluster was selected based on a reference bridge candidate identified through the survey discussed in Section 3.1.1.1.1, the desire to have some of the clusters used in this work to overlap with the clusters being used in the larger LTBPP program, and the added benefit that a promising candidate was in close proximity to the research team's location in Delaware. As a result, inspection reports were requested for the three reference bridge candidates identified by the Maryland state coordinator. Upon reviewing these reports, it was found that all

three satisfied the criteria for inferior overall performance and thus it was decided to move forward with establishing a cluster around one of these three bridges. The specific process of choosing the reference, proximate, cluster, and field bridges for this cluster is discussed below in Sections 3.2.1.2.1 through 3.2.1.2.4.

3.2.1.2.1 Reference Bridge Selection

For the reasons discussed in the previous paragraph, a reference bridge in Maryland was the most desirable option for this research. Thus, the inspection reports for the three reference bridge candidates identified by the Maryland state coordinator were requested and reviewed. This showed that all three bridges met the desired criteria for inferior overall performance and were suitable candidates for further evaluation. In order to select which of the three would become the reference bridge for this cluster, differences in the condition states of these bridges were compared and emphasis was placed on choosing the bridge with the overall worst condition states of the UWS components. Specifically, the condition states of the three items were reviewed and compared for each structure: the interior girders, the exterior girders, and the pack rust, which in these cases represents pack rust that is developing between UWS cross-frames. A comparison of the data for these three items and three bridges is shown in Table 3.12. The condition state data for the interior and exterior girders is given in linear feet. Pack rust is measured in a count based on number of cross-frames with pack rust.

Table 3.12: Potential Reference Bridges Comparison, Maryland

Bridge ID	Condition Rating	Exterior Girder Condition State (LF)					Interior Girder Condition State (LF)					Pack Rust Condition State (Count)					Sum of Percentages in highest condition state	Sum of Percentages in second highest condition state	Sum of Percentages in 2 highest condition states
		1	2	3	4	5	1	2	3	4	5	1	2	3	4	5			
C22	**6**		**400**	**104**			**888**						**14**	**41**			0.21	1.54	1.75
C17	**6**		**464**	**16**			**900**		**60**				**11**		**44**		0.90	0.97	1.86
C43	**6**	**446**	**20**	**30**			**936**	**8**	**48**					**17**	**63**		0.90	0.26	1.16

Based on this data, it was observed that for these three structures both the interior and exterior girder condition states vary between 1 and 3 and the pack rust condition states vary between 2 and 4. Based on the observation that Bridge C17 as the largest percentages of these members in the highest condition states, as quantified by taking the sums of the percentages of the elements in the highest two condition states, this bridge was selected as the reference bridge. Furthermore, Bridge C17 is the only one of the three structures to have some portion of the elements in each of the two most severe condition states for each element of the condition states populated by these three bridges.

3.2.1.2.2 Proximate Bridge Selection

A GIS point of reference analysis (described in Section 2.2.2) was conducted on the Maryland reference bridge with a radius of 50 miles, in the same way as was done for the New York cluster discussed in Section 3.2.1.1. As before, the results are then filtered to exclude bridges newer than 20 years old and older than 49 years old, for reasons previously explained in Section 2.1.1.1.4. An excerpt of the resulting proximate bridges is displayed in Table 3.13 (following the same format as used previously in Table 3.10), with the proximate bridges classified by their appropriate parametric categories. In this case there are a total of 174 proximate bridges within the cluster, some of which are located within Virginia. Due to this large volume of proximate bridges, only the bridges in categories of interest or that will ultimately be included in the cluster for other reasons (as discussed in Section 3.2.1.2.3) are listed in the table for conciseness.

Table 3.13: Proximate Bridges in Parametric Categories of Interest, Maryland

			PRIMARY VARIABLES										SECONDARY VARIABLES												CONDITION ATTRIBUTES			
CATEGORY	STRUCTURE ID	CROSSING TYPE	ADT UNDER STRUCTURE		VERTICAL UNDER-CLEARANCE (m)		MINIMUM LATERAL UNDER-CLEARANCE (m)		RELATIVE HUMIDITY (%)		SNOWFALL (in)		TOW (hours/year)		SNOWFALL (inches)		Cl (mg/L)		NO3 (mg/L)		SO4 (mg/L)		AGE (years)		SUPER STRUCTURE RATING	
			Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value?	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L
1	C1	Highway	237523	H	4.97	L	3.4	L	3F, 3G, 0H	H	23.4	H	3119	H	23.4	H	0.217	L	0.768	L	0.851	L	26	L	7	L
1	C2	Highway	53480	H	5	L	3	L	3F, 3G, 0H	H	23.5	H	2786	H	23.5	H	0.236	H	0.619	L	0.671	L	25	L	7	L
2	C3	Highway	96798	H	5	L	3	L	3F, 3G, 0H	H	18.7	L	3119	H	18.7	L	0.217	L	0.768	L	0.851	L	22	L	6	L
2	C4	Highway	167695	H	4.92	L	2.0	L	2F, 8G, 2H	H	18.2	L	2786	H	18.2	L	0.236	H	0.619	L	0.671	L	32	H	6	L
2	C5	Highway	272854	H	5	L	1	L	3F, 3G, 0H	H	18.7	L	3119	H	18.7	L	0.217	L	0.768	L	0.851	L	22	L	7	L
4	C6	Highway	93710	H	5	L	4	L	4F, 8G, 0H	L	21.9	L	2319	L	21.9	L	0.236	H	0.619	L	0.671	L	25	L	7	L
4	C7	Highway	93710	H	5	L	4	L	4F, 8G, 0H	L	21.9	L	2319	L	21.9	L	0.236	H	0.619	L	0.671	L	25	L	7	L
4	C8	Highway	93710	H	5	L	4	L	4F, 8G, 0H	L	21.9	L	2319	L	21.9	L	0.236	H	0.619	L	0.671	L	23	L	7	L
6	C9	Highway	71700	H	5	L	7	H	3F, 3G, 0H	H	22.4	L	2319	L	22.4	L	0.217	L	0.768	L	0.851	L	37	H	6	L
6	C10	Highway	183230	H	5	L	6.1	H	3F, 3G, 0H	H	15.7	L	2786	H	15.7	L	0.236	H	0.619	L	0.671	L	41	H	6	L
6	C11	Highway	78741	H	5	L	10.4	H	3F, 3G, 0H	H	18.7	L	3119	H	18.7	L	0.217	L	0.768	L	0.851	L	22	L	7	L
7	C12	Highway	68623	H	5	L	7	H	4F, 8G, 0H	L	27.8	H	2518	H	27.8	H	0.217	L	0.768	L	0.851	L	28	L	7	L
7	C13	Highway	59322	H	5	L	7	H	4F, 8G, 0H	L	27.8	H	2518	H	27.8	H	0.217	L	0.768	L	0.851	L	27	L	7	L
7	C14	Highway	183237	H	5	L	8	H	4F, 8G, 0H	L	25.3	H	2319	L	25.3	H	0.217	L	0.768	L	0.851	L	29	H	7	L
7	C15	Highway	68761	H	5	L	8	H	4F, 8G, 0H	L	25.3	H	2319	L	25.3	H	0.217	L	0.768	L	0.851	L	27	L	7	L
8	C16	Highway	91300	H	5	L	7	H	4F, 8G, 0H	L	20.4	L	2319	L	20.4	L	0.236	H	0.619	L	0.671	L	25	L	7	L
8	**C17**	**Highway**	**71700**	**H**	**5**	**L**	**7**	**H**	**4F, 8G, 0H**	**L**	**22.4**	**L**	**2319**	**L**	**22.4**	**L**	**0.217**	**L**	**0.768**	**L**	**0.851**	**L**	**39**	**H**	**6**	**L**
8	C18	Highway	88600	H	5	L	7.3	H	5F, 7G, 0H	L	21.9	L	2319	L	21.9	L	0.236	H	0.619	L	0.671	L	22	L	7	L
8	C19	Highway	66303	H	5	L	6.4	H	4F, 8G, 0H	L	22.4	L	2319	L	22.4	L	0.236	H	0.619	L	0.671	L	32	H	7	L
8	C20	Highway	66303	H	5	L	6.4	H	4F, 8G, 0H	L	22.4	L	2319	L	22.4	L	0.236	H	0.619	L	0.671	L	32	H	7	L
8	C21	Highway	91300	H	5	L	7	H	4F, 8G, 0H	L	20.4	L	2319	L	20.4	L	0.236	H	0.619	L	0.671	L	25	L	7	L
8	C22	Highway	85270	H	4	L	7	H	5F, 7G, 0H	L	22.4	L	2319	L	22.4	L	0.217	L	0.768	L	0.851	L	39	H	6	L
10	C23	Highway	89620	H	5.66	H	2.0	L	2F, 8G, 2H	H	18.2	L	2786	H	18.2	L	0.236	H	0.619	L	0.671	L	30	H	5	L
10	C24	Highway	218345	H	5.71	H	2.0	L	2F, 8G, 2H	H	18.2	L	2786	H	18.2	L	0.236	H	0.619	L	0.671	L	30	H	7	L
10	C25	Highway	181082	H	5.18	H	2.0	L	2F, 8G, 2H	H	18.2	L	2786	H	18.2	L	0.236	H	0.619	L	0.671	L	30	H	7	L
10	C26	Highway	63813	H	5.02	H	2.0	L	3F, 3G, 0H	H	21.8	L	3347	H	21.8	L	0.217	L	0.768	L	0.851	L	31	H	6	L
24	C27	Highway	13020	L	5	L	11	H	4F, 8G, 0H	L	22.4	L	2319	L	22.4	L	0.217	L	0.768	L	0.851	L	39	H	5	L
24	C28	Highway	4180	L	5	L	6.1	H	5F, 7G, 0H	L	22.4	L	2319	L	22.4	L	0.236	H	0.619	L	0.671	L	32	H	7	L
24	C29	Highway	50192	H	5	L	6	H	5F, 7G, 0H	L	21.9	L	2319	L	21.9	L	0.236	H	0.619	L	0.671	L	22	L	7	L
24	C30	Highway	47240	L	4	L	6	H	4F, 8G, 0H	L	21.9	L	2319	L	21.9	L	0.236	H	0.619	L	0.671	L	35	H	7	L
24	C31	Highway	33812	L	5	L	7	H	5F, 7G, 0H	L	15.7	L	2319	L	15.7	L	0.236	H	0.619	L	0.671	L	29	H	7	L
24	C32	Highway	33812	L	5	L	6	H	5F, 7G, 0H	L	15.7	L	2319	L	15.7	L	0.236	H	0.619	L	0.671	L	29	H	7	L
24	C33	Highway	36052	L	5	L	7	H	5F, 7G, 0H	L	15.7	L	2319	L	15.7	L	0.236	H	0.619	L	0.671	L	29	H	7	L
24	C34	Highway			4	L	7.8	H	4F, 8G, 0H	L	20.4	L	2319	L	20.4	L	0.236	H	0.619	L	0.671	L	25	L	7	L
24	C35	Highway	13020	L	5	L	11	H	4F, 8G, 0H	L	22.4	L	2319	L	22.4	L	0.217	L	0.768	L	0.851	L	39	H	5	L
~~20~~,34	C36	Highway+Railroad			5	L	3.4	L	4F, 8G, 0H	L	15.7	L	2319	L	15.7	L	0.236	H	0.619	L	0.671	L	28	L	7	L
~~20~~,34	C37	Highway+Railroad			5	L	2	L	5F, 7G, 0H	L	15.7	L	2319	L	15.7	L	0.236	H	0.619	L	0.671	L	23	L	7	L
3,34	C38	Highway+Railroad	110382	H	5	L	3	L	4F, 8G, 0H	L	25.3	H	2319	L	25.3	H	0.217	L	0.768	L	0.851	L	29	H	6	L
36	C39	Railroad			9.54	H	8	H	4F, 8G, 0H	L	21.8	L	3347	H	21.8	L	0.217	L	0.768	L	0.851	L	27	L	7	L
36	C40	Railroad			16	H	42	H	4F, 8G, 0H	L	20.4	L	2319	L	20.4	L	0.236	H	0.619	L	0.671	L	29	H	6	L
36	C41	Railroad			7	H	5.6	L	4F, 8G, 0H	L	20.4	L	2727	H	20.4	L	0.236	H	0.619	L	0.671	L	26	L	8	H
13,35,39	C42	Highway+Railroad+Waterway	63020	H	6	H	8	H	3F, 3G, 0H	H	27.8	H	2518	H	27.8	H	0.217	L	0.768	L	0.851	L	38	H	7	L
	MEAN		77172		5		6		3.8F, 8.1G, 0.1H		23.5		2489		23.5		0.243		0.712		0.785		30		7	
	STANDARD DEV		97222		2		7		0.8F, 0.6G, 0.4H		4.6		312		4.6		0.042		0.079		0.093		6		1	
Statistics	MAX		685102		20		62		2F, 8G, 2H		35		3347		35		0.296		0.821		0.936		42		8	
	MIN		200		4		0		5F, 7G, 0H		16		2101		16		0.033		0.429		0.523		21		5	
	MEDIAN		48932		5		6		4F, 8G, 0H		22.40		2319		22.40		0.217		0.768		0.851		28		7	

3.2.1.2.3 Cluster Bridge Selection

The cluster bridge selection for this cluster follows the same process as previously described for the New York cluster, although unique differences in any two populations occur and result in slightly different judgments about which bridges are ultimately included as cluster bridges. Specifically, after identifying the proximate bridges, the statistical analysis of the cluster was performed to: calculate the median value of each of the influential variables, then classify each parametric value as high or low, and ultimately categorize each bridge into one of the parametric categories.

The next step was to identify the categories of interest. Because the reference bridge was categorized as Category 8, the remaining highway categories representing varying the primary variables independently are Categories 4, 6, 7, 16, and 24. The rail category with the same categorization of vertical under-clearance and humidity (the only two primary variables considered for rail crossings) as the Category 8 reference bridge is Category 34. Category 36 represents varying the vertical under-clearance of the rail crossings. Lastly, Categories 1 and 32 represent the worst- and best-case scenarios with respect to severity of environment and would both ideally be included. However, no bridges populate Category 32 and thus this category was not included.

The specific logic of selecting each of the bridges used to represent these categories is detailed as follows. The resulting list of cluster bridges is summarized in Table 3.14.

- Category 1, worst-case scenario: Two bridges (Bridges C1 and C2) populate Category 1 and both of these two were selected as cluster bridges.

- Category 4, vary lateral under-clearance: Three bridges populate Category 4. These three have identical parametric values except for their ages, which varies between only 23 and 25 years, at the time of this writing. The two oldest structures, C6 and C7, are 25 years old at the time of this writing and are selected.
- Category 6, vary humidity: Three Category 6 bridges existed and the two of these most similar to the reference bridge (Bridges C9 and C10) with the exception of humidity were selected as cluster bridges. It was later discovered that Bridge C10 was reconstructed in 2011. Thus this category is currently only populated by a single structure.
- Category 7, vary snowfall: Seven Category 7 bridges exist. Three of the seven bridges have equal values equal to the highest average annual snowfall within this category (27.8 in). The two of these (Bridges C12 and C13) with the remaining parameters are as close to the reference bridge as possible are selected as cluster bridges.
- Category 8, baseline category: In addition to the reference bridge, nine other bridges populate Category 8. The selection of which of these bridges would be used as cluster bridge was made after the other cluster bridges were selected and represents the remaining Category 8 bridge whose parametric values are most representative of the other cluster bridges. Bridge C16 is selected to fill this role.
- Category 16, vary vertical under-clearance: Because no Category 16 bridges existed in this cluster, Category 10 (which only differs in that lateral under-clearance is low rather than high, as is the case for

Category 16 and the reference bridge) is used in substitution. This decision was based on the hypothesis that lateral under-clearance may be the least significant of the primary variables and the observation that Category 10 was one of the more heavily-populated categories. Of the six Category 10 bridges, the two with the most extreme variations in vertical under-clearance relative to the reference bridge are selected as cluster bridges (Bridges C23 and C24).

- Category 24, vary ADT: Fourteen Category 24 bridges exist. Of the possible choices the one that was closest to the reference bridge (Bridge C27) while have a low ADT and the one with the lowest ADT (Bridge C28) are selected as cluster bridges.
- Category 34, vary crossing type to railroad: Three bridges exist in Category 34. While all three are classified as having low humidity (as required for the Category 34 designation), only two of the three have the exact same humidity as the reference bridge. Since only humidity and vertical under-clearance are primary variables for railroad crossings and no other variables were significantly different between the three bridges, this was the deciding factor in choosing Bridges C36 and C38 as cluster bridges.
- Category 36, vary vertical under-clearance of railroad crossing: There are 17 Category 36 bridges. The two of these with the highest vertical under-clearances (Bridges C39 and C40) were selected as cluster bridges.

Other bridges were also included in the cluster because there superstructure condition rating was much higher or lower than expected relative to the structure's age. These include Bridges C41 and C42 having better than average performance for this cluster, where Bridge C41 is one of only two (identical) bridges in this cluster that have a superstructure condition rating of 8 and Bridge C42 is has a relatively high rating for its age despite have relatively severe climate (high snowfall and high humidity) as well as crossing a roadway with a high ADT, a railroad, and a waterway. Conversely, Bridge C3 is included since it is the newest structure (with an age of 22 years at the time of this writing) with a superstructure rating of 6.

As discussed previously for the New York cluster, once these bridges were selected, the condition versus age of these Maryland cluster bridges was also plotted relative to the same data for the proximate bridges to ensure that the cluster bridges adequately represent the condition of the larger population of which they are a part. This comparison is shown in Figure 3.4, where it is demonstrated through the trend lines shown here that this is the case, with the trend line for the cluster bridges having only a slightly more negative slope that is offset by a slightly higher y-intercept.

