Final Report

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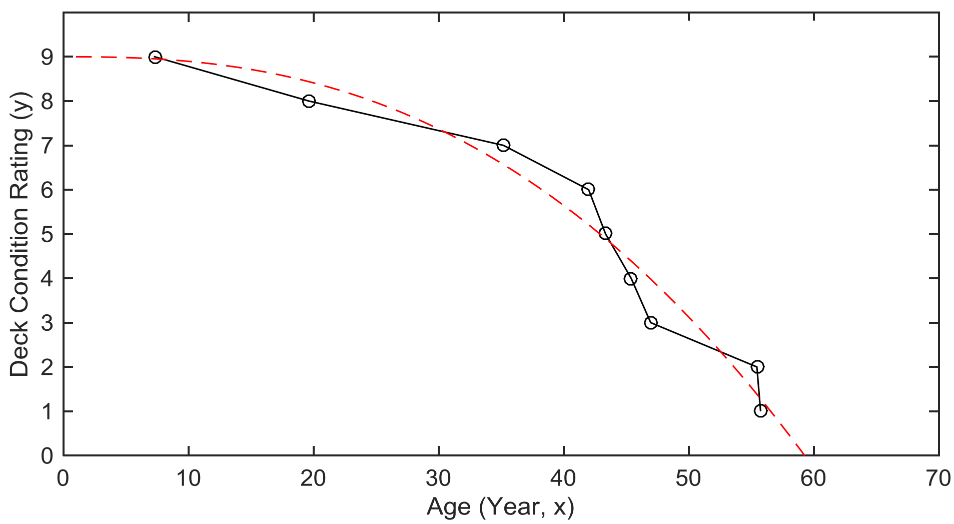
DEVELOPING DETERIORATION MODELS FOR WYOMING BRIDGES



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16. Abstract

Deterioration models for the Wyoming Bridge Inventory were developed using both stochastic and deterministic models. The selection of explanatory variables is investigated and a new method using LASSO regression to eliminate human bias in explanatory variable selection. The cross validation technique is used to determine the minimum number of explanatory variables. The relative significance of candidate variables is used to rank the explanatory variables in hierarchical order.

The deterministic deterioration models are developed by using curve-fitting methods for the mean of bridge ages for each condition rating. In order to improve the accuracy in the model, bridges are split into the multiple subsets using first two explanatory variables for deck, superstructure, and substructure. Although the deterministic deterioration model is insufficient to predict condition ratings for a specific bridge, it is worthy to observe a general feature of how the functionality of bridges becomes worse over time.

The stochastic models are developed to capture the uncertainty in the deterioration process using the Markov chain. The transition probability matrix is estimated using percentage prediction method, which counts the numbers corresponding to the element of transition probability matrix. The same subsets used in the deterministic deterioration models are considered. For each subset, zoning technique is used such that the bridge data is grouped for every 30 years to estimate transition probability matrix separately.

The source codes are provided for the future update of bridge inventory and stochastic deterioration models. A computer program is used develop and plot deterioration models. A simple guideline is also included so that the user can access the source codes conveniently.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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CHAPTER 1 INTRODUCTION

PROBLEM STATEMENT

Every four years, the American Society of Civil Engineers (ASCE) issues the America's Infrastructure Report Card, which provides a comprehensive assessment of the nation's major infrastructures. An Advisory Council of ASCE member assigns the grades according to the following eight criteria: capacity, condition, funding, future need, operation and maintenance, public safety, resilience, and innovation. The investigation reported that one in nine of the nation's bridges are rated as structurally deficient and the average age of the nation's 607,380 bridges is currently 42 years. The Federal Highway Administration (FHWA) estimates the expected annual maintenance cost as $20.5 billion, while only $12.8 billion is being spent and the grade of 2013 was marked C+ (Herrmann 2013).

The goal of infrastructure preservation is to cost-effectively and efficiently improve asset performance, as measured by attributes such as service life (US DOT 1999). Current bridge management systems use the deterministic, Markov chain, or semi-Markov process to predict future performance and service life. Many states have successfully developed deterioration models for their inventory (Cesare et al. 1992; Frangopol et al. 2004; Agrawal 2010). Determining the effectiveness of one method (e.g., deterministic versus Markov based) was the focus of several research projects (Morcous et al. 2002; Thomas 2011; Sobanjo et al. 2010; Arawal et al. 2010). The development of these models requires information regarding the past performance of the assets to be compiled and analyzed.

The efforts to maintain structural performance and to establish the roadmap for bridge maintenance stimulates Wyoming to develop an effective bridge management system. According to the statistical investigation for the Nation's bridges (Davis et al. 2013), Wyoming is one of the 15 states where the number of deficient bridges is increasing by 4.4 percent compared to 2011. The amount of traffic on deficient bridges is recorded as 871,031 vehicles. These statistic results also increase the demand for effective bridge management, which promises reliable service life of bridge systems.

Wyoming bridges have been inspected and the data regarding their geometry, function, environment and condition is available, and the purpose of this project is to develop statistical relationships between the gathered bridge data, tailored for bridge management. Although previous research has successfully developed deterioration models for other inventories, several challenges are left for effective deterioration model estimation. Mostly, the selection of explanatory variables is based on engineering judgment such that several design variables are considered significant factors affecting bridge performance directly. The manual selection of candidate variables is not always effective for various states and possibly exclude important factors. Several variables provide duplicated information, which should be eliminated or combined to represent structural deficient effectively.

OBJECTIVE

The project aims to develop deterioration models representing general bridges in Wyoming. Biennial bridge inspection data is used to determine the representative bridge model using deterministic and Markov chain methods. The suggested framework is based on several statistical methods and aims to determine optimal sets for the estimation of deterioration model. The National Bridge Inventory (NBI) data cumulated over the last three decades are analyzed to confirm the reliability. Additionally, average temperature, elevation, and precipitation information for each bridge in Wyoming was included for the analysis.

REPORT ORGANIZATION

This report presents a procedure to develop deterioration model for bridges in Wyoming. A set of NBI data archived by the Wyoming Department of Transportation (WYDOT) is investigated to derive a set of bridge deterioration models that can be classified as deterministic and stochastic models.

Chapter 2 analyzes the condition rating data and describes the applied filters to confine bridge inventory. Chapter 3 describes the candidate variables, which can be used to develop deterioration models. A total of 27 NBI inspection data and additional information from 1983 to 2014 are analyzed and their distribution is investigated. Chapter 4 presents a framework to determine explanatory variables amongst the candidates. Statistical methods including covariance analysis and penalized regression are applied to eliminate human influence from selection of important/explanatory variables. Chapter 5 shows the deterministic deterioration models for deck, superstructure, and substructure using the explanatory variables for Wyoming bridges. Chapter 6 presents the stochastic deterioration models using the Markov chain. The report ends with brief conclusions and the direction of future research to monitor bridges effectively.

CHAPTER 2 DATA ANALYSIS

INTRODUCTION

In order to assess the performance of bridges in the United States, a standard criteria has been provided by the United States Department of Transportation (USDOT). The performance criteria is specified by ten indices as shown in Table 1 so that the decision makers and engineers are able to prepare an appropriate maintenance plan according to the condition ratings. The Recording and Coding Guide for Structure Inventory and Appraisal of the Nation's Bridges has been revised over time to provide specific instructions for bridge monitoring (USDOT 1995).

Table 1. Description of condition ratings for bridge elements

State	Description
N	Not Applicable
9	Excellent Condition
8	Very Good Condition
7	Good Condition
6	Satisfactory Condition
5	Fair Condition
4	Poor Condition
3	Serious Condition
2	Critical Condition
1	"Imminent" Failure Condition
0	Failed Condition

DATA FILTERING

Although the inspection data is digitalized into the numeric values or string variables, missing information exists due to human error, inspection uncertainties, insufficient inspection equipment, and so forth. In order to implement the reliable data only for the development of deterioration models, the bridge inspection belonging to the following list is removed:

- Not applicable and blank data.
- Non-bridge data.
- Bridges with unrecorded major inspection data.
- Bridges with unrecorded major maintenance actions.

Based on the 2014 inspection data, WYDOT monitored the total of 3,127 bridges, which are narrowed down to 2,202 by removing the bridge information belonging to the above list.

Matlab® (© 1994-2016 The MathWorks, Inc.) commands are used for the filtering of which the specific is described as follows.

Not Applicable and Blank Data

Table 2. Number of bridge components at each condition rating for Year Built of 2014 inspection record

Condition Rating	Deck	Superstructure	Substructure
N	480	476	476
9	7	5	5
8	42	171	48
7	807	1048	1348
6	950	1045	894
5	567	380	273
4	165	435	60
3	83	43	22
2	22	4	1
1	4	0	0
0	0	0	0
Blank	0	0	0
Total	3,127	3,127	3,127

Table 3. Number of bridge components at each condition rating for Year Built of 1998 inspection record

Condition Rating	Deck	Superstructure	Substructure
N	395	400	396
9	5	486	4
8	102	276	87
7	1,037	892	1,200
6	750	380	1,007
5	543	435	263
4	145	121	55
3	36	43	24
2	11	4	1
1	13	0	1
0	0	0	0
Blank	294	294	293
Total	3,331	3,331	3,331

The NBI data is inspected to count the number of elements for each condition rating. Table 2 and Table 3 are analysis results for 1998 and 2014 NBI data, which indicates 21 percent of 1998 and 15 percent of 2014 condition ratings are N (not applicable) or blanked (no information). These tables represent the example of the potential inconsistencies in the NBI data from year to year. For each year, the bridge information corresponding to 'N' and 'no information' is removed.

Non-Bridge Data

There are cases that the culverts, tunnels, or miscellaneous structures are listed in the database. Mostly, these are inspection data for culverts, which are duplicated with bridge records. Table 4 shows the number of non-bridge records in each inspection year since 1983.

Table 4. Number of non-bridge records in each inspection year

Year	All Records	Non-Bridge Data	Year	All Records	Non-Bridge Data
1983	3,139	299	1999	3,413	667
1984	3,118	303	2000	3,421	680
1985	3,108	304	2001	3,387	681
1986	3,106	305	2002	3,392	695
1987	3,084	311	2003	3,356	703
1988	3,101	332	2004	3,352	707
1989	3,104	342	2005	3,344	705
1990	2,833	336	2006	3,345	712
1991	2,787	335	2007	3,349	715
1992	3,142	582	2008	3,355	720
1993	3,160	594	2009	3,355	738
1994	3,177	600	2010	3,358	741
1995	3,294	612	2011	3,367	749
1996	3,110	440	2012	3,400	762
1997	3,302	623	2013	3,099	474
1998	3,331	644	2014	3,127	494

Bridges with Unrecorded Major Inspection Data

A framework has been developed for the appropriate selection of explanatory variables (Chang et al. 2015). This framework considers all variables that are believed to affect bridge performance amongst the NBI inspection data. Forty items are selected as a candidate for which all bridges contain the appropriate information. The bridges with insufficient inspection data are removed and the number of bridges shown in Table 5 is actually investigated for the analysis. The detail of candidate variables and the suggested framework are explained in Chapter 4.

Table 5. Number of bridges used for analysis in each inspection year

Year	All Records	# for Analysis	Year	All Records	# for Analysis
1983*	3,139	2,282	1999	3,413	1,886
1984*	3,118	2,287	2000	3,421	1,891
1985*	3,108	2,272	2001	3,387	2,361
1986*	3,106	2,272	2002	3,392	2,374
1987*	3,084	2,274	2003	3,356	2,363
1988*	3,101	2,280	2004	3,352	2,360
1989*	3,104	2,286	2005	3,344	2,347
1990*	2,833	2,314	2006	3,345	2,339
1991*	2,787	2,314	2007	3,349	2,339
1992*	3,142	1,839	2008	3,355	2,200
1993*	3,160	1,846	2009	3,355	2,203
1994*	3,177	1,914	2010	3,358	2,221
1995*	3,294	1,943	2011	3,367	2,225
1996*	3,110	1,913	2012	3,400	2,222
1997	3,302	1,885	2013	3,099	2,209
1998	3,331	1,891	2014	3,127	2,202

The years with the * symbol denote several inspection variables that are excluded due to missing data.

Bridges with Unrecorded Major Maintenance Actions

Most bridges have undergone maintenance, repair, and reconstruction actions during their service life, but this information is not fully recorded in NBI inspection data. In order to account for the absence of maintenance history, a 50-year window is used for each condition rating and the outliers are filtered out (Hatami and Morcous 2011). Specifically each condition rating uses the following criteria for acceptance as inventory data.

Table 6. Number of bridges with unrecorded major maintenance actions

Condition Rating	Age Reconstructed (if exists)		# of Bridges (# of Outliers)		
	Min (years)	Max (years)	Deck	Superstructure	Substructure
9	0	30	7 (1)	0 (0)	5 (0)
8	0	40	42 (7)	5 (0)	48 (9)
7	0	50	807 (241)	171 (31)	1,348 (334)
6	10	60	950 (106)	1,048 (385)	894 (122)
5	20	70	567 (46)	1,045 (168)	273 (45)
4	30	80	165 (20)	282 (52)	60 (16)
3	40	90	83 (28)	74 (23)	22 (4)
2	50	100	22 (13)	25 (9)	1 (0)
1	60	110	4 (3)	1 (0)	0 (0)
Total	·	·	2647 (465)	2651 (668)	2651 (530)

ANALYSIS PROCEDURE

In Wyoming, the NBI data has been accumulated since 1983 and archived for convenient use. Based on the previously presented filtering, the bridge data with insufficient information and duplicates are removed. This procedure results in nearly 2,000 bridges available for analysis for each year.

CHAPTER 3 CLASSIFICATION PARAMETERS

INTRODUCTION

The deterioration model for bridge elements can be defined as various functions associated with bridge design, major material, structure types, traffic, and other circumstances. Since the NBI data provides more than 100 items/information, it is a challenge to determine a set of significant variables to develop deterioration models accurately. Previous research has normally used the engineering judgment without sufficient explanation to determine explanatory variables, which potentially excludes significant variables and results in inaccurate deterioration models.

As part of the study to develop deterioration models, this chapter presents the parametric study of candidate variables. In Chapter 4, the results from this chapter are then used to determine explanatory variables in a new method that attempts to mitigate human bias in explanatory variable selection. Of the NBI data, only 27 variables are considered important to bridge structural or deterioration behavior. Additionally, precipitation, average temperature, and elevation information were included for the analysis using the geographical coordinates of each bridge. In this chapter, the general statistical information for Wyoming bridges is discussed.

HIGHWAY AGENCY DISTRICT

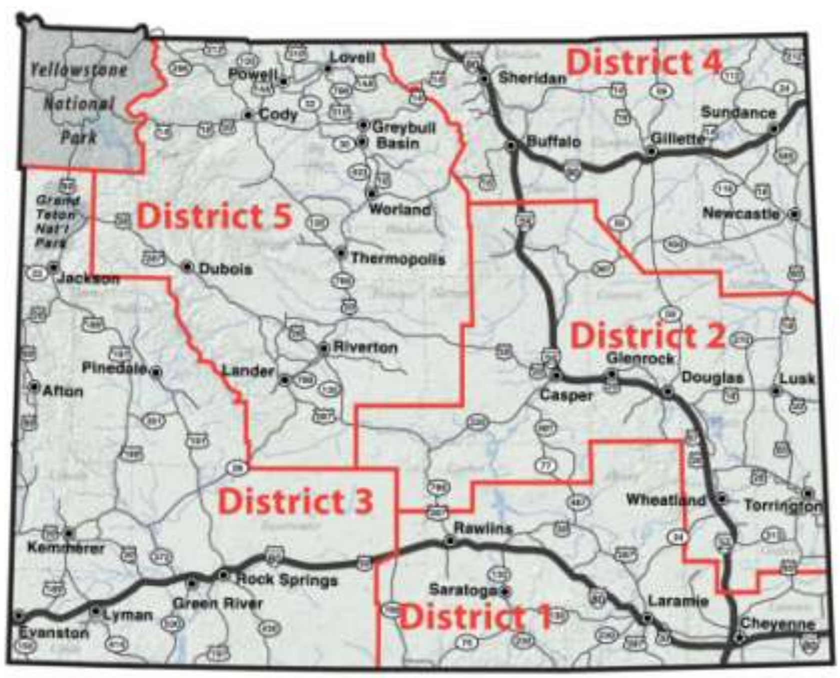


Figure 1. Photo. District map of Wyoming (retrieved from **https://www.dot.state.wy.us/home/news_info/district_news_info.default.html** on May 1st, 2015)

The *Highway Agency District* distinguishes the location of bridges, which are distinguished by five districts excluding Yellowstone National Park area. Figure 1 illustrates the district map of

Wyoming, which includes three Interstates, 15 US and 191 Wyoming Highways, and numerous local roads. The number of bridges in each district is distributed as shown in Table 7. Districts 2 and 4 contain a few more bridges compared to other districts.

Table 7. Distribution of bridges in Wyoming

Highway Agency	Frequency	Percentage
District 1	369	16.76
District 2	520	23.61
District 3	381	17.30
District 4	536	24.34
District 5	396	17.98
Total	2,202	100

ROUTE SIGNING PREFIX

The *Route Signing Prefix* is a child under Inventory Route category and distinguishes the class of route with eight variations, as presented in Table 8. Almost 40 percent of bridges are located on Interstate highways,

Table 8. Distribution of route signing prefix

Route Signing Prefix	Frequency	Percentage
1 Interstate Highway	863	39.19
2 U.S. Highway	340	15.44
3 State Highway	383	17.39
4 County Highway	470	21.34
5 City Street	88	4.00
6 Federal Lands Road	28	1.27
7 State Lands Road	0	0
8 Other	30	1.36
Total	2,202	100

BASE HIGHWAY NETWORK

The *Base Highway Network* is a Boolean operator, which distinguishes whether the inventory route is on the base network or not. Amongst 2,202 bridges, 1,275 (57.90 percent) are on the base network whereas the rest of them are not.

MAINTENANCE RESPONSIBILITY

The NBI classifies the maintenance agency(s) responsible for the structures with 29 variations and is presented in Table 9. More than 95 percent are under the maintenance of state and county highway agencies.

Table 9. Distribution of Maintenance responsibility

Agency	Frequency	Percentage
01 State HW	1,627	73.89
02 County HW	454	20.62
03 Town/Township HW	51	2.32
04 City/Municipal HW	28	1.27
11 State Park/Forest/Res.	1	0.05
12 Local Park/Forest/Res.	0	0
21 Other State	1	0.05
25 Other Local	0	0
26 Privates	0	0
27 Railroad	0	0
31 State Toll Authority	0	0
32 Local Toll Authority	0	0
60 Other Federal	0	0
61 Indian Tribal Govt.	0	0
62 Bur. of Indian Affairs	19	0.86
63 Bur. of Fish/Wildlife	0	0
64 U.S. Forest Service	0	0
66 Nat'l Park Service	18	0.82
67 TN Valley Authority	0	0
68 Bur. of Land Mgmt.	0	0
69 Bur. of Reclamation	0	0
70 Corps of Engr.(civil)	0	0
71 Corps of Engr.(Mil.)	0	0
72 Air Force	3	0.14
73 Navy/Marines	0	0
74 Army	0	0
75 NASA	0	0
76 MWAA	0	0
80 Unknown	0	0
Total	2,202	100

FUNCTIONAL CLASSIFICATION OF INVENTORY ROUTE

The *Functional Classification of Inventory Route* is distributed into six for rural and another six for urban areas as shown in Table 10. The rural area contains nearly 86 percent of total bridges in the state.

Table 10. Distribution of functional classification of inventory route

Functional Classification		Frequency	Percentage
Rural	01 Principal Arterial – Interstate	712	32.33
	02 Principal Arterial – Other	250	11.35
	06 Minor Arterial	126	5.72
	07 Major Collector	230	10.45
	08 Minor Collector	113	5.13
	09 Local	470	21.34
Urban	11 Principal Arterial – Interstate	151	6.86
	12 Principal Arterial – Other	4	0.18
	14 Other Principal Arterial	52	2.36
	16 Minor Collector	30	1.36
	17 Collector	34	1.54
	19 Local	30	1.36
Total		2,202	100

YEAR BUILT

The *Year Built* is the most important keyword to describe the deterioration model for bridges. Four digits indicate the year of construction, which can be converted into the age. In this study, reconstruction is unused due to the inaccuracy about which part is replaced or rebuilt. The oldest bridge in the inventory was built in 1903. Since then, the *Year Built* is discretized for every two decades. Nearly 90 percent of total bridges are built between 1941 and 2000, as presented in Table 11.

Table 11. Distribution of year built

Year Built	Frequency	Percentage
1901 – 1920	8	0.36
1921 – 1940	71	3.22
1941 – 1960	338	15.35
1961 – 1980	1,132	51.41
1981 – 2000	475	21.57
2001 – 2015	178	8.08
Total	2,202	100

LANES ON THE STRUCTURE

Lanes on the structure is a subcategory of item 28 (*Lanes on and under the Structure*) and the information potentially duplicated with the width of the bridge. For Wyoming bridges, the number of lanes varies from one to five (mostly two lanes) and the distribution is shown in Table 12.

Table 12. Distribution of lanes on the structure

Number of Lanes	Frequency	Percentage
1	94	4.27
2	2,056	93.37
3	13	0.59
4	34	1.54
5	5	0.23
Total	2,202	100

LANES UNDER THE STRUCTURE

Lanes under the structure is a subcategory of item 28 (*Lanes on and under the Structure*) and the information is potentially duplicated with the width of the bridge. For Wyoming bridges, the number of lanes is varied between zero to five (mostly zero or two lanes) and the distribution is shown in Table 13.

Table 13. Distribution of lanes under the structure

Number of Lanes	Frequency	Percentage
0	1,654	75.11
1	19	0.86
2	442	20.07
3	2	0.09
4	79	3.59
5	4	0.18
6	2	0.09
Total	2,202	100

AVERAGE DAILY TRAFFIC

The amount of traffic passing over each bridge had been counted and recorded for the *Average Daily Traffic* and average daily truck traffic is also recorded. More than 97 percent of bridges carry less than 10,000 vehicles in a day as presented in
Table 14.

Table 14. Distribution of average daily traffic

Average Daily Traffic	Frequency	Percentage
0 – 5,000	1,790	81.29
5,001 – 10,000	357	16.21
10,001 – 15,000	40	1.82
15,001 – 20,000	12	0.54
20,001 -	3	0.14
Total	2,202	100

DESIGN LOAD

The *Design Load* is translated into the code between zero to nine to indicate the live load that the structure was originally designed for and is presented in Table 15.

Table 15. Distribution of design load

Design Load Code	Frequency	Percentage
1 M 9	7	0.32
2 M 13.5	72	3.27
3 MS 13.5	22	1.00
4 M 18	71	3.22
5 MS 18	838	38.06
6 MS 18+Mod	816	37.06
7 Pedestrian	0	0
8 Railroad	0	0
9 MS 22.5	117	5.31
0 Other/Unknown	259	11.76
Total	2,202	100

SKEW

The *Skew* is the angle between the centerline of a pier and a line normal to the roadway centerline. Normally, a skew is less than 15 degrees; approximately 30 percent bridges are constructed with a skew angle larger than 15 degrees as presented in Table 16.

Table 16. Distribution of skew

Skew Angle	Frequency	Percentage
0 – 15	1,565	71.07
15 – 30	296	13.44
30 – 45	250	11.35
45 – 60	83	3.77
60 – 75	8	0.36
Total	2,202	100

TYPE OF SERVICE ON BRIDGE

Type of Service on Bridge is a sub-category of item 42 (*Type of Service*) and describes the type of service on the bridge with ten variations. As shown in Table 17, 95 percent of bridges play a role in highway or over-passing structure.