3.2.1.2.4 Field Bridge Selection

Following the same process as previously described for the New York cluster in Section 3.2.1.1.4, the inspection reports for all of the cluster bridges listed in Table 3.14 were requested, received, and then reviewed to identify the best- and worst-performing bridges to serve as the field bridges. Bridge C1 was selected as the field bridge representing the extreme of good performance within this cluster, especially

Table 3.14 : Cluster Bridges, Maryland

			PRIMARY VARIABLES																SECONDARY VARIABLES												CONDITION ATTRIBUTES			
CATEGORY	STRUCTURE ID	CROSSING TYPE	ADT UNDER STRUCTURE		VERTICAL UNDER-CLEARANCE (m)		MINIMUM LATERAL UNDER-CLEARANCE (m)		RELATIVE HUMIDITY (%)		SNOWFALL (in)		TOW (hours/year)		SNOWFALL (inches)		Cl (mg/L)		NO3 (mg/L)		SO4 (mg/L)		AGE (years)		SUPER STRUCTURE RATING	
			Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value?	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L
1	C1	Highway	237529	H	4.97	L	3.4	L	3F, 9G, 0H	H	23.4	H	3119	H	23.4	H	0.217	L	0.768	L	0.851	L	26	L	7	L
1	C2	Highway	53480	H	5	L	3	L	3F, 9G, 0H	H	23.5	H	2786	H	23.5	H	0.296	H	0.619	L	0.671	L	25	L	7	L
2	C3	Highway	96738	H	5	L	3	L	3F, 9G, 0H	H	18.7	L	3119	H	18.7	L	0.217	L	0.768	L	0.851	L	22	L	6	L
4	C6	Highway	93710	H	5	L	4	L	4F, 8G, 0H	L	21.9	L	2319	L	21.9	L	0.296	H	0.619	L	0.671	L	25	L	7	L
4	C7	Highway	93710	H	5	L	4	L	4F, 8G, 0H	L	21.9	L	2319	L	21.9	L	0.296	H	0.619	L	0.671	L	25	L	7	L
6	C9	Highway	71700	H	5	L	7	H	3F, 9G, 0H	H	22.4	L	2319	L	22.4	L	0.217	L	0.768	L	0.851	L	37	H	6	L
6	C10	Highway	183230	H	5	L	6.1	H	3F, 9G, 0H	H	15.7	L	2786	H	15.7	L	0.296	H	0.619	L	0.671	L	41	H	6	L
7	C12	Highway	68623	H	5	L	7	H	4F, 8G, 0H	L	27.8	H	2518	H	27.8	H	0.217	L	0.768	L	0.851	L	28	L	7	L
7	C13	Highway	53922	H	5	L	7	H	4F, 8G, 0H	L	27.8	H	2518	H	27.8	H	0.217	L	0.768	L	0.851	L	27	L	7	L
8	C16	Highway	31300	H	5	L	7	H	4F, 8G, 0H	L	20.4	L	2319	L	20.4	L	0.296	H	0.619	L	0.671	L	25	L	7	L
8	**C17**	**Highway**	**71700**	**H**	**5**	**L**	**7**	**H**	**4F, 8G, 0H**	**L**	**22.4**	**L**	**2319**	**L**	**22.4**	**L**	**0.217**	**L**	**0.768**	**L**	**0.851**	**L**	**39**	**H**	**6**	**L**
10	C23	Highway	89620	H	5.66	H	2.0	L	2F, 8G, 2H	H	18.2	L	2786	H	18.2	L	0.296	H	0.619	L	0.671	L	30	H	5	L
10	C24	Highway	218345	H	5.71	H	2.0	L	2F, 8G, 2H	H	18.2	L	2786	H	18.2	L	0.296	H	0.619	L	0.671	L	30	H	7	L
24	C27	Highway	13020	L	5	L	11	H	4F, 8G, 0H	L	22.4	L	2319	L	22.4	L	0.217	L	0.768	L	0.851	L	33	H	5	L
24	C28	Highway	4180	L	5	L	6.1	H	5F, 7G, 0H	L	22.4	L	2319	L	22.4	L	0.296	H	0.619	L	0.671	L	32	H	7	L
~~20~~,34	C36	Highway+Railroad			5	L	3.4	L	4F, 8G, 0H	L	15.7	L	2319	L	15.7	L	0.296	H	0.619	L	0.671	L	28	L	7	L
~~3~~,34	C38	Highway+Railroad	110982	H	5	L	3	L	4F, 8G, 0H	L	25.3	H	2319	L	25.3	H	0.217	L	0.768	L	0.851	L	29	H	6	L
36	C39	Railroad			9.54	H	8	H	4F, 8G, 0H	L	21.8	L	3347	H	21.8	L	0.217	L	0.768	L	0.851	L	27	L	7	L
36	C40	Railroad			16	H	42	H	4F, 8G, 0H	L	20.4	L	2319	L	20.4	L	0.296	H	0.619	L	0.671	L	29	H	6	L
36	C41	Railroad			7	H	5.6	L	4F, 8G, 0H	L	20.4	L	2727	H	20.4	L	0.296	H	0.619	L	0.671	L	26	L	8	H
13,35,39	C42	Highway+Railroad+Waterway	69020	H	6	H	8	H	3F, 9G, 0H	H	27.8	H	2518	H	27.8	H	0.217	L	0.768	L	0.851	L	38	H	7	L
Statistics	MEAN		77172		5		6		3.8F, 8.1G, 0.1H		23.5		2489		23.5		0.243		0.712		0.785		30		7	
	STANDARD DEV		97222		2		7		0.8F, 0.6G, 0.4H		4.6		312		4.6		0.042		0.079		0.093		6		1	
	MAX		685102		20		62		2F, 8G, 2H		35		3347		35		0.296		0.821		0.936		42		8	
	MIN		200		4		0		5F, 7G, 0H		16		2101		16		0.093		0.429		0.529		21		5	
	MEDIAN		48932		5		6		4F, 8G, 0H		22.40		2319		22.40		0.217		0.768		0.851		28		7	

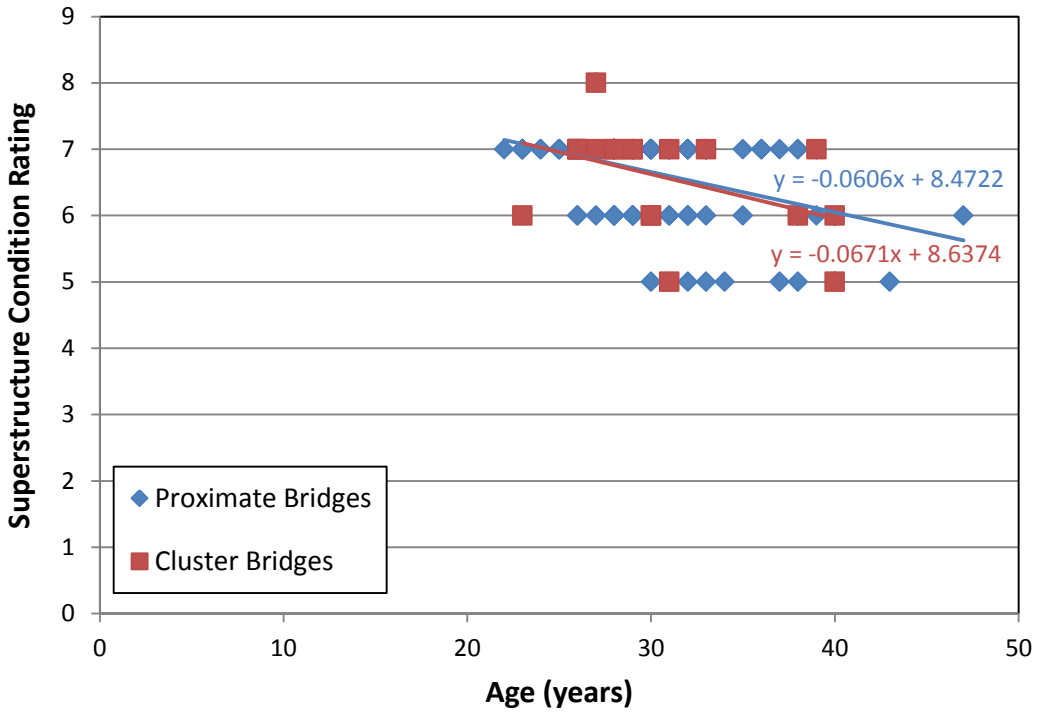

Figure 3.4: Superstructure Condition Rating versus Age, Maryland

relative to the fact that this is a Category 1 bridge, which has the worst-case combination of parametric classifications. It is noted as having only minor rust scale and no other UWS related issues were mentioned in the inspection report. With the exception of the 3% of the girders that are located beneath a leaking joint, the remainder of these 27-year-old girders (at the time of this writing) are in Condition State 1. In evaluating which cluster bridge would best represent the worst performance within this cluster, it was noticed that many of the bridges in this cluster had a significant portion of the girders, in particular the exterior girders, painted. After removing these bridges as strong candidates for field inspections, Bridge C89 was selected as the second field bridge. The inspection report for this structure notes

areas with heavier than normal rusting and in particular the exterior lower flanges are noted as having slightly heavier than normal rusting along the edges for their full length. The inspection reports for all cluster bridges will be discussed in Section 4.2.2.

3.2.1.3 Good Coastal (Texas)

Texas was selected to represent the good coastal cluster based on the observation that the survey response from the Texas state coordinator differed from that of other agencies along the Gulf Coast in that no bridges with inferior overall performance were identified and the general indication throughout the survey responses that UWS bridges within Texas are performing well coupled with the fact that these perceptions are based on a significant population of UWS bridges. As a result, suitable reference, proximate, cluster, and field bridges within Texas and along the Gulf Coast were identified. The sequence in which these bridges were identified differed in this case relative to the previous example in the fact that this selection process began with identifying a focused geographic region, from which proximate bridges were identified. Next a set of cluster bridges, representative of this larger sample and enabling the single parameter variations described above, were selected. Then, after reviewing inspection reports of this selected subset, reference and field bridges were selected. Sections 3.2.1.3.1 through 3.2.1.3.4 describe these selections in the corresponding sequence.

3.2.1.3.1 Proximate Bridge Selection

To begin the process of forming a cluster along the Gulf Coast of Texas, GIS was first used to map the bridges in this region, which can be seen in Figure 3.5. Applying the somewhat arbitrary criteria that a coastal bridge is defined as one within

50 miles of the coastline, it was observed that all of the bridges in Texas that satisfy this criteria are also within a 50 mile radius of one another, concentrated near Houston, Texas. Thus, this geographical boundary was used to determine the proximate bridges for this cluster. This resulted in 75 proximate bridges for this cluster. For conciseness, an excerpt of the attributes of those in the parametric categories of greatest interest (which will be identified in the following section, 3.2.1.3.2) are listed in Table 3.15.

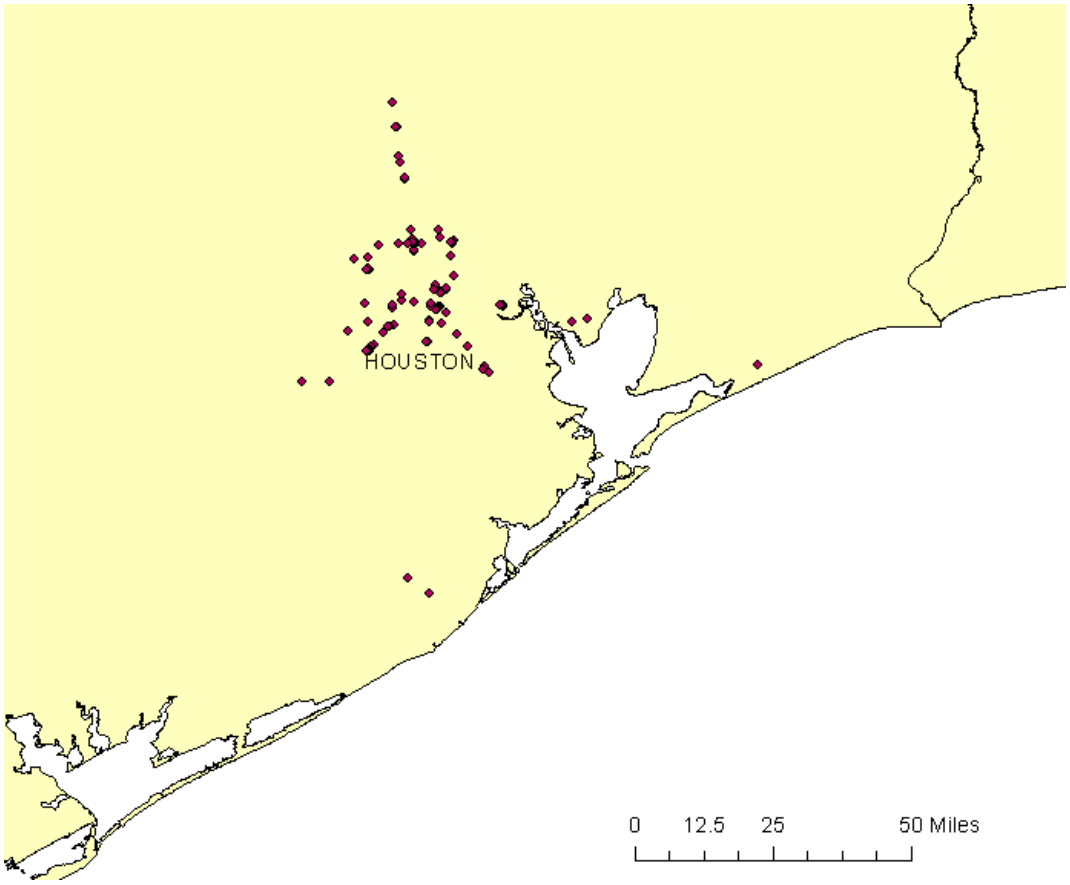

Figure 3.5: Possible Proximate Bridges, Texas

Table 3.15: Proximate Bridges in Parametric Categories of Interest, Texas

			PRIMARY VARIABLES				SECONDARY VARIABLES								CONDITION ATTRIBUTES			
CATEGORY	STRUCTURE ID	CROSSING TYPE	DISTANCE TO COAST (miles)		RELATIVE HUMIDITY (%)		TOW (hours/year)		Cl (mg/L)		NO3 (mg/L)		SO4 (mg/L)		AGE (years)		SUPER STRUCTURE RATING	
			Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L
1	D1	Waterway	0	L	1G, 1H	H	4102	H	0.565	L	0.611	L	0.793	L	34	H	7	L
1	D2	Waterway	0	L	10G, 2H	H	3733	L	0.565	L	0.611	L	0.793	L	31	H	7	L
2	D3	waterway	27	H	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	23	L	7	L
2	D4	highway	2	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	33	H	8	L
2	D5	highway	2	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	33	H	7	L
2	D6	Highway	2	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	33	H	8	L
2	D7	highway	2	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	33	H	8	L
2	D8	highway	2	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	33	H	8	L
2	D9	Highway	9	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	20	L	6	L
2	D10	Highway	6	L	12G, 0H	L	4030	L	0.565	L	0.611	L	0.793	L	24	H	8	L
2	D11	highwayy	6	L	12G, 0H	L	4030	L	0.565	L	0.611	L	0.793	L	24	H	8	L
2	D12	Highway+Railroad	3	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	33	H	7	L
2	D13	highway	3	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	33	H	8	L
2	D14	highway	3	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	24	H	8	L
2	D15	Highway	3	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	24	H	7	L
2	D16	Highway	6	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	24	H	6	L
2	D17	Highway	6	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	32	H	8	L
2	D18	Highway	2	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	27	H	5	L
2	D19	Highway	2	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	20	L	8	L
2	D20	Highway+Waterway	1	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	22	L	7	L
2	D21	highway	0	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	22	L	8	L
2	D22	highway+railroad	4	L	12G, 0H	L	4030	L	0.565	L	0.611	L	0.793	L	24	H	8	L
2	D23	Highway+Railroad	3	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	24	H	6	L
2	D24	highway	3	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	24	H	8	L
2	D25	highway	3	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	24	H	8	L
2	D26	waterway	7	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	43	H	7	L
2	D27	railroad	4	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	23	L	8	L
2	D28	Waterway	0	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	30	H	8	L
2	D29	railroad	4	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	23	L	8	L
2	D30	waterway	7	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	27	H	7	L
2	D31	watway	7	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	27	H	7	L
2	D32	waterway	4	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	32	H	8	L
2	D33	waterway	4	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	32	H	8	L
4	D34	Highway	12	H	11G, 1H	H	4030	L	0.565	L	0.611	L	0.793	L	23	L	6	L
4	D35	Highway	12	H	11G, 1H	H	4030	L	0.565	L	0.611	L	0.793	L	23	L	8	L
4	D36	Highway	12	H	11G, 1H	H	4030	L	0.565	L	0.611	L	0.793	L	23	L	7	L
	MEAN		10		11.8G, 0.2H		4138		0.565		0.611		0.793		25		7	
	STANDARD DEV		8		1.3G, 1.3H		167		0.000		0.000		0.000		5		1	
Statistics	MAX		28		1G, 1H		4416		0.565		0.611		0.793		43		8	
	MIN		0		12G, 0H		3733		0.565		0.611		0.793		20		5	
	MEDIAN		3		12G, 0H		4053		0.565		0.611		0.793		23		8	

3.2.1.3.2 Cluster Bridge Selection

After the proximate bridges were identified, the statistical analysis of the cluster was performed using the same methodology as described in the prior examples discussed in this chapter to: calculate the median value of each of the influential variables, then classify each parametric value as high or low, and ultimately categorize each bridge into one of the parametric categories.

The next step in the process is to identify the categories of interest. Because there are only two primary variables and thus four parametric combinations for the coastal clusters, this process is more straightforward than for the deicing clusters discussed previously. This process is also somewhat simplified by the fact that a reference bridge has not yet been identified and thus the categories of interest can be simply taken as the targeted categories previously discussed in Section 3.1.3.3 and shown in Table 3.7. Namely, these are Categories 1, 2, and 4, which represent the worst-case scenario of Category 1 and then independently varying humidity (via Category 2) and distance to the coast (via Category 4).

Given the general objective to have a minimum of approximately 10 bridges per cluster and three categories of interest, having three or four bridges in each of these categories was envisioned prior to performing the parametric analysis. However, because of a highly uneven distribution of bridges into these categories, this was not possible. Instead, Categories 1 and 4 were populated with only two and three bridges, respectively. Thus, all of the bridges (Bridges D1, D2, D34, D35, and D36) in these two categories were selected as cluster bridges.

It was then observed that there were appreciable differences in two of the secondary parameters of the Category 1 and Category 4 bridges. Most notably, the

age (at the time of this writing) of all the Category 1 bridges is between 31 and 34 years while the age of all the Category 4 bridges is 23 years. Furthermore, all of the Category 1 bridges are waterway crossings while all Category 4 bridges are highway crossings. Thus, the bridges selected as Category 2 cluster bridges were selected in order to bridge the gap between these parameters and continue to enable a significant amount of single parameter comparisons.

Additionally, even though both Categories 1 and 2 contain bridges with low distance to the coast, both of the two bridges in Category 1 have a distance to the coast equal to 0 miles, while the distance to the coast of the numerous Category 2 bridges ranges between 0 and 9 miles. The distance to the coast of all three of the Category 4 bridges is 12 miles. Thus, this was also taken into consideration by considering distance to the coast as a specific distance in the parameter variations versus a bracketed range of high and low given the potential significant influences this parameter may have over a 12 mile range and the potential for some of the Category 2 bridges to have a distance to the coast more similar to the Category 4 bridges (which differ in their high versus low categorization) than the Category 1 bridges (which are both classified as low distance to the coast).

Thus, for the above reasons, the bridges were reclassified (and relabeled to add clarity) based on their value of distance to the coast expressed in miles, their high or low ("H" or "L", respectively) humidity classification, their service type (e.g., highway crossing, railroad crossing, etc. using the numerical service type codes from the NBI that were previously defined in Section 2.1.1.1.1, and their age at the time of this writing bracketed into five year ranges. Cluster bridges were then selected so that

each of these four parameters could be independently varied and have at least two pairs of bridges to compare as each variable was altered.

As an example of the labeling system, Bridge 2, L, 20-24, 1 is 2 miles from the coast, with low humidity, between 20 and 24 years old, and has service type 1, which represents a highway crossing. These labels may be followed by additional labels in parentheses. Here a "C" represents a county-owned bridge, meaning that element level data is not available for the structure, while a numerical entry represents the superstructure condition rating to distinguish different bridges that would otherwise have the same label.

A final consideration in the choices of cluster bridges is that the UWS inventory provided by the Texas state coordinator contained both bridges that were owned by the state agency as well as those owned by local agencies. After a preliminary set of cluster bridges was compiled, it was discovered that the condition state information (which has been deemed essential to the desk study phase of this work and will be subsequently discussed in Chapter 4) only exists for state owned bridges. Thus, the cluster was reconfigured so that nearly all of the bridges (with only one exception for a bridge that had identical parametric values to the Category 1 bridges except for humidity) would be state-owned bridges so that condition state information would be available.

The resulting matrix of bridges is illustrated by Table 3.16. Here it is shown that for each of the two primary variables (distance and humidity) and two dependent variables that vary significantly between the Category 1 and Category 4 bridges (service type and age), there are at least two pairs of bridges that can be used to evaluate potential influences due to these variables. For example, the influences of

distance to the coast can be evaluated by comparing Bridge 2, L, 20-24, 1 versus Bridge 6, L, 20-24, 1 versus Bridge 9, L, 20-24, 1 (which have identical parametric values except for the distance to the coast varying between 2, 6, and 9 miles, respectively) as well as comparing Bridge 2, L, 30-34, 1 versus Bridge 6, L, 30-34, 1.

Table 3.16: Matrix of Bridges, Texas

	Compare …			
Base	**Distance**	**Humidity**	**Service**	**Age**
2, L, 20-24, 1	**6, L, 20-24, 1**		**1, L, 20-24, 6**	**2, L, 30-34, 1**
	9, L, 20-24, 1		**3, L, 20-24, 4 (7)**	
2, L 30-34, 1	**6, L, 30-34, 1**	**0, H, 30-34, 5**	**3, L, 30-34, 4**	**2, L, 20-24, 1**
		0, L, 30-34, 5 (C)		
6, L, 20-24, 1				**6, L, 30-34, 1**
9, L, 20-24, 1		12, H, 20-24, 1		

All of the pairs and sets of three (for example Bridges 2, L, 20-24,1 1, L, 20-24, 6, and 3, L 20-24, 4 (7)) bridges shown in Table 3.16 are highly similar to one another with minimal variation between the influential parameters. In fact, all of the highlighted cells have exactly the same parametric values with the exception of the parameter of interest for that set of bridges. The entries in bold (which are all but one entry) have the same parametric categorizations except for the parameter of interest for that set of bridges. The remaining pair of bridges (9, L, 20-24, 1 and 12, H, 20-24, 1) are used to evaluate variations in humidity. In addition to this variation, these two bridges are also in different distance to the coast categories with the former bridge being classified as low distance to the coast and the latter being classified as high

distance to the coast. However, this difference is mitigated by the fact the difference in these two values is only 3 miles.