Table 17. Distribution of type of service on bridge

Type of Service	Frequency	Percentage
1 Highway	1,774	80.56
2 Railroad	0	0
3 Pedestrian-Bicycle	0	0
4 Highway-Railroad	0	0
5 Highway-Pedestrian	108	4.90
6 Overpass/2nd Level	318	14.44
7 3rd Level	2	0.09
8 4th Level	0	0
9 Building/Plaza	0	0
0 Other	0	0
Total	2,202	100

TYPE OF SERVICE UNDER BRIDGE

Type of Service under Bridge is a sub-category of item 42 (*Type of Service*) and describes the type of service under the bridge with ten variations. As shown in
Table 18, more than 60 percent of bridge are supposed to pass over waterways.

Table 18. Distribution of type of service under bridge

Type of Service	Frequency	Percentage
1 Highway	513	23.30
2 Railroad	108	4.90
3 Pedestrian-Bicycle	0	0
4 Highway-Railroad	24	1.09
5 Waterway	1,337	60.72
6 Highway-Waterway	11	0.50
7 Railroad-Waterway	11	0.50
8 Highway-Waterway-Railroad	0	0
9 Building/Plaza	0	0
0 Other	198	8.99
Total	2,202	100

MATERIAL AND/OR DESIGN

The types of material used for bridge superstructure are distinguished from zero to nine, and are listed in Table 19.

Table 19. Distribution of kind of material and/or design

Material Type	Frequency	Percentage
1 Concrete	104	4.72
2 Concrete Continuous	751	34.11
3 Steel	344	15.62
4 Steel Continuous	777	35.29
5 PS Concrete	157	7.13
6 PS Concrete Continuous	10	0.45
7 Wood/Timber	59	2.68
8 Masonry	0	0
9 Aluminum/Cast Iron/Wrought Iron	0	0
0 Other	0	0
Total	2,202	100

TYPE OF DESIGN AND/OR CONSTRUCTION

Type of Design and/or Construction indicates the predominant type of design and/or type of construction amongst 23 variations. As presented in Table 20, three major structure types are Slab, Stringer/multi-beam or girder, and Tee beam, which account for almost 95 percent of total bridges.

Table 20. Distribution of type of design and/or construction

Structure Type	Frequency	Percentage
01 Slab	430	19.53
02 Stringer / multi-beam or girder	1,260	57.22
03 Girder and floor beam system	24	1.09
04 Tee beam	379	17.21
05 Box beam or girders – Multiple	34	1.54
06 Box beam or girders – Single or spread	2	0.09
07 Frame (except frame culverts)	22	1.00
08 Orthotropic	0	0
09 Truss – Deck	2	0.09
10 Truss – Thru	40	1.82
11 Arch – Deck	1	0.05
12 Arch – Thru	0	0
13 Suspension	0	0
14 Stayed girder	0	0
15 Movable – Lift	0	0
16 Movable – Bascule	0	0
17 Movable – Swing	0	0
18 Tunnel	0	0
19 Culvert (includes frame culverts)	0	0
20 Mixed types	0	0
21 Segmental box girder	0	0
22 channel beam	7	0.32
00 Other	1	0.05
Total	2,202	100

NUMBER OF SPANS IN MAIN UNIT

The *Number of Spans in Main Unit* is mostly less than six as shown in Table 21.

Table 21. Distribution of number of spans in main unit

Number of Spans	Frequency	Percentage
1 – 2	469	21.30
3 – 4	1,472	66.85
5 – 6	218	9.90
7 – 8	28	1.27
9 – 10	6	0.27
11 – 12	3	0.14
13 – 14	3	0.14
15 – 16	1	0.05
17 –18	2	0.09
Total	2,202	100

INVENTORY ROUTE, TOTAL HORIZONTAL CLEARANCE

Inventory Route, Total Horizontal Clearance defines the clear distance between restrictions of the route on or under the structure and the distribution of this parameter is presented in Table 22. When no restriction exists, it represents the roadway surface and shoulders. According to the NBI guideline, the purpose of this item is to provide the large available clearance for the movement of wide loads.

Table 22. Distribution of inventory route, total horizontal clearance

Number of Spans	Frequency	Percentage
0 – 5	103	4.68
5 – 10	795	36.10
10 – 15	1,223	55.54
15 – 20	51	2.32
20 – 25	26	1.18
25 – 30	4	0.18
Total	2,202	100

LENGTH OF MAXIMUM SPAN

The *Length of Maximum Span* is measured from the centerline of the bridge. The mean and standard deviation of length of maximum span is 17.27 m (56.567 ft) and 10.54 m (34.58 ft). The length of maximum span is shorter than 40 m (131 ft) for 95 percent of bridges, and the specific distribution, is presented in Table 23.

Table 23. Distribution of length of maximum span

Length (*m*)	Frequency	Percentage
0 – 20	1,597	72.52
20 – 40	514	23.34
40 – 60	76	3.45
60 – 80	12	0.54
80 –	3	0.14
Total	2,202	100

STRUCTURE LENGTH

The distribution of *Structure Length*, which is measured between inside faces of exterior walls, is presented in Table 24. Most bridges (95 percent) are less than 100 *m* and only 13 bridges are longer than 200 *m*. The mean and standard deviation of the structure length is the 42.32 *m* (138.85 *ft*) and 38.39 *m* (129.95 *ft*).

Table 24. Distribution of structure length

Length (*m*)	Frequency	Percentage
0 – 50	1,638	74.39
50 – 100	452	20.53
100 – 150	76	3.45
150 – 200	23	1.04
200 –	13	0.59
Total	2,202	100

BRIDGE ROADWAY WIDTH (CURB TO CURB)

The *Bridge Roadway Width* represents the minimum distance between curbs or rails on the structure roadway. Its distribution, presented in Table 25, is similar to *Inventory Route*, *Total Horizontal Clearance*. The mean and standard deviation of structure length is 10.55 *m* (34.61 *ft*) and 2.98 *m* (9.78 *ft*).

Table 25. Distribution of bridge roadway width (curb-to-curb)

Width (*m*)	Frequency	Percentage
0 – 5	102	4.63
5 – 10	790	35.88
10 – 15	1,227	55.72
15 – 20	51	2.32
20 – 25	26	1.18
25 – 30	6	0.27
Total	2,202	100

DECK WIDTH (OUT TO OUT)

The *Deck Width* measures the out-to-out width of structures and is presented in Table 26. Also, similar distribution with slightly longer values is observed when it is compared to *Inventory Route*, *Total Horizontal Clearance* and *Bridge Roadway Width*. The mean and standard deviation of structure length is the 11.56 *m* (37.93 *ft*) and 3.44 *m* (11.29 *ft*).

Table 26. Distribution of deck width (out-to-out)

Width (*m*)	Frequency	Percentage
0 – 5	74	3.36
5 – 10	505	22.93
10 – 15	1,472	66.85
15 – 20	91	4.13
20 – 25	36	1.63
25 – 30	24	1.09
Total	2,202	100

DECK STRUCTURE TYPE

Eight types are used to classify bridges using *Deck Structure Type*. Table 27 reveals that a concrete cast-in-place is widely used in Wyoming bridges.

Table 27. Distribution of deck structure type

Type Code	Frequency	Percentage
1 Concrete Cast-in-Place	1,850	84.01
2 Concrete Precast Panels	136	6.18
3 Open Grating	0	0
4 Closed Grating	0	0
5 Steel Plate	0	0
6 Corrugated Steel	108	4.90
7 Aluminum	0	0
8 Wood/Timber	108	4.90
9 Other	0	0
Total	2,202	100

TYPE OF WEARING SURFACE

The *Type of Wearing Surface* distinguishes eight wearing materials, as presented in Table 28. More than 40 percent of bridges are in bare deck (none from the table) condition. The latex concrete and bituminous are widely used as a wearing material.

Table 28. Distribution of type of wearing surface

Wearing Surface Type	Frequency	Percentage
1 Monolithic Concrete	16	0.73
2 Integral Concrete	3	0.14
3 Latex Concrete/Similar	584	26.52
4 Low Slump Concrete	0	0
5 Epoxy Overlay	53	2.41
6 Bituminous	532	24.16
7 Wood/Timber	46	2.09
8 Gravel	63	2.86
9 Other	11	0.50
0 None	894	40.60
Total	2,202	100

TYPE OF MEMBRANE

The *Type of Membrane* is defined by six descriptions of which more than 90 percent are constructed of built-up type as presented in Table 29.

Table 29. Distribution of type of membrane

Membrane Type	Frequency	Percentage
1 Built-up	0	0
2 Preformed Fabric	172	7.81
3 Epoxy	0	0
8 Unknown	3	0.14
9 Other	18	0.82
0 None	2,009	91.24
Total	2,202	100

DECK PROTECTION

The *Deck Protection* defines what reinforcing or protection is applied to the deck of bridge amongst nine options. The distribution of deck protection is presented in Table 30. Only 15 percent of total bridges are protected mostly using epoxy coated reinforcing.

Table 30. Distribution of deck protection

Protection Type	Frequency	Percentage
1 Epoxy Coated Reinforcing	287	13.03
2 Galvanized Reinforcing	0	0
3 Other Coated Reinforcing	4	0.18
4 Cathodic Protection	1	0.05
6 Polymer Impregnated	0	0
7 Internally Sealed	1	0.05
8 Unknown	16	0.73
9 Other	19	0.86
0 None	1,874	85.10
Total	2,202	100

AVERAGE DAILY TRUCK TRAFFIC

The *Average Daily Truck Traffic* is a percentage proportion of *Average Daily Traffic*. The Average Daily Truck Traffic distribution is presented in Table 31. Nearly 70 percent of bridges carry less than 20 percent of total vehicles in a day.

Table 31. Distribution of average daily truck traffic

ADTT ()	Frequency	Percentage
0 – 10	729	33.11
10 – 20	801	36.38
20 – 30	347	15.76
30 – 40	52	2.36
40 – 50	209	9.49
50 –	64	2.91
Total	2,202	100

DESIGNATED NATIONAL NETWORK

The *Designated National Network* is a Boolean operator to distinguish the structure is a part of the national network for trucks or not. Amongst 2,202 bridges, 1,244 (56.49 percent) number of bridges belongs to the national network for trucks.

PRECIPITATION

The *Precipitation* is interpolated based on the local rainfall data and location of the bridges (PRISM Climate Group 2004). The Precipitation distribution is presented in Table 32. The annual precipitation in Wyoming is around 15.75 *in* (400 *mm*), which is significantly less than the national average (30 in or 767 *mm*). The mean and standard deviation of 2014 precipitation data are calculated as 14.09 *in* (358 *mm*) and 5.51 *in* (140 *mm*).

Table 32. Distribution of precipitation

Precipitation (*in*)	Frequency	Percentage
0 – 7.87	192	8.72
7.87 – 15.75	1,512	68.66
15.75 – 23.62	468	21.25
23.62 – 31.50	25	1.14
31.50 – 39.37	4	0.18
39.37 – 47.25	1	0.05
Total	2,202	100

AVERAGE TEMPERATURE

The *Average Temperature* is interpolated based on the local temperature data and location of the bridges (PRISM Climate Group 2004). The *Average Temperature* distribution is presented in Table 33. The annual average temperature in Wyoming is around 46.4 degrees Fahrenheit (°F), which is ranked at 46th among states in United States. The mean 2014 average temperature is calculated as 43.9 °F.

Table 33. Distribution of average temperature

Temperature (°F)	Frequency	Percentage
28.4 – 32.0	4	0.18
32.0 – 35.6	19	0.86
35.6 – 39.2	127	5.77
39.2 – 42.8	408	18.53
42.8 – 46.4	1,274	57.86
46.4 – 50.0	370	16.80
Total	2,202	100

ELEVATION

The *Elevation* for existing bridges is stationary information (PRISM Climate Group 2004). Due to the geographical properties of Wyoming's bridges, most bridges are constructed at relatively high elevation, as presented in Table 34. The mean and standard deviation of 2014 elevation data are calculated as 5,577 *ft* (1.7 *km*) and 1,280 *ft* (0.39 *km*).

Table 34. Distribution of elevation

Elevation (*ft*)	Frequency	Percentage
0 – 1,640	0	0
1,640 – 3,281	1	0.05
3,281 – 4,921	942	42.78
4,921 – 6,562	772	35.06
6,562 – 8,202	475	21.57
8,202 – 9,843	12	0.54
9,843 – 11,483	0	0
Total	2,202	100

CHAPTER 4 EXPLANATORY VARIABLE SELECTION WITHOUT ANTHROPOGENIC BIAS

INTRODUCTION

In order to design accurate bridge deterioration models, vast volumes of inspection data have to be analyzed to extract statistically meaningful information. The selection of explanatory variables aims to conduct data analysis efficiently and to capture the statistically significant factors for the development of deterioration models, which supports the policy makers' decision for effective bridge monitoring systems.

This chapter presents a framework to determine explanatory variables, which can be used to develop deterioration models representing general bridges in Wyoming and other states. Biennially inspected bridge inspection data followed by the NBI is used to extract the representative bridge model. A framework, based on the several statistical methods, is used to determine optimal sets for the deterioration model development.

FRAMEWORK TO DETERMINE EXPLANATORY VARIABLES

The framework starts from the data normalization so that the bias due to scale cannot affect the analysis. In order to eliminate the duplicated variable selection, a covariance analysis is conducted and a covariance matrix, containing all considered variables, is constructed for each year. Each element of the covariance matrix is the measure of correlation between associated random variables, where a higher value indicates that two variables are providing the same information. When two or more variables are highly correlated, the variable with the highest correlation to condition ratings is retained and the other is removed from further consideration.

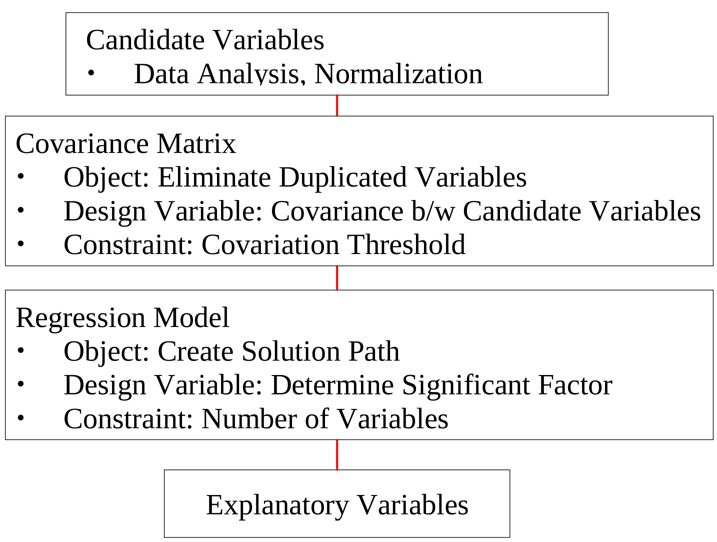


Figure 2. Chart. Framework for selection of explanatory variables

A regression model is established to determine which variable is relatively important and how many of them are most likely required, for which penalized regression is investigated. Least

Absolute Shrinkage and Selection Operator (LASSO) is a well-known version of penalized regression, which will be demonstrated to automate the explanatory variable selection process. A cross validation scheme is used to optimize the number of variables. As a result, it produces a solution path depending on the minimal number of significant variables and ranks variable importance. The entire framework is illustrated in Figure 2.

Covariance Matrix

Covariance is a measure to quantify the correlation of two random variables. For a matrix form of inspection data $\mathrm{X} \in \Re^{m \times n}$, which is normalized from the m number of original inspection bridge data with n categories, the element of covariance matrix Σ_{ij} corresponding to ith and jth column vectors X_i and X_j of X, is defined as:

$$\Sigma_{ij} = \mathrm{cov}\left(X_i, X_j\right) = \mathrm{E}\left[(X_i - \mu_i)(X_j - \mu_j)\right]$$

Figure 3. Equation. Element of covariance matrix

Figure 3. Equation, $[\mu_i, \mu_j]$ are the mean of $[X_i, X_j]$, respectively; $\mathrm{E}[\cdot]$ denotes the expectation function. The diagonal element Σ_{ii} indicates the variance of random vector X_i and becomes unity if X_i is normally distributed. In this paper, all inspection data were normalized to the maximum values. Accordingly, each element of a covariance matrix marks a value between -1 and 1.

A covariance matrix is used to facilitate the decision making process when candidate variables are considered as duplicates. When the two or more random variables are considered as highly correlated, one can be selected as the representative variable. The covariance indices between condition rating and all associated variables are calculated and the highly correlated variable is chosen.

Penalized Linear Regression

A linear regression model with n observations can be defined as shown in Figure 4. Equation.

$$y = \mathrm{X}\beta + \varepsilon$$

Figure 4. Equation. Linear regression for condition rating $\boldsymbol{y}$

In Figure 4. Equation, $y \in \Re^m$ and denotes the normalized condition ratings for m bridges and $\beta \in \Re^n$ is a coefficient vector, which minimizes the error of regression model; ε is the corresponding error, which is considered as a stochastic contribution with zero mean and non-zero covariance.

For a more accurate prediction of multivariate regression model, Tibshirani (1996) proposed a method called Least Absolute Shrinkage and Selection Operator (LASSO), which is based on a penalized least square procedure. The LASSO estimator is defined as:

$$\hat{\beta}_L = \arg\min \left[(\tilde{y} - \mathrm{X}\beta)^{\intercal}(\tilde{y} - \mathrm{X}\beta) + \lambda \sum_{j=1}^{n} \left|\beta_j\right| \right]$$

Figure 5. Equation. Estimation of regression coefficient $\widehat{\boldsymbol{\beta}}_{\boldsymbol{L}}$ using LASSO penalized regression procedure

In Figure 5. Equation, $\lambda \geq 0$ is a tuning parameter. The performance of LASSO estimator has been improved and compared from numerous studies (Osborne et al. 2000; Efron et al. 2004; Tibshirani et al. 2005; Zou et al. 2007).

The selection of the tuning parameter affects the accuracy of the LASSO model. In general, a smaller value for the tuning parameter requires more variables' contribution for the estimation and requires high computational costs. Furthermore, a small value for the tuning parameter makes decision-making process difficult due to redundant and duplicated information. In order to estimate the accuracy of LASSO resultants and to provide a rigorous evidence for model selection, cross validation is utilized (Tibshirani 1996).

Cross Validation Procedures

For ith test data X, the rest (i.e. training data) is used to estimate the stationary LASSO coefficients. The normalized errors between LASSO models from test and training data are averaged and compared to the increase of the tuning parameter. For cross validation, a candidate data set X is randomly split into k mutually exclusive subsets $\mathrm{X}^{\langle 1 \rangle}$, $\mathrm{X}^{\langle 2 \rangle}$, ..., $\mathrm{X}^{\langle k \rangle}$ (k-fold) with approximately the same sample size. Throughout the research, five-fold cross validation is used (i.e. k = 5). Each subset, containing a bit more than 400 samples, was trained over the rest of samples for five times each. The optimal tuning parameter and the corresponding number of explanatory variables are determined when the mean square error is minimized.

EXPLANATORY VARIABLES

The LASSO function is used to estimate the prediction coefficient vector. The tuning parameter, λ, affects the number of variables in the regression model such that the larger value results in the lower number of variables. The 2014 NBI data contained a total of 3,127 bridges in Wyoming and after eliminating duplicate or omitted data 2,302 remain that include the required data to conduct statistical analysis.

Using the above framework, the LASSO based methodology can be applied to determine the relative importance of candidate variables and the mean squared errors versus tuning parameter can be observed. Strictly speaking, the number of variables minimizing the mean square error of cross validation are obtained as, 26, 24, and 22 for deck, superstructure, and substructure, respectively. These are the numbers of variables, according to LASSO that will develop a regression model with absolute minimum square error. Statistically, these are the optimal values, functionally, however, much fewer explanatory variables will be used, as discussed below.

Deck LASSO Analysis

The solution path for deck condition rating is illustrated in Figure 6, showing that the increase of the λ results in more variables participation for the regression model. The first five explanatory variables are plotted with solid line and the rest are plotted with dots.

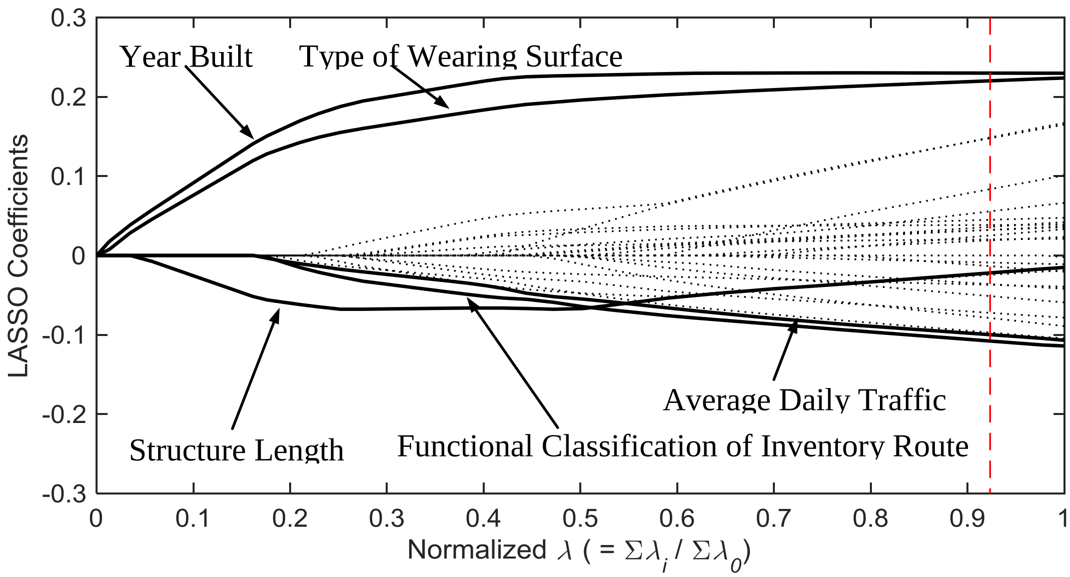


Figure 6. Graph. Solution path for deck condition ratings by LASSO

The auxiliary line around 0.92 of normalized tuning parameter indicates the solution to minimize the linear square error based on cross validation analysis. This auxiliary line corresponds to 26 explanatory variables for this tuning parameter for deck condition ratings. The relative importance can be determined by identifying the LASSO coefficients that show the largest value in the solution path along with the increasing λ. The explanatory variables are listed, ranked in order of importance to the model, with λ in Table 35 where some are classified as significant variables simultaneously.

LASSO regression is tested five times for deck element condition ratings using the fivefold cross validation technique and found error to be statistically minimized when 26 variables are used. Using this many variables would be cumbersome, would give a false sense of accuracy and is not recommended for bridge deterioration modeling. The sequential order of these variables shows how sensitive the deck condition model is to the different parameters. Although the covariance analysis eliminates the duplicated, there are many variables requiring engineering judgment for similar information such as [Structure Length and Length of Maximum Span], [Average Daily Traffic and Average Daily Truck Traffic], [Lanes on the Structure and Deck Width (Out to Out)], and so forth. This method provides a rigorous approach to choose explanatory variables for decision makers.

Table 35. LASSO selection of 26 explanatory variables for deck condition ratings

λ	# of Items	Variable
1.538E-01	2	Year Built; Type of Wearing Surface
1.277E-01	1	Structure Length
6.656E-02	2	Functional Classification of Inventory Route Average Daily Traffic
6.065E-02	1	Lanes on the Structure
5.035E-02	2	Highway Agency District Average Temperature
4.588E-02	1	Skew
4.180E-02	3	Maintenance Responsibility Design Load Number of Spans in Main Unit
3.809E-02	1	Precipitation
2.625E-02	1	Lanes under the Structure
2.180E-02	1	Deck Width (Out to Out)
1.986E-02	2	Deck Structure Type Kind of Material and/or Design
1.810E-02	1	Designated National Network
1.649E-02	2	Length of Maximum Span Type of Membrane;
1.502E-02	1	Average Daily Truck Traffic
1.247E-02	1	Elevation
1.035E-02	2	Type of Design and/or Construction Deck Protection
8.597E-03	1	Type of Service under Bridge
5.925E-03	1	Type of Service on Bridge

The top five variables selected by LASSO regression are year built, type of wearing surface, structure length, functional classification of inventory route and average daily traffic. Many of these variables may have been selected using expert judgment as they “make sense”. Structure length, however, is not typically thought to influence the deck condition. There is anecdotal evidence from the authors and others (particularly from those in the structural health-monitoring field) that structure length affects deterioration, however, it has yet to be proven. The proposed explanatory variable selection method was able to identify this as an important parameter (third most important) statistically where it was only anecdotal before. Functional classification of the inventory route, as discussed above, is a categorical variable indicating route type (e.g., urban, rural, arterial), but not truly geographical and maintenance responsibility where usually districts are used to make this distinction in other models (Morcous and Hatami 2011). It is thought that this variable is related to ADT, but this was not shown to be the case with the covariance analysis so it is providing significantly different (statistically uncorrelated) information.