Due to carefully selecting these bridges such that bridges are used to make multiple comparisons when possible, there are 14 bridges shown in Table 3.17 that allow for comparisons between six pairs of bridges and three sets of three bridges. These nine comparisons allow each of these primary and secondary variables to be evaluated through two unique comparisons, with the exception of age, which can be evaluated through three unique comparisons.

After the bridges that are shown in Table 3.17 were selected based on their parametric values, an evaluation was made to determine the extent to which these bridges were representative of the larger population of proximate bridges with respect to their combinations of age and superstructure condition ratings. This revealed that this process did not result in including any bridges with a superstructure condition rating below 7, while there were a small number of bridges with lower superstructure condition ratings within the proximate bridge population. As a result three additional bridges, two with a superstructure condition rating of 6 (Bridges 6, L, 20-24, 1 (6) and 3, L, 20-24,4 (6)) one with a superstructure condition rating of 5 (Bridge 2, L 25-29, 1) were added as cluster bridges.

The summary details of these cluster bridges, which are listed by the labels discussed above as well as the labels originally given to the proximate bridges in Table 3.15 are shown in Table 3.17. In addition to the typical details of the cluster bridges summarized in these tables, the reasons for including each of the bridges is also included here for added clarity of the rationale of bridge selections. Lastly, Figure 3.6 shows that the superstructure condition rating versus age of the selected

cluster bridges well represents these characteristics of the larger population of proximate bridges.

3.2.1.3.3 Reference and Field Bridge Selection

The inspection reports for all of the selected cluster bridges were requested, received, and then reviewed in a process similar to that used in establishing the field bridges for the previously-discussed clusters (where the summary of all inspection reports for this cluster will be discussed in Section 4.2.3). However, in this case, the inspection reports are reviewed to identify a reference bridge in addition to field bridges. In addition, because three bridges will be subjected to field evaluation and there are three parametric combination categories considered in this cluster, it was desired to select one bridge from each of these three categories. A final consideration was that the sole problematic issue related to UWS performance that had been noted in the survey response from the Texas state coordinator was corrosion issues on some box caps; thus it was considered desirable to include at least one bridge with this type of pier configuration if possible.

As a result, Bridge D1 was an obvious choice to fill one of these two roles as the inspection notes for this structure indicated that UWS components of this structure exhibited section loss, pack rust, and cracking of a fracture-critical detail (which may have been caused by pack rust based on the research teams interpretation of the field notes). This is abnormal for this population of bridges and thus this bridge was deemed the worst performing within the cluster. TxDOT also records ratings of the main steel members in a format appearing to mirror the superstructure condition rating system and these members have a rating of 4; with the exception of one other structure whose main members have suffered impact damage, all other bridges in this

Table 3.17: Cluster Bridges, Texas

				PRIMARY VARIABLES				SECONDARY VARIABLES								CONDITION ATTRIBUTES			
CATEGORY	STRUCTURE ID	LABEL	CROSSING TYPE	DISTANCE TO COAST (miles)		RELATIVE HUMIDITY (%)		TOW (hours/year)		CI (mg/L)		NO3 (mg/L)		SO4 (mg/L)		AGE (years)		SUPER STRUCTURE RATING	
				Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L
1	D1	0, H, 30-34, 5	Waterway	0	L	1G, 11H	H	4102	H	0.565	L	0.611	L	0.793	L	34	H	7	L
1	D2	0, H, 30-34, 5	Waterway	0	L	10G, 2H	H	3733	L	0.565	L	0.611	L	0.793	L	31	H	7	L
2	D6	2, L, 30-34, 1	Highway	2	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	33	H	8	L
2	D9	9, L, 20-24, 1	Highway	9	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	20	L	6	L
2	D10	6, L, 20-24, 1	Highway	6	L	12G, 0H	L	4030	L	0.565	L	0.611	L	0.793	L	24	H	8	L
2	D12	3, L, 30-34, 4	Highway+Railroad	3	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	33	H	7	L
2	D15	3, L, 20-24, 4	Highway	3	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	24	H	7	L
2	D16	6, L, 20-24, 1(6)	Highway	6	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	24	H	6	L
2	D17	6, L, 30-34,1	Highway	6	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	32	H	8	L
2	D18	2, L 25-29, 1	Highway	2	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	27	H	5	L
2	D19	2, L, 20-24, 1	Highway	2	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	20	L	8	L
2	D20	1, L, 20-24, 6	Highway+Waterway	1	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	22	L	7	L
2	D23	3-4, L, 20-24,4 (6)	Highway+Railroad	3	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	24	H	6	L
2	D28	0, L, 30-34, 5	Waterway	0	L	12G, 0H	L	4053	L	0.565	L	0.611	L	0.793	L	30	H	8	L
4	D34	12, H, 20-24, 1	Highway	12	H	11G, 1H	H	4030	L	0.565	L	0.611	L	0.793	L	23	L	6	L
4	D35	12, H, 20-24, 1	Highway	12	H	11G, 1H	H	4030	L	0.565	L	0.611	L	0.793	L	23	L	8	L
4	D36	12, H, 20-24, 1	Highway	12	H	11G, 1H	H	4030	L	0.565	L	0.611	L	0.793	L	23	L	7	L
Statistics	MEAN			10		11.8G, 0.2H		4138		0.565		0.611		0.793		25		7	
	STANDARD DEV			8		1.3G, 1.3H		167		0.000		0.000		0.000		5		1	
	MAX			28		1G, 11H		4416		0.565		0.611		0.793		43		8	
	MIN			0		12G, 0H		3733		0.565		0.611		0.793		20		5	
	MEDIAN			9		12G, 0H		4053		0.565		0.611		0.793		23		8	

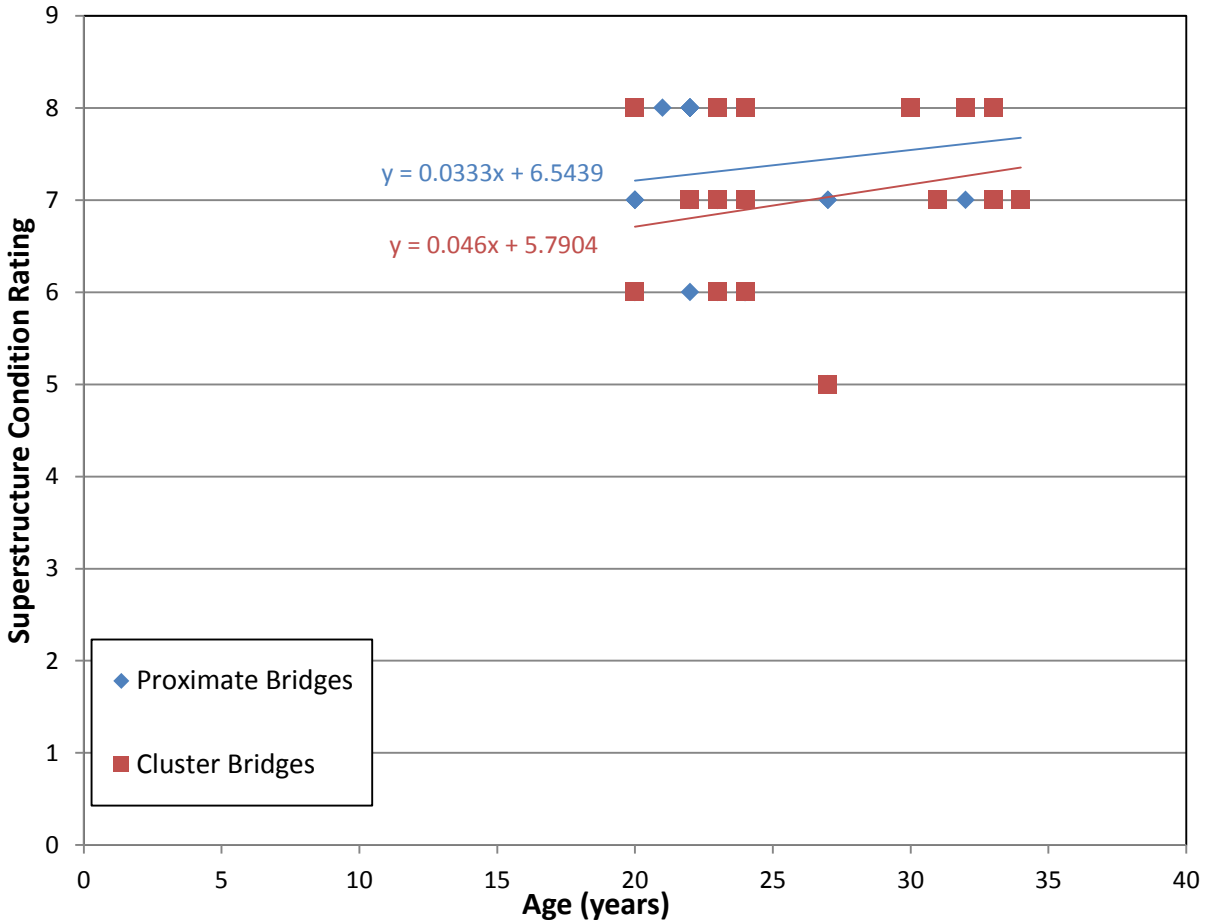

Figure 3.6: Superstructure Condition Rating vs. Age, Texas

population have a rating for the main members of 7 or 8, with the majority having a rating of 8 (see Table 3.17). This bridge is in Category 1 based on its parametric combination of low distance to the coast and high humidity and was ultimately selected as one of the field bridges for this cluster.

The ideal choice for representing parametric combination Category 2 was Bridge D6 because this was identified in Table 3.16 as a base bridge which represented single parameter variations relative to other structures for all four parameters invested. Upon review of the inspection report for this structure it was revealed that this structure was in good condition, especially relative to its age of 33 years at the time of this writing, with UWS-related issues noted. This bridge also has a superstructure condition rating of 8 and a steel main member rating of 8, the highest values that exist within this population of bridges with ages greater than or equal to 20 years at the time of this writing. Since the purpose of this cluster was primarily to evaluate good performance along the Texas Gulf Coast, which this bridge clearly exhibits, this bridge was selected as the reference bridge for this cluster.

The final field bridge was selected from Category 4 so that all three categories would be represented in the field work. There are three bridges in this category and their condition varies, with superstructure condition ratings of 6, 7, and 8. Bridge D36, which has a superstructure condition rating of 7, was deemed to be the best choice to represent the average performance of the Category 4 bridges. This bridge also has a box cap that is painted on the exterior but unpainted on the interior, an additional feature of interest that was desirable to include in the field work as discussed above. Thus, Bridge D36 was selected as the final field bridge for this cluster.

These choices enable all three parametric combination categories to be evaluated in the field and cover the range of performance from poor to average for this population to good.

3.2.2 Phase III

Phase III of this research will involve analyzing other clusters using the same methods developed in this work. The anticipated scope of these clusters can be classified into two categories: those based on additional state-recommended inferior-performing UWS bridges and additional good clusters identified by the research team or based on FHWA-recommended regions where UWS is thought to perform well. While all specific reference, proximate, cluster, and field bridge selections for these clusters are not needed at this time, an amount of preliminary work is needed to evaluate the viability of all potential clusters and develop the prioritized list of Phase 3 interests that is a deliverable of the Phase II efforts of this project. This preliminary work is described in Sections 3.2.2.1 and 3.2.2.2 below.

3.2.2.1 Inferior-Performing Clusters

It is anticipated that the Phase III inferior-performing clusters will involve deicing clusters and coastal clusters (consistent with Phase II) and will also include combined deicing and coastal clusters. Reference bridge candidates in these three categories have previously been identified through the survey of state coordinators discussed in McConnell et al (2012) (which is summarized in Section 3.1.1.1.1) and are listed in Table 3.1. The inspection reports for these structures have been requested and will be reviewed to confirm that they meet the criteria for inferior overall performance and are thus suitable for further evaluation before proceeding with any of

these clusters. To date, the proximate bridges within a specified radius of each reference bridge have been identified and the listing of these bridges for each cluster is provided in Appendix C. The process for determining these proximate bridges was the same as has been discussed in Section 3.1.2 except that if the proposed reference bridge was younger than 20 years, then the population included as proximate bridges included all bridges less than 49 years of age. This information can be used to assess the opportunities available for forming informative clusters when prioritizing clusters for future work.

3.2.2.2 Good Clusters

Tentative plans also exist for several potential Phase 3 clusters based on good performing bridges. These include one additional good-performing deicing cluster (located in Colorado) and several other regions included for the primary purpose of verifying good performance in other potentially severe environments that have been reported in prior literature given that no problems specific to these potential causes of inferior UWS performance were reported in the state coordinator surveys (previously discussed in Section 3.1.1.1.1). At this stage, bridge selections for the Colorado cluster have been fully completed because this was a potential Phase 2 cluster. For the remaining categories, the proximate bridges have been identified with bridges of ages less than 49 years old included in the population (which can be further filtered by age in future work if applicable). Listings of these proximate bridges are given in Appendix D. It is envisioned that the remaining classes of bridges will be selected in a manner similar to that used for the Texas cluster, where the distribution of bridges into various parametric categories was evaluated in order to select a cohesive set of cluster

bridges then the inspection reports of these bridges were requested and reviewed to determine the bridges of greatest interest to serve as reference and field bridges.

The regions of potential interest are as follows.

- Denver, Colorado is of interest because two bridges in this vicinity are among those on a short list of bridges nationwide that have good performance despite being in service for an extended period of time while also being in a region with high annual snowfall amounts and crossing a highway with a high ADT, as previously discussed in Section 3.2.1.1.
- The Chicago, Illinois and Gary, Indiana area was of interest because this region is known to have high atmospheric sulfur concentrations coupled with the use of deicing agents. However, no inventory of UWS bridges in Indiana has been provided. Thus, the proximate bridges in this cluster were identified by finding the geographic center of Chicago and establishing a 50 mile radius around this point.
- The North Carolina coastline was of interest because of the low usage of deicing agents but elevated levels of atmospheric chloride. The proximate bridges for this cluster include all UWS bridges in North Caroline within 50 miles of the coast.
- The bread basket region was of interest for the high level of nitrates present in this area. Figure 3.7 from NADP (2010) displays the nitrate ion wet deposition levels in the US. Possible geographies for such a cluster where then explored by evaluating stations where

nitrate levels were high, while sulfate levels were low. Specifically, the average nitrate and sulfate levels at all stations where such data was available was compiled and the stations were then sorted based on the difference in the nitrate and sulfate levels at each station. The locations of these stations were then evaluated to assess their location relative to regions with high concentrations of nitrates based on Figure 3.7 and an informal definition of the bread basket guided by United States Department of Agriculture data on corn production for grain by county (USDA 2010). This data indicates that North Dakota, South Dakota, Nebraska, Minnesota, Iowa, Wisconsin, and Illinois each contain multiple counties producing more than 20 million bushels of corn in 2010. Thus, a station in one of these states that also had a large difference in nitrate and sulfate levels was sought. Additionally, the median values for the nitrate and sulfate levels at all stations were calculated and then the values at each station were classified as "high" or "low" relative to the median. If the value was above the median it was "high" and if the value was equal to or less than the value it was "low". An additional criteria for the cluster was locations classified as "high" in nitrate and "low" in sulfate.

Four stations with high levels of nitrates but low levels of sulfates were thus identified, in South Dakota, Nebraska, North Dakota, and Minnesota, based on these criteria. The required radii that would then be necessary to result in a minimum of 10 proximate bridges

was then evaluated for each of these candidates. This revealed that the South Dakota and Nebraska locations resulted in the greatest number of proximate bridges for the smallest radius. Thus, proximate bridges for clusters centered around both of these stations were identified.

- Southern Arkansas was of interest due to high amounts of annual rainfall, coupled with low amounts of deicing agents and atmospheric salts in this region. The station with the highest annual precipitation within Southern Arkansas, labeled as Langley, where the annual snowfall is 3 inches or less, was taken as the cluster center. The proximate bridges were then found by creating a 50 mile radius around the Langley Station.

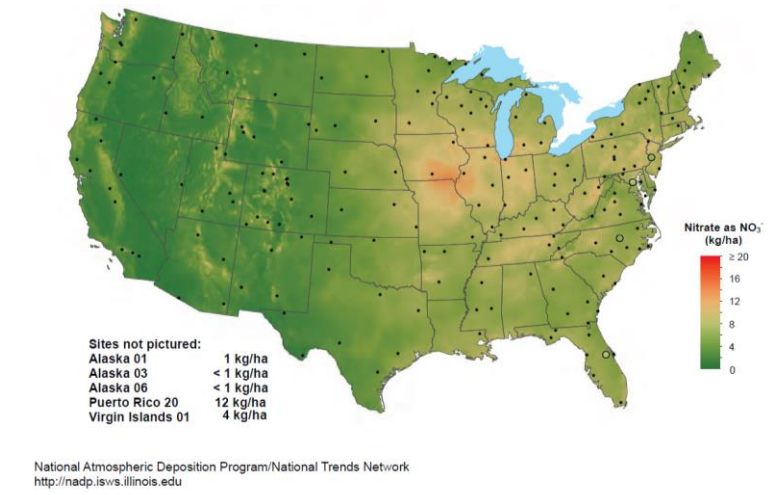

Figure 3.7: US Nitrate ion wet deposition, 2010 (NADP, 2012)

- For the same reason as the southern Arkansas cluster, Seattle, Washington was also of interest as Seattle is known to have high amounts of rainfall through the year. The proximate bridges for this cluster were identified by finding a station near Seattle with the highest annual precipitation and establishing a 125 mile radius around this point. This radius was necessary to meet the minimum requirement of 10 bridges in a cluster. The station identified was labeled as Cedar Lake and is approximately 40 miles from Seattle.
- The Hampton Roads/Norfolk region of Virginia was also identified as an area of interest because the Virginia Department of Transportation mentioned that the UWS bridges in this region are performing well (Ocel 2012). Thus, the proximate bridges in this cluster were identified by finding the geographic center of Hampton Roads and establishing a 50 mile radius around this point.

3.2.2.3 Colorado

Colorado is cluster that is a part of the Phase III portion of this project. Section 3.2.1.1 descried how two bridges in the vicinity of Denver, Colorado area are of interest. Those two bridges have high superstructure ratings although being in service for an extended period of time. This region experiences high annual snowfall amounts and crosses a highway with a high ADT.

3.2.2.3.1 Reference Bridge

There are two bridges in Colorado (E4 and E5) that fit the criteria for a good deicing cluster reference bridge as previously discussed in Section 3.2.1.1. Inspection

reports for both of these two structures were requested, received, and reviewed in order to select one of the two as a reference bridge. As a result it was revealed that both bridges had conditions as expected based on their superstructure condition ratings. Furthermore 100% of the UWS components of both structure were found to be in Condition State 1 (the best category, as will be discussed in Section 4.2.3). However, the inspection notes comment that a small amount of corrosion exists on the flanges of Bridge E5, thus Bridge E4 was selected as the best choice for a reference bridge representing good performance.

3.2.2.3.2 Proximate and Cluster Bridges

For this case where there are only 10 proximate bridges, all proximate bridges (summarized in Table 3.18) were chosen as cluster bridges since this was the minimum cluster size desired. It is noted that the majority of these bridges serve in a common interchange between I-70 and I-76 and all of these bridges are located within 1 mile of one another. Due to this close proximity, the values of many of the environmental variables are constant throughout the cluster.

3.2.2.3.3 Field Bridges

Bridge E5 was the best performing cluster bridge with light rust on web and flange exteriors. Since the reference bridge represented the best UWS performance within the cluster population, it was desirable for at least one of the field bridges to represent the other extreme of worst performance. The bridge with the worst

Table 3.18: Proximate/Cluster Bridges, Colorado

			PRIMARY VARIABLES														SECONDARY VARIABLES								CONDITION ATTRIBUTES			
CATEGORY	STRUCTURE ID	CROSSING TYPE	ADT UNDER STRUCTURE		VERTICAL UNDER-CLEARANCE (m)		MINIMUM LATERAL UNDER-CLEARANCE (m)		RELATIVE HUMIDITY (%)		SNOWFALL (in)		TOW (hours/year)		Cl (mg/L)		NO3 (mg/L)		SO4 (mg/L)		AGE (years)		SUPER-STRUCTURE RATING	
			Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L	Value	H / L
12	E1	Highway	183000	H	6	H	3	L	9E, 3F, 0G	L	62.6	L	1034	L	0.045	L	0.822	L	0.421	L	28	L	7	L
28	E2	Highway	62500	L	8	H	6.0	L	9E, 3F, 0G	L	62.6	L	1034	L	0.045	L	0.822	L	0.421	L	31	L	7	L
20	E3	Highway	62500	L	5	L	6	L	9E, 3F, 0G	L	62.6	L	1034	L	0.045	L	0.822	L	0.421	L	31	L	8	H
20	**E4**	**Highway**	**84000**	L	**5**	L	**3.0**	L	**9E, 3F, 0G**	L	**62.6**	L	**1034**	L	**0.045**	L	**0.822**	L	**0.421**	L	**31**	L	**8**	H
20	E5	Highway	84000	L	5	L	3.0	L	9E, 3F, 0G	L	62.6	L	1034	L	0.045	L	0.822	L	0.421	L	31	L	8	H
W	E6	Waterway		L		L		L	9E, 3F, 0G	L	62.6	L	1034	L	0.045	L	0.822	L	0.421	L	32	H	7	L
24	E7	Highway		L	5	L	8.8	H	9E, 3F, 0G	L	62.6	L	1034	L	0.045	L	0.822	L	0.421	L	33	H	3	L
24	E8	Highway		L	5	L	9.1	H	9E, 3F, 0G	L	62.6	L	1034	L	0.045	L	0.822	L	0.421	L	33	H	3	L
W	E9	Waterway		L		L		L	9E, 3F, 0G	L	62.6	L	1034	L	0.045	L	0.822	L	0.421	L	33	H	8	H
W	E10	Waterway		L		L		L	9E, 3F, 0G	L	62.6	L	1034	L	0.045	L	0.822	L	0.421	L	33	H	7	L
Statistics	MEAN		95200		6		6		9E, 3F, 0G		62.6		1034		0.045		0.822		0.421		32		7	
	STANDARD DEV		50245		1		3		0E, 0F, 0G		0.0		0		0.000		0.000		0.000		2		2	
	MAX		183000		8		9		9E, 3F, 0G		62.6		1034		0.045		0.822		0.421		33		8	
	MIN		62500		5		3		9E, 3F, 0G		62.6		1034		0.045		0.822		0.421		28		3	
	MEDIAN		84000		5		6		9E, 3F, 0G		62.6		1034		0.045		0.822		0.421		32		7	

performance is Bridge E10, which is noted as having yellow/orange discoloration on girders and is the only bridge within the cluster having any of the girders in Condition State 3 (although this is only 1%). Thus, this bridge was selected as one of the field bridges. However, this bridge is an I-girder bridge crossing a waterway while the majority of the bridges in this cluster are box girders crossing highways. Thus, for the second field bridge, the worst of this latter type of structure was desired. This was not a straightforward choice since all of these bridges are performing well with a few exceptions related to corrosion inside of the boxes. However, Bridge E3 was selected since this is the only highway crossing where any corrosion on the outside of the box is noted, even though 100% of the girders of this structure have been described as being in Condition State 1.

Chapter 4

DESK STUDY OF UWS CLUSTERS

Chapter 3 discussed the selection of proximate, cluster, field and reference bridges, with the general methodology being described in Section 3.1 and examples for the specific clusters established to date in Section 3.2. Based on these bridge selections, Chapter 4 describes how data from the cluster, reference, and field bridges was organized to enable conclusions regarding the performance of UWS bridges in later work. Ultimately it is desirable to evaluate performance on a general basis, as a function of the influential parameters identified in Section 3.1.3.1, and between the various clusters considered herein. This process is based largely on review of the owner's inspection reports, and is thus referred to as the "desk study", the full methodology of which is described in Section 4.1. A subsection to this, Section 4.1.2, describes how data from the field evaluations completed as part of the present research work will be used to further inform and complete the desk study. The portions of the desk study complete at this time for four of the Phase II clusters (New York, Maryland/Virginia, Texas, Louisiana) are discussed in Section 4.2 and the preliminary aspects of the desk study that have been completed for one of the potential Phase III clusters (Colorado) are discussed in Section 4.3.

4.1 Methodology

The subsequent sections will describe the methodology of how the inspection reports for the cluster bridges were examined, interpreted, and organized.

4.1.1 Inspection Report Data

As discussed in Section 3.1.4, the most-recent inspection reports for each cluster bridge were requested from their owners. Quantitative and qualitative information in these reports was used in the desk study as described in the following sections. In most cases, this was largely based on the ASSHTO Commonly Recognized (CoRe) Element bridge inspection reporting system (FHWA 2006), a consistent nationwide classification system for structural and non-structural bridge elements that is used by a majority of owners and described in Sections 4.1.1.1 through 4.1.1.3. However, some agencies adopt other methods. New York is the one specific example of this encountered in Phase 2, which will be further discussed in Section 4.2.1.

4.1.1.1 Commonly Recognized (CoRe) Structure Elements

Each CoRe element may be referenced by a text label or a numerical code and the correlation between these two items for elements considered in this work are listed in Table 4.1. These specific CoRe elements related to UWS performance include: items specifically coded as unpainted steel including closed web/box girders (Element 101), open girders/beam (Element 106), stringers (Element 112), floor beam (Element 151), pin and hanger assemblies (Element 160), and bearings (Elements 310, 311, and 313); items such as pack rust (Element 357) that directly related to corrosion of steel elements; and various types of drainage devices and joints such as pourable joint seal (Element 301), compression joint seal (Element 302), assembly joint/seal (Element 303), and open expansion joint (Element 304) whose performance directly affects the performance of the structural elements beneath them. Furthermore, the CoRe elements can be subdivided into sub-elements at the owner's discretion; for example,

exterior steel open girder - unpainted (Element 170) and interior steel open girder - unpainted (Element 171) are optional girder sub-elements used by some agencies. This results in the exact CoRe elements that are evaluated for a specific structure to have some slight variations, but the general process of identifying the UWS components, steel corrosion related smart flags other local problems that affect performance such as steel fatigue (Element 357), traffic impact (Element 362), and section loss (Element 363) (which is further discussed in Section 4.1.4), and drainage and / or joint elements potentially affecting UWS performance that are of interest is consistent. Diaphragms and cables vertical were Non-Core elements that were also examined.

Table 4.1: CoRe Elements Considered in Desk Study

CoRe Element	Element Number
Closed Web/Box Girder, Steel Unpainted	101
Open Girder/Beam, Steel Unpainted	106
Stringer, Steel Unpainted	112
Floor Beam, Steel Unpainted	151
Pin and Hanger Assembly, Steel Unpainted	160
Pourable Joint Seal, Other	301
Compression Joint Seal, Other	302
Assembly Joint/Seal, Other	303
Open Expansion Joint, Other	304
Elastomeric Bearing, Other	310
Movable Bearing, Other	311
Fixed Bearing, Other	313
Steel Fatigue	356
Pack Rust	357
Traffic Impact	362
Section Loss	363

4.1.1.2 Condition States

The quantitative data associated with each CoRe element is generally expressed by condition states, is intended to be as "objective and repeatable" as possible (FHWA 2006), making it the ideal dataset to compare performance versus time and between structures. The condition state data provides two types of information regarding deterioration, the severity and extent. An integer scale of 1 to 5 is used for most elements to represent the severity of any deterioration, where 1 generally indicates good condition and 5 indicates some action or analysis is needed to further assess the element, with the general criteria for each condition state being as follows (FHWA 2006).

1. Protected- Protective systems sound and functioning to prevent deterioration
2. Exposed- Protective systems partially or completely failed
3. Attacked- Element experiencing active attack, but not yet damaged
4. Damaged- Element has lost material such that serviceability is suspect
5. Failed- Element no longer serves intended function

Specifically for girders, the condition states are defined in the American Association of State and Highway and Transportations Officials (AASHTO) Bridge Element Inspection Guide Manual as follows (Johnson, M. B. and Jensen, P. (2010).

1. No evidence of active corrosion
2. Little or no active corrosion; surface or freckled rust may have formed
3. Surface or freckled rust is prevalent, but there is no section loss
4. Section loss is measureable but does not yet warrant structural analysis

5. Corrosion has caused section loss sufficient to warrant structural analysis

The amount of each CoRe element in each condition state is provided to indicate the extent of the deterioration. For example, for girders this is typically expressed in linear feet of the girders in each condition state, while the condition of the diaphrams may be expressed as a count of the diaphragms in each condition state. In another words, an element can be in more than one condition state.

4.1.1.3 Smart Flags

In contrast to condition state information, "smart flags" are used as indictors to highlight problems that are not readily translated into the condition state rating system because they do not follow the deterioration patterns of a CoRe element or they do not share the same level of "distress" as the CoRe element (FHWA 2006). For example, the smart flag for pack rust is of interest to this research and does not follow the same logic of the condition state system in the fact that pack rust is considered as a binary state that is either present or not rather than indicating the severity of the pack rust since this already indicates a rather advanced state of corrosion.

4.1.2 Analysis of Inspection Report Information

Based on the inspection report data discussed in Section 4.1.1., a summary table of this information is compiled for each cluster as discussed in Section 4.1.2.1 through 4.1.2.3. Examples of this will be subsequently discussed in Section 4.1.2.

4.1.2.1 Statistics

As mentioned above, CoRe elements can be in one or more condition states. Thus, the percentage of each relevant CoRe element (see Table 4.1) was computed

from the quantities of the distribution of each element among the distribution states that were provided in the inspection reports. For example the excerpt from an inspection report that is shown in Table 4.2 indicates 1,130 total linear feet of open unpainted steel girders (CoRe Element 106) that are in four different condition states: 1,049 linear feet in Condition State 1, 56 linear feet in Condition State 3, 24 linear feet in Condition State 4, and 1 linear foot in Condition State 5. The percentages in each condition state can be readily computed as: 93%, 0%, 5%, 2%, and 0% in condition states 1 through 5, respectively. This allows for comparisons between structures of different sizes and configurations to be made with greater ease. Any relevant smart flags that are associated with specific condition states are also noted so that the cause for advanced condition states can be more readily revealed as corrosion-related issues (e.g., if the pack rust smart flag is present) or non-corrosion related issues (e.g., if the traffic impact smart flag is present).

Table 4.2: Excerpt of Condition State Data in Typical Inspection Report

No.	Description	Unit	State 1	State 2	State 3	State 4	State 5	Total
92	Reinforced Concrete Sidewalk	LF	444	8	0	0	0	452
106	Steel Open Girder, Unpainted	LF	1,049	0	56	24	1	1,130
210	Reinforced Concrete Pier Wall	LF	15	0	0	0	0	15

4.1.2.2 Qualitative Descriptions

In addition, if the condition state of the element is greater than 1, it is frequently the case that quantitative and / or qualitative text descriptions accompany the condition state data. For example, statements such as “Surface rust on superstructure steel “ provide a qualitative understanding of the reason why 5% the girders of this structure were placed in Condition State 3. Or, often more specific

statements such as “Rust scale with up to 1/16” section loss on bottom flange (5’L each)“, further explain the specific situation of a given element. All such statements were read and lists of keywords associated with each CoRe element are noted when possible (although the presence, extent and detail of such notes varies considerably among different structures). For example, keywords and/or smart flags such as corrosion, pack rust, rust/scale, and section loss reflect UWS-related issues potentially affecting structural performance while keywords and / or smart flags such as impact or missing bolts are not considered UWS-related issues.

4.1.2.3 Photographs

The qualitative descriptions previously discussed in Section 4.1.2.2 often refer to specific photographs that are included elsewhere in the inspection report, which are valuable in further clarifying the condition of various elements and are noted in the condition summary report of each cluster. These photographs were also useful in illustrating the surroundings of the bridges, which provided insight on planning field work in some cases.

4.1.3 Cluster Data Comparisons

Pending the completion of the field evaluations of each reference and cluster bridge, an effort will be made to correlate the condition state statistics, qualitative descriptions and photographs with field data in a process similar to that conducted in the Phase 1 report of this project (McConnell et al 2012). The purpose of this will be to inform the cause and effect relationships between the influential variables considered and the observed condition of the structures, observed in both the inspection reports and field evaluations.

In addition, comparisons will be made between the various clusters considered. For example the performance and environment of the good and inferior clusters within the deicing and coastal categories will be compared. It may also be informative to conduct a similar comparison of good deicing and good coastal clusters as well as inferior coastal and inferior deicing clusters to better understand the relative uniqueness or similarities of such environments.

4.2 Phase II Examples

To date, desk studies have been completed for the New York, Maryland, and Texas clusters. The Louisiana cluster is a work in progress and also discussed. The data, findings, and any modifications made to the general methodology are described below for each cluster.

4.2.1 New York

New York does not use the CoRe element condition state but rather has its own similar rating system based on a 1 to 7 integer-based rating scale, which has its own advantages and disadvantages. In addition to the numerical ratings being more refined in the New York system, an advantage of this system is that a specific evaluation item for steel components is the "paint" condition, which refers directly to paint of painted structures and the UWS condition otherwise. Thus, in contrast to the CoRe condition states for UWS members, which may reflect corrosion issues, fatigue issues, or traffic impact issues, there is a direct indicator of the weathered condition of the UWS elements in the New York evaluation system. The rating scale for UWS "paint" condition is as follows, where it should also be noted that the numerical scale is in a sequence opposite to the CoRe rating system in that here 7 represents the best

condition and 1 represents the worst condition. The New York State Bridge Manual describes the conditions as follows (NYSDOT 2014).

7. The patina is tight. The color of the surface will range from light yellow orange (new steel) to dark chocolate or purple (steel exposed under good conditions with proper wetting and drying cycles). The texture of the surface is either mill scale or granular in nature, both adhering tightly when subjected to vigorous wire brushing. Some minor loss of the mill scale or granular surface material is normal under vigorous brushing.
6. The patina is generally tight with proper color and texture as described for the 7 rating on the majority of the surface. Isolated areas (e.g. under bridge joints) may have different darker colors or non-adhering textures. This may be the early signs of future problems or just portions of the patina forming at different rates.
5. The overall surface may show signs of possible patina formation problems. The surface contains portions that are dark black indicating that the protective oxide layer is not forming. The surface in these isolated areas has a coarse texture or is granular with small flakes (under ¼ inch dia.) that are not adhering when subjected to a vigorous wire brushing.
4. The surface is typically dark black indicating that the protective oxide layer is not forming and probably will not form. The surface also typically has a coarse texture with non-adhering small flakes (under ⅜ inch dia.) and may have some evidence of plate delamination. There

may be continuous rusting evidenced by occasional accumulations of flakes on the top of the bottom flange or on the ground or by the ability to remove much of the flaking with vigorous wire brushing.

3. The surface is uniformly dark black indicating that the protective oxide layer has not formed. The surface has a coarse texture that is principally non-adhering medium flakes (under ½ inch dia.) with some plate delaminations. There is continuous rusting of the steel evidenced by frequent accumulations of flakes or sheet delaminations on the top of the bottom flange or on the ground or by the ability to easily remove much of the flaking and delaminated sheets with a wire brush or chipping hammer.
2. The majority of the surface is black, indicating a significant failure of the protective oxide layer formation. The surface has a coarse texture that has large flakes (greater than ½ inch dia.) with little or no adhesion and there is extensive plate delamination. There is continuous rusting of the steel evidenced by consistent and extensive accumulations of flakes or sheet delaminations on the top of the bottom flange or on the ground or by the ability to easily remove much of the flaking and delaminated sheets with a wire brush or chipping hammer. These are indications that advanced section loss may have taken place.
1. The entire surface is black indicating a complete failure of the protective oxide layer formation. The entire surface has a coarse texture of large flakes (greater than ½ inch dia.) that demonstrate no adhesion and there is significant plate delamination. There is continuous rusting

of the steel evidenced by consistent and extensive accumulations of flakes or sheet delaminations on the top of the bottom flange or on the ground or by the ability able to easily remove much of the flaking and delaminated sheets with a wire brush or chipping hammer.

The primary disadvantage of the New York evaluation system relative to the goals of this project is that a single numerical rating is assigned to each component in each span. In other words, in contrast to the CoRe evaluation system where the distribution of each element in each condition state is reported, a single value is used to note the most severe condition that is observed and also generally reflect the range of the conditions observed. For example New York's unpainted weathering steel rating of 6 indicates a situation corresponding to some of the element likely being classified in Condition State 1 and some of the same element being classified as Condition State 2 using the CoRe system.

To ameliorate the issue of the New York data being expressed in a different format, after observing some conceptual similarities between the New York and CoRe evaluation systems and at the research team's request, Table 4.4 was provided by NYSDOT to give a general idea of how the New York condition ratings could be approximated as CoRe condition states. This data was specifically supplied by NYSDOT personnel for unpainted open steel girders and then equally adopted to convert the condition states of all UWS members from the New York rating system to the CoRe rating system. This allows for the New York data to be more readily compared to corresponding data from other clusters.

Table 4.3 shows inspection report details for the New York cluster bridges. The first two columns of data detail the bridge label and parametric combination

described in Section 3.1.3.2. Bridges that crossed more than one attribute (e.g., a highway and a railroad) were initially categorized for both crossing types and a final categorization was made after the parametric combinations of interest were finalized. As a result, some entries in this table and similar tables that will later be presented for other clusters have multiple categories listed, but the one of these that was not crossed out is the category to which the bridge was ultimately assigned, as previously described in Section 3.1.3.3. The "condition" portion of the table summarizes the inspection reports and both the original element-level ratings for each of the New York bridges and then the conversion of this data into the CoRe format based on Table 4.4. Also shown here is the keyword summary of the qualitative description for the UWS condition for each bridge. The next set of columns display the superstructure condition rating and age were taken from the NBI. The last set of columns refer to the bridges' configuration. This information will serve as the foundation for the future components of the desk study to be completed at a later date.

4.2.2 Maryland

Table 4.5 shows the desk study summary table from the Maryland Cluster. This data is compiled using the methodology described in Section 4.1 with no revisions to the process being necessary in this case. Other than the lack of need for converting among different rating systems, the format of this data is identical to that reviewed in the Section 4.2.1 for the New York cluster. In this cluster, photographs are only available for the Virginia bridge and the reference bridge. This information will serve as the foundation for the future components of the desk study to be completed at a later date.

Table 4.3: Inspection Report Summary, New York

LABELS AND PARAMETRIC VALUES		CONDITION													CONFIGURATION		
Bridge ID	Category	Condensed Summary	NYSDOT Rating Scale: Percentage of Spans with "Paint" Ratings of:							CoRE Rating Scale: Condition State of UWS Components				Super Structure Rating (NBI)	Age (NBI)	Girder Type	Max Span Length (meters)	Total Length (meters)
			1	2	3	4	5	6	7	1	2	3	4					
A1	2	leakage					100%			50%	50%			8	26	I	35.3	36.8
A2	33	extensive corrosion at ends and bearing, presumably due to leakage but not explictly stated					100%			50%	50%			8	35	I	22.8	23.7
A3	6	no UWS related issues noted						100%		75%	25%			8	31	I	47.8	132.2
A5	6	steel patina not functioning					100%			50%	50%			8	29	I	56.3	57.9
A9	10	significant amount of girders have delaminations about 1/16 to 1/8" thick			100%						15%	50%	35%	7	30	I	72.8	140.8
A10	10	minor section loss					66.7%	33.3%		58%	42%			8	30	I	46.6	134.1
A11	14	moderate corrosion and section loss on girders					100%			50%	50%			8	29	I	51.2	51.8
A16	24	only bearing corrosion noted					100%			50%	50%			8	24	I	34.7	36.3
A19	26	minor rusting and flaking					100%			50%	50%			6	42	I	90.8	308.4
A20	30	corrosion attibuted to leaking joint					100%			50%	50%			8	30	I	30.7	32.3
A21	30	leaking joint					100%			50%	50%			8	30	I	32.6	34.1
A23	31	no UWS related issues						100%		75%	25%			8	22	I	57.9	339.8
A25	33	corrosion (large depth and length), problems with patina due to moisture from deck joint - sheets of rust; remainder of steel "5 or better"				40%	40%	20%		35%	39%	20%	6%	7	32	I	19.5	87.7
A26	33	leakage related corrosion				71.4%	28.6%			14%	25%	36%	25%	6	32	I	30.1	176.1
A33	37	leakage related corrosion					100%			50%	50%			8	31	I	36.5	37.1
A36	18,39	only bearing corrosion noted					100%			50%	50%			6	42	I	90.8	308.5
A37	26,35	section loss due to previous leakage				50%		50%		38%	30%	25%	8%	8	31	I	50.9	445.6
A38	39,35	leakage					100%			50%	50%			8	26	I	36.5	52.4
A39	W	active corrosion throughout bridge - water crossing		100%								50%	50%	5	25	I	33.5	34.1
A40	W	no UWS related issues noted; water crossing							100%	100%				9	33	I	38.1	39

Table 4.4: Conversation of New York Condition Rating to Ratio in CoRe Element Condition States

	Distribution to CoRe Rating (1=100%)			
NYSDOT Rating	1	2	3	4
7	1	0	0	0
6	0.75	0.25	0	0
5	0.5	0.5	0	0
4	0	0.35	0.5	0.15
3	0	0.15	0.5	0.35
2	0	0	0.5	0.5
1	0	0	0.25	0.75

4.2.3 Texas

The Texas cluster desk study summary table is shown below in Table 4.6, which follows the format of the table shown in Section 4.2.2. This information will serve as the foundation for the future components of the desk study to be completed at a later date.