Superstructure

The solution path for superstructure condition rating is illustrated in Figure 7. The first five explanatory variables are plotted with a solid line and the rest are plotted with dots. The auxiliary line around 0.86 of normalized tuning parameter indicates the minimized linear square error based on cross validation analysis. The number of explanatory variables per the LASSO regression analysis is 24 for the superstructure condition rating. The relative importance can be determined by accounting for the LASSO coefficients they have shown an increase in the tuning parameter in the solution path.

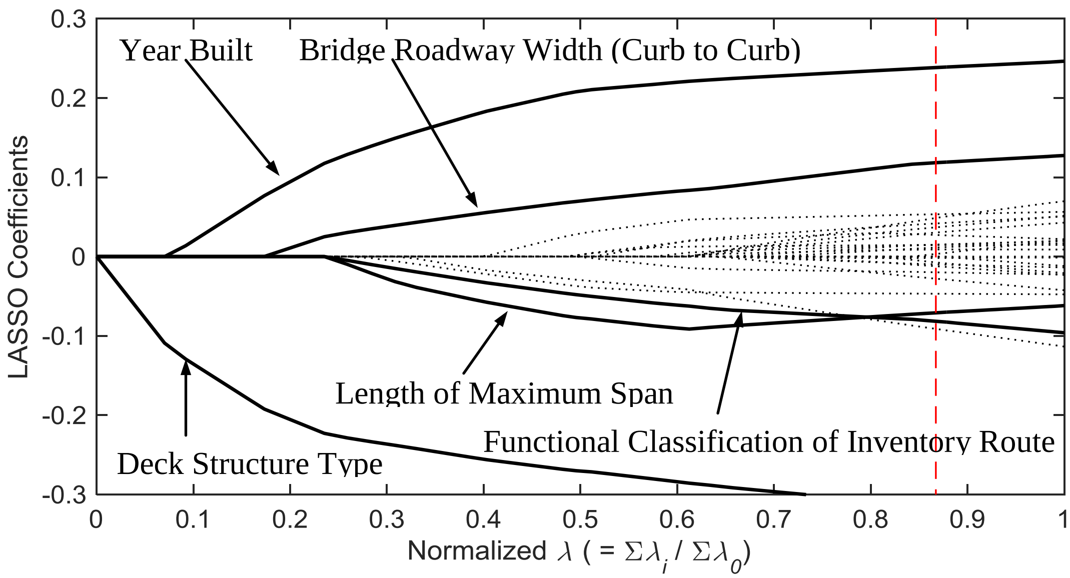


Figure 7. Graph. Solution path for superstructure condition ratings by LASSO

For the Superstructure Condition Ratings, the LASSO regression method was tested five times for deck element condition ratings using cross validation technique and minimizes the error of regression when 24 variables are participated. The sequential order of these variables shows how sensitively superstructure condition ratings is predicted. As discussed above, it is not appropriate to use so many variables, but to select the most impactful using the ranked importance in Table 36. When looking at the ranked list as a whole, the variables related the type of super structure, deck structure and its length are considered more sensitive than traffic and climate variables.

The top five variables per the LASSO regression are: Deck Structure Type, Year Built, Bridge Roadway Width (Curb to Curb), Functional Classification of Inventory Route and Length of Maximum Span. Deck Structure Type is considered most sensitive to the superstructure element and Year Built is ranked second, which did not occur for the Deck or Substructure analyses. This is interesting as it indicates the age of the bridge is less important than the deck type itself. Furthermore, it is often said (anecdotally) in bridge engineering circles that as the deck deteriorates then the rest of the bridge begins to deteriorate. The results from the LASSO regression seem to, if not confirm this, then imply that the superstructure deterioration is highly related to the deck type or perhaps flexibility (e.g., timber versus cast-in-place concrete).

Table 36. LASSO selection of 24 explanatory variables for superstructure condition ratings

λ	# of Items	Variable
3.196E-01	1	Deck Structure Type
2.203E-01	1	Year Built
1.519E-01	1	Bridge Roadway Width (Curb to Curb)
9.537E-02	2	Functional Classification Of Inventory Route; Length of Maximum Span
8.689E-02	1	Type of Design and/or Construction;
7.214E-02	1	Structure Length
4.972E-02	1	Maintenance Responsibility
2.845E-02	2	Deck Protection; Average Temperature
2.593E-02	1	Type of Service on Bridge
2.362E-02	1	Kind of Material and/or Design
1.628E-02	1	Type of Membrane
1.484E-02	1	Precipitation
1.352E-02	1	Number of Spans in Main Unit
1.232E-02	2	Route Signing Prefix Type of Wearing Surface
1.122E-02	4	Lanes on the Structure Lanes under the Structure Skew Designated National Network
1.023E-02	1	Highway Agency District
9.317E-02	1	Type of Service under Bridge
5.852E-02	1	Elevation

Substructure

The solution path for substructure condition rating is illustrated in Table 37. The first five explanatory variables are plotted with solid line and the rest are plotted with dots.
The auxiliary line around 0.71 of normalized tuning parameter indicates the solution to minimize the linear square error based on cross validation analysis. The LASSO analysis results in 22 coefficients participation at least to develop a regression model for substructure condition ratings, which is the smallest number amongst investigated bridge elements. The relative importance can be determined by accounting for the LASSO coefficients that have shown an increase in the tuning parameter in the solution path.

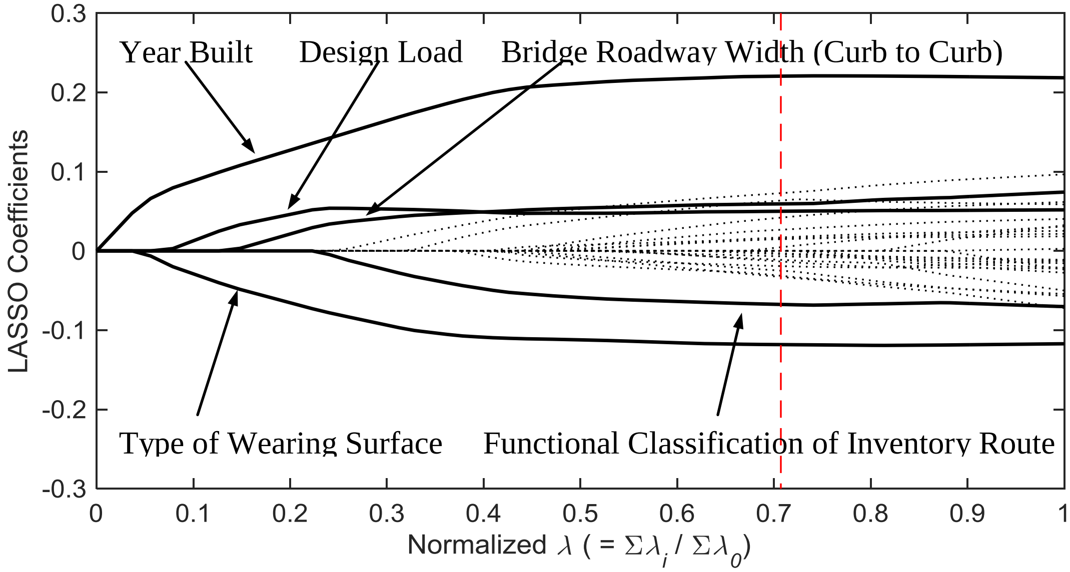


Figure 8. Graph. Solution path for substructure condition ratings by LASSO

Table 37. LASSO selection of 22 explanatory variables for substructure condition ratings

λ	# of Items	Variable
2.558E-01	1	Year Built
2.124E-01	1	Type of Wearing Surface
1.935E-01	1	Design Load
1.464E-01	1	Bridge Roadway Width (Curb to Curb)
9.193E-02	1	Functional Classification of Inventory Route
8.376E-02	1	Average Daily Truck Traffic
5.774E-02	1	Average Temperature
4.367E-02	2	Route Signing Prefix Type of Membrane
3.626E-02	1	Skew
3.304E-02	1	Type of Service on Bridge
3.010E-02	1	Type of Service under Bridge
2.743E-02	3	Highway Agency Network Maintenance Responsibility Kind of Material and/or Design
2.499E-02	1	Precipitation
2.277E-02	1	Lanes under the Structure
2.075E-02	2	Number of Spans in Main Unit; Structure Length
1.570E-02	1	Deck Structure Type
1.430E-02	1	Type of Design and/or Construction
1.187E-02	1	Deck Protection

The LASSO regression was tested five times for the substructure element condition ratings using cross validation technique and minimizes the error of regression when 22 variables are used. The sequential order of these variables shows how sensitively substructure condition ratings is predicted.

Year Built and Type of Wearing Surface are ranked first and second, which is the same with deck condition ratings. Bridge Roadway Width (Curb to Curb) is highly ranked, similar to the superstructure element. Functional Classification of Inventory Route is considered within top five explanatory variables as same as the deck and superstructure elements.

EXPLANATORY VARIABLE SELECTION SUMMARY

In general, the LASSO requires almost all variables to construct optimized regression models. This is not realistic for the case of bridge management and potentially misleading about the methods accuracy. However, it is meaningful to determine the sequential order of significance in inspection data pool. The deterioration models, which are specified in the next chapter, clearly show their own characteristic and help decision making process for efficient bridge monitoring.

Top five explanatory variables from the LASSO procedure are used to develop deterioration models. *Year Built* and *Functional Classification of Inventory Route* are commonly selected for all elements. *Type of Wearing Surface* is selected both for deck and substructure elements. *Bridge Roadway Width (Curb to Curb)* is selected both for superstructure and substructure elements. The LASSO regression coefficients for these top ranked variables are generally increased with increasing λ. The decrease in this parameter indicates the regression model starts to include highly correlated variables.

CHAPTER 5 DETERMINISTIC DETERIORATION MODELS

INTRODUCTION

Deterioration is defined as a process of decline in condition ratings from normal operating conditions, due to the physical and chemical changes of bridge components (Abed-Al-Rahim and Johnston 1995). These changes are often interpreted as damage on the structural system, and require maintenance action, but it is difficult to quantify the accurate amount of changes and its effect on the structural system. The deterioration models compensate these challenges so that the statistical approach is adopted to investigate the general trend of structural performance in individual elements.

The estimation of deterioration rates for bridge elements is normally classified into two categories: 1) deterministic and 2) stochastic approaches. For deterministic models, the measure of bridge condition is expressed with deterministic values without probabilistic contribution, whereas stochastic approach reflects uncertainties. Although the stochastic approach enables it to design the more realistic deterioration models, the deterministic approach is still meaningful to investigate the bridge inventory classification, to design probabilistic distribution according to explanatory variables. Furthermore, WYDOT may decide after using both types that a deterministic model fits their needs.

In this chapter, deterministic deterioration models are developed for the first four explanatory variables identified in the previous chapter. For individual explanatory variables, the distribution according to the specific indices is investigated. The deterioration curves for the indices containing sufficient number of inspection data to develop deterioration model using a power function.

DECK

The deck condition ratings for 2014 bridges are depicted versus Year Built (Age) and of which the mean is plotted (Figure 9). The 2014 inspection for deck are mostly distributed between the level 3 (Serious Condition) and 7 (Good Condition), and rare population over 8 (Very Good Condition). Immediate maintenance and repair action is required for the bridges belong to 1 (“Imminent” Failure Condition) and 2 (Critical Condition) (Weseman 1995). In Figure 9, the mean of Year Built for each condition rating (solid gray curve) shows almost linear relationship for which the trend curve is generated (dashed line). The frequency corresponding to each condition ratings is used as a weighing factor for regression model.

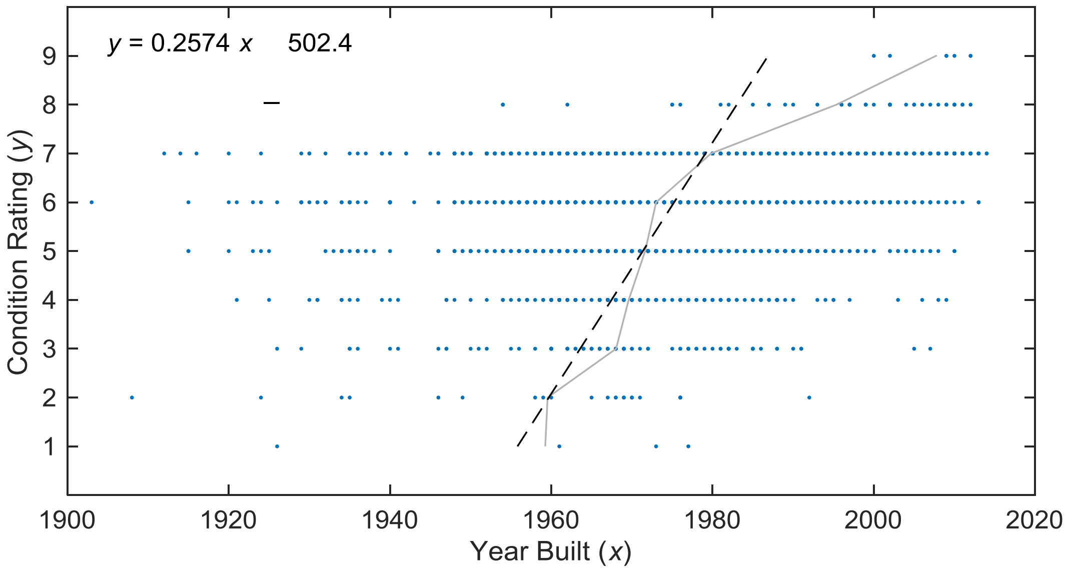


Figure 9. Graph. Condition rating versus year built for bridge deck at year 2014

The mean of age for each condition rating is calculated and used to develop a general deterioration model for all deck elements (Figure 10). The mean of age plotted with circle for each condition rating is connected with solid line. The power function is used to develop a deterioration model. The number of bridges associated with a condition rating is used as a weighting factor and the fitting curve is forced to pass through a condition rating of nine at zero age. In the following sections, deterioration models for smaller subsets of bridges, based on the above LASSO analysis and will be created to predict the deck deterioration more accurately.

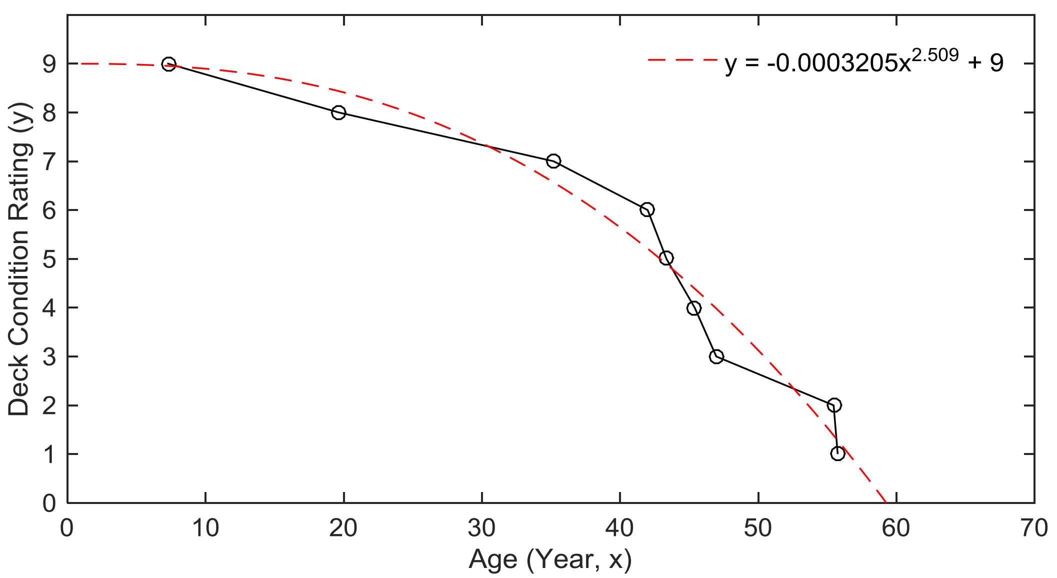


Figure 10. Graph. General deterioration model for deck elements

Type of Wearing Surface

Type of Wearing Surface (WS) is discretized into ten indices. The distribution of individual indices is illustrated with bar graph and the percentage portion is calculated. Figure 11 shows that nearly 92 percent of Wyoming bridges are bare decked (WS0, 41 percent), latex concrete or similar additive (WS3, 27 percent), and bituminous (WS6, 24 percent). The bar graphs for each state indicate the number of bridges corresponding to the deck condition ratings, respectively.

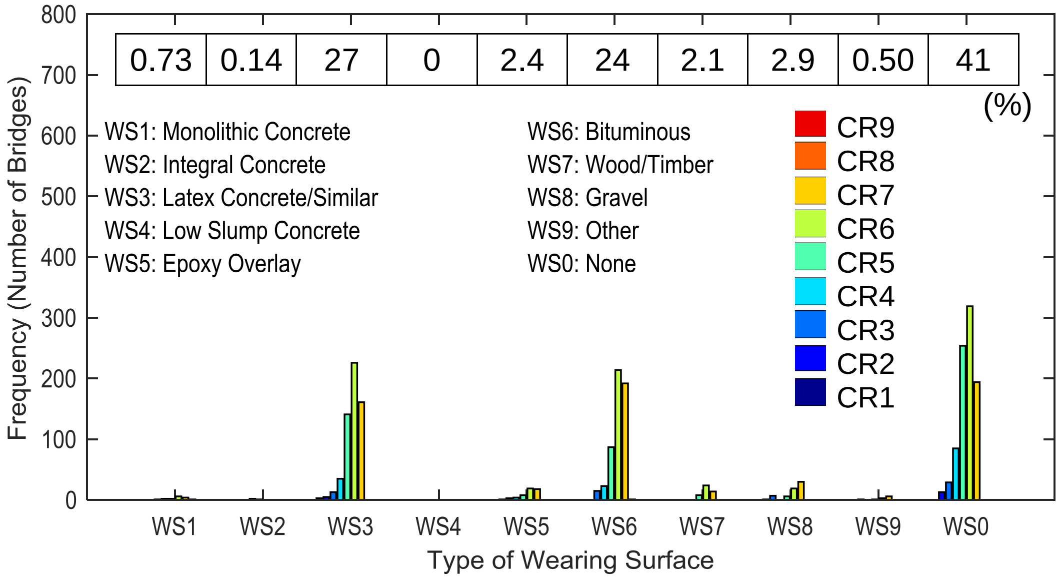


Figure 11. Chart. Distribution for Type of Wearing Surface

For eight types of wearing surface, the deterioration model is developed in Figure 12. WS2 (Integral Concrete) and WS4 (Low Slump Concrete) are not included due to the insufficient number or zero proportion in Wyoming. The mean of age corresponding to the condition ratings are plotted with the (○) symbol and connected with a gray solid line. The deterioration model is developed for each indices using a power function. The curve is forced to pass through the condition rate of nine for zero age. Linear curves are developed for WS1, WS5, WS7, and WS9, which are uncommon types and low portion (less than 3 percent) of total bridges. All the bridges covered with WS3 are typically older and there were no bridges that obtained condition ratings over eight. The mean of ages are mostly between 40 and 50 years and the deterioration curve drops fast when it passes this range.

Deterioration of WS3 bridges are clearly independent of age. From the data, it seems that Latex Concrete wearing surfaces are no longer used in Wyoming, but were popular at one time. Because of the grouping of latex modified wearing surfaces within a ten-year range, the deterioration model is an exceptionally poor fit. Amongst major wearing surface types (WS3, WS6, and WS0), the WS6 covered bridges deteriorate slowly and the WS0 shows moderate level. Other wearing surface types (WS1, WS2, WS4, WS5, WS7, WS8 and WS9) have very few bridges within the subset making their accuracy dubious and the fits typically poor.

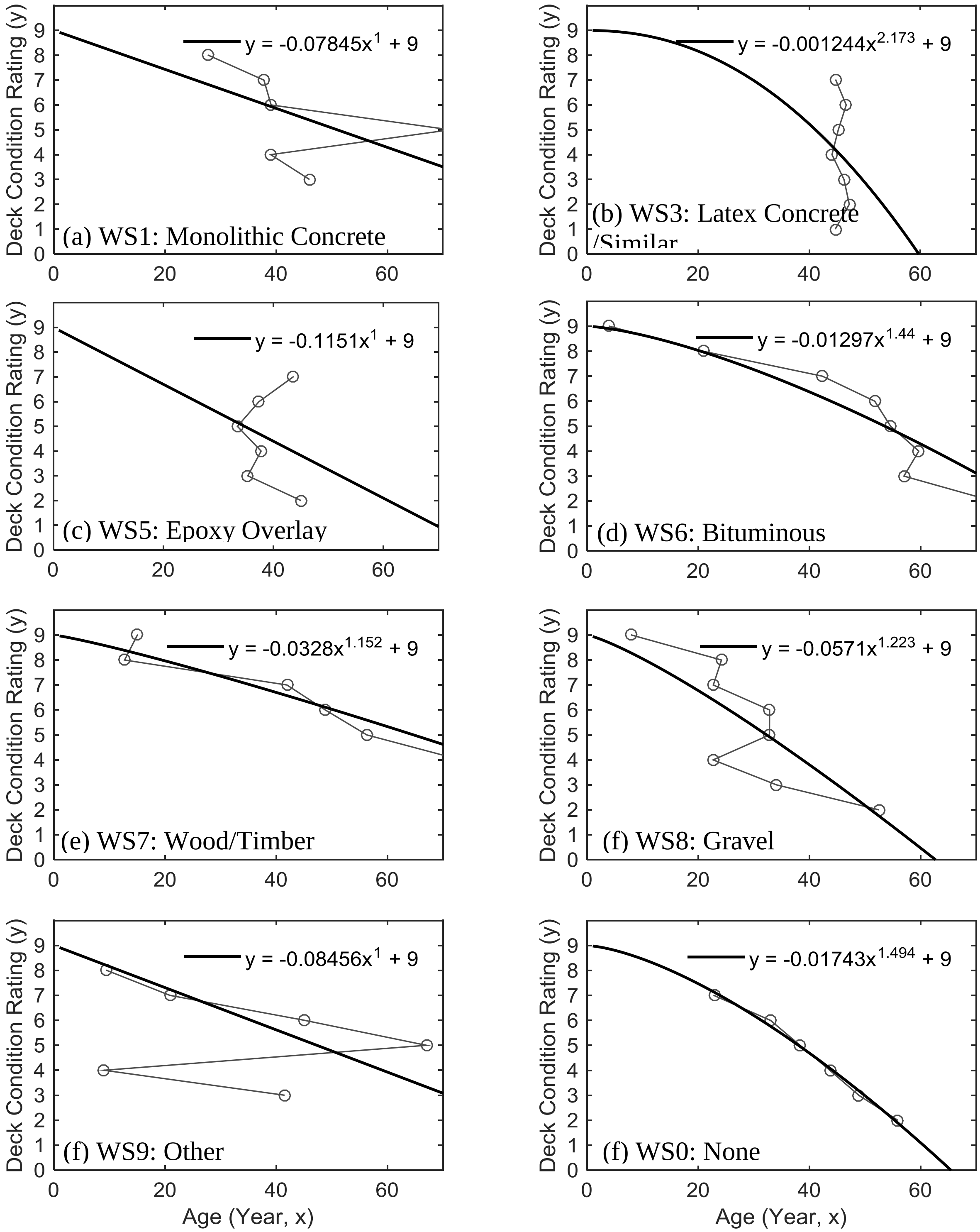


Figure 12. Graph. Deterioration models for Type of Wearing Surface

Structure Length

The LASSO solution path identified the Structure Length (SL) as more significant compared to the Length of Maximum Span, concluding that the condition rating of deck elements is dependent more on the entire bridge, not individual spans. Figure 13 illustrates the distribution of bridges, which were split every 50 m (164 ft) long up to 200 m (656 ft) (SL1 – SL4) and the rest (SL5). Almost 95 percent of bridges are shorter than 100 m (328 ft) long with more bridges in SL1 than SL2.