4.2.4 Louisiana

The Louisiana cluster desk study summary table is shown below in Table 4.7, which follows the format of the table shown in Section 4.2.2. This information will serve as the foundation for the future components of the desk study to be completed at a later date.

Table 4.5: Inspection Reports Summary, Maryland

LABELS AND PARAMETRIC VALUES		CONDITION								CONFIGURATION		
Bridge ID	Category	Condensed Summary	Condition State of UVS Components Summary					Super Structure Rating (NBI)	Age (NBI)	Girder Type	Max Span Length (meters)	Total Length (meters)
			1	2	3	4	5					
C1	1	minor rust scale	97%	3%				7	27	I	36.6	73.8
C2	1	pitting on steel and thin layer of scale on girder		100%				7	26	I	36.9	37.5
C3	2	UWS portions of the webs (interior and exterior) have areas with slightly heavier than desired rusting (in first 6" of the webs above the lower flanges		100				6	23	I	54.9	95.4
C6	4	mill scale on girder	100%					7	26	I	49.4	98.5
C7	4	rust on girder	100%					7	26	I	45.1	81.4
C9	6	rust/scale on girders and bearings, leaking joints, pack rust, broken welds		98%	2%			6	38	I	42.7	86.9
C11	6	isolated moderate rusting; remaining UWS in good condition; extensive painting, No UWS CS data	NA	NA	NA	NA	NA	7	23	I	50.3	93.3
C12	7	mill scale on girder, leaking joints	100%					7	29	I	46.3	89.3
C13	7	bearing issues	100%					7	28	I	43.6	78.6
C16	8	bearing issues	100%					7	26	I	33.2	68
C17	8	rust/scale on girder, leaking joint and bearing issues, pack rust, broken welds	0-94	0-97	3-6			6	40	I	36.6	74.7
C23	10	up to 100% section loss and rust/scale on girder, appears isolated to area beneath leaking joints	93%	0%	5%	2%		5	31	I	37.8	68.9
C24	10	freckled rust on bearings and ends of girder	94%	6%				7	31	I	56.4	105.5
C27	24	pack rust, steel fatigue, cracks	100%					5	40	I	43.3	88.1
C28	24	areas w/ heavier than normal rusting; slightly heavier than normal rusting along the edges of the exterior lower flanges for their full length, leaking joints	0-78	8-86	14			7	33	I	26.2	27.4
C36	~~20~~,34	thin layer of scale on girder	92%	8%				7	29	I	23.5	60.4
C38	~~3~~,34	minor rust scale on girders	100%					6	30	I	49.4	93.3
C39	36	leaking joints, laminating corroison and rust/scale on griders, rust on bearings	97%	3%				7	28	I	21.3	48.5
C40	36	rust/scale, rust pack, leaking compression joints, rusting bearings	98-100		0-2			6	30	I	48.8	752.2
C41	36	minor scaling on girder	100%					8	27	I	26.8	69.2
C42	13,35,39	orange-colored rust; beam ends have heavier rust, pitting, and some scale		96-98	2-4			7	39	I	31.1	202.7

Table 4.6: Inspection Reports Summary, Texas

LABELS AND PARAMETRIC VALUES		CONDITION								CONFIGURATION		
Bridge ID	Category	Condensed Summary	Condition State of UWS Components Summary					Super Structure Rating (NBI)	Age (NBI)	Girder Type	Max Span Length (meters)	Total Length (meters)
			1	2	3	4	5					
D1	1	pack rust, section loss	100%					4	34	I	88.4	1310.2
D2	1	laminar corrosion	100%					7	31	I	85.3	855.6
D6	2		100%					8	33	I	40.8	317
D9	2	light surface rust	100%					6	20	I	26.5	792.5
D10	2		100%					8	24	I	35.1	158.8
D12	2	"surface rust" inside unpainted box cap, corrosion and section loss of box cap components	100%					7	33	I	45.4	738.8
D15	2	"minor edge delaminations"	100%					7	23	I	47.2	492.9
D16	2	issues with moisture inside painted interiors of box caps	100%					6	23	I and U	45.7	2765.8
D17	2		100%					8	32	I	38.1	171.6
D18	2	impact damage	99%	1%				5	27	I	15.8	58.8
D19	2		100%					8	20	N/A	24.1	96.9
D20	2		100%					7	22	I	53.3	566.6
D23	2		100%					6	24	I	64	734.6
D28	2		N/A					8	30	I	57.9	370
D34	4		100%					6	23	I	38.7	170.1
D35	4		100%					8	23	I	68.6	542.5
D36	4		100%					7	23	I	68.6	542.5

Table 4.7: Inspection Reports Summary, Louisiana

Bridge ID	CONDITION												BRIDGE CONFIGURATON		
	Condensed Summary	Condition State of UWS Components Summary									Super Structure Rating (NBI)	Age (NBI)	Girder Type	Max Span Length (meters)	Total Length (meters)
		1	2	3	4	5	G	F	P	C					
B1	corrosion in areas above bearings, some pin and hanger connections have shorter bolts	100%									7	38	I	91.4	1236
B3	1 bolt not completely inserted in girder 10	100%									5	32	I	51.8	737.6
B5		100%									7	33	I	27.4	192
B14	Cause of debris in the caps/girders are the open joints/flood water. localized moderate flaking corrosion, minor to moderate section loss in girder webs, splice plates and splice plate mechanical connectors, plate girders have local moderate to heavy pack-rust						100%				6	37	I	106.7	6379.2
B17	minor collision damage, cause of debris in the cap/girders are the open joints. Flood waters can reach superstructure. steel spans have localized moderate flaking corrosion, minor to moderate local section loss in the girder webs, splice plates and splice mechanical connectors. The interior girders have the same detrioration (lessor degree). minor to moderate pack rust between the splice plates and girder webs/girder bottom flanges. gusset/lateral brace interfaces have minor pack rust.						100%				6	37	I	106.7	6379.2
B18	most spans concrete, and spalling of shear keys in concrete spans is only note concerning superstructure performanc, with exception of joints in cs > 1	100%									7	34	I	12.2	207.3
B20	concrete spans appear to govern rating	100%									6	27	I	62.5	1005.8
B24	joints need to be resealed	75%	25%								7	34	I	30.5	76.2
B25	weld in top flange in girder 2 span 4 has small cracks, girder 1 and 3 in span 2 have collosion damage	100%									7	37	I	34.4	106.1
B26	Not Available										7	26	Not Availabl	30.5	262.1
B28	Not Available										8	35	Not Availabl	54.9	317.6

4.3 Phase III Work in Progress - Colorado

The Colorado cluster desk study summary table is displayed in Table 4.8, which follows the format of the tables previously shown in Sections 4.2.2 and 4.2.3. The inspection reports for this cluster did not provide photographs but the qualitative comments for these structures provided a greater-than-typical level of detail, which at least partially compensates for this. Furthermore, pictures for specific potential field bridges were requested from Colorado Department of Transportation (CDOT) to obtain visual information on this subset of bridges.

Table 4.8: Inspection Report Summary, Colorado

LABELS AND PARAMETRIC VALUES		CONDITION								CONFIGURATION		
Bridge ID	Category	Condensed Summary	Condition State of UWS Components Summary					Super Structure Rating (NBI)	Age (NBI)	Girder Type	Max Span Length (meters)	Total Length (meters)
			1	2	3	4	5					
E1	12	no UWS related issues	100%	0%	0%	0%	0%	7	28	U	56.1	233.2
E2	28	weld cracks , light rust on top flange and longitudinal stiffeners at Girders A&B (both sides), rough welds, pigeon droppings	99%	1%	0%	0%	0%	7	31	U	51.2	52.7
E3	20	(Exterior) Steel not weathering uniformly, little corrosion on flanges	100%	0%	0%	0%	0%	8	31	U	46.5	48
E4	20	no UWS related issues	100%	0%	0%	0%	0%	8	31	U	60.7	61.7
E5	20	light rust on exterior (photos indicate this statement applies to webs and/or flanges)	100%	0%	0%	0%	0%	8	31	U	60.9	62.7
E6	W	light brown to orange color on girders, corrosion on one girder, stiffeners are not at full height, scrape marks on Girders D,E, and F. R1 to light R2 corrosion on 1 sole plate	85%	15%	0%	0%	0%	7	33	I	27	104.5
E7	24	nicks and scrapes on 2 girders, poor welds and cracking at multiple diaphragms and in webs, corrosion along bottom flange inside Girder E, heavy pigeon droppings	95%	5%	0%	0%	0%	3	33	U	38.6	39.9
E8	24	no UWS related issues	100%	0%	0%	0%	0%	3	33	U	41	42.4
E9	W	no UWS related issues	100%	0%	0%	0%	0%	8	32	I	21.1	54.1
E10	W	R1 corrosion on girder ends, yellow/orange discoloration on girders, grafitti on Abutment 1 ends, anchor bolts missing for bearing	83%	16%	1%	0%	0%	7	33	I	26.2	53.6

Chapter 5

CONCLUSIONS

5.1 Summary

The objective of the larger research project to which the research presented in this thesis contributes is to review the performance of UWS bridges in various environmental, chemical, and geographical conditions in the US using a mathematical and statistically driven process that will provide quantifiable information regarding UWS performance in differing environments. In furtherance of this goal, first a national UWS inventory and database was created. This process began by asking representatives in 52 transportation agencies to identify the UWS bridges within their inventory, with 46 representatives accommodating this request. Microsoft Access was then used to extract the agency-identified UWS bridges from the NBI database, which contains information about each bridge's structural attributes and condition. Next, GIS was used to associate climatic, chemical, and geographical variables to each bridge location.

The next phase of research involved selecting subsets of bridges from this national inventory for further consideration for varying degrees of more detailed evaluation, including field evaluations. To accomplish this, a statistically driven process was created and implemented to form matrices of bridges in geographic proximity to one another, which are termed bridge "clusters". These matrices contain pairs of similar bridges with each pair only differing in the values of one of the potentially influential environmental variables so that the influence of the variables of

interest can be independently assessed. The environments of interest in these evaluations focused on coastal locations and overpasses over heavily salted roadways.

The third component of this research was to develop a process for analyzing the performance of the selected bridges, based on compiling data from the owner's inspection reports. Specific emphasis was placed on the quantitative data reflected by the condition states of UWS CoRe elements. Key words relating to UWS issues or corrosion and photographs displaying conditions were also used to supplement the quantitative analysis.

5.2 Conclusions

The national UWS created in this work was demonstrated to be a valuable tool for systematically selecting bridges for further evaluation and better understanding the specific environmental conditions for all known UWS structures. This database can also be used in future work in order to expand the scope of work to consider additional clusters. Furthermore, the UWS database would enable future statistical analysis of correlations between various environmental conditions and structural performance, which could be highly valuable for revealing cause and effect relationships between inferior performance and environment.

Four clusters were successfully created in this work and have been evaluated in related field work. These clusters represent ranges of performance under the two primary environments of interest: (1) overpasses crossing heavily-salted and high volume roadways and (2) coastal locations. As a result, it was shown that the methodology of using a statistical method for categorizing the bridges, identifying categories of greatest interest, and selecting specific bridges within these categories that was used for creating these clusters is effective. This process takes into account

the different parameters causing poor performance and provides a basis of comparison for bridges of different parametric categories. It is concluded that this method is promising as means for providing quantifiable data for UWS performance. Thus, this methodology is recommended for employment in the creation of any future UWS clusters.

A system for compiling data on the bridge clusters was also created and piloted in this work. This method has also been revealed as an effective organizational scheme for further evaluating UWS performance of specific bridges and assessing comparisons and contrasts between various bridges in similar and differing conditions in future work.

5.3 Future Work

Recommended future work includes evaluating additional clusters throughout the US in regions with inferior and good UWS performance in order to provide a larger sample size on which quantifiable recommendations for updating FHWA TA 5140.22. It is recommended that these clusters include those based on bridges that state coordinators revealed were not performing well (discussed in Section 3.1.1.1.1), particularly those in heavy deicing area, regions near the coast, or combinations thereof. The inspection reports for these potential reference bridges have been requested, which will streamline future progress on these clusters. Furthermore, the proximate bridges within a specified radius of each of these reference bridges have been identified through GIS and are listed in the Appendix. This information can be used to assess the opportunities available for forming informative clusters when prioritizing clusters for future work.

It would also be of interest to future work to evaluate bridges performing well despite locations in various extreme climate conditions, where specific regions of interest were discussed in Section 3.2.2.2. One of these is a Colorado-based deicing cluster. The bridge selections for this cluster have been fully completed. Proximate bridges have been identified for the remaining possible clusters and are listed in the Appendix. A statistical method could be used to determine the remaining classes of bridges in a manner similar to the process used for the clusters described in Chapter 3 and 4 when a reference bridge was not initially known. The remaining phases of field and desk work could then proceed as done for Phase II clusters discussed herein.

In addition to creating new clusters, field work has been conducted to the Maryland, New York, Louisiana, and Texas clusters. Various samples of corrosion products have been collected for the selected field and reference bridges. Those samples can be reviewed and then compared and contrasted to the environmental, chemical, climatic, and bridge attribute data already available in the UWS database for the purpose of evaluating potential cause and effect relationships between environment, corrosion product chemical composition, and NBI superstructure ratings.

REFERENCES

Albrecht, P., and Naeemi, A. H. (1984). "Performance of Weathering Steel in Bridges," National Cooperative Highway Research Program, Report 272, Transportation Research Board, Washington DC.

American Iron and Steel Institute, (1982). "Performance of Weathering Steel in Highway Bridges: A First Phase Report." American Iron and Steel Institute, Pittsburgh, PA.

American Iron and Steel Institute (1995). "Performance of Weathering Steel in Highway Bridges: A Third Phase Report", American Iron and Steel Institute, Pittsburgh, PA.

Appleman, B.R. (1987). "Painting Over Soluble Salts: A Perspective" JPCL, October 1987, pp. 68-82.

Coomarasamy et al. (2008), "Analysis of Corrosion Products Formed on Some of Ontario's Weathering Steel Bridges," Ministry of Ontario Transportation, Paper No. 08199, 2008 National Association of Corrosion Engineers (NACE) International Conference, Marcch 16-18, 2008, New Orleans, LA.

Culp, J.D. & Tinklenberg, G.L. (1980). "Interim Report on Effects of Corrosion on Bridges of Unpainted A588 Steel and Paint Steel Types" (Research Report Number R-1142) Michigan Transportation Commission, Lansing, Michigan.

Environmental Protection Agency EPA (2012) "Frequent Questions about Geospatial Data and Records" *Records* < http://www.epa.gov/records/faqs/geospatial.htm> (June 2013)

ESRI (Environmental Systems Resource Institute). 2012. ArcGIS 10.1. ESRI, Redlands, California.

Friedland, I., Ghasemi, H. and Chase, S. (2007). "The FHWA Long-Term Bridge Performance Program", Turner-Fairbank Highway Research Center, McLean VA.

FHWA (1995). "Recording and Coding Guide for the Superstructure Inventory and Appraisal of the Nation's Bridges", Report FHWA/PD-96/001, FHWA, Office of Engineering, Bridge Division, Bridge Management Branch, Washington, DC.

FHWA (2006). "Bridge Inspector's Reference Manual", Publication No FHWA NHI 03-001, Federal Highway Administration (FHWA) United States Department of Transportation Washington, DC.

Johnson, M. B. and Jensen, P. (2010) "AASHTO Bridge Element Inspection Guide Manual" 1st Ed., United States of America

McConnell, J., Mertz, D., Shenton, H., Lee, S., and Roda, A. (2012). "Long-Term Bridge Performance (LTBP) Program: Evaluation of Unpainted Weathering Steel Highway Bridge Performance Phase I Report", Center for Innovative Bridge Engineering, University of Delaware, Newark, DE.

McDad, B., Laffrey, D.C., Dammann, M. and Medlock, R.D. (2000). "Performance of Weathering Steel in TxDOT Bridges," Texas Department of Transportation, Project 0-1818.

McMahon, B. and McFadden, R (2014) "Session 2.4: Weathering Steel," New York State Department of Transportation, Region 4, NY

National Association of Corrosion Engineers (2010), "Corrosion- Atmospheric Corrosion ." *NACE Resource Center,* http://events.nace.org/library/corrosion/AtmCorros/TOW.asp (October 3, 2012)

National Atmospheric and Deposition Program (2012). "National Trends Network." *National Atmospheric and Deposition Program*, < http://nadp.sws.uiuc.edu/NTN/> (June 5, 2012)

National Atmospheric and Deposition Program (2012). "Annual NTN Maps by Year." *National Atmospheric and Deposition Program*, <http://nadp.isws.illinois.edu/ntn/annualmapsbyyear.aspx> (June 5, 2012)

National Geodatic Survey (2013). "National Geodatic Suvery: Frequently Asked Questions." NOAA <http://geodesy.noaa.gov/faq.shtml#WhatNAD > (March 7, 2013)

National Oceanic and Atmospheric Administration (2002). "The Climate Atlas of United States" Climate Atlas (CD-ROM), National Climatic Data Center, Asheville, NC.

National Oceanic and Atmospheric Administration (2008). "Average Relative Humidity." *National Climatic Data Center,* http://www.ncdc.noaa.gov/oa/climate/online/ccd/avgrh.html (September 7, 2012)

New York State Department of Transportation NYSDOT (2014). "Bridge Inspection Manual" *NYSDOT Website* <https://www.dot.ny.gov/divisions/engineering/structures/repository/manuals/inspection/nysdot_bridge_inspection_manual_2014.pdf > (March 2013)

Nickerson, R.L (1994), "Weathering Steel Bridges: a 1994 Review of Performance," Public Works, 125(11): 49-50.

NOAA OCS. "NOAA Office of Coast Survey (OCS) Shorelines." *NOAA Shoreline Website*, <http://shoreline.noaa.gov/data/datasheets/ocsshore.html> (October 10, 2012)

NOAA OCS. "Electronic Navigational Charts: NOAA ENC." *NOAA Office of Coast Survey,* < http://www.nauticalcharts.noaa.gov/mcd/enc/index.htm> (October 10, 2012)

Raman, A. and Naszrazadani, S. (1989). "Corrosion Problems in Some Louisiana Bridges and Suggested Remedies," Paper No. 165 Louisiana State University, Department of Mechanical Engineering, Baton Rouge, LA

United States Department of Agriculture USDA (2010) "Charts and Maps" *National Agricultural Statistics Service* < http://www.nass.usda.gov/Charts_and_Maps/Crops_County/index.asp> (June 2013)

Wiss, Janney, Elstner Associates (WJE), Inc. (2013). “Assessment of Weathering Steel Bridge Performance in Iowa and Development of Inspection and Maintenance Techniques”, WJE and Iowa Department of Transportation, Ames, IA.

Appendix A

CAUS Humidity Maps

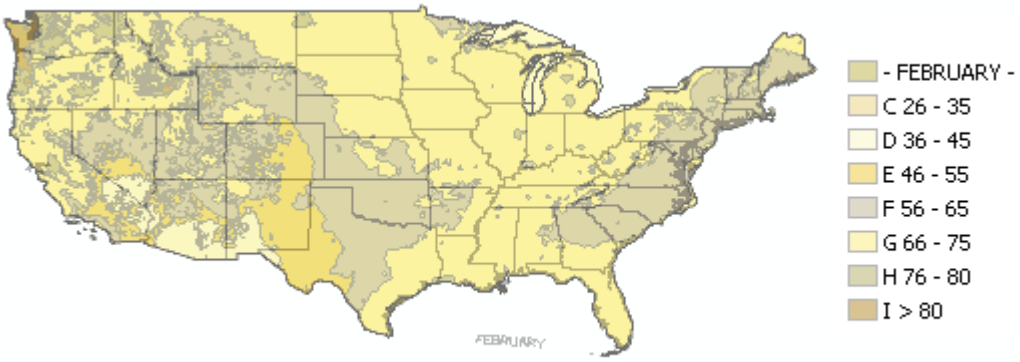

Figure A.1: CAUS February Humidity

Figure A.2: CAUS March Humidity

Figure A.3: CAUS April Humidity

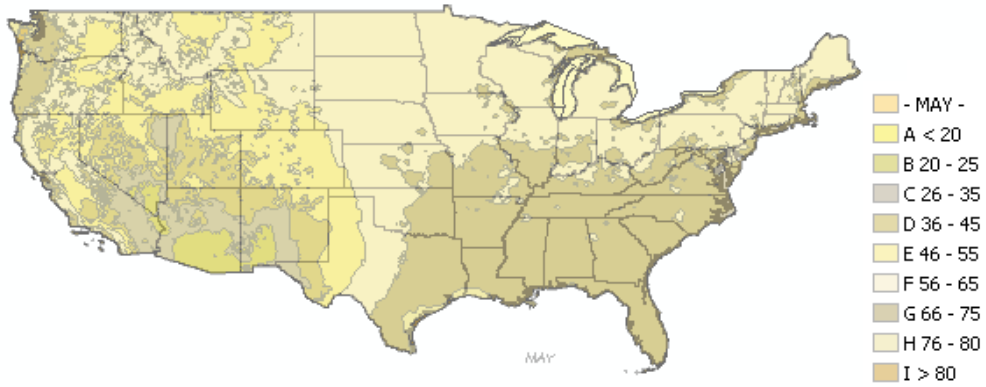

Figure A.4: CAUS May Humidity

Figure A.5: CAUS June Humidity

Figure A.6: CAUS July Humidity

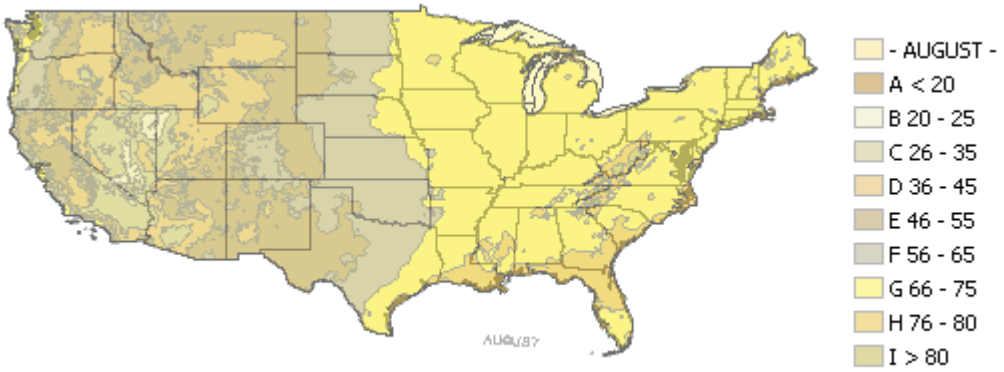

Figure A.7: CAUS August Humidity

Figure A.8: CAUS September Humidity

Figure A.9: CAUS October Humidity

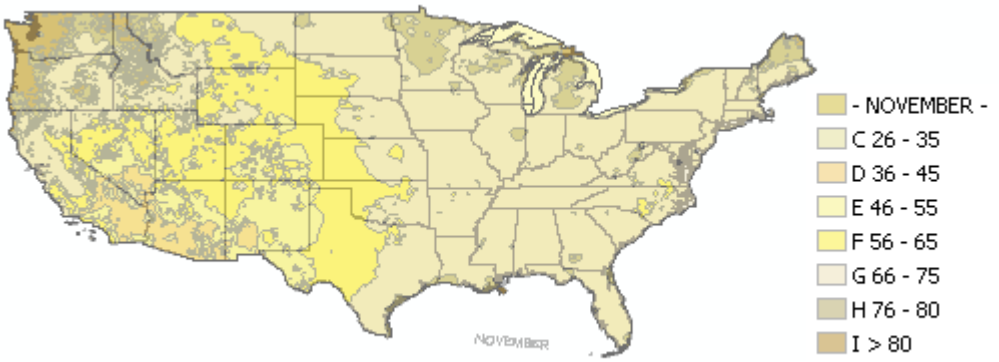

Figure A.10: CAUS November Humidity

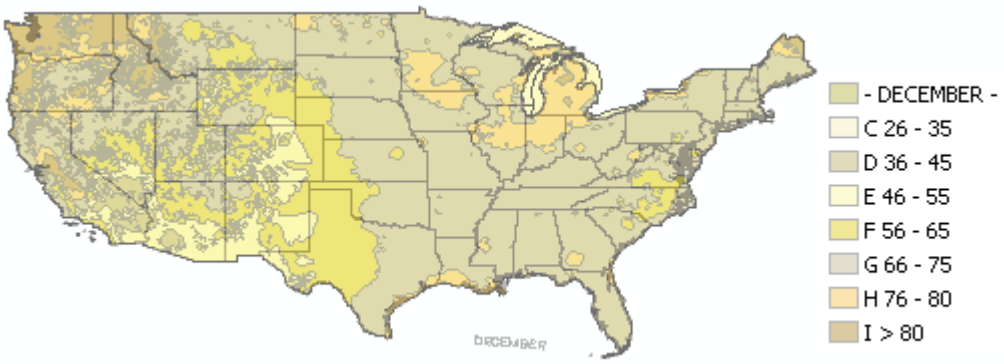

Figure A.11: CAUS December Humidity

Figure A.12: CAUS Annual Humidity

Appendix B

UWS Survey

FHWA Long-Term Bridge Performance Program
EVALUATION OF
UNPAINTED WEATHERING-STEEL HIGHWAY-BRIDGE PERFORMANCE

Survey to State Coordinators

February 7, 2012

Please answer the following questions pertaining to your agency's use of unpainted weathering steel in highway bridges. All participants are asked to answer Questions 1 and 6. Those answering "yes" to Question 1a should also answer Questions 2 – 4. If you answer "no" to either Question 1a or 1b, please also answer Question 5. Responses can be typed directly into this document and returned via email attachment to righman@udel.edu.

Question 1, for all participants

1. (a) Does your agency have bridges using unpainted weathering steel highway in its inventory? (yes/no)
   (b) If so, does your agency continue to construct bridges using unpainted weathering steel? (yes/no)

Questions 2 – 4, for agencies currently or previously using unpainted weathering steel in highway bridges

2. Briefly describe your general perception of the overall performance of unpainted weathering steel in highway bridges within your agency. Note that by "overall performance" we are interested in performance away from problematic details such as leaking joints, details that trap moisture and debris, etc.

3. Identify which of your bridges using unpainted weathering steel are exhibiting the worst overall performance (approximately 1 to 3 bridges would be most helpful to us).

4. For the bridges identified in Question 3, briefly elaborate on the condition of these bridges and the environment (i.e., climate, physical surroundings, exposure to deicing agents) in which they are located.

Question 5, for agencies never or not currently using unpainted weathering steel in highway bridges

5. Briefly describe the reasons why your agency does not use unpainted weathering steel in highway bridges.

Question 6, for all participants

6. (a) Does your agency have records of the amount of deicing agents used on an annual basis?
   (b) If so, how is it quantified (e.g., gross tons, tons per district, miles/ton, etc.), and would you be able to provide this data?

Appendix C

Proximate Bridges for Potential Phase III State-Recommended Inferior Performing Bridges

As discussed in Chapter 3, the proximate bridges have been identified for each of the state-recommended inferior performing bridges that may be candidates for further evaluation in later phases of this work. These state-recommended bridges are listed below in Table C.1 along with the criteria used to create each listing of proximate bridges. Otherwise the same process for identifying proximate bridges here as was used in Chapter 3. If an agency recommended multiple bridges that were near one another, this would occasionally result in the same listing of proximate bridges for multiple state-recommended clusters. In these cases (i.e., Alabama and Colorado) only one listing of proximate bridges is provided, which is equally applicable to any of the corresponding state-recommended bridges. If the bridges were farther apart and resulted in different sets of proximate bridges, then separate tables display the results. Another subtle difference in the tables that follow is that the radius used to select proximate bridges was increased if necessary to provide a minimum of 10 bridges within the desired age group. State-recommended bridges older than 20 years had proximate bridges within the age range of 20 to 49 years and bridges state-recommended bridges with ages less than 20 years had proximate bridges within the age range of 1 to 49 years. These criteria are summarized in Table C.1.

Tables C.2 through C.17 list the resulting proximate bridges within these clusters. The bridges are listed alphabetically by state (when relevant) and then in

ascending order by bridge ID number. The state-recommended bridges are highlighted in each table.

Table C.1: Summary of State Recommended Inferior Performing Bridge Clusters

	BRIDGE DESCRIPTION		PROXIMATE BRIDGE CRITERIA	
STATE	ID	AGE (years)	RADIUS (miles)	AGE RANGE (years)
Alabama	12321	33	150	20 - 49
Alabama	12322	33	150	20 - 49
Colorado	F-11-AO	11	50	1 - 49
Colorado	F-11-AP	36	50	20 - 49
Colorado	F-11-AT	36	50	20 - 49
Connecticut	3830	37	50	20 - 49
Iowa	41331	11	50	1 - 49
Maine	1004	26	50	20 - 49
Maine	2928	35	50	20 - 49
Massachusetts	A18001AE8DOTNBI	17	50	1 - 49
Massachusetts	B230213T5DOTNBI	34	50	20 - 49
Michigan	4586	40	50	20 - 49
Michigan	8097	6	50	1 - 49
Minnesota	62861	40	50	20 - 49
Pennsylvania	10473	3	50	1 - 49
Pennsylvania	25435	38	50	20 - 49
Rhode Island	170	32	50	20 - 49
Washington	0011490A0000000	32	150	20 - 49
Wyoming	CCC	37	100	20 - 49

Table C.2: Alabama Cluster based on 12321 and 12322, Proximate Bridges

BRIDGE ID	STATE
12321	Alabama
12322	Alabama
023608360801331	Louisiana
023800620508961	Louisiana
024400463208671	Louisiana
625204501805821	Louisiana
625204501805822	Louisiana
625204540410066	Louisiana
625208521103301	Louisiana
625300130906091	Louisiana
625930401900011	Louisiana
11000100300654A	Mississippi
11000100300654B	Mississippi
11000100300755A	Mississippi
11000100300755B	Mississippi
21000840161324A	Mississippi
21000840161324B	Mississippi
210001101807630	Mississippi

Table C.3: Colorado Cluster based on F-11-AO, F-11-AP, and F-11-AT, Proximate Bridges

BRIDGE ID	STATE
F-08-AH	Colorado
F-08-AI	Colorado
F-08-AL	Colorado
F-08-AM	Colorado
F-08-AN	Colorado
F-08-BC	Colorado
F-08-BD	Colorado
F-08-BI	Colorado
F-11-AO	Colorado
F-11-AP	Colorado
F-11-AS	Colorado
F-11-AT	Colorado
F-12-AK	Colorado
F-12-AL	Colorado
F-12-AM	Colorado
F-12-AN	Colorado
F-12-AO	Colorado
F-12-AP	Colorado
F-12-AS	Colorado
F-12-AT	Colorado
F-12-CA	Colorado
F-15-AD	Colorado
F-15-CQ	Colorado

Table C.4: Connecticut Cluster based on 3830, Proximate Bridges

BRIDGE ID	STATE
665	Connecticut
1875	Connecticut
2563	Connecticut
2568	Connecticut
2928	Connecticut
3564	Connecticut
3586	Connecticut
3588	Connecticut
3589	Connecticut
3591	Connecticut
3592	Connecticut
3607	Connecticut
3729	Connecticut
3830	Connecticut
3831	Connecticut
3832	Connecticut
3835	Connecticut
3836	Connecticut
3912	Connecticut
3913	Connecticut
3915	Connecticut
3916	Connecticut
3917	Connecticut
3918	Connecticut
3923	Connecticut
3924	Connecticut
3925	Connecticut
3927	Connecticut
3928	Connecticut
3982	Connecticut
4008	Connecticut
4038	Connecticut
4194	Connecticut
4264	Connecticut
4272	Connecticut
4276	Connecticut

Table Continued C.4: Connecticut Cluster based on 3830, Proximate Bridges

BRIDGE ID	STATE
4277	Connecticut
4280	Connecticut
4295	Connecticut
4305	Connecticut
4310	Connecticut
4312	Connecticut
4316	Connecticut
4337	Connecticut
4340	Connecticut
4341	Connecticut
4345	Connecticut
4351	Connecticut
4357	Connecticut
4382	Connecticut
4383	Connecticut
4386	Connecticut
4387	Connecticut
4388	Connecticut
4398	Connecticut
4621	Connecticut
4626	Connecticut
5157	Connecticut
5226	Connecticut
5230	Connecticut
5231	Connecticut
5233	Connecticut
5241	Connecticut
5261	Connecticut
5270	Connecticut
5279	Connecticut
5283	Connecticut
5300	Connecticut
5302	Connecticut
5304	Connecticut
5306	Connecticut
5307	Connecticut

Table Continued C.4: Connecticut Cluster based on 3830, Proximate Bridges

BRIDGE ID	STATE
5308	Connecticut
5309	Connecticut
5312	Connecticut
5317	Connecticut
5330	Connecticut
5331	Connecticut
5333	Connecticut
5352	Connecticut
5354	Connecticut
5358	Connecticut
5374	Connecticut
5433	Connecticut
5521	Connecticut
5542	Connecticut
5555	Connecticut
5556	Connecticut
5558	Connecticut
5573	Connecticut
5643	Connecticut
5746	Connecticut
5796	Connecticut
5843	Connecticut
5849	Connecticut
5862	Connecticut
5863	Connecticut
5923	Connecticut
5924	Connecticut
6008	Connecticut
6070	Connecticut
6151	Connecticut
6248	Connecticut
6299	Connecticut
5844A	Connecticut
5844B	Connecticut
5844C	Connecticut
5844D	Connecticut

Table Continued C.4: Connecticut Cluster based on 3830, Proximate Bridges

BRIDGE ID	STATE
1023410	New York
1036140	New York
1036190	New York
1037970	New York
1072679	New York
1072689	New York
1073220	New York
1073231	New York
1073232	New York
1073240	New York
1367500	New York
1367510	New York
3344070	New York
3345500	New York

Table C.5: Iowa Cluster based on 41331, Proximate Bridges

BRIDGE ID	STATE
4111	Iowa
12491	Iowa
13101	Iowa
13111	Iowa
13201	Iowa
15225	Iowa
40521	Iowa
40970	Iowa
40980	Iowa
40991	Iowa
41001	Iowa
41141	Iowa
41151	Iowa
41331	Iowa
41441	Iowa
41451	Iowa
41591	Iowa
41601	Iowa
41631	Iowa
41641	Iowa
42061	Iowa
42321	Iowa
42431	Iowa
42491	Iowa
42511	Iowa
42521	Iowa
42571	Iowa
42611	Iowa
42621	Iowa
42641	Iowa
42711	Iowa
42721	Iowa
42731	Iowa
42740	Iowa
42761	Iowa
42841	Iowa

Table Continued C.5: Iowa Cluster based on 41331, Proximate Bridges

BRIDGE ID	STATE
42871	Iowa
42891	Iowa
42921	Iowa
42951	Iowa
42961	Iowa
50995	Iowa
51221	Iowa
51301	Iowa
51311	Iowa
504520	Iowa
504625	Iowa
601356	Iowa
601770	Iowa
601935	Iowa
606515	Iowa
606755	Iowa
606760	Iowa
606775	Iowa
606780	Iowa
606825	Iowa
606830	Iowa
606920	Iowa
607220	Iowa
607280	Iowa
607285	Iowa
608565	Iowa
608570	Iowa
608630	Iowa
608680	Iowa
608950	Iowa
609255	Iowa
609260	Iowa
609280	Iowa
609365	Iowa
609395	Iowa
609695	Iowa

Table Continued C.5: Iowa Cluster based on 41331, Proximate Bridges

BRIDGE ID	STATE
609810	Iowa
609815	Iowa
609860	Iowa
609865	Iowa
609935	Iowa
609940	Iowa
609945	Iowa
609995	Iowa
700000	Iowa
700005	Iowa

Table C.6: Maine Cluster based on 1004, Proximate Bridges

BRIDGE ID	STATE
11	Maine
30	Maine
246	Maine
589	Maine
685	Maine
802	Maine
1004	Maine
1037	Maine
1203	Maine
1221	Maine
1223	Maine
1260	Maine
1262	Maine
1529	Maine
1552	Maine
2123	Maine
2252	Maine
2264	Maine
2373	Maine
2635	Maine
2866	Maine
2908	Maine
2961	Maine
3076	Maine
3080	Maine
3369	Maine
3406	Maine
3460	Maine
3523	Maine
5339	Maine
5451	Maine
6195	Maine
6210	Maine
6311	Maine
1401060017700	New Hampshire
1701910014000	New Hampshire

Table Continued C.6: Maine Cluster based on 1004, Proximate Bridges

BRIDGE ID	STATE
1702020017200	New Hampshire
1702630016800	New Hampshire
2401250017700	New Hampshire
2401670017400	New Hampshire
3201830008700	New Hampshire
3501530009200	New Hampshire
3901490002800	New Hampshire
3901730014100	New Hampshire
5400460003000	New Hampshire
5401640006300	New Hampshire
5701940009300	New Hampshire
7400800011300	New Hampshire
8700520011700	New Hampshire
8701310009500	New Hampshire
8701320007900	New Hampshire
8701320008600	New Hampshire
8701320009500	New Hampshire
8701440006700	New Hampshire
9100620007700	New Hampshire
9700440011300	New Hampshire
9701050008900	New Hampshire
11601420009400	New Hampshire
11601970007700	New Hampshire
11602350005900	New Hampshire
12601400008800	New Hampshire
13500720013000	New Hampshire
13501270007700	New Hampshire
13901210004700	New Hampshire
13901220005800	New Hampshire
13901230005200	New Hampshire
14101300011000	New Hampshire
14101800009800	New Hampshire
14102050009500	New Hampshire
14102090006600	New Hampshire
14801320010800	New Hampshire
14801330010900	New Hampshire

Table Continued C.6: Maine Cluster based on 1004, Proximate Bridges

BRIDGE ID	STATE
14801400010200	New Hampshire
14801410010400	New Hampshire
14801590010200	New Hampshire
14801710009200	New Hampshire
14801730009300	New Hampshire
14801910008900	New Hampshire
14801940009300	New Hampshire
14801960009200	New Hampshire
15000940011200	New Hampshire
15001460014200	New Hampshire
15301610008900	New Hampshire
15301850009000	New Hampshire
15301870006500	New Hampshire
15301880007900	New Hampshire
15301880008000	New Hampshire
17300980011500	New Hampshire
17301140011500	New Hampshire
17301410012200	New Hampshire
17301620011000	New Hampshire
17301870010900	New Hampshire
17302160011200	New Hampshire
17302190011200	New Hampshire
17302190012400	New Hampshire
17302370012600	New Hampshire
17601920010100	New Hampshire
19801410005900	New Hampshire
21800400004400	New Hampshire
22200300009700	New Hampshire
22200510009400	New Hampshire
22200590009600	New Hampshire
22200710011600	New Hampshire
22200820008300	New Hampshire
23300680012700	New Hampshire
23301780016300	New Hampshire
23601220010900	New Hampshire
24000750003600	New Hampshire

Table Continued C.6: Maine Cluster based on 1004, Proximate Bridges

BRIDGE ID	STATE
24000790003200	New Hampshire
24000880014000	New Hampshire
25201300011100	New Hampshire
25201390010900	New Hampshire
25201410004400	New Hampshire
25401100010600	New Hampshire
25401750014100	New Hampshire
25402220018000	New Hampshire
25402390015200	New Hampshire
26401180008500	New Hampshire
26601380011300	New Hampshire
28401950009100	New Hampshire
28401950009300	New Hampshire
28401970008500	New Hampshire

Table C.7: Maine Cluster based on 2928, Proximate Bridges

BRIDGE ID	STATE
864	Maine
896	Maine
923	Maine
924	Maine
1096	Maine
1409	Maine
1558	Maine
2014	Maine
2266	Maine
2314	Maine
2503	Maine
2570	Maine
2753	Maine
2771	Maine
2913	Maine
2928	Maine
3229	Maine
3301	Maine
3742	Maine
5108	Maine
5126	Maine
5243	Maine