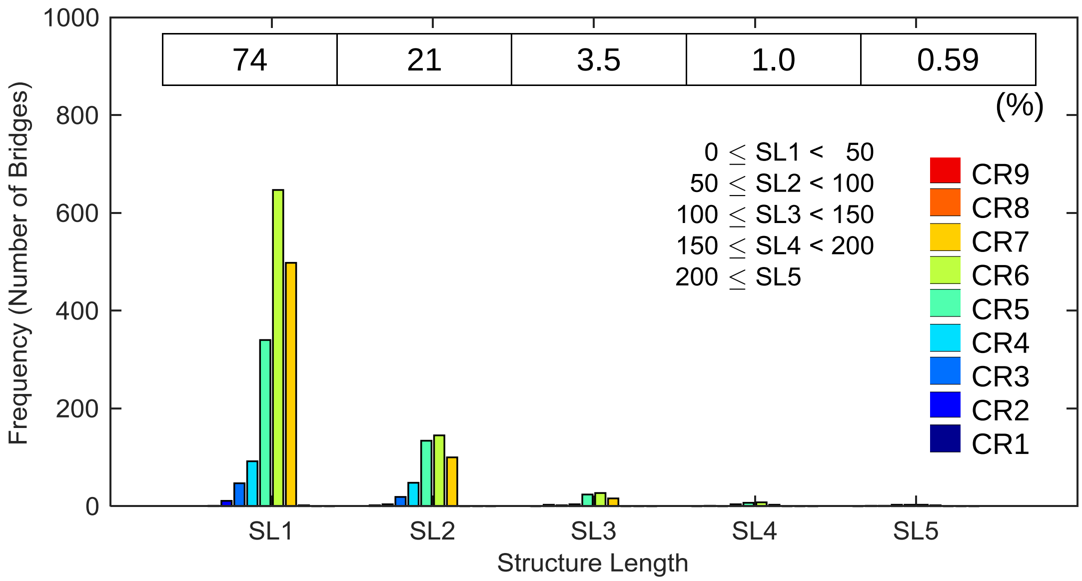


Figure 13. Chart. Distribution for Structure Length

The deterioration models for SL1 to SL4 are developed for deck condition ratings and illustrated in Figure 14, showing the faster deterioration using power function for the deck element of longer bridges (SL4) in general. The deterioration models for SL1 and SL2 are similar in shape, but SL3 and SL4 produce very different deterioration curves. If condition ratings below 4 were to be omitted, deterioration models would show longer bridges deteriorate much more rapidly than shorter bridges.

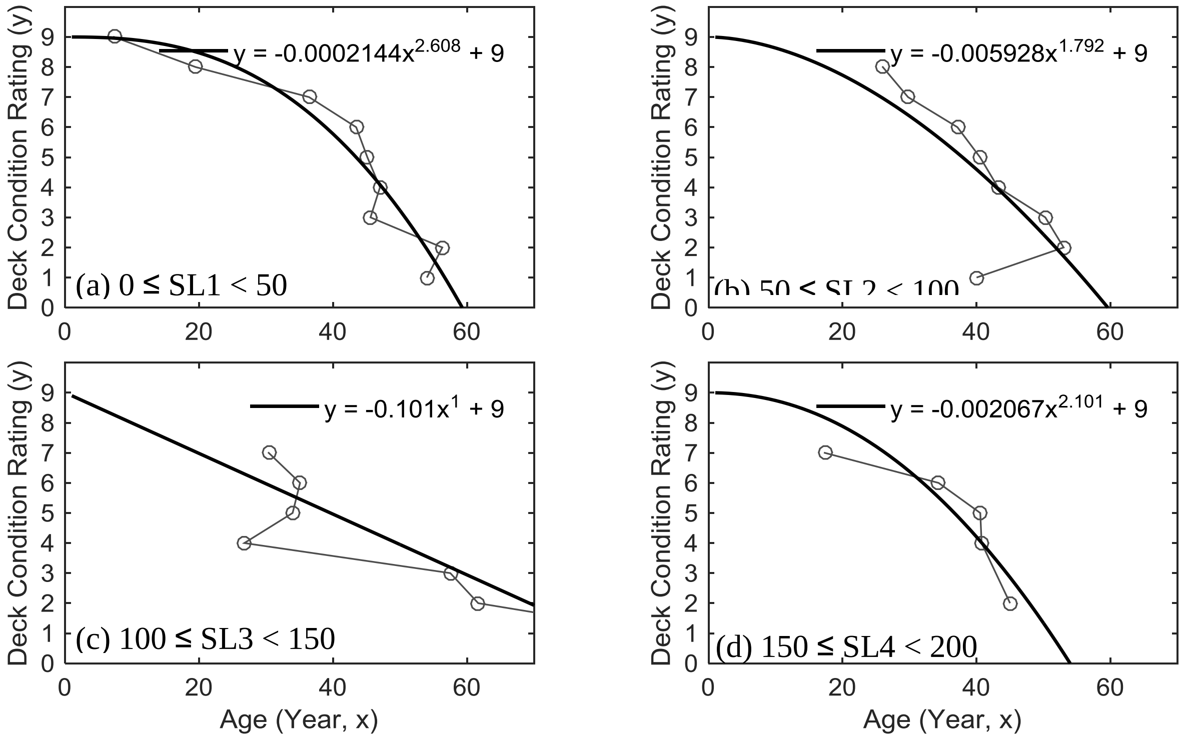


Figure 14. Graph. Deterioration models for Structure Length

Functional Classification Of Inventory Route

The distribution of the variable Functional Classification of Inventory Route (FC) is plotted in Figure 15. A total of 12 indices exist and 86 percent of the bridges belong to the Rural category. Only four indices contain more than 10 percent of total population, which are FC01 (Principal Arterial – Interstate), FC02 (Principal Arterial – Other), FC07 (Major Collector), and FC09 (Local) under the Rural category. Most bridges are older than 30 years and only FC09 contains mostly recently built bridges.

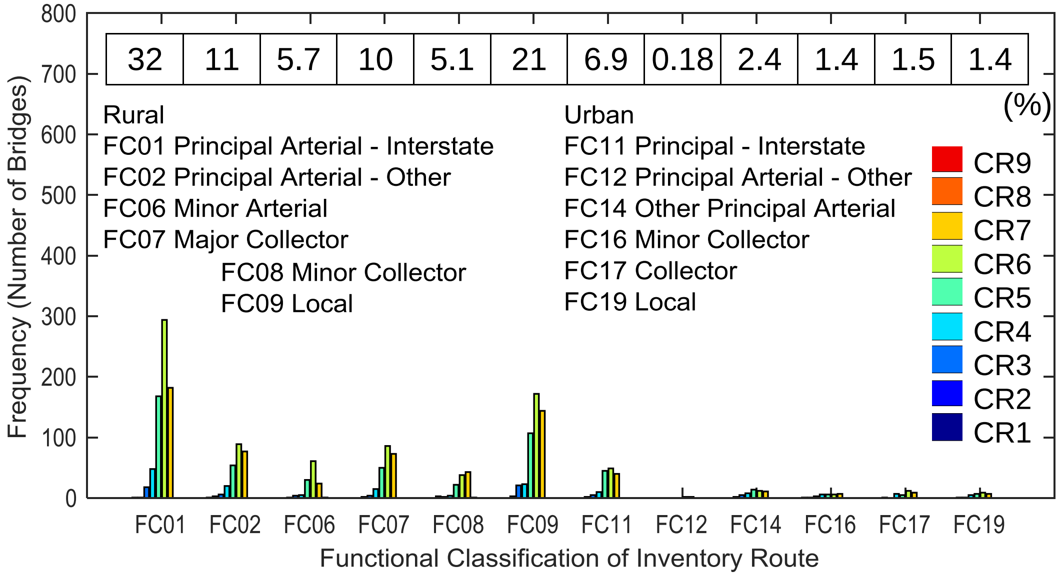


Figure 15. Chart. Distribution for Functional Classification of Inventory Route

Deterministic deterioration models are developed for rural and urban categories in Figure 16 and 17, respectively. Rural local bridges (FC09) have a considerable number of newer bridges based on Figure 16, whereas the other categories tend to have older structures. This could play a significant role in the accuracy of the models for FC.

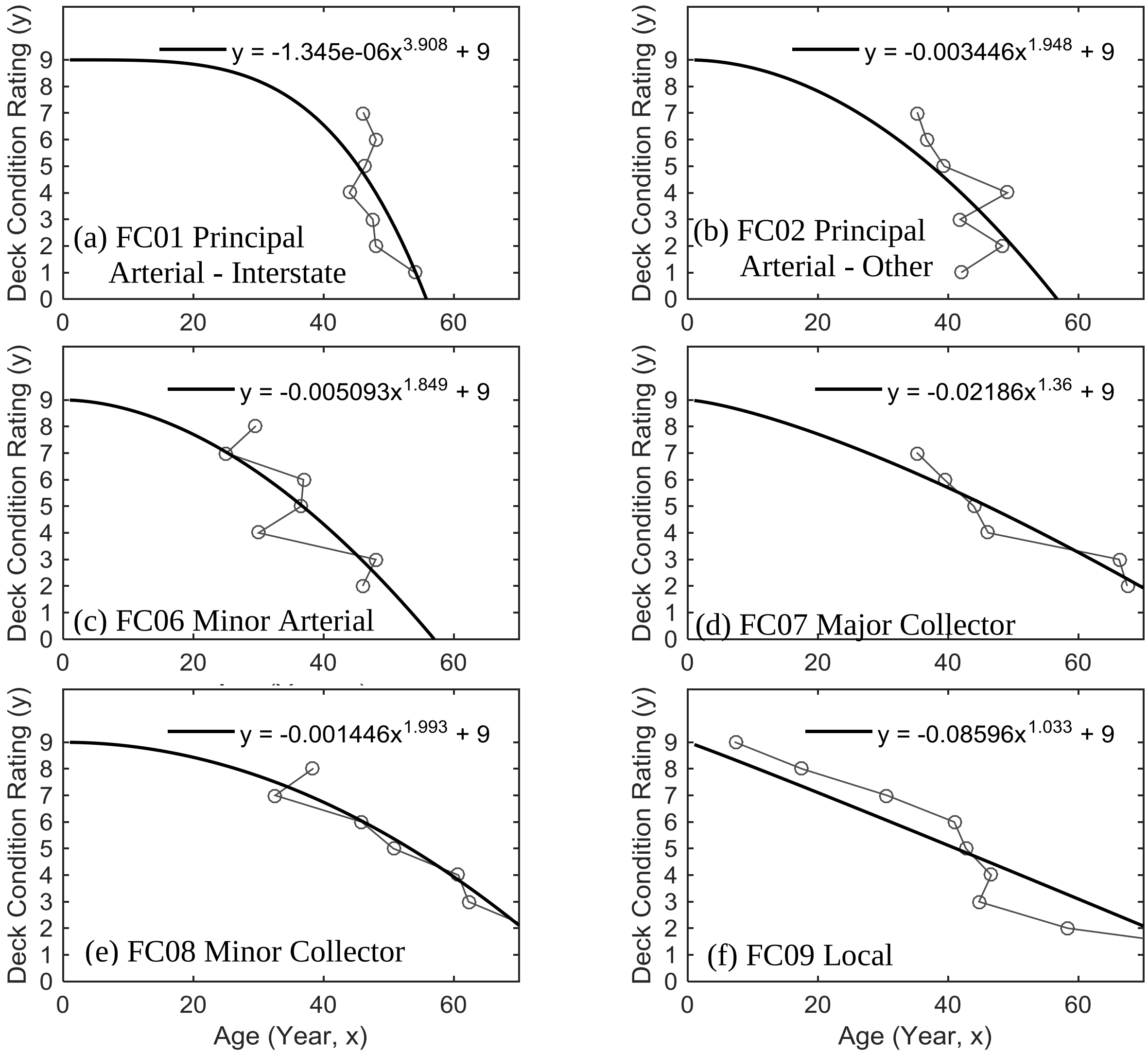


Figure 16. Graph. Deterioration models for Functional Classification of Inventory Route belonging to the rural category

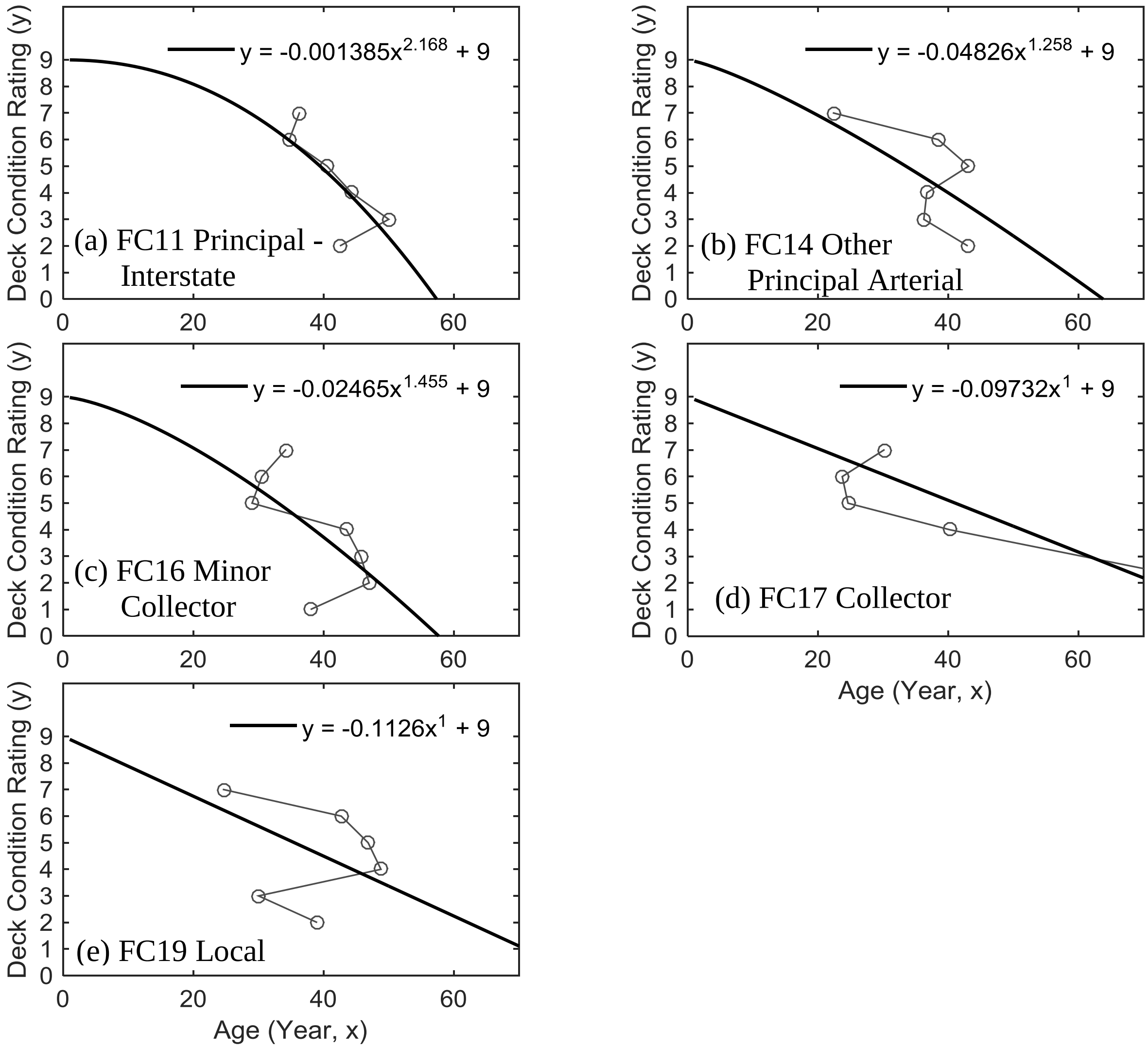


Figure 17. Graph. Deterioration models for Functional Classification of Inventory Route belonging to the urban category

Average Daily Traffic

Average Daily Traffic is selected as an explanatory variable only for deck element condition rating. The distribution of average daily traffic is shown in Figure 18 where the number of traffic is generally less than 10,000 vehicles. More than 97 percent of bridges belong to ADT1 and ADT2 and the deterioration models are developed up to ADT4.

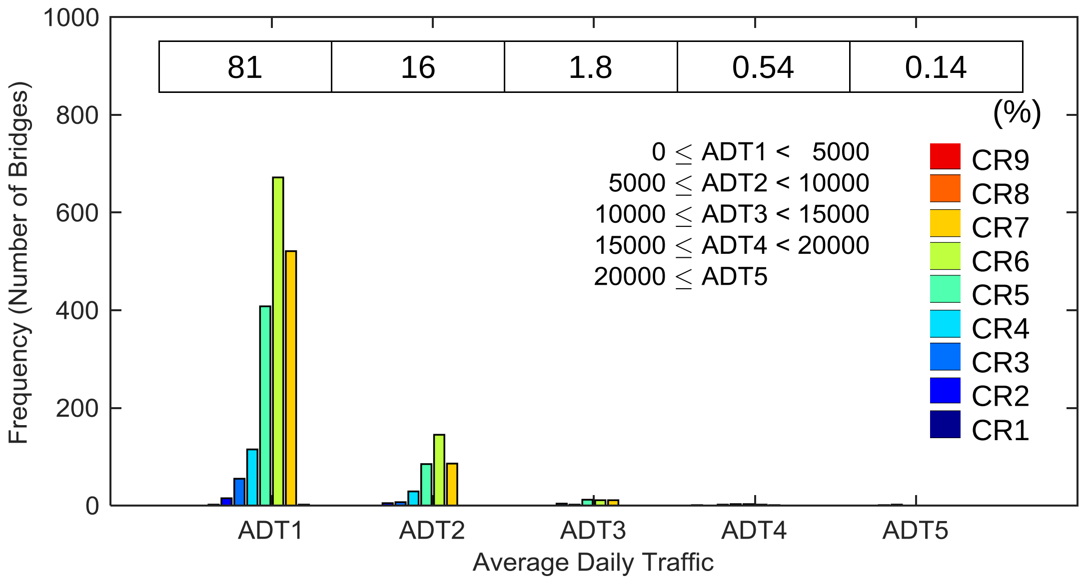


Figure 18. Chart. Distribution for Average Daily Traffic

Deterioration curves for ADT categories are presented in Figure 19. The bridges belonging to the ADT1, ADT2, and ADT3 categories perform similarly at younger ages, but show significantly different behavior at older ages. Most of the bridges that belong to ADT2 and ADT3 are older and do not have condition ratings over seven, which is potentially skewing the data. The data in ADT4 is very limited and shows no significant trend, but a linear model was fitted to the data.

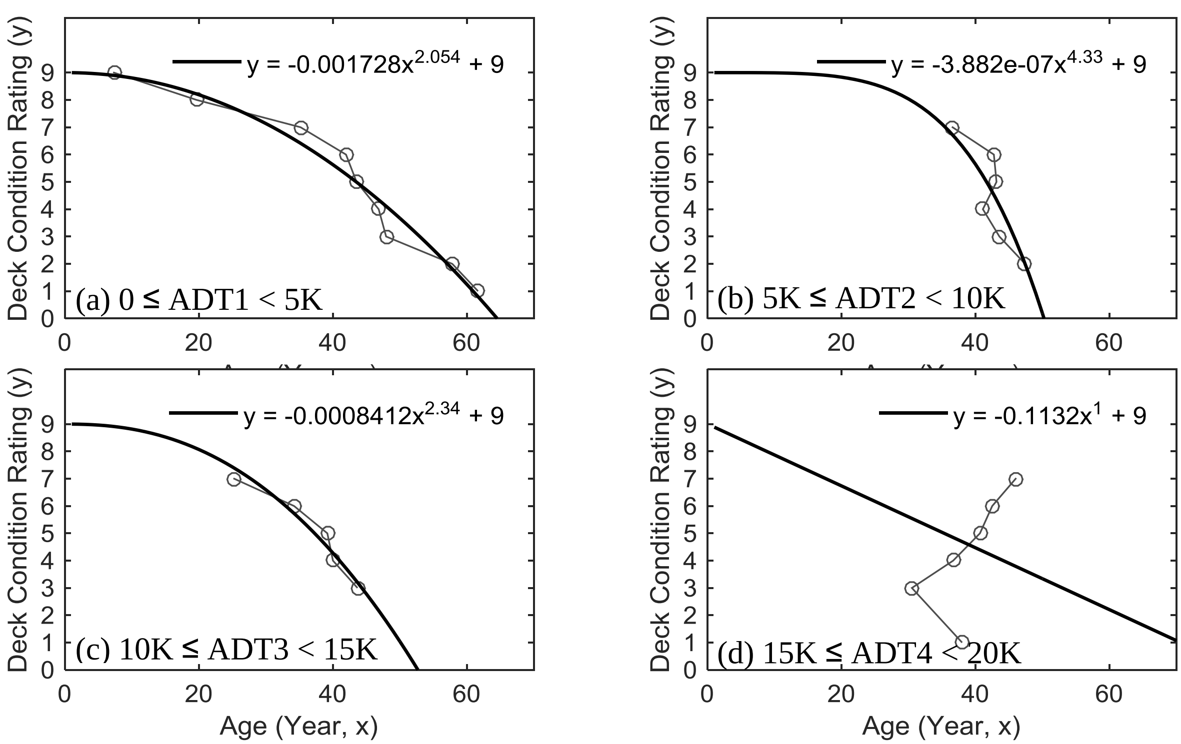


Figure 19. Graph. Deterioration models for Average Daily Traffic

SUPERSTRUCTURE

The superstructure condition ratings for 2014 bridges are depicted versus Year Built (Age) where the mean is plotted (Figure 20). The 2014 inspection results for superstructure condition rating are mostly distributed between the level 4 (Poor Condition) and 8 (Very Good Condition), and few population on 9 (Excellent Condition) and 2 Critical Condition). The mean of Year Built for each condition rating (gray curve) is fairly close to a linear relationship for which the trend curve is created with dashed line.

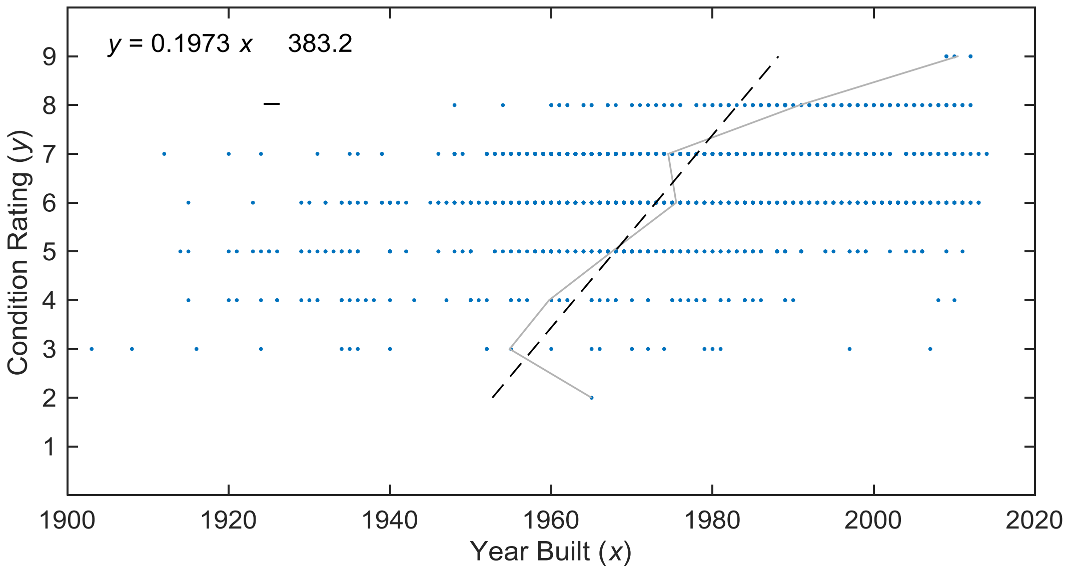


Figure 20. Graph. Condition rating versus year built for bridge superstructure at year 2014

The mean age for each condition rating is calculated and used to develop a deterioration model (Figure 21) for the entire dataset. The mean of age plotted with a circle for each condition rating is connected with a solid line. The cubic order polynomial function is used to develop a deterioration model. The number of bridges associated with condition rating is used as a weighting factor and the fitted curve is forced to pass through a condition rating of nine for zero age. In the following sections, deterioration models for smaller subsets of bridges, based on the above LASSO analysis, will be created to more accurately predict the superstructure deterioration.