Table C.8: Massachusetts Cluster based on A18001AE8DOTNBI, Proximate Bridges

BRIDGE ID	STATE
988	Connecticut
4018	Connecticut
4757	Connecticut
5319	Connecticut
A090032QKMUNNBI	Massachusetts
A090052QLMUNNBI	Massachusetts
A09029AU5DOTNBI	Massachusetts
A16019400DOT634	Massachusetts
A16031AP8DOT634	Massachusetts
A16032B59DOT634	Massachusetts
A160733HXMUNNBI	Massachusetts
A18001AE8DOTNBI	Massachusetts
B04011AY9DOTNBI	Massachusetts
B04011AYADOTNBI	Massachusetts
B04012734DOTNBI	Massachusetts
B04012737DOTNBI	Massachusetts
B04013761DOTNBI	Massachusetts
B110042TNDOTNBI	Massachusetts
B120019CPDOTNBI	Massachusetts
B12002ANJMUNNBI	Massachusetts
B120112MRDOT634	Massachusetts
B12021AY8DOTNBI	Massachusetts
B120228G2DOTNBI	Massachusetts
B120228G3DOTNBI	Massachusetts
B120238YBDOTNBI	Massachusetts
B120238YNDOTNBI	Massachusetts
B120248G0DOTNBI	Massachusetts
B120258V9DOTNBI	Massachusetts
B120268FRDOTNBI	Massachusetts
B1603538CMUNNBI	Massachusetts
B161093H8DOT634	Massachusetts
B161593HCDOT634	Massachusetts
B161623HBDOT634	Massachusetts
B161643H9DOT634	Massachusetts
B161693HMDOT634	Massachusetts
B161723HJDOT634	Massachusetts

Table Continued C.8: Massachusetts Cluster based on A18001AE8DOTNBI, Proximate Bridges

BRIDGE ID	STATE
B1618638LMUNNBI	Massachusetts
B162013GNDOT634	Massachusetts
B162813BMDOTNBI	Massachusetts
B162813BPDOTNBI	Massachusetts
B162813BQDOTNBI	Massachusetts
B162813BRDOTNBI	Massachusetts
B162813BTDOTNBI	Massachusetts
B162813BUDOTNBI	Massachusetts
B162813BVDOTNBI	Massachusetts
B162813CEDOTNBI	Massachusetts
B162813CGDOTNBI	Massachusetts
B162813DUDOTNBI	Massachusetts
B162813DWDOTNBI	Massachusetts
B162813DYDOTNBI	Massachusetts
B162813EADOTNBI	Massachusetts
B162813EBDOTNBI	Massachusetts
B162813EDDOTNBI	Massachusetts
B162813EEDOTNBI	Massachusetts
B162818R8DOTNBI	Massachusetts
B163904F7DOTNBI	Massachusetts
B163904FQDOTNBI	Massachusetts
B163904FRDOTNBI	Massachusetts
B163904FTDOTNBI	Massachusetts
B163904FUDOTNBI	Massachusetts
B170104BHDOT634	Massachusetts
B2101036FDOTNBI	Massachusetts
B2102736EDOTNBI	Massachusetts
B2105734RDOTNBI	Massachusetts
B2105834TDOTNBI	Massachusetts
B2105934UDOTNBI	Massachusetts
B2106434XDOTNBI	Massachusetts
B2300392BDOTNBI	Massachusetts
B230203MVDOTNBI	Massachusetts
B230213T5DOTNBI	Massachusetts
B230223T4DOTNBI	Massachusetts

Table Continued C.8: Massachusetts Cluster based on A18001AE8DOTNBI, Proximate Bridges

BRIDGE ID	STATE
B250224CFDOT634	Massachusetts
B250483V4DOTNBI	Massachusetts
C010153FRDOT634	Massachusetts
C010204DHDOTNBI	Massachusetts
C02002ADAMUNNBI	Massachusetts
C0200636YDOT634	Massachusetts
C02008AE6DOT634	Massachusetts
C02024371DOT634	Massachusetts
C020268FWDOTNBI	Massachusetts
C020278FTDOTNBI	Massachusetts
C04020AG6DOTNBI	Massachusetts
C08001A4RDOTNBI	Massachusetts
C08001ACMDOTNBI	Massachusetts
C080032MYDOT634	Massachusetts
C0801285PDOTNBI	Massachusetts
C080129TJDOTNBI	Massachusetts
C080148VVDOTNBI	Massachusetts
C080157D4DOTNBI	Massachusetts
C080178EFDOTNBI	Massachusetts
C080178EGDOTNBI	Massachusetts
C0801885UDOTNBI	Massachusetts
C0801985QDOTNBI	Massachusetts
C08024AY7DOTNBI	Massachusetts
C08029AYEDOTNBI	Massachusetts
C08029AYFDOTNBI	Massachusetts
C08031762DOTNBI	Massachusetts
C08042AYBDOTNBI	Massachusetts
C08042AYCDOTNBI	Massachusetts
C08044841DOTNBI	Massachusetts
C08044842DOTNBI	Massachusetts
C080466G6DOTNBI	Massachusetts
C080466G8DOTNBI	Massachusetts
C0804785VDOTNBI	Massachusetts
C0804785WDOTNBI	Massachusetts
C090033FNDOT634	Massachusetts

Table Continued C.8: Massachusetts Cluster based on A18001AE8DOTNBI, Proximate Bridges

BRIDGE ID	STATE
D030162T6DOTNBI	Massachusetts
D030162T7DOTNBI	Massachusetts
D05044B1GDOTNBI	Massachusetts
D05045B1HDOTNBI	Massachusetts
D050478FUDOTNBI	Massachusetts
D050478FVDOTNBI	Massachusetts
D05048AXGDOTNBI	Massachusetts
E010154BKDOT634	Massachusetts
F010143T7DOTNBI	Massachusetts
F0200840BDOT634	Massachusetts
F09007418DOT634	Massachusetts
G050232UBDOTNBI	Massachusetts
H1500547LDOTNBI	Massachusetts
I010032R7MUNNBI	Massachusetts
L010103X6DOTNBI	Massachusetts
L010103X6DOTNBI	Massachusetts
L010143X7DOTNBI	Massachusetts
L0402232CDOT634	Massachusetts
L0402332DDOT634	Massachusetts
L15001ALJDOT634	Massachusetts
L1500490FDOT634	Massachusetts
L150062N9DOT634	Massachusetts
L150082N3DOT634	Massachusetts
L150102NCDOT634	Massachusetts
L150102NDDOT634	Massachusetts
L150102NEDOT634	Massachusetts
L150132N8DOT634	Massachusetts
L150222BNMUNNBI	Massachusetts
L150232BVMUNNBI	Massachusetts
L1505387LMUNNBI	Massachusetts
L15082AQBDOTNBI	Massachusetts
L15082AQCDOTNBI	Massachusetts
L15083BA0DOTNBI	Massachusetts
L15083BA1DOTNBI	Massachusetts
L15084BA2DOTNBI	Massachusetts

Table Continued C.8: Massachusetts Cluster based on A18001AE8DOTNBI, Proximate Bridges

BRIDGE ID	STATE
L15084BA3DOTNBI	Massachusetts
M010074ECDOTNBI	Massachusetts
M010083AFDOTNBI	Massachusetts
M010153EUDOTNBI	Massachusetts
M03014ALEDOT634	Massachusetts
M03015AMCDOT634	Massachusetts
M07002AMBDOTNBI	Massachusetts
M120014DXDOTNBI	Massachusetts
M120153G1DOT634	Massachusetts
M120194DYDOTNBI	Massachusetts
M120253B5DOTNBI	Massachusetts
M120273B6DOTNBI	Massachusetts
M120283B7DOTNBI	Massachusetts
M120293B8DOTNBI	Massachusetts
M120303B9DOTNBI	Massachusetts
M120363B4DOTNBI	Massachusetts
M120393B3DOTNBI	Massachusetts
M17022AQ7DOTNBI	Massachusetts
M180104BWDOT634	Massachusetts
M18048ADTDOTNBI	Massachusetts
N0601471FDOTNBI	Massachusetts
N10015AVUDOT634	Massachusetts
N16008830MUNNBI	Massachusetts
N160463VNDOTNBI	Massachusetts
N250223VVDOTNBI	Massachusetts
N250233VWDOTNBI	Massachusetts
P13047AEHDOTNBI	Massachusetts
Q01003B2RMBTNBI	Massachusetts
Q010492GTDOTNBI	Massachusetts
Q010512GUDOTNBI	Massachusetts
Q010512GVDOTNBI	Massachusetts
Q010519PNDOTNBI	Massachusetts
R03001AD9DOT634	Massachusetts
S0100932QDOT634	Massachusetts
S0501531YDOTNBI	Massachusetts

Table Continued C.8: Massachusetts Cluster based on A18001AE8DOTNBI, Proximate Bridges

BRIDGE ID	STATE
S070059PUDOT634	Massachusetts
S08011B65DOTNBI	Massachusetts
S170073G4DOT634	Massachusetts
S170173GEDOT634	Massachusetts
S3400232YDOT634	Massachusetts
T01003AGWDOT634	Massachusetts
T010283N8DOTNBI	Massachusetts
T010583YFDOTNBI	Massachusetts
T010593RVDOTNBI	Massachusetts
T010593RWDOTNBI	Massachusetts
T090118HJDOTNBI	Massachusetts
T09014AYDDOTNBI	Massachusetts
T090216G9DOTNBI	Massachusetts
T0902284YDOTNBI	Massachusetts
T09022854DOTNBI	Massachusetts
W03020411DOT634	Massachusetts
W03021412DOT634	Massachusetts
W04008AL5MUNNBI	Massachusetts
W060084C4DOT634	Massachusetts
W060154C3DOT634	Massachusetts
W130052P8DOT634	Massachusetts
W130062P3DOT634	Massachusetts
W130102P5DOT634	Massachusetts
W130152MHDOTNBI	Massachusetts
W380012NWDOT634	Massachusetts
W380042NUDOT634	Massachusetts
W380302MBDOTNBI	Massachusetts
W430042NYDOT634	Massachusetts
1170	Rhode Island
1810	Rhode Island
2000	Rhode Island
3480	Rhode Island
3570	Rhode Island
3590	Rhode Island
5190	Rhode Island

Table Continued C.8: Massachusetts Cluster based on A18001AE8DOTNBI, Proximate Bridges

BRIDGE ID	STATE
5200	Rhode Island
7040	Rhode Island
7970	Rhode Island
7980	Rhode Island
8240	Rhode Island
8410	Rhode Island
8412	Rhode Island
8650	Rhode Island
8652	Rhode Island
8660	Rhode Island
9280	Rhode Island
9300	Rhode Island
9330	Rhode Island
9340	Rhode Island
9530	Rhode Island
9780	Rhode Island
9790	Rhode Island

Table C.9: Massachusetts Cluster based on B230213T5DOTNBI), Proximate Bridges

BRIDGE ID	STATE
5319	Connecticut
A090032QKMUNNBI	Massachusetts
A16019400DOT634	Massachusetts
B1603538CMUNNBI	Massachusetts
B161093H8DOT634	Massachusetts
B161623HBDOT634	Massachusetts
B161693HMDOT634	Massachusetts
B162813BMDOTNBI	Massachusetts
B162813BPDOTNBI	Massachusetts
B162813BQDOTNBI	Massachusetts
B162813BRDOTNBI	Massachusetts
B162813BTDOTNBI	Massachusetts
B162813BUDOTNBI	Massachusetts
B162813BVDOTNBI	Massachusetts
B162813CEDOTNBI	Massachusetts
B162813CGDOTNBI	Massachusetts
B162813DUDOTNBI	Massachusetts
B162813DWDOTNBI	Massachusetts
B162813DYDOTNBI	Massachusetts
B162813EADOTNBI	Massachusetts
B162813EBDOTNBI	Massachusetts
B162813EDDOTNBI	Massachusetts
B162813EEDOTNBI	Massachusetts
B162818R8DOTNBI	Massachusetts
B163904F7DOTNBI	Massachusetts
B163904FRDOTNBI	Massachusetts
B163904FTDOTNBI	Massachusetts
B163904FUDOTNBI	Massachusetts
B170104BHDOT634	Massachusetts
B2101036FDOTNBI	Massachusetts
B2102736EDOTNBI	Massachusetts
B2105734RDOTNBI	Massachusetts
B2105834TDOTNBI	Massachusetts
B2105934UDOTNBI	Massachusetts
B2106434XDOTNBI	Massachusetts
B230203MVDOTNBI	Massachusetts

Table Continued C.9: Massachusetts Cluster based on B230213T5DOTNBI, Proximate Bridges

BRIDGE ID	STATE
B230213T5DOTNBI	Massachusetts
B230223T4DOTNBI	Massachusetts
C010153FRDOT634	Massachusetts
C090033FNDOT634	Massachusetts
F010143T7DOTNBI	Massachusetts
F09007418DOT634	Massachusetts
L150132N8DOT634	Massachusetts
L150232BVMUNNBI	Massachusetts
L1505387LMUNNBI	Massachusetts
M010074ECDOTNBI	Massachusetts
M010153EUDOTNBI	Massachusetts
M120014DXDOTNBI	Massachusetts
M120194DYDOTNBI	Massachusetts
Q01003B2RMBTNBI	Massachusetts
Q010492GTDOTNBI	Massachusetts
Q010512GUDOTNBI	Massachusetts
Q010512GVDOTNBI	Massachusetts
S170073G4DOT634	Massachusetts
S170173GEDOT634	Massachusetts
T010583YFDOTNBI	Massachusetts
T010593RVDOTNBI	Massachusetts
T010593RWDOTNBI	Massachusetts
W03020411DOT634	Massachusetts
W03021412DOT634	Massachusetts
W060154C3DOT634	Massachusetts
W430042NYDOT634	Massachusetts
170	Rhode Island
1170	Rhode Island
1810	Rhode Island
3480	Rhode Island
3570	Rhode Island
7040	Rhode Island
7970	Rhode Island
7980	Rhode Island
8240	Rhode Island

Table Continued C.9: Massachusetts Cluster based on B230213T5DOTNBI, Proximate Bridges

BRIDGE ID	STATE
8410	Rhode Island
8412	Rhode Island
8650	Rhode Island
8652	Rhode Island
8660	Rhode Island
9280	Rhode Island
9300	Rhode Island
9330	Rhode Island
9530	Rhode Island
9780	Rhode Island

Table C.10: Michigan Cluster based on 8097, Proximate Bridges

BRIDGE ID	STATE
2637	Michigan
2647	Michigan
2667	Michigan
2668	Michigan
2669	Michigan
2670	Michigan
2671	Michigan
2672	Michigan
2673	Michigan
2674	Michigan
2675	Michigan
2676	Michigan
2677	Michigan
2678	Michigan
2679	Michigan
2693	Michigan
2694	Michigan
2695	Michigan
2696	Michigan
2697	Michigan
2698	Michigan
2699	Michigan
2749	Michigan
2837	Michigan
5357	Michigan
5358	Michigan
5359	Michigan
5360	Michigan
5361	Michigan
5845	Michigan
6074	Michigan
6075	Michigan
6076	Michigan
6077	Michigan
6078	Michigan
6079	Michigan
6080	Michigan

Table Continued C.10: Michigan Cluster based on 8097, Proximate Bridges

BRIDGE ID	STATE
6081	Michigan
6082	Michigan
6083	Michigan
6084	Michigan
6085	Michigan
6086	Michigan
6087	Michigan
6088	Michigan
6089	Michigan
6090	Michigan
6091	Michigan
6092	Michigan
6093	Michigan
6094	Michigan
6095	Michigan
6096	Michigan
6097	Michigan
6098	Michigan
6099	Michigan
6100	Michigan
6101	Michigan
6102	Michigan
6103	Michigan
6104	Michigan
6105	Michigan
6106	Michigan
6107	Michigan
6108	Michigan
6109	Michigan
6110	Michigan
6115	Michigan
6116	Michigan
6117	Michigan
6118	Michigan
6119	Michigan
6120	Michigan

Table Continued C.10: Michigan Cluster based on 8097, Proximate Bridges

BRIDGE ID	STATE
6121	Michigan
6122	Michigan
6123	Michigan
6124	Michigan
6125	Michigan
6150	Michigan
6426	Michigan
6430	Michigan
7169	Michigan
7180	Michigan
7181	Michigan
7182	Michigan
7200	Michigan
7207	Michigan
7208	Michigan
7209	Michigan
7210	Michigan
7211	Michigan
7212	Michigan
7213	Michigan
7214	Michigan
7215	Michigan
7216	Michigan
7217	Michigan
7218	Michigan
7219	Michigan
7220	Michigan
7221	Michigan
7246	Michigan
7803	Michigan
7883	Michigan
7891	Michigan
7965	Michigan
7966	Michigan
7967	Michigan
7968	Michigan

Table Continued C.10: Michigan Cluster based on 8097, Proximate Bridges

BRIDGE ID	STATE
7969	Michigan
7970	Michigan
7971	Michigan
7972	Michigan
7973	Michigan
7974	Michigan
7975	Michigan
7976	Michigan
7977	Michigan
7978	Michigan
7979	Michigan
7980	Michigan
8097	Michigan
8098	Michigan
8115	Michigan
8116	Michigan
8117	Michigan
8118	Michigan
8119	Michigan
8120	Michigan
8121	Michigan
8122	Michigan
8123	Michigan
8124	Michigan
8125	Michigan
8126	Michigan
8127	Michigan
8128	Michigan
8129	Michigan
8269	Michigan
9927	Michigan
9928	Michigan
9933	Michigan
9934	Michigan
9947	Michigan
9948	Michigan

Table Continued C.10: Michigan Cluster based on 8097, Proximate Bridges

BRIDGE ID	STATE
9968	Michigan
9977	Michigan
10255	Michigan
10819	Michigan
10823	Michigan
10834	Michigan
10835	Michigan
10840	Michigan
10841	Michigan
10848	Michigan
10907	Michigan
10920	Michigan
10921	Michigan
10922	Michigan
10923	Michigan
10924	Michigan
11006	Michigan
11010	Michigan
11099	Michigan
11100	Michigan
11101	Michigan
11102	Michigan
11111	Michigan
11135	Michigan
11137	Michigan
11143	Michigan
11338	Michigan
11350	Michigan
11352	Michigan
11353	Michigan
11354	Michigan
11355	Michigan
11356	Michigan
11357	Michigan
11358	Michigan
11359	Michigan

Table Continued C.10: Michigan Cluster based on 8097, Proximate Bridges

BRIDGE ID	STATE
11361	Michigan
11362	Michigan
11363	Michigan
11364	Michigan
11365	Michigan
11407	Michigan
11465	Michigan
11466	Michigan
11467	Michigan
11485	Michigan
11486	Michigan
11487	Michigan
11488	Michigan
11489	Michigan
11490	Michigan
11491	Michigan
11492	Michigan
11493	Michigan
11494	Michigan
11495	Michigan
11496	Michigan
11497	Michigan
11498	Michigan
11499	Michigan
11500	Michigan
11501	Michigan
11502	Michigan
11503	Michigan
11504	Michigan
11505	Michigan
11506	Michigan
11507	Michigan
11508	Michigan
11509	Michigan
11510	Michigan
11511	Michigan

Table Continued C.10: Michigan Cluster based on 8097, Proximate Bridges

BRIDGE ID	STATE
11512	Michigan
11513	Michigan
11514	Michigan
11515	Michigan
11516	Michigan
11517	Michigan
11518	Michigan
11519	Michigan
11520	Michigan
11521	Michigan
11522	Michigan
11523	Michigan
11524	Michigan
11525	Michigan
11526	Michigan
11527	Michigan
11528	Michigan
11529	Michigan
11530	Michigan
11541	Michigan
11542	Michigan
11544	Michigan
11545	Michigan
11546	Michigan
11548	Michigan
11549	Michigan
11550	Michigan
11551	Michigan
11552	Michigan
11553	Michigan
11555	Michigan
11556	Michigan
11557	Michigan
11558	Michigan
11559	Michigan
11560	Michigan

Table Continued C.10: Michigan Cluster based on 8097, Proximate Bridges

BRIDGE ID	STATE
11561	Michigan
11562	Michigan
11563	Michigan
11564	Michigan
11565	Michigan
11566	Michigan
11567	Michigan
11568	Michigan
11569	Michigan
11570	Michigan
11571	Michigan
11572	Michigan
11573	Michigan
11574	Michigan
11575	Michigan
11576	Michigan
11578	Michigan
11579	Michigan
11580	Michigan
11581	Michigan
11582	Michigan
11584	Michigan
11585	Michigan
11586	Michigan
11587	Michigan
11588	Michigan
11589	Michigan
11590	Michigan
11592	Michigan
11593	Michigan
11594	Michigan
11596	Michigan
11597	Michigan
11598	Michigan
11607	Michigan
11608	Michigan