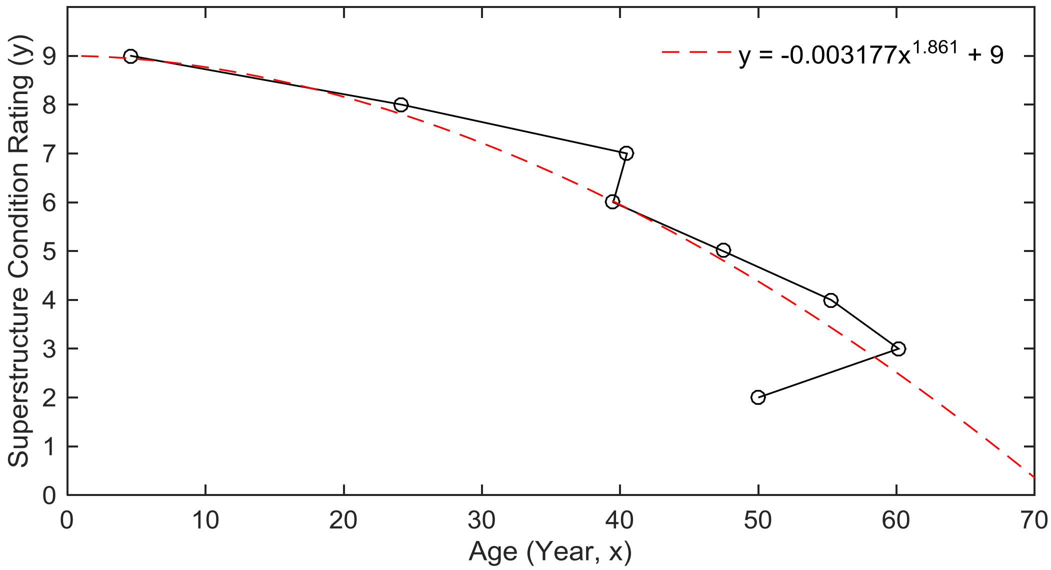


Figure 21. Graph. General deterministic deterioration model for superstructure elements

Deck Structure Type

Deck Structure Type (DST) is the first explanatory variable identified by LASSO analysis for substructure deterioration. The distribution of Deck Structure Type for each condition rating is plotted in Figure 22. Most bridges belong to DST1 (Concrete Cast-in-Place) and the rest are constructed with DST2 (Concrete Precast Panels), DST6 (Corrugated Steel), and DST8 (Wood / Timber).

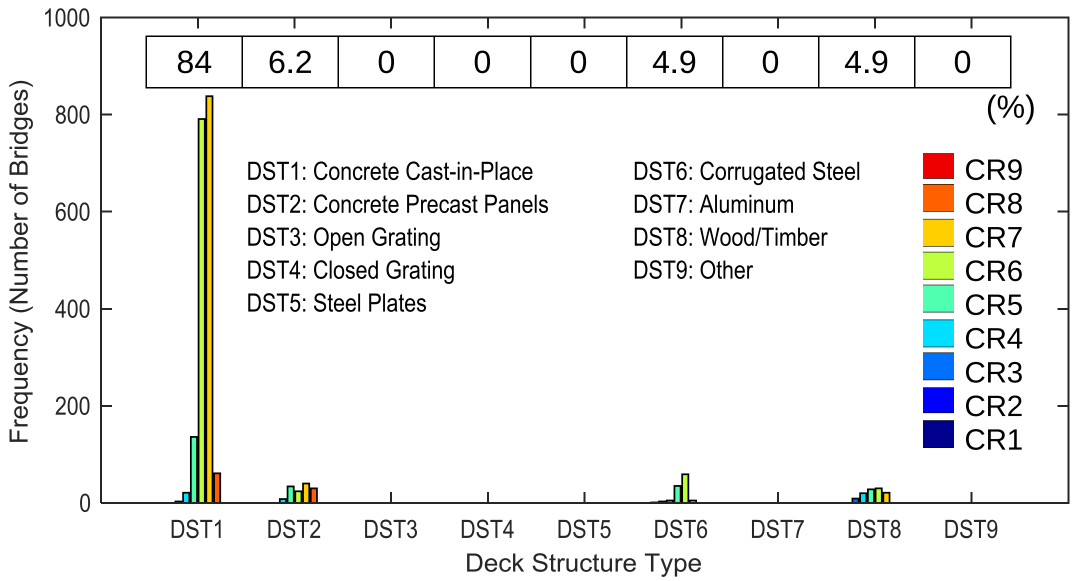


Figure 22. Chart. Distribution for Deck Structure Type

The deterioration models for DST1, DST2, DST6, and DST8 are developed (Figure 23). The curve fitting results for DST1 in a similar deterioration model shape to entire bridge set, but there are no entries with condition ratings over eight or under two. DST2 and DST6 show faster deterioration compared to DST1 and DST8, which perform very well and predict 60 years before reaching a condition rating of 4.

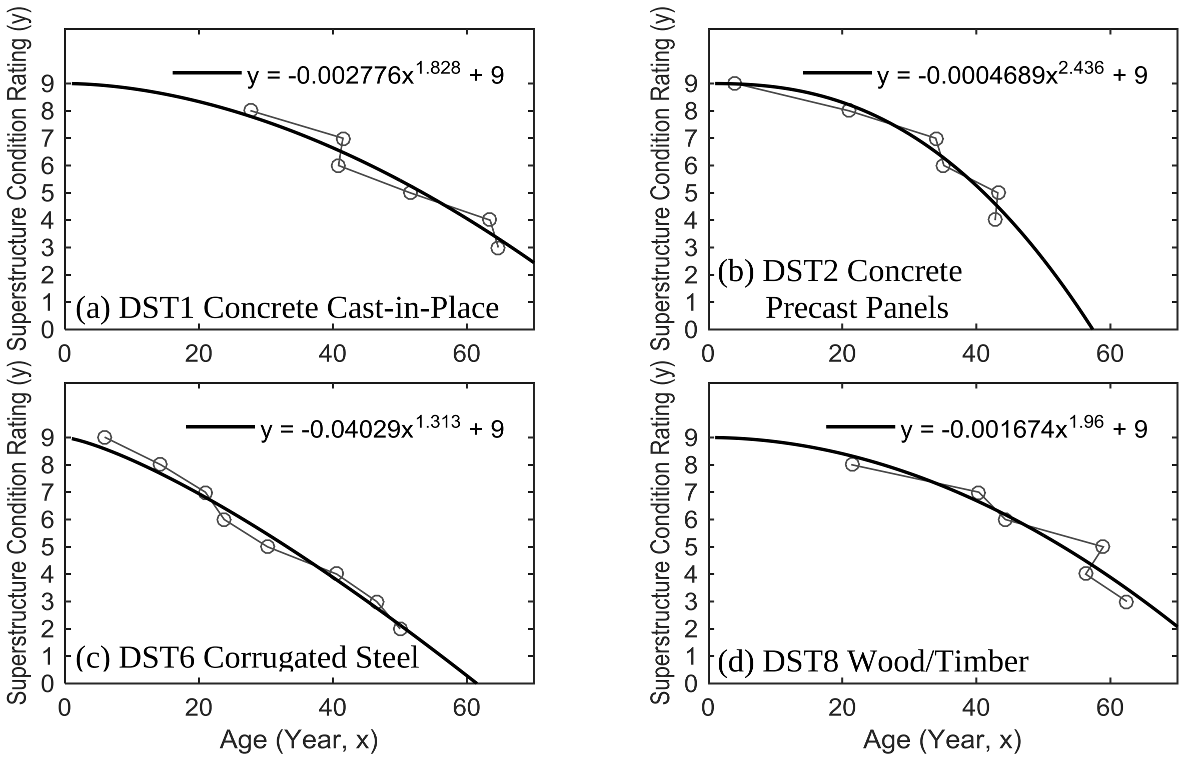


Figure 23. Graph. Deterioration models for Deck Structure Type

Bridge Roadway Width (Curb to Curb)

Bridge Roadway Width (Curb to Curb) is selected as the second explanatory variable by LASSO analysis. The bridge data is split into five groups (BRW1 – BRW5) with an interval of 5 m (16.4 ft) and the distribution for each condition rating is plotted in Figure 24. More than 90 percent of bridges belong to BRW2 (5 – 10 m, 16.4 – 32.8 ft) and BRW3 (10 – 15 m, 32.8 – 49.2 ft).

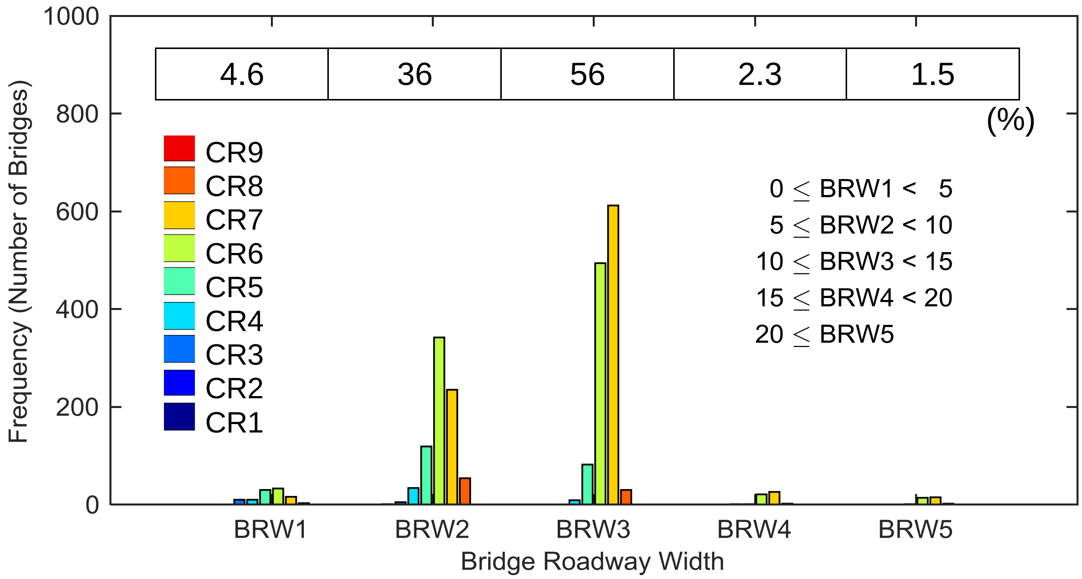


Figure 24. Chart. Distribution for Bridge Roadway Width (Curb to Curb)

The deterioration models are developed for all indices (Figure 25). The curve fitting using power function shows a general trend that the wider the curb-to-curb roadway width, the faster the deterioration. The exception is the very small datasets of BRW4 and BRW5, which do not contain enough data to provide a reliable comparison. Due to the small bridge inventory, the poor fitting is observed for BRW5.

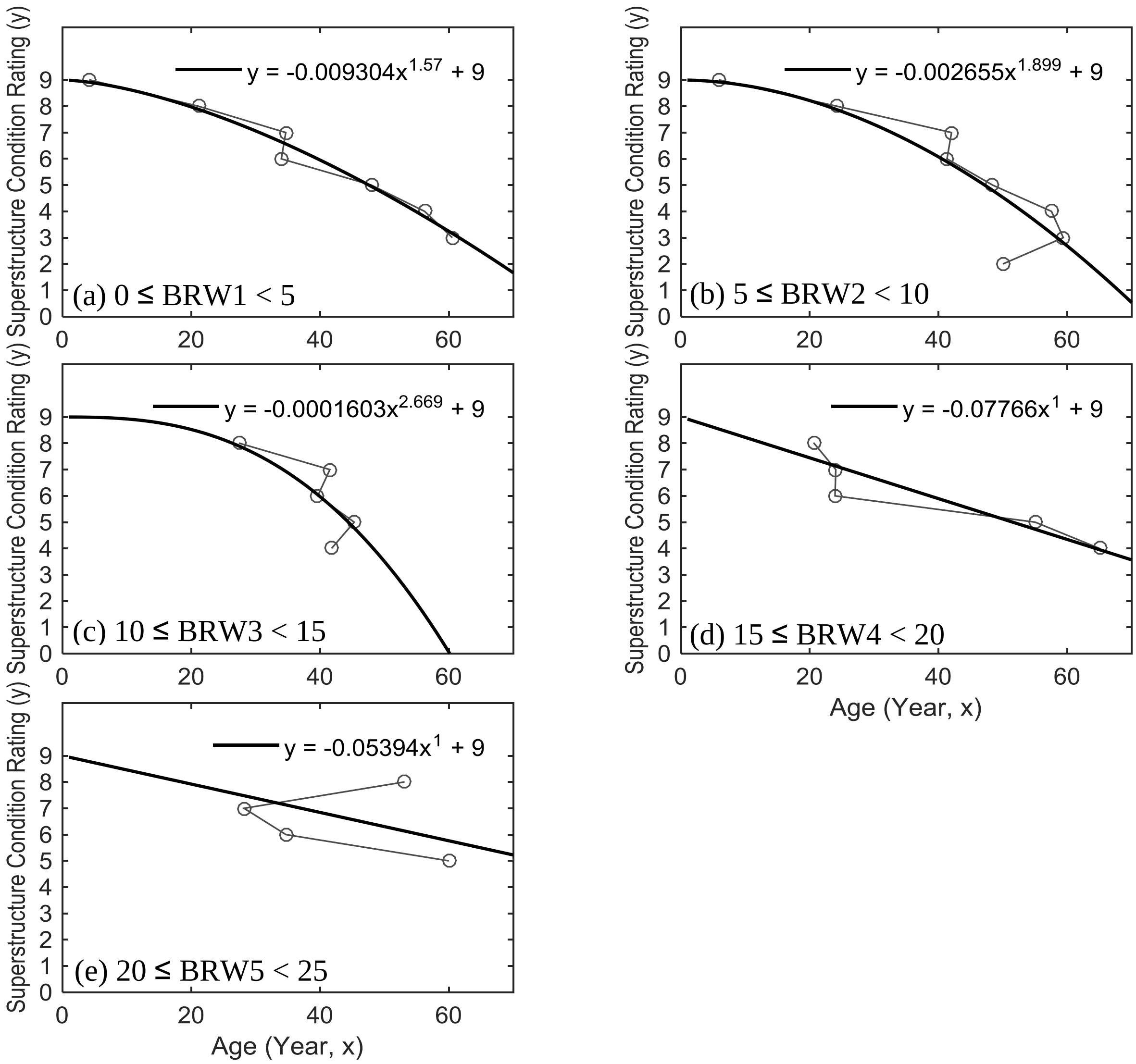


Figure 25. Graph. Deterioration models for Bridge Roadway Width (Curb to Curb)

Functional Classification Of Inventory Route

Functional Classification of Inventory Route (FC) is selected for the development of the superstructure deterioration models. The percentage of indices are the same with the deck element, however the distribution of condition ratings for each index varies as shown in Figure 26.

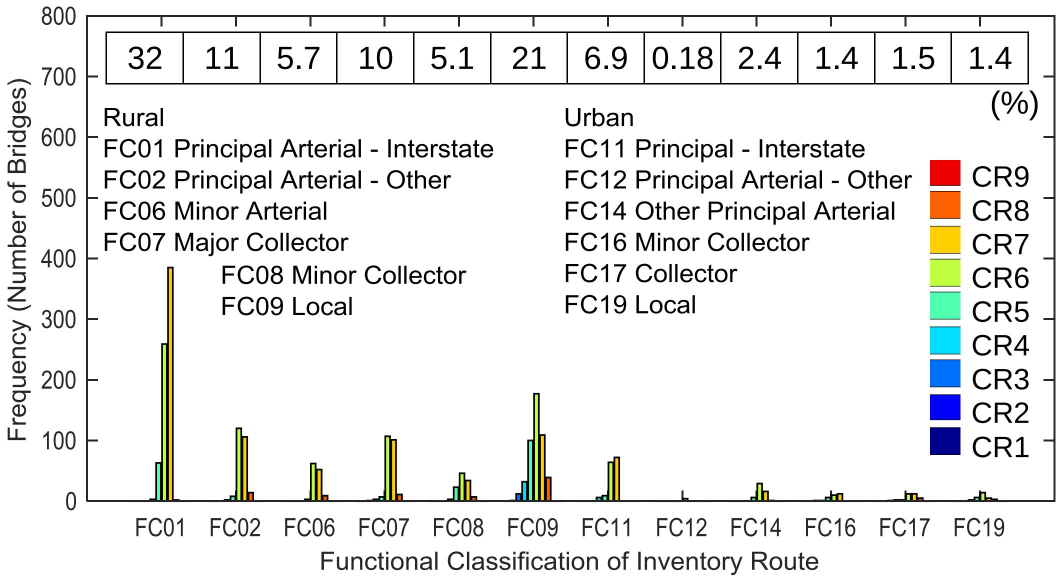


Figure 26. Chart. Distribution for Functional Classification of Inventory Route

The deterioration models are developed for all types of Functional Classification of Inventory Route except FC12 in Figure 27. The condition rating versus the mean age for FC01 (Principal Arterial – Interstate) shows an inverse relationship compared to the general deterioration models. Even though FC01 contains the most bridges, there is significant distortion due to the bridge age ranges present in the data. For FC01, FC14 (Other Principal Arterial), and FC17 (Collector) the deterioration models are presented as linear functions due to the poor makeup of their datasets. The remaining deterioration models have similar shapes, but FC11 (Principal – Interstate) and FC16 (Minor Collector) deteriorate the fastest. FC09 (Local) includes relatively newer bridges and shows faster deterioration compared to the others.

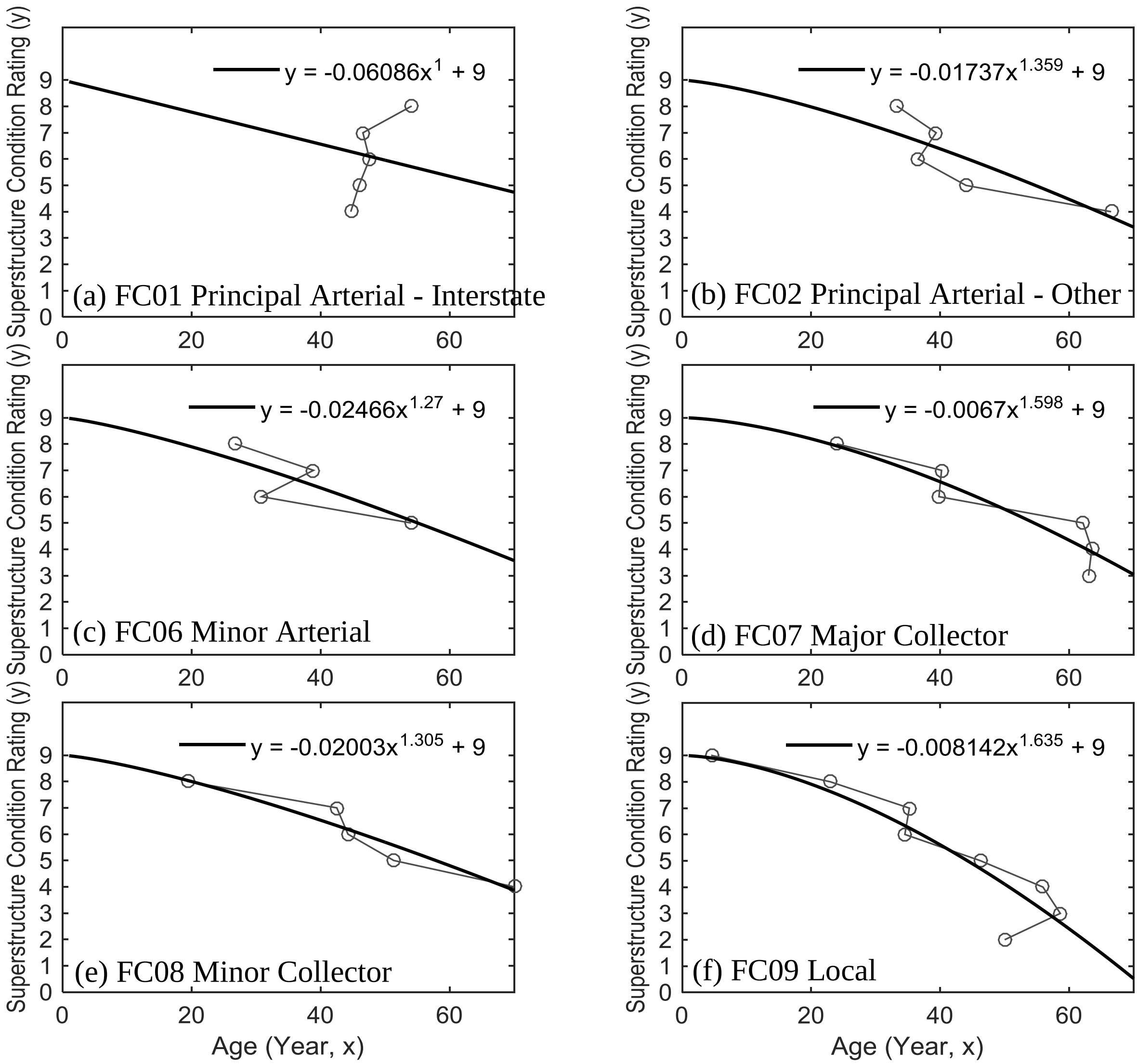


Figure 27. Graph. Deterioration models for Functional Classification of Inventory Route

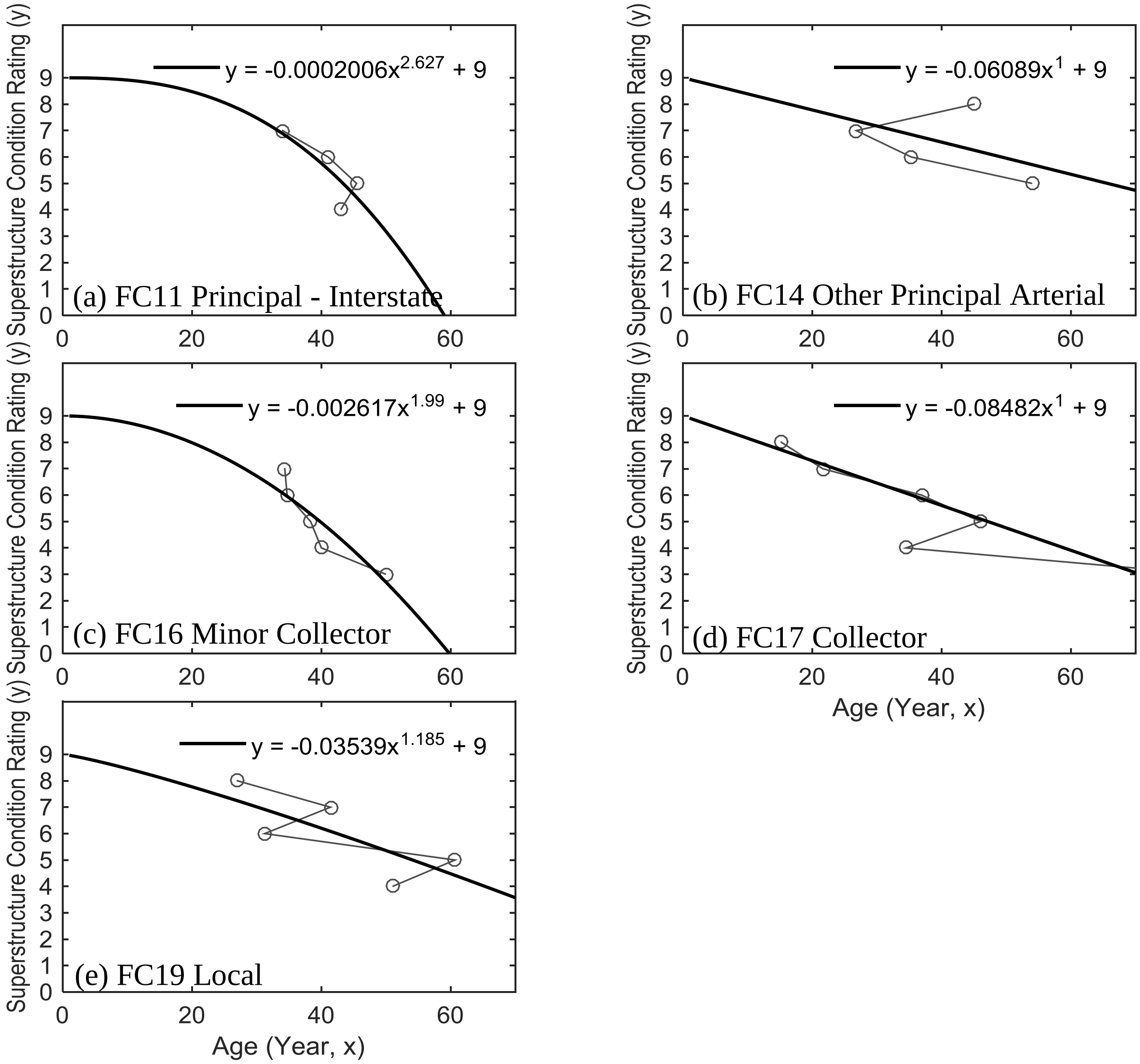


Figure 28. Graph. Deterioration models for Functional Classification of Inventory Route

Length of Maximum Span

The Length of the Maximum Span is listed as an explanatory variable at the same level as Functional Classification of Inventory Route during LASSO analysis. The bridge data is split into LMS1 – LMS5 with an interval length of 20 m (65.6 ft). The distribution of LMS shows that almost 96 percent bridges have their maximum spans less than 40 m (131 ft) (Figure 29).

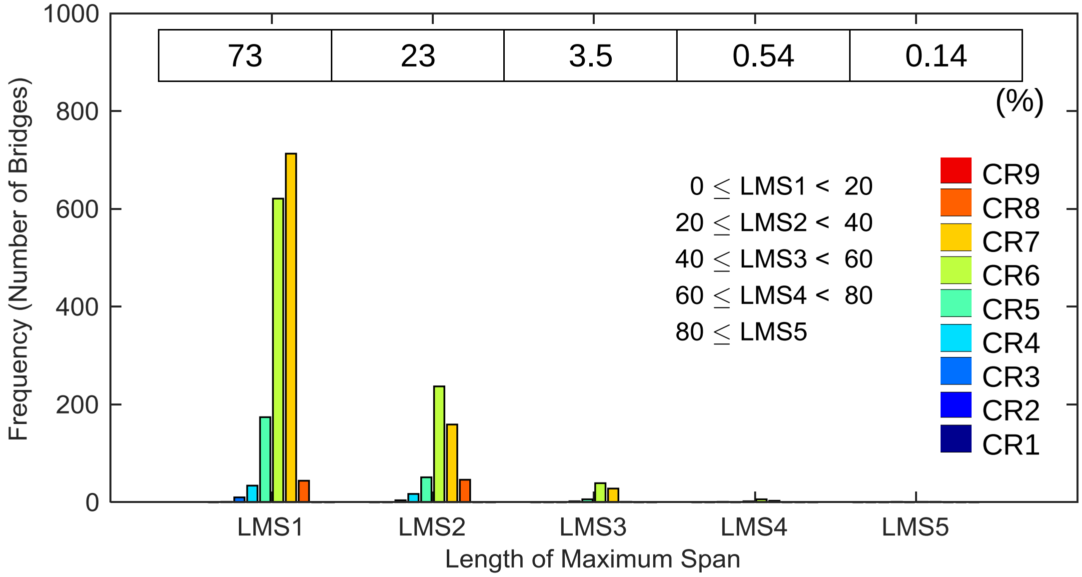


Figure 29. Chart. Distribution for Length of Maximum Span

The deterioration models for LMS1 to LMS4 are developed as shown in Figure 30. At the beginning, the mean condition ratings for new bridges is higher for LMS1 but it deteriorates significantly faster for older bridges (~36 years and older). It seems that spans in LMS2 deteriorate the slowest, whereas LMS1 and LMS3 deteriorate at a similar rate. There is very little data within LMS4 to make strong comparisons; however, it seems that the general trend indicates longer maximum spans deteriorate slower.

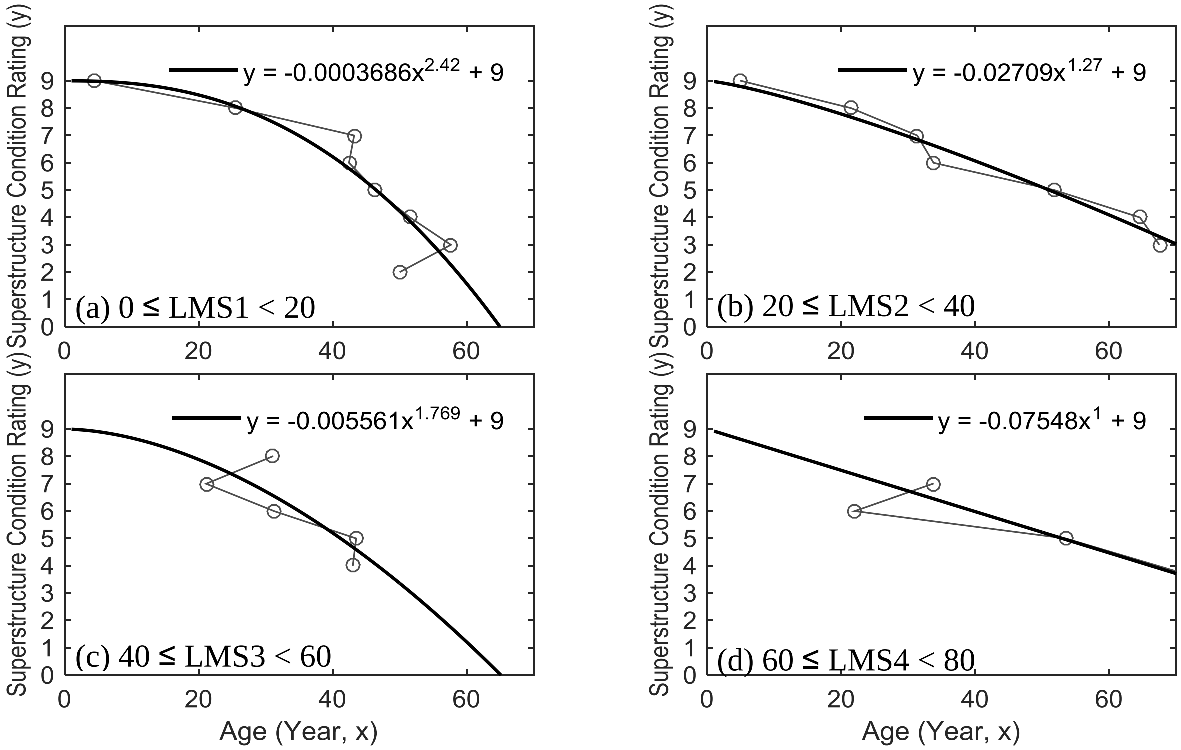


Figure 30. Graph. Deterioration models for Length of Maximum Span

SUBSTRUCTURE

The substructure condition ratings for 2014 bridges are depicted versus Year Built (Age) and of which the mean is plotted (Figure 31). The 2014 inspection results for superstructure are mostly distributed between the level 4 (Poor Condition) and 7 (Good Condition), and few bridge condition ratings are noted over 8 (Very Good Condition) and 2 (Critical Condition). No data exists for 1 (“Imminent” Failure Condition). The mean of Year Built for each condition rating (gray curve) is almost a linear relationship for which the tread curve is created with dashed line.

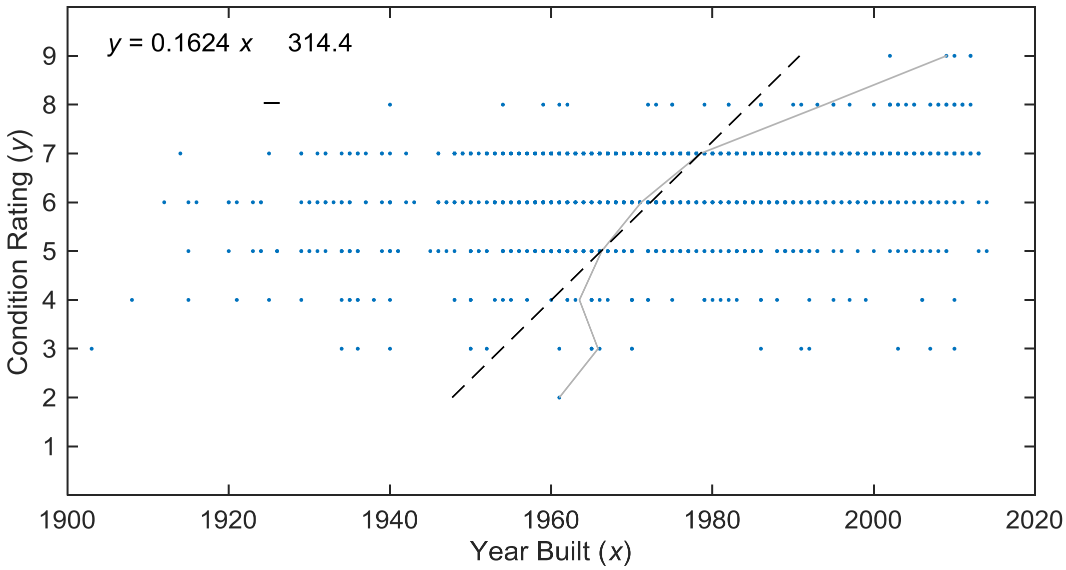


Figure 31. Graph. Condition rating versus year built for bridge substructure at year 2014

The mean age for each condition rating is calculated and used to develop a deterioration model (Figure 32) for the entire dataset. The mean age is plotted with a circle for each condition rating and connected with solid line. A power function is used to develop the deterministic deterioration models. The number of bridges associated with a condition rating is used as a weighting factor and the fitted curve is forced to pass through a condition rating of nine at zero age. In the following sections, deterioration models for smaller subsets of bridges, based on the above LASSO analysis, will be created to predict the substructure deterioration more accurately.

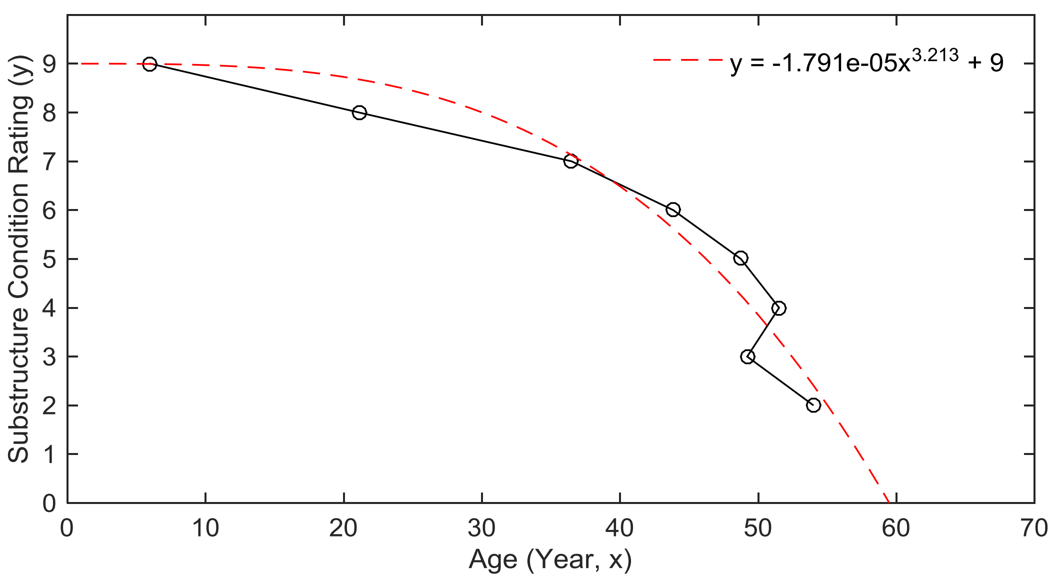


Figure 32. Graph. Deterioration model for substructure elements

Type of Wearing Surface

The Type of Wearing Surface (WS) includes ten indices and their distribution and is illustrated in Figure 33. For all types except WS2 and WS4, the deterioration models are developed (Figure 34). Similar to the deck deterioration models, WS3 (Latex Concrete/Similar) shows faster deterioration for older bridges. Due to the small number of data samples, the deterioration models for WS1 (Monolithic Concrete), WS5 (Epoxy Overlay), and WS9 (Other) show poor fitting results. The relationship between substructure performance and wearing surface is unclear, but the data from LASSO and presented in Figure 34 clearly show significant disparity between categories, especially the three main values WS3, WS6 and WS0.

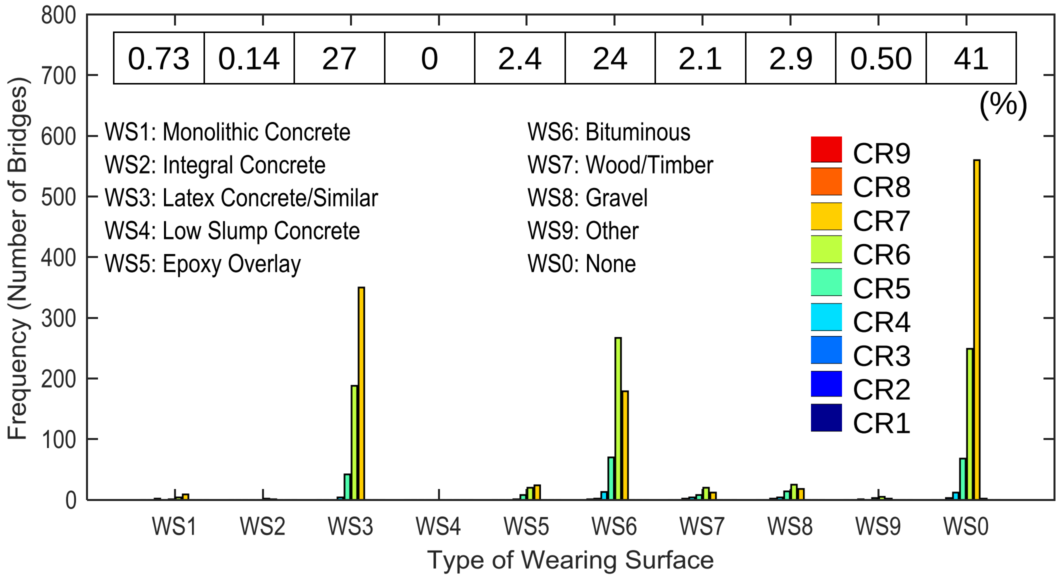


Figure 33. Chart. Distribution for Type of Wearing Surface

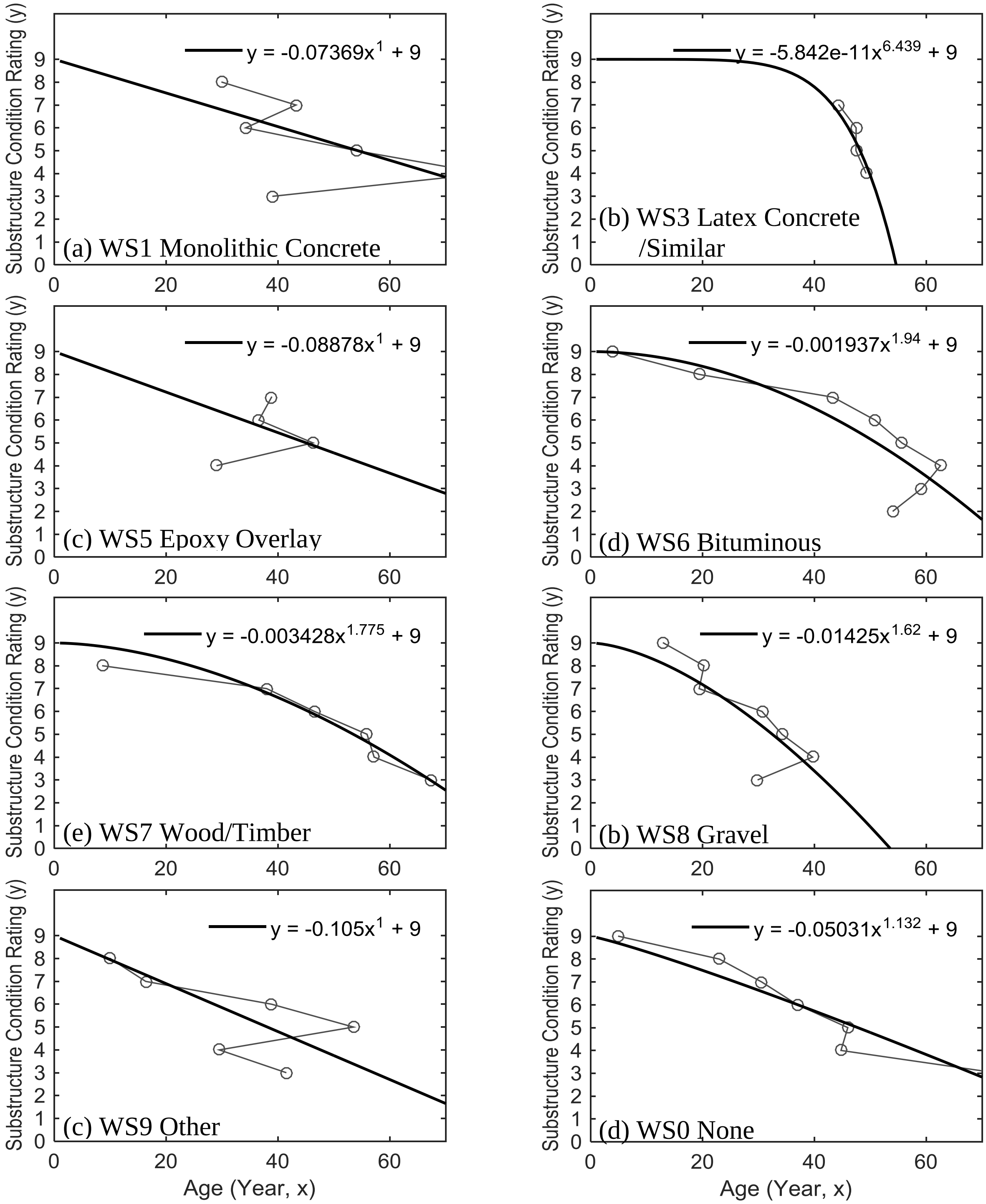


Figure 34. Graph. Deterioration models for Wearing Surface

Design Load

The Design Load is selected as the second explanatory variable for substructure condition ratings, based on the LASSO rankings in the previous chapter. Ten indices exist and three (DL5, DL6, and DL0) contain more than 87 percent of total bridge inventory (Figure 35).

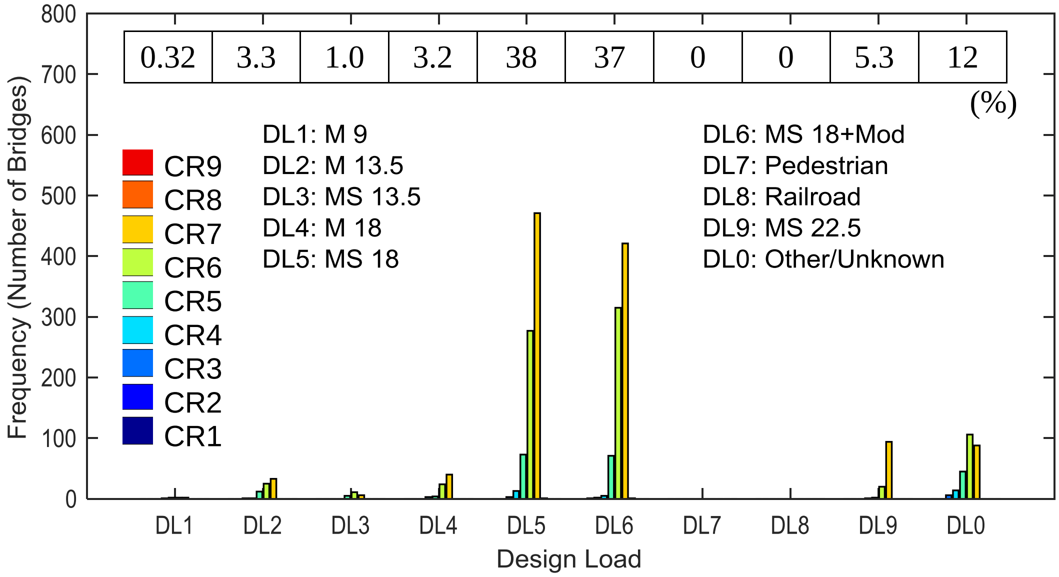


Figure 35. Chart. Distribution for Design Load

The deterioration models are developed for all indices except DL7 (Pedestrian) and DL8 (Railroad), which contain zero bridges (Figure 36). DL9 indicates very quick deterioration even though the average ages of all bridges in this subset are less than 20 years old. DL1, DL2 and DL3 contain relatively few data points so linear models were fit to their data. The mean age curve for DL6 has a gap in average age for bridge CR8 to CR7, possibly displaying deterioration somewhat better than DL1 – DL3, but is modeled with a linear fit as the trend is unclear.