Table Continued C.10: Michigan Cluster based on 8097, Proximate Bridges

BRIDGE ID	STATE
11611	Michigan
11612	Michigan
11613	Michigan
11614	Michigan
11734	Michigan
11756	Michigan
11850	Michigan
11851	Michigan
11852	Michigan
11884	Michigan
11885	Michigan
11895	Michigan
11896	Michigan
11897	Michigan
11898	Michigan
11899	Michigan
11900	Michigan
11904	Michigan
11905	Michigan
11907	Michigan
11908	Michigan
11909	Michigan
11910	Michigan
11911	Michigan
11912	Michigan
11913	Michigan
11914	Michigan
11915	Michigan
11918	Michigan
11921	Michigan
11922	Michigan
11923	Michigan
11924	Michigan
11925	Michigan
11926	Michigan
11927	Michigan

Table Continued C.10: Michigan Cluster based on 8097, Proximate Bridges

BRIDGE ID	STATE
11943	Michigan
11944	Michigan
11945	Michigan
11946	Michigan
11947	Michigan
11948	Michigan
11949	Michigan
11950	Michigan
11951	Michigan
11952	Michigan
11953	Michigan
11955	Michigan
11956	Michigan
11959	Michigan
11961	Michigan
11964	Michigan
11965	Michigan
11966	Michigan
11967	Michigan
11968	Michigan
11975	Michigan
11976	Michigan
11978	Michigan
11979	Michigan
11980	Michigan
12048	Michigan
12077	Michigan
12089	Michigan
12124	Michigan
12167	Michigan
12177	Michigan
12345	Michigan
12391	Michigan
12393	Michigan
12665	Michigan
12666	Michigan

Table C.11: Michigan Cluster based on 4586, Proximate Bridges

BRIDGE ID	STATE
131	Michigan
132	Michigan
133	Michigan
134	Michigan
321	Michigan
775	Michigan
777	Michigan
887	Michigan
888	Michigan
894	Michigan
897	Michigan
898	Michigan
977	Michigan
1407	Michigan
4586	Michigan
4859	Michigan
4860	Michigan
4861	Michigan
8722	Michigan
8723	Michigan
8724	Michigan
8725	Michigan
8732	Michigan
8733	Michigan
8734	Michigan
8735	Michigan
8736	Michigan
8737	Michigan
8745	Michigan
8746	Michigan
10390	Michigan
13639	Michigan

Table C.12: Minnesota Cluster based on 62861, Proximate Bridges

BRIDGE ID	STATE
10007	Minnesota
10507	Minnesota
10514	Minnesota
10515	Minnesota
13505	Minnesota
19010	Minnesota
19075	Minnesota
19077	Minnesota
19512	Minnesota
19811	Minnesota
19812	Minnesota
19866	Minnesota
19889	Minnesota
19893	Minnesota
25520	Minnesota
25521	Minnesota
25522	Minnesota
25526	Minnesota
25528	Minnesota
25531	Minnesota
25532	Minnesota
25535	Minnesota
25540	Minnesota
25541	Minnesota
25547	Minnesota
25554	Minnesota
25560	Minnesota
27045	Minnesota
27047	Minnesota
27049	Minnesota
27050	Minnesota
27053	Minnesota
27056	Minnesota
27058	Minnesota
27060	Minnesota
27062	Minnesota
27070	Minnesota

Table Continued C.12: Minnesota Cluster based on 62861, Proximate Bridges

BRIDGE ID	STATE
27081	Minnesota
27241	Minnesota
27532	Minnesota
27542	Minnesota
27552	Minnesota
27565	Minnesota
27570	Minnesota
27576	Minnesota
27606	Minnesota
27608	Minnesota
27621	Minnesota
27639	Minnesota
27663	Minnesota
27728	Minnesota
27796	Minnesota
30505	Minnesota
30508	Minnesota
40001	Minnesota
43509	Minnesota
43517	Minnesota
48011	Minnesota
48012	Minnesota
62028	Minnesota
62050	Minnesota
62091	Minnesota
62513	Minnesota
62523	Minnesota
62526	Minnesota
62527	Minnesota
62528	Minnesota
62530	Minnesota
62531	Minnesota
62532	Minnesota
62541	Minnesota
62838	Minnesota
62861	Minnesota

Table Continued C.12: Minnesota Cluster based on 62861, Proximate Bridges

BRIDGE ID	STATE
62870	Minnesota
66509	Minnesota
66510	Minnesota
66511	Minnesota
66513	Minnesota
66515	Minnesota
66518	Minnesota
66520	Minnesota
66523	Minnesota
71007	Minnesota
71008	Minnesota
86505	Minnesota
86506	Minnesota
86507	Minnesota
27053A	Minnesota
27727B	Minnesota
9217E	Minnesota
9217W	Minnesota
9600N	Minnesota
9600S	Minnesota

Table C.13: Pennsylvania Cluster based on 25435, Proximate Bridges

BRIDGE ID	STATE
1011830	New York
1011870	New York
1012320	New York
1012450	New York
1012480	New York
1014900	New York
1015010	New York
1015020	New York
1015050	New York
1016300	New York
1023460	New York
1029440	New York
1035580	New York
1041520	New York
1043170	New York
1046390	New York
1047750	New York
2014370	New York
2214490	New York
2215180	New York
2215360	New York
2218200	New York
2218210	New York
2258340	New York
3027950	New York
3316640	New York
3321550	New York
3322840	New York
3323690	New York
3325300	New York
3325310	New York
3326130	New York
3328030	New York
3328270	New York
3328280	New York

Table Continued C.13: Pennsylvania Cluster based on 25435, Proximate Bridges

BRIDGE ID	STATE
3328310	New York
3328390	New York
3328550	New York
3329830	New York
3330760	New York
3330790	New York
3367230	New York
6041450	New York
6041460	New York
6064870	New York
6072771	New York
6072772	New York
6600050	New York
6600149	New York
6600159	New York
6600179	New York
15739	Pennsylvania
25435	Pennsylvania

Table C.14: Pennsylvania Cluster based on 10473, Proximate Bridges

BRIDGE ID	STATE
1009 221	Delaware
1073C017	Delaware
1073D017	Delaware
1147 270	Delaware
1148A330	Delaware
1213 000	Delaware
1223 6278	Delaware
1230 352	Delaware
1260 346	Delaware
1262N336	Delaware
1262S336	Delaware
1264N336	Delaware
1264S336	Delaware
1279W003	Delaware
1281 366	Delaware
1282 366	Delaware
1287W018	Delaware
1315N067	Delaware
1315S067	Delaware
1320 397	Delaware
1503 447	Delaware
1505 000	Delaware
1509 000	Delaware
1527 334	Delaware
1531 006	Delaware
1555 356	Delaware
1567 220	Delaware
1585 049	Delaware
1609 237	Delaware
1609A000	Delaware
1609B000	Delaware
1609D000	Delaware
1629 027	Delaware
1641 387	Delaware
1645 351	Delaware
1698A000	Delaware
1718 339	Delaware

Table Continued C.14: Pennsylvania Cluster based on 10473, Proximate Bridges

BRIDGE ID	STATE
1814 009	Delaware
1815 009	Delaware
1831 060	Delaware
100000030142010	Maryland
100000030212012	Maryland
100000030298010	Maryland
100000030305010	Maryland
100000030307011	Maryland
100000030307012	Maryland
100000030308010	Maryland
100000030309010	Maryland
100000030310010	Maryland
100000030312010	Maryland
100000030313010	Maryland
100000030314011	Maryland
100000030314012	Maryland
100000030315011	Maryland
100000030315012	Maryland
100000030316010	Maryland
100000030317011	Maryland
100000030317012	Maryland
100000030319011	Maryland
100000030319012	Maryland
100000030321010	Maryland
100000030323011	Maryland
100000030323012	Maryland
100000030324010	Maryland
100000030325010	Maryland
100000030326010	Maryland
100000030327011	Maryland
100000030327012	Maryland
100000030328010	Maryland
100000030329010	Maryland
100000030330010	Maryland
100000030331010	Maryland
100000030332010	Maryland

Table Continued C.14: Pennsylvania Cluster based on 10473, Proximate Bridges

BRIDGE ID	STATE
100000030333011	Maryland
100000030333012	Maryland
100000030334011	Maryland
100000030334012	Maryland
100000030335010	Maryland
100000030336010	Maryland
100000030337011	Maryland
100000030337012	Maryland
100000030338010	Maryland
100000030339010	Maryland
100000030370010	Maryland
100000030374010	Maryland
100000030376010	Maryland
100000070010010	Maryland
100000070019013	Maryland
100000070019014	Maryland
100000070031010	Maryland
100000070049010	Maryland
100000070051010	Maryland
100000120023010	Maryland
100000120037010	Maryland
100000120073010	Maryland
100000120075010	Maryland
4809	Pennsylvania
5211	Pennsylvania
5213	Pennsylvania
5435	Pennsylvania
10331	Pennsylvania
10360	Pennsylvania
10435	Pennsylvania
10448	Pennsylvania
10457	Pennsylvania
10473	Pennsylvania
10489	Pennsylvania
10500	Pennsylvania
10551	Pennsylvania

Table Continued C.14: Pennsylvania Cluster based on 10473, Proximate Bridges

BRIDGE ID	STATE
10552	Pennsylvania
10663	Pennsylvania
10679	Pennsylvania
10713	Pennsylvania
10716	Pennsylvania
10718	Pennsylvania
10776	Pennsylvania
14372	Pennsylvania
14563	Pennsylvania
14979	Pennsylvania
15266	Pennsylvania
15318	Pennsylvania
15337	Pennsylvania
15450	Pennsylvania
15451	Pennsylvania
15452	Pennsylvania
21004	Pennsylvania
21218	Pennsylvania
21258	Pennsylvania
21826	Pennsylvania
21952	Pennsylvania
22032	Pennsylvania
22167	Pennsylvania
22169	Pennsylvania
27153	Pennsylvania
27308	Pennsylvania
27424	Pennsylvania
27713	Pennsylvania
27819	Pennsylvania
28132	Pennsylvania
28217	Pennsylvania
28229	Pennsylvania
37971	Pennsylvania
38402	Pennsylvania
38563	Pennsylvania
38678	Pennsylvania

Table Continued C.14: Pennsylvania Cluster based on 10473, Proximate Bridges

BRIDGE ID	STATE
38721	Pennsylvania
38830	Pennsylvania
38898	Pennsylvania
38961	Pennsylvania
38987	Pennsylvania
38997	Pennsylvania
38999	Pennsylvania
39100	Pennsylvania
39101	Pennsylvania
39109	Pennsylvania
39110	Pennsylvania
39112	Pennsylvania
39121	Pennsylvania
39137	Pennsylvania
39161	Pennsylvania
39221	Pennsylvania
39242	Pennsylvania
39261	Pennsylvania
39268	Pennsylvania
39382	Pennsylvania
39441	Pennsylvania
40737	Pennsylvania
40870	Pennsylvania
41028	Pennsylvania
41242	Pennsylvania
43098	Pennsylvania
43099	Pennsylvania
43229	Pennsylvania
44233	Pennsylvania
44234	Pennsylvania
45204	Pennsylvania

Table C.15: Rhode Island Cluster based on 170, Proximate Bridges

BRIDGE ID	STATE
665	Connecticut
1875	Connecticut
2563	Connecticut
2568	Connecticut
3836	Connecticut
3915	Connecticut
4621	Connecticut
5319	Connecticut
5521	Connecticut
5643	Connecticut
5923	Connecticut
170	Rhode Island
1170	Rhode Island
1810	Rhode Island
3480	Rhode Island
3570	Rhode Island
7040	Rhode Island
7970	Rhode Island
7980	Rhode Island
8240	Rhode Island
8410	Rhode Island
8412	Rhode Island
8650	Rhode Island
8652	Rhode Island
8660	Rhode Island
9200	Rhode Island
9280	Rhode Island
9300	Rhode Island
9330	Rhode Island
9530	Rhode Island
9780	Rhode Island

Table C.16: Washington Cluster based on 0011490A0000000, Proximate Bridges

BRIDGE ID	STATE
02320A102 00460	Oregon
09722 047C06111	Oregon
11037A140900000	Oregon
11039A140900000	Oregon
11040A140900000	Oregon
11041A140900000	Oregon
16545 010600037	Oregon
0011490A0000000	Washington
0011599A0000000	Washington
0011802A0000000	Washington
0011866A0000000	Washington
0012115A0000000	Washington
0012630A0000000	Washington
0012912A0000000	Washington
0012967A0000000	Washington

Table C.17: Wyoming Cluster based on CCC, Proximate Bridges

BRIDGE ID	STATE
CCC	Wyoming
DAX	Wyoming
DDB	Wyoming
DED	Wyoming
DEM	Wyoming
DGW	Wyoming
DIW	Wyoming
DIY	Wyoming
DLG	Wyoming
DLH	Wyoming
DLI	Wyoming
DZO	Wyoming
EUO	Wyoming
EWU	Wyoming

Appendix D

Proximate Bridges for Potential Phase III Good Performing Clusters

As previously discussed in Chapter 3, the proximate bridges for good performing clusters that are possible clusters for further evaluation in later phases of this work have been identified. These good clusters are listed below in Table D.1 along with the criteria used to create each listing of proximate bridges. Otherwise the same process for identifying proximate bridges here as was used in Chapter 3. Tables D.2 through D.8 show the proximate bridges within the clusters. The bridges are listed alphabetically by state (when relevant) and then in ascending order by bridge ID number.

Table D.1: Summary of Good Clusters for Phase III

Location	Purpose	RADIUS (miles)	AGE RANGE (years)
Hampton Roads	Proximity to Coast	50	1 - 49
North Carolina	Proximity to Coast	50	1 - 49
Arkansas	High Rainfall	50	1 - 49
Seattle	High Rainfall	125	1 - 49
Bread Basket	High Nitrates	75	1 - 49
Chicago	High Sulfates	50	1 - 49

Table D.2: Hampton Roads Cluster, Proximate Bridges

BRIDGE ID	STATE
290043	North Carolina
290044	North Carolina
17895	Virginia
18200	Virginia
18221	Virginia
20399	Virginia
20668	Virginia
20813	Virginia
21045	Virginia
21047	Virginia
21206	Virginia
21210	Virginia
21212	Virginia
21811	Virginia
21826	Virginia
21891	Virginia
22029	Virginia
22262	Virginia
25281	Virginia
25282	Virginia
26143	Virginia
26145	Virginia
26146	Virginia
26149	Virginia
26150	Virginia
28011	Virginia
29370	Virginia

Table D.3: North Carolina Cluster, Proximate Bridges

BRIDGE ID	STATE
150001	North Carolina
150157	North Carolina
170016	North Carolina
190083	North Carolina
190084	North Carolina
290043	North Carolina
290044	North Carolina
470381	North Carolina
470382	North Carolina
650133	North Carolina
650134	North Carolina
650138	North Carolina
650139	North Carolina
650140	North Carolina
830063	North Carolina
830124	North Carolina
830129	North Carolina
830184	North Carolina
910009	North Carolina
1270101	North Carolina
1270158	North Carolina
1270209	North Carolina
1270210	North Carolina
1270214	North Carolina
1270215	North Carolina
1270216	North Carolina
1270217	North Carolina
1270290	North Carolina
1270291	North Carolina
1270292	North Carolina
1270293	North Carolina
1290042	North Carolina
1290044	North Carolina
1290045	North Carolina
1290057	North Carolina
1290058	North Carolina

Table Continued D.3: North Carolina Cluster, Proximate Bridges

BRIDGE ID	STATE
1290059	North Carolina
1310023	North Carolina
1470060	North Carolina
1910360	North Carolina
1910361	North Carolina
1950060	North Carolina
1950229	North Carolina

Table D.4: Arkansas Cluster, Proximate Bridges

BRIDGE ID	STATE
4388	Arkansas
4492	Arkansas
4540	Arkansas
4556	Arkansas
4592	Arkansas
4598	Arkansas
4637	Arkansas
4652	Arkansas
4655	Arkansas
4656	Arkansas
4661	Arkansas
4688	Arkansas
4703	Arkansas
4704	Arkansas
4734	Arkansas
4742	Arkansas
4767	Arkansas
4783	Arkansas
4809	Arkansas
4827	Arkansas
4857	Arkansas
4860	Arkansas
4862	Arkansas

Table Continued D.4: Arkansas Cluster, Proximate Bridges

BRIDGE ID	STATE
4870	Arkansas
4892	Arkansas
4903	Arkansas
5435	Arkansas
5796	Arkansas
5872	Arkansas
5877	Arkansas
5878	Arkansas
5904	Arkansas
6049	Arkansas
6082	Arkansas
6083	Arkansas
6178	Arkansas
6179	Arkansas
6182	Arkansas
6183	Arkansas
6184	Arkansas
6185	Arkansas
6288	Arkansas
6306	Arkansas
6307	Arkansas
6308	Arkansas
6309	Arkansas
6310	Arkansas
6332	Arkansas
6342	Arkansas
6344	Arkansas
6361	Arkansas
6381	Arkansas
6381	Arkansas
6388	Arkansas
6429	Arkansas
6429	Arkansas
6448	Arkansas
6486	Arkansas
6591	Arkansas

Table Continued D.4: Arkansas Cluster, Proximate Bridges

BRIDGE ID	STATE
6611	Arkansas
6620	Arkansas
6651	Arkansas
6652	Arkansas
6653	Arkansas
6717	Arkansas
6749	Arkansas
6751	Arkansas
6751	Arkansas
6766	Arkansas
6818	Arkansas
6819	Arkansas
6927	Arkansas
6930	Arkansas
6973	Arkansas
7018	Arkansas
7021	Arkansas
7022	Arkansas
7023	Arkansas
7034	Arkansas
7066	Arkansas
7172	Arkansas
21616	Arkansas
21676	Arkansas
22870	Arkansas
23502	Arkansas
A3706	Arkansas
A3814	Arkansas
A3815	Arkansas
A3816	Arkansas
A3818	Arkansas
A6426	Arkansas
A6807	Arkansas
A6808	Arkansas
A6809	Arkansas
A6875	Arkansas

Table Continued D.4: Arkansas Cluster, Proximate Bridges

BRIDGE ID	STATE
A6876	Arkansas
B3706	Arkansas
B3814	Arkansas
B3815	Arkansas
B3816	Arkansas
B3818	Arkansas
B6426	Arkansas
B6807	Arkansas
B6808	Arkansas
B6809	Arkansas
B6875	Arkansas
B6876	Arkansas
230580000000000	Oklahoma

Table D.5: Seattle Cluster, Proximate Bridges

BRIDGE ID	STATE
16545 010600037	Oregon
20855 002 03898	Oregon
21218 002 06444	Oregon
0011490A0000000	Washington
0011599A0000000	Washington
0011802A0000000	Washington
0011866A0000000	Washington
0012115A0000000	Washington
0012630A0000000	Washington
0012912A0000000	Washington
0012967A0000000	Washington

Table D.6: Bread Basket Cluster based on SD99, Proximate Bridges

BRIDGE ID	STATE
7222330	South Dakota
7267330	South Dakota
8068084	South Dakota
9126149	South Dakota
23186100	South Dakota
42064030	South Dakota
42065030	South Dakota
50175207	South Dakota
50175210	South Dakota
50176207	South Dakota
50176210	South Dakota
50177199	South Dakota
50178199	South Dakota
50179191	South Dakota
50180180	South Dakota
50181180	South Dakota
58101321	South Dakota
68120077	South Dakota

Table D.7: Bread Basket Cluster based on NE99, Proximate Bridge

BRIDGE ID	STATE
S002 20305	Nebraska
S021 05328	Nebraska
S021 06165	Nebraska
S025 10441	Nebraska
S026 15009R	Nebraska
S030 16001	Nebraska
S030 17901	Nebraska
S040 07115	Nebraska
S047 04922	Nebraska
S080 19900	Nebraska
S080 22249	Nebraska
S083 05519	Nebraska
S183 04981	Nebraska
S183 07233	Nebraska
S283 05035	Nebraska

Table D.8: Chicago Cluster, Proximate Bridges

BRIDGE ID	STATE
16027222209	Illinois
16033904077	Illinois
16061704278	Illinois
16095404581	Illinois
16095504582	Illinois
16250413023	Illinois
16276933485	Illinois
22005705545	Illinois
22018935895	Illinois
32009935856	Illinois
49001711203	Illinois
49006811260	Illinois
56001513121	Illinois
99015021842	Illinois
99026211124	Illinois
99026301886	Illinois

Appendix E

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