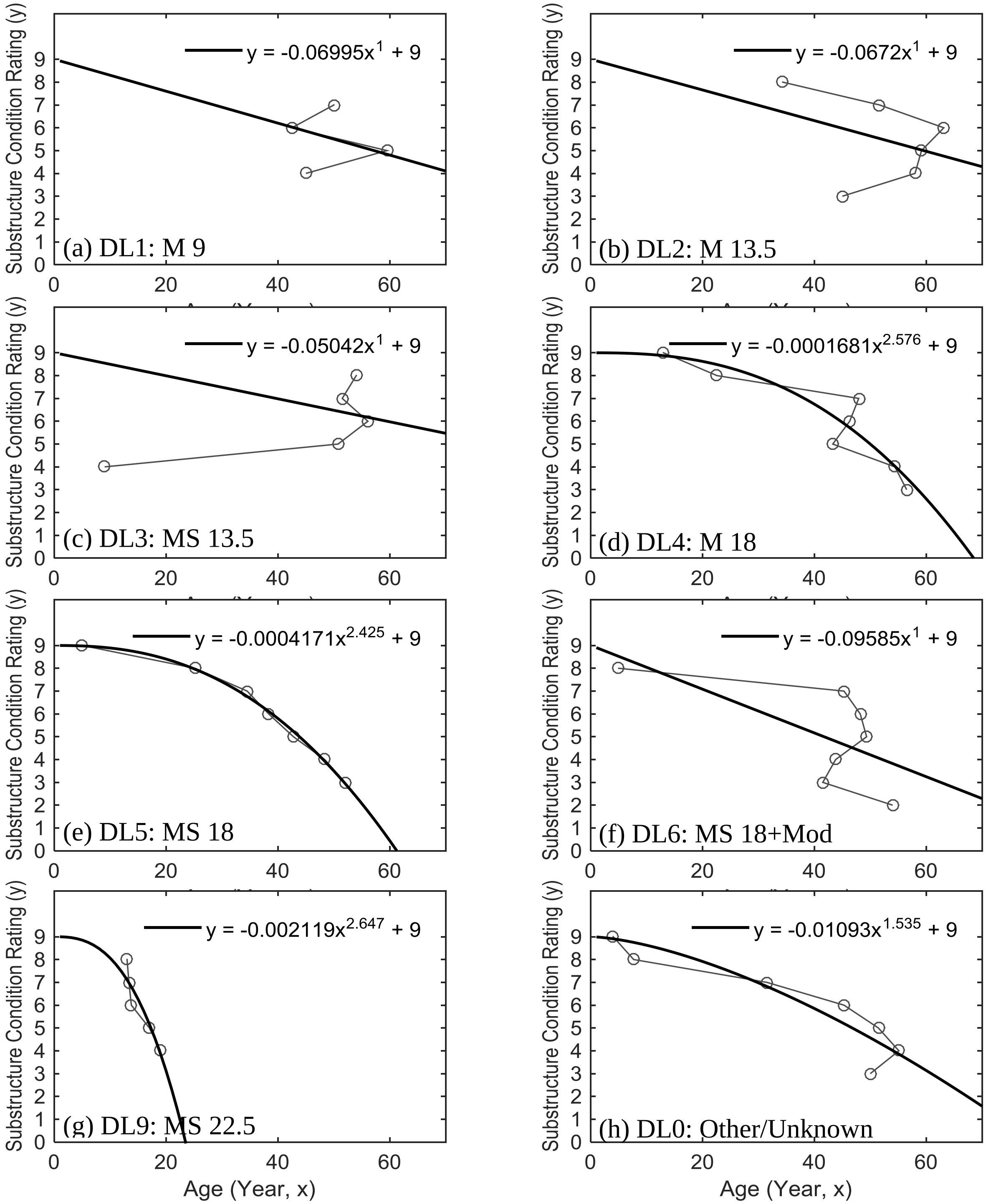


Figure 36. Graph. Deterioration models for Design Load

Bridge Roadway Width (Curb to Curb)

Bridge Roadway Width (Curb to Curb) is selected as the third explanatory variable by LASSO analysis. The bridge data is split into five groups (BRW1 – BRW5) with an interval of 5 m (16.4 ft) and the distribution for each condition rating is plotted in Figure 37. More than 90 percent of bridges belong to BRW2 (5 – 10 m, 16.4 – 32.8 ft) and BRW3 (10 – 15 m, 32.8 – 49.2 ft).

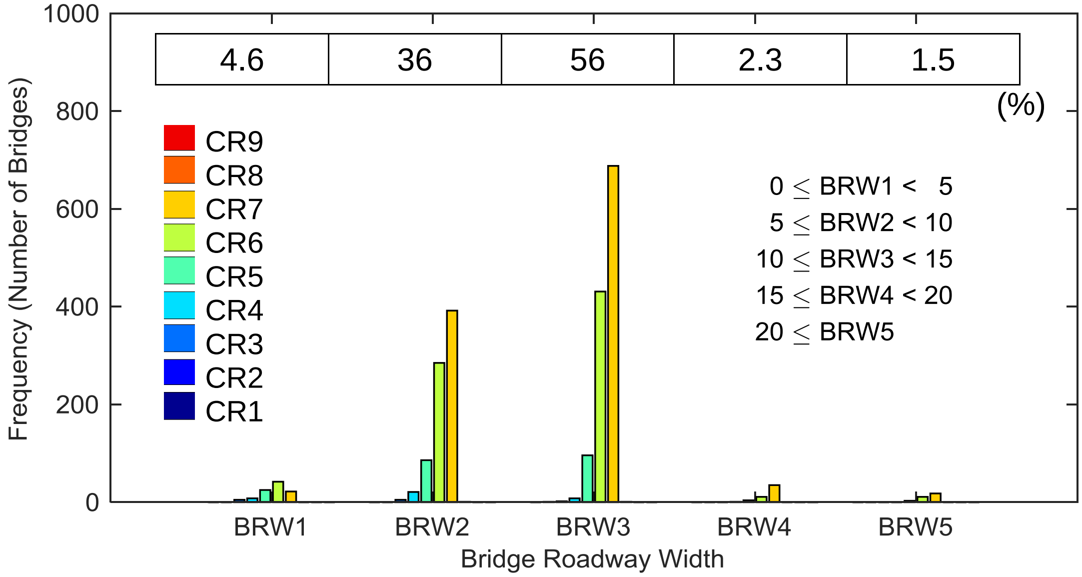


Figure 37. Chart. Distribution for Bridge Roadway Width (Curb to Curb)

The deterioration models are developed for all indices (Figure 38). The curve fitting using power function results in very similar deterioration models for BRW1, BRW2, and BRW3. An almost linear relationship is derived for BRW4 and BRW5 where there are very few data points.

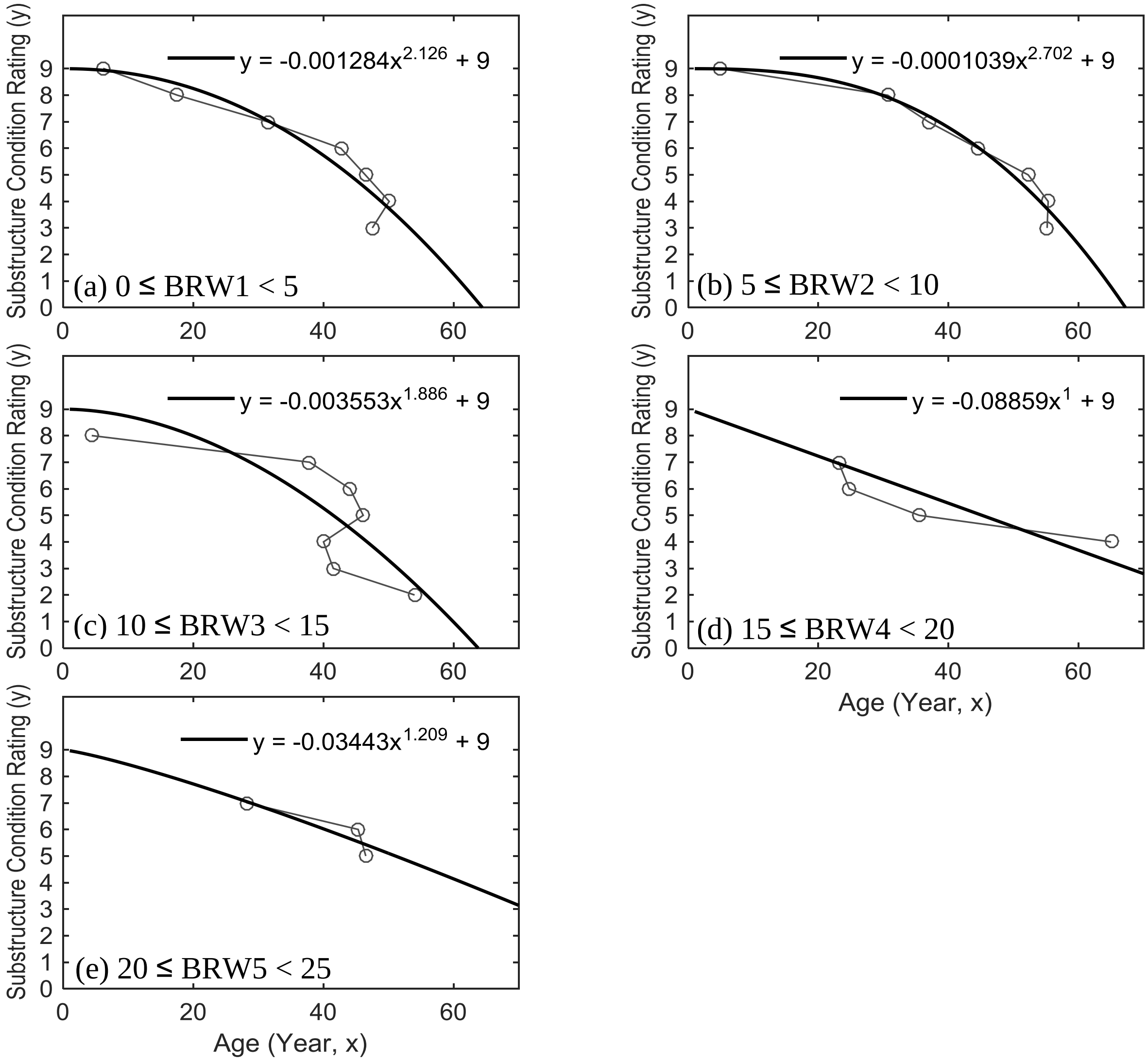


Figure 38. Graph. Deterioration models for Bridge Roadway Width (Curb to Curb)

Functional Classification of Inventory Route

The Functional Classification of Inventory Route (FC) was selected for the development of substructure deterioration models. The percentage for indices are the same with the deck and superstructure element, however the distribution of condition ratings for each index varies as shown in Figure 39.

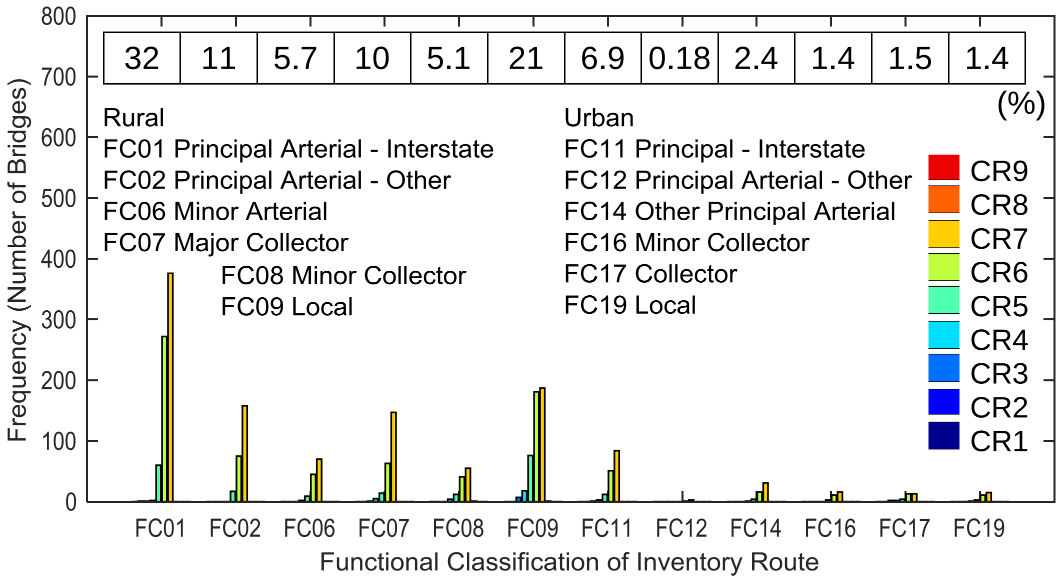


Figure 39. Chart. Distribution for Functional Classification of Inventory Route

The deterioration models are developed for all types of Functional Classification of Inventory Route except FC12 (Principal Arterial – Other) in Figure 40 and 41 for rural and urban categories, respectively. FC01 (Principal Arterial – Interstate) and FC16 (Minor Collector) show slightly faster deterioration, and FC07 (Major Collector), FC09 (Local), and FC14 (Other Principal Arterial) show similar fitting curve in their shapes. FC01 generally includes old bridges so that the mean age for all condition ratings is more than 40 years. Only FC08 and FC09 include bridges with substructure condition rating of nine.

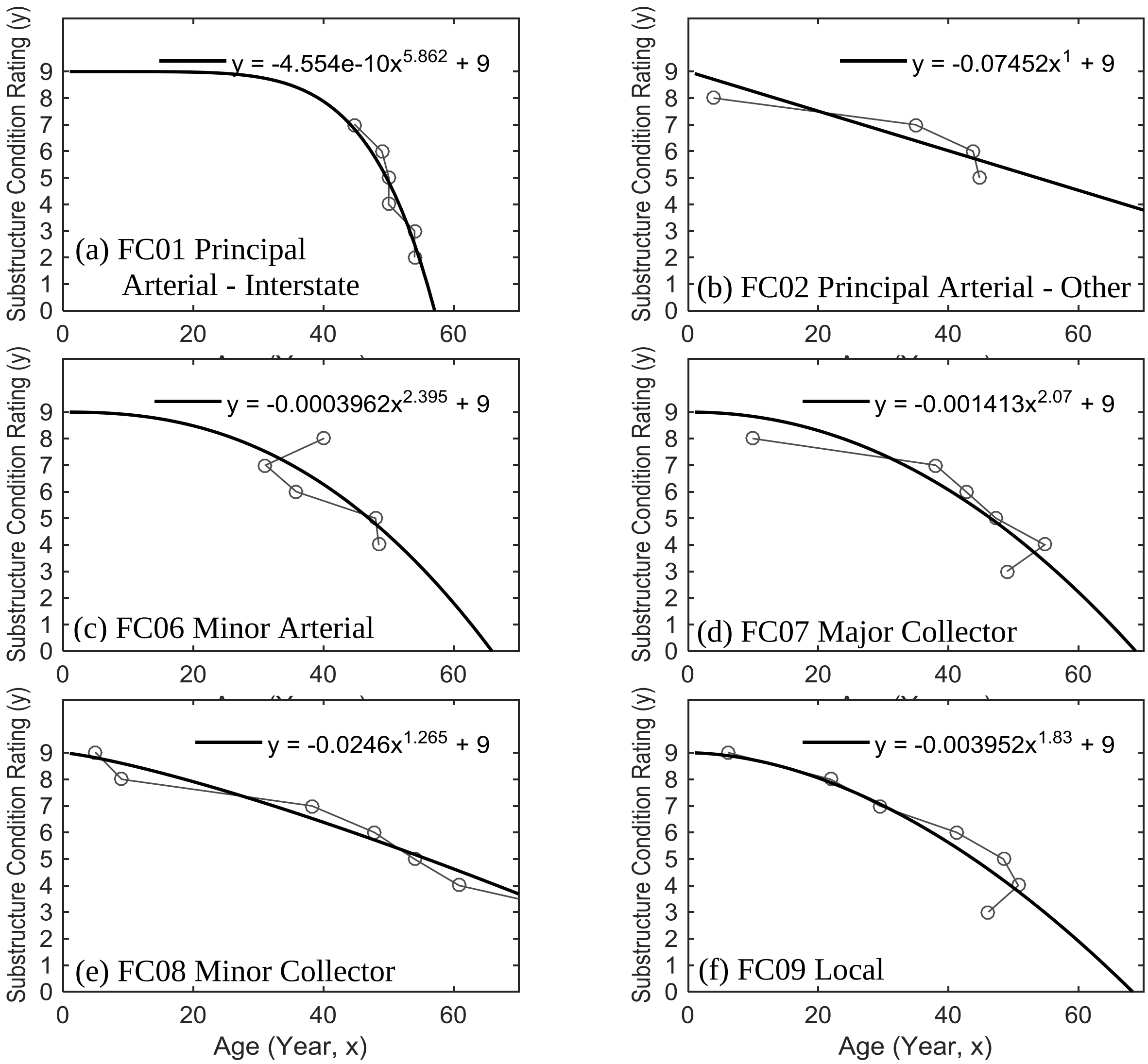


Figure 40. Graph. Deterioration models for Functional Classification of Inventory Route

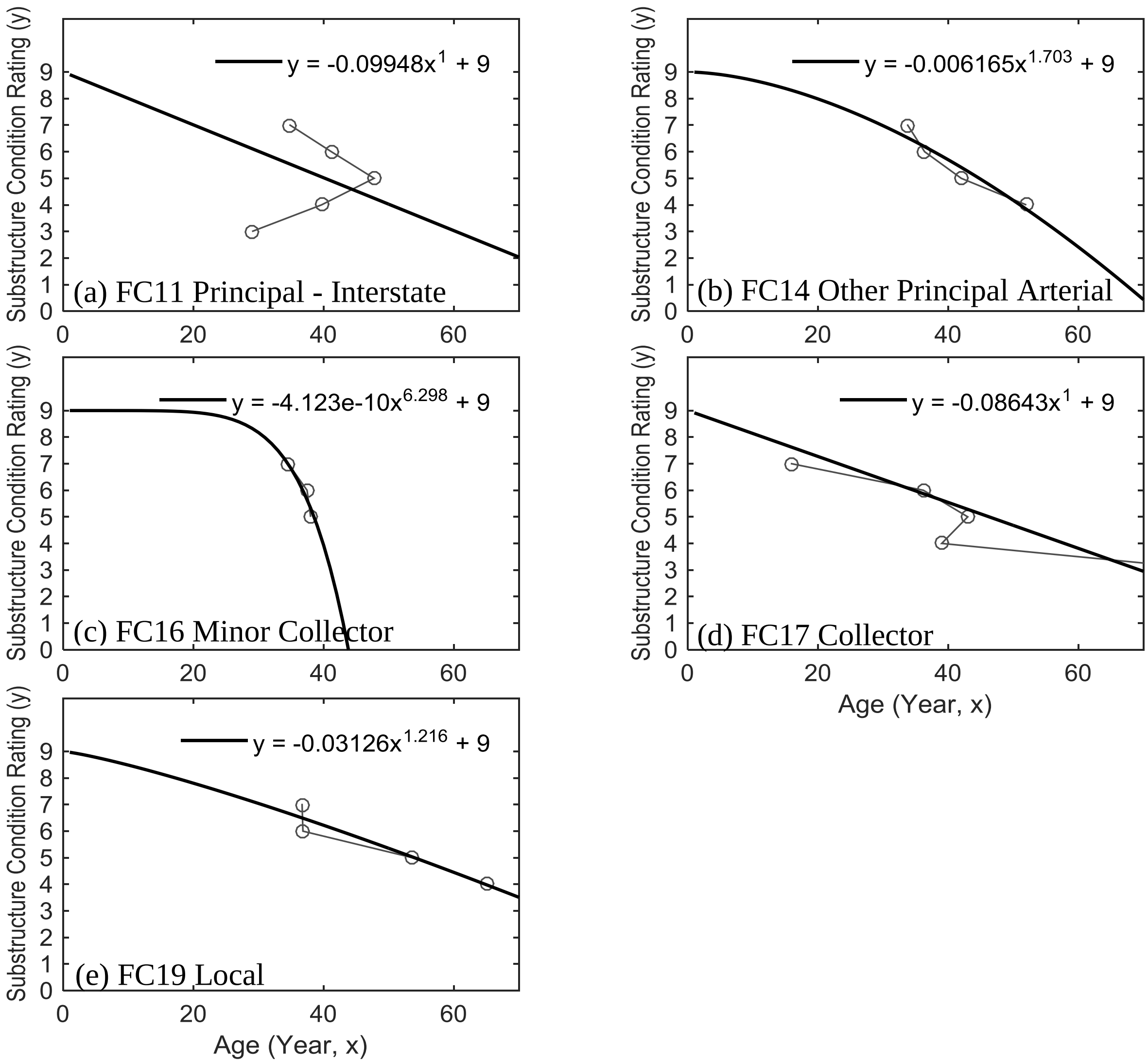


Figure 41. Graph. Deterioration models for Functional Classification of Inventory Route

CHAPTER 6 STOCHASTIC DETERIORATION MODELS

INTRODUCTION

Stochastic processes are widely implemented in engineering applications and applied sciences to account for both well-known and poorly understood random behavior. In the field of infrastructure deterioration, stochastic processes are used to model various types of uncertainty and randomness, which contribute normally to deterioration processes. Amongst several approaches to model uncertainty is the Markov Decision Process (MDP). This process has been used for infrastructure condition rating prediction for many years. MDPs are convenient to implement for time based deterioration models with the consideration of current and previous condition state information (Cesare et al. 1992; Agrawal et al. 2010; Hatami and Morcous 2011).

Alternatively, fuzzy logic methods can be used to determine the structural importance factor for element level inspection data (Tee et al. 1988; Melhem and Aturaliya 1994). In this process, each condition state is fuzzified using triangular mapping function and bridge ratings for deck, superstructure, and substructure. Although the results demonstrate the effectiveness of fuzzy logic to predict condition ratings, several difficulties exist for design of fuzzy problems, such as structural importance quantification and fuzzy shape mapping. Additionally, the accuracy of the NBI Translator algorithm, which converts element level condition ratings to NBI condition ratings, has been criticized (Aldemir-Bektas and Smadi 2008; Sobanjo et al. 2008).

In this report, MDP, specifically Markov chains, are used to develop stochastic deterioration models. The Markov chain process formulates the probability characteristics of changes between different states i and j based on the following assumption that the probability of future state j of the system depends on its entire history.

$$P_{ij} = \Pr\{X_{n+1} = j | X_0 = i_0, \dots, X_{n-1} = i_{n-1}, X_n = i\}$$

Figure 42. Equation. Definition of element in transition probability matrix

If the future state is governed solely by the present state of the system, the conditional probability shown in Figure 42 can be simply expressed as:

$$P_{ij} = \Pr\{X_{n+1} = j | X_n = i\}$$

Figure 43. Equation. Simplified definition of element in transition probability matrix

Numerous studies have been conducted to estimate the transition probability in order to quantify the possible damage on the structural component and establish monitoring plan (Estes and Frangopol 2001; Frangopol et al. 2004; Saydam et al. 2012). A typical Makov chain for stationary bridge deterioration considering m discrete states can be shown as:

$$P = \begin{bmatrix} p_{11} & p_{12} & p_{13} & \cdots & p_{1m} \\ 0 & p_{22} & p_{23} & \cdots & p_{2m} \\ 0 & 0 & p_{33} & \cdots & p_{3m} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & p_{mm} \end{bmatrix}$$

Figure 44. Equation. Transition probability matrix

In Figure 44. Equation, p_{ij} denotes the probability of an element decaying from state i to j in one discretized time step (e.g., an annual event for bridge maintenance). The elements of *P* when $i < j$ are zeros (i.e., cells below the diagonal) since the condition state cannot be improved without intervention. The states of the system are mutually exclusive and collectively exhaustive after each transition, so that the sum of each row in *P* is unity. Figure 44. Equation, can be simplified by assuming that the probability of a bridge element decays only by a single state within one interval (two years in this case). The typical transition probability matrix is defined as:

$$P = \begin{bmatrix} p_{11} & 1 - p_{11} & 0 & \cdots & 0 \\ 0 & p_{22} & 1 - p_{22} & \cdots & 0 \\ 0 & 0 & p_{33} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & 1 \end{bmatrix}$$

Figure 45. Equation. Simplified transition probability matrix

Using total probability theory, the n stage state probability q_n can be calculated as

$$q_n = q_{n-1}P = q_{n-2}P^2 = \cdots = q_0P^n$$

Figure 46. Equation. $\boldsymbol{n}$ stage state probability

In Figure 46. Equation, q_0 is the state probability vector at initial stage.

The elements of the transition probability matrix can be is estimated by either minimizing the sum of prediction error, similar to linear regression, or counting the number of deficient bridges between two inspections. The minimization problem can be solved by the following equation.

$$\widehat{\mathrm{P}} = \arg\min \left[\sum_{j=1}^{N} \left| y_{n,j} - R_{\mathrm{P},n} \right| \right] \quad \text{subject to } 0 \leq p_{ii} \leq 1 \text{ for } i = 1, 2, \cdots, 9$$

Figure 47. Equation. Estimated transition probability matrix using optimization approach

In Figure 47. Equation, *N* denotes the number of bridges belonging to a subset and; $y_{n,j}$ is the observed condition rating at n stage of jth bridge. For each transition probability matrix, eight unknowns ($p_{11}, \cdots, p_{88}$) have to be estimated by minimizing the sum of error between prediction and actual inspection. Alternatively, the number corresponding to all elements is counted and each row is normalized such that the sum becomes unity.

A bridge deterioration model highly affected by age (year built) and it was demonstrated by the results of LASSO in a previous chapter and Chang et al. (2016). In order to incorporate the effects of historic data and improve the condition rating accuracy, the effect of bridge age is considered using a zoning technique (Butt et al. 1987; Jiang et al. 1988). For the zoning technique, the initial condition rating vector for the (i+1)th group is updated for every thirty-year interval. The zoning technique enables the emphasis of Year Built (age), which is commonly considered a significant variable for the development of deterioration models (Jiang et al. 1988).

Wyoming has owned over 4,000 unique bridges based on the NBI report from 1991 to 2014, but currently only 3,127 bridges are being managed, ranking 41th amongst US states. Based on the authors' experience, this number is insufficient to develop a transition probability matrix using the optimization approach. Interestingly, due to the lack of information corresponding to several condition ratings (insufficient number of bridge data), some diagonal cells of the transition probability matrix p_{ii} are optimized as zero and $p_{i,i+1}$ will become unity. For this reason, in this report the actual numbers are counted and normalized to develop transition probability matrix.

Table 38. Example of transition probability matrices using Markov chain process

CR	Initial transition probability matrix									Five years later								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.77	0.23	0	0	0	0	0	0	0	0.27	0.41	0.28	0.04	0	0	0	0	0
8	0	0.78	0.22	0	0	0	0	0	0	0	0.29	0.55	0.15	0.01	0	0	0	0
7	0	0	0.9	0.1	0	0	0	0	0	0	0	0.59	0.36	0.05	0	0	0	0
6	0	0	0	0.94	0.06	0	0	0	0	0	0	0	0.73	0.24	0.02	0	0	0
5	0	0	0	0	0.96	0.04	0	0	0	0	0	0	0	0.82	0.16	0.02	0	0
4	0	0	0	0	0	0.94	0.06	0	0	0	0	0	0	0	0.73	0.25	0.01	0
3	0	0	0	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.86	0.11	0.03
2	0	0	0	0	0	0	0	0.9	0.1	0	0	0	0	0	0	0	0.59	0.41
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

A matrix shown in left part of Table 38 is an example of transition probability model for an age group (less than thirty years old when inspected) from deck element of all bridges. The non-zero two elements in the first row indicate the probability that a condition rating of 9 will remain 9 (77 percent) or decrease to 8 (23 percent). After five years operation, the transition probability matrix changes into the right part of Table 38, which is obtained by taking P_i^5.

DECK

Deterioration Model without Consideration of Explanatory Variables

The deterioration model for deck element is developed using the entire inspection data (Figure 48), for which two transition probability matrices based on 30 years interval (Table 39) is used. The bridges less than 30 years old show that the faster deterioration at the early age and become almost linear. This trend lasts for the bridges older than 30 years old. After 60 years, the condition rating for deck element, started with 9 (excellent condition) becomes little less than 4 (Poor Condition).

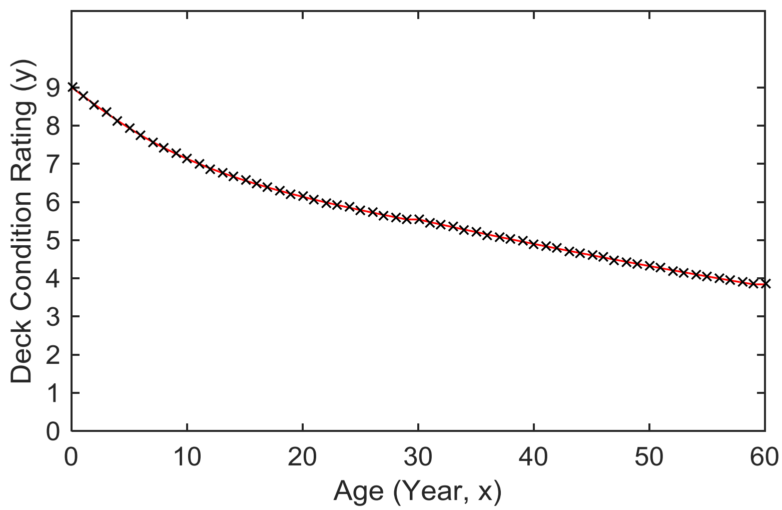


Figure 48. Graph. Deterioration model for deck element

Table 39. Transition probability matrices for deck element

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.77	0.23	0	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0
8	0	0.78	0.22	0	0	0	0	0	0	0	0.74	0.26	0	0	0	0	0	0
7	0	0	0.9	0.1	0	0	0	0	0	0	0	0.89	0.11	0	0	0	0	0
6	0	0	0	0.94	0.06	0	0	0	0	0	0	0	0.94	0.06	0	0	0	0
5	0	0	0	0	0.96	0.04	0	0	0	0	0	0	0	0.94	0.06	0	0	0
4	0	0	0	0	0	0.94	0.06	0	0	0	0	0	0	0	0.94	0.06	0	0
3	0	0	0	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.95	0.05	0
2	0	0	0	0	0	0	0	0.9	0.1	0	0	0	0	0	0	0	0.98	0.02
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Deterioration Models for Subsets Associated with Two Explanatory Variables

Based on the ranking system, the first two significant factors for the deck element condition rating are *Type of Wearing Surface* and *Structural Length*. For the purpose of this analysis, the minimum number of bridges within a subset is limited to 50. This results in development of stochastic deterioration models mostly conducted for the combination of [WS3: Latex Concrete/Similar; WS5: Epoxy Overlay; WS6: Bituminous; WS7: Wood/Timber; WS8: Gravel; WS0: None] and [0 < SL1 < 50; 50 ≤ SL2 < 100]. The bridges outside of these subsets, which are members of subsets of < 50 are then combined together to develop a single deterioration model for this extra set.

The first deterioration model presented was generated for WS3 and SL1 (Figure 49). The 6,806 individual inspection data from 393 bridges are used to develop the deterioration model. Figure 49 shows a rapid decrease for newer bridges and almost linear decrease for older bridges. This is different from the deterministic bridge deterioration models in the previous section. The prediction of 2014 condition rating is compared with the actual inspection result (Figure 49b). The maximum condition ratings are 9 (Excellent condition), which is rarely observed during the inspection period. Even though the shape of deterioration model is different with the determinist deterioration models, Figure 49b demonstrates the effectiveness of using Markov chain to predict condition.

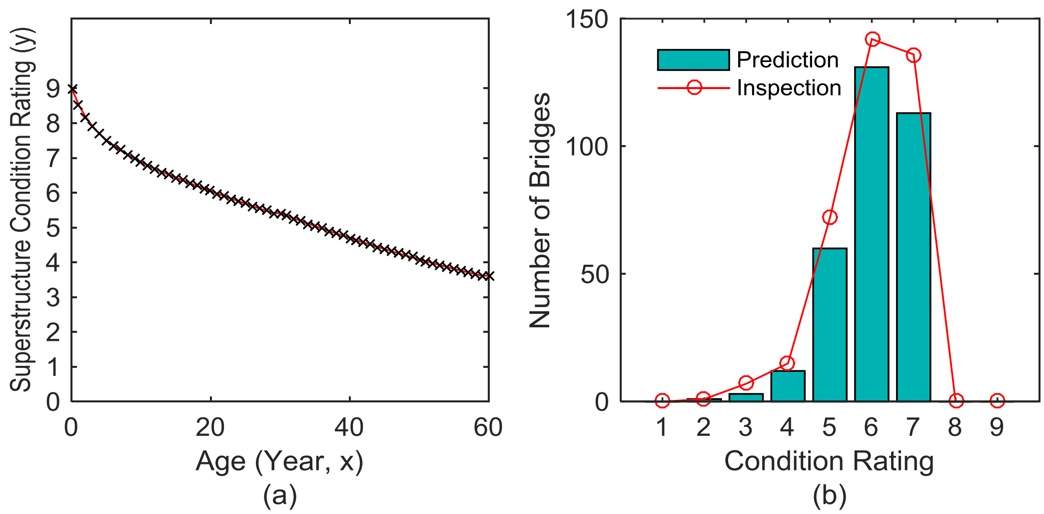


Figure 49. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS3 (Latex Concrete/Similar) and SL1 (0 – 50 m) bridges

There are nine more deterioration models for deck element condition rating. From the second deterioration model, only the significant aspect will be pointed out. The second deterioration model was developed for WS3 and SL2 (Figure 50). 2,159 inspection data was used from 154 bridges.

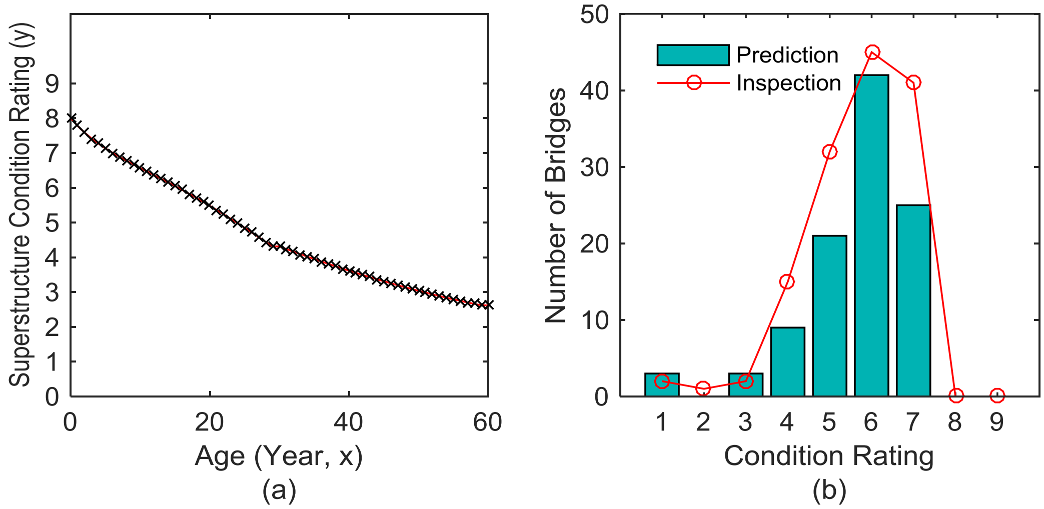


Figure 50. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS3 (Latex Concrete/Similar) and SL2 (50 – 100 m) bridges

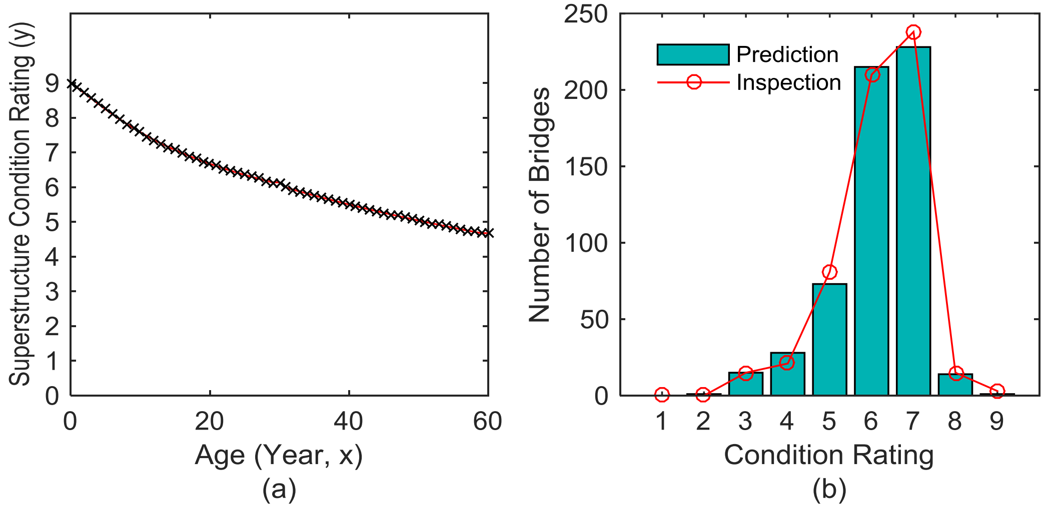


Figure 51. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS6 (Bituminous) and SL1 (0 – 50 m) bridges

The third deterioration model was for WS6 and SL1 (Figure 51) where 9,806 bridge inspections have been used from 640 bridges. Compared to the deterioration model for WS3-SL1 and WS3-SL2, the curve decreases slowly. The fourth deterioration model was developed for WS7 and SL1 (Figure 52) and 1,028 inspection data from 110 bridges has been used to show accuracy in Figure 52b.

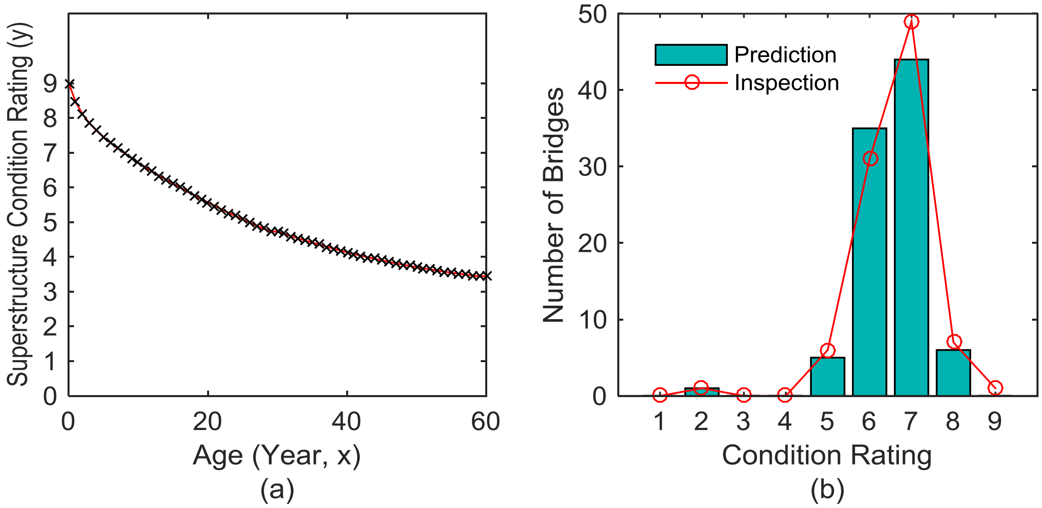


Figure 52. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS7 (Wood/Timber) and SL1 (0 – 50 m) bridges

The fifth deterioration model was developed for WS8 and SL1 (Figure 53) and 1,973 inspection data from 143 bridges were used to assess the accuracy in Figure 53b.

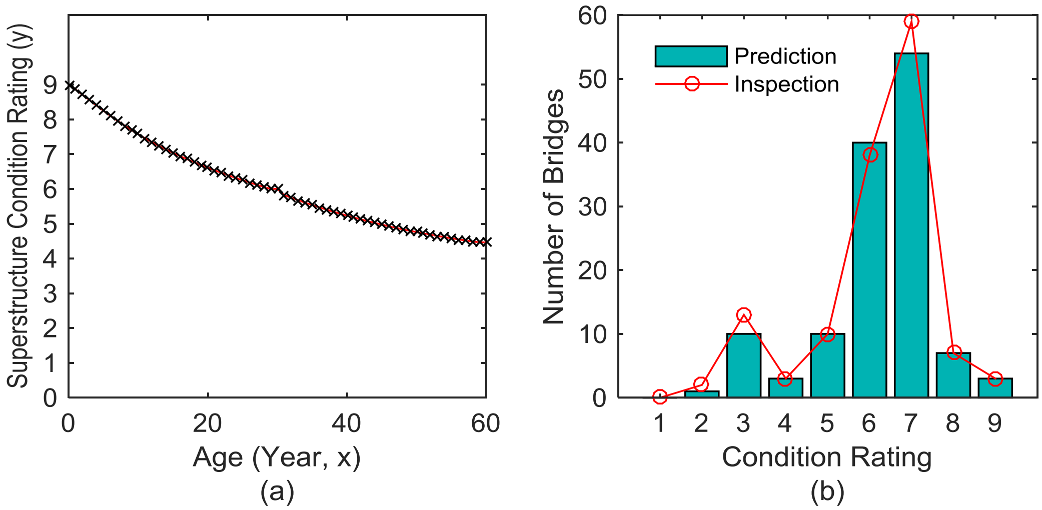


Figure 53 (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS8 (Gravel) and SL1 (0 – 50 m) bridges

The sixth and seventh deterioration models were developed for [WS0 and SL1] and [WS0 and SL2], for which 11,676 and 3,466 inspection data from 697 and 269 bridges were investigated, respectively.

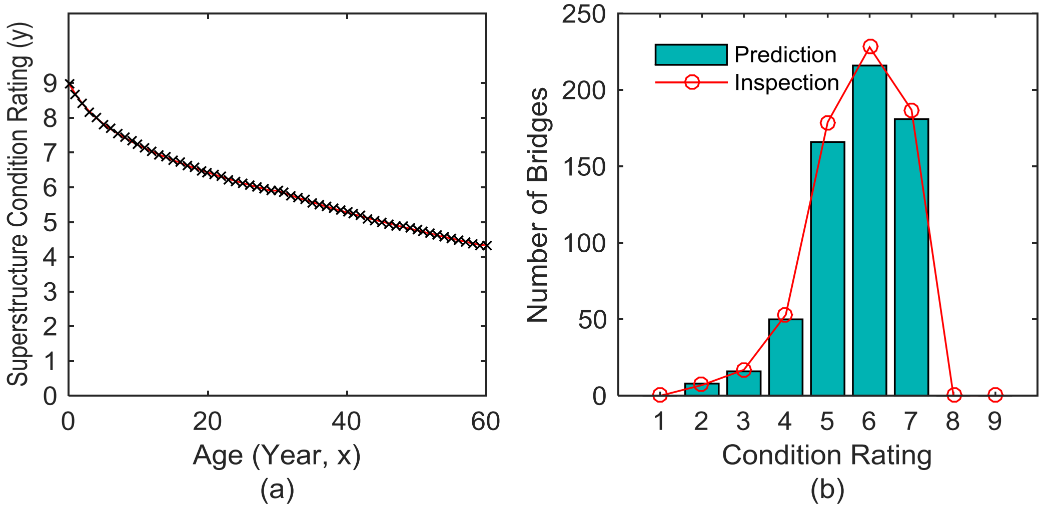


Figure 54. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS0 (None) and SL1 (0 – 50 m) bridges

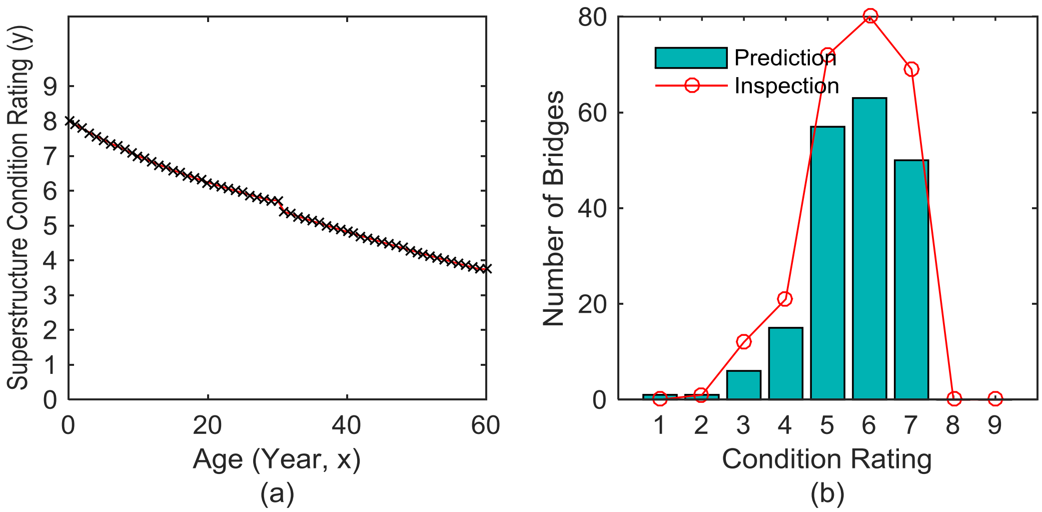


Figure 55. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS0 (None) and SL2 (50 – 100 m) bridges

The eighth deterioration model was developed for WS5 using 863 inspection data from 55 bridges. The ninth deterioration model is developed for WS0 and SL3 to SL5 using 863 inspection data from 65 bridges. These two models are based on relatively small number of subsets, near the 50-bridge cutoff, but deterioration models were successfully developed.

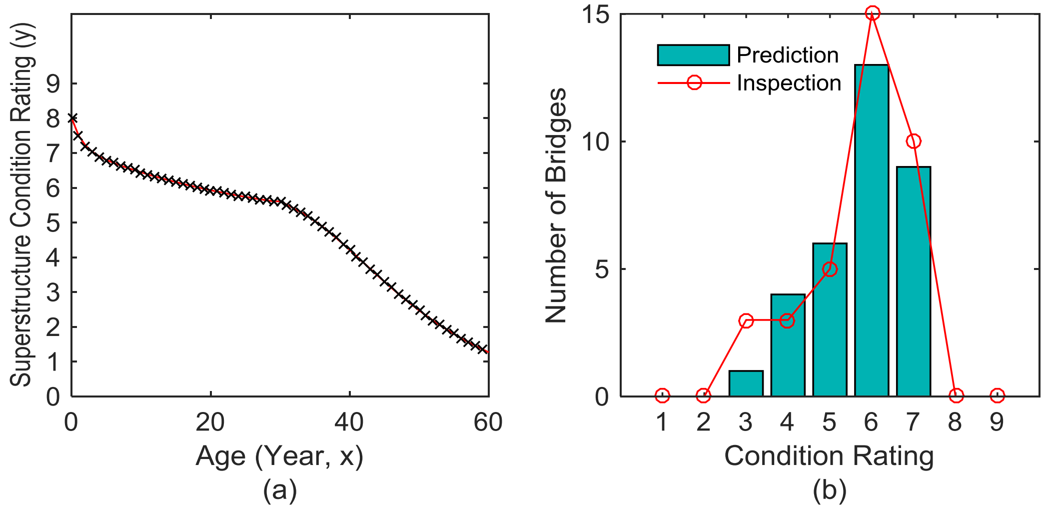


Figure 56. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS5 (Epoxy Overlay) and SL1 – SL5 bridges

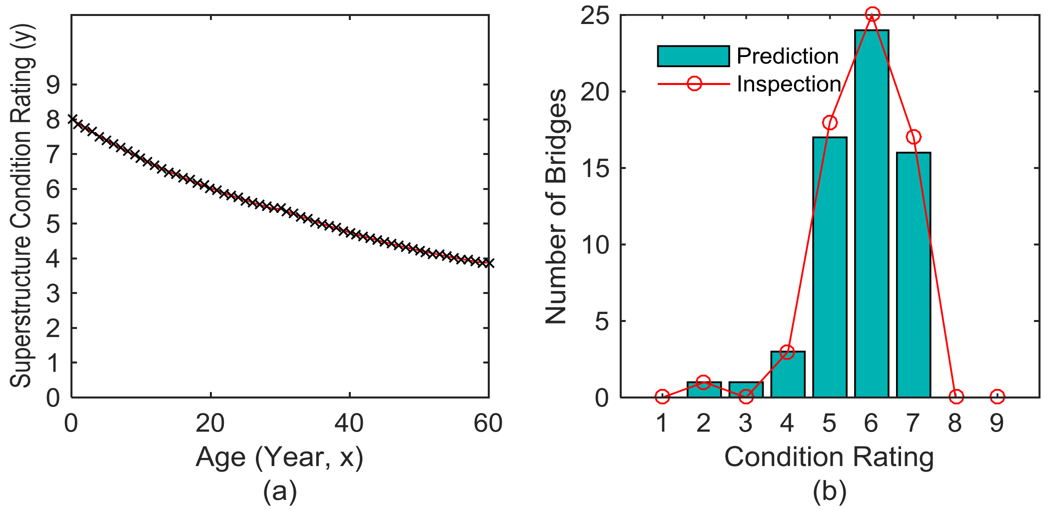


Figure 57. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS0 (None) and SL3 – SL5 (100 m ~) bridges

The final deck deterioration model was developed for the “extra” bridges, which are excluded from the previous deterioration models (Figure 58). A total of 1,977 inspection data from 162 bridges were used to develop the deterioration model.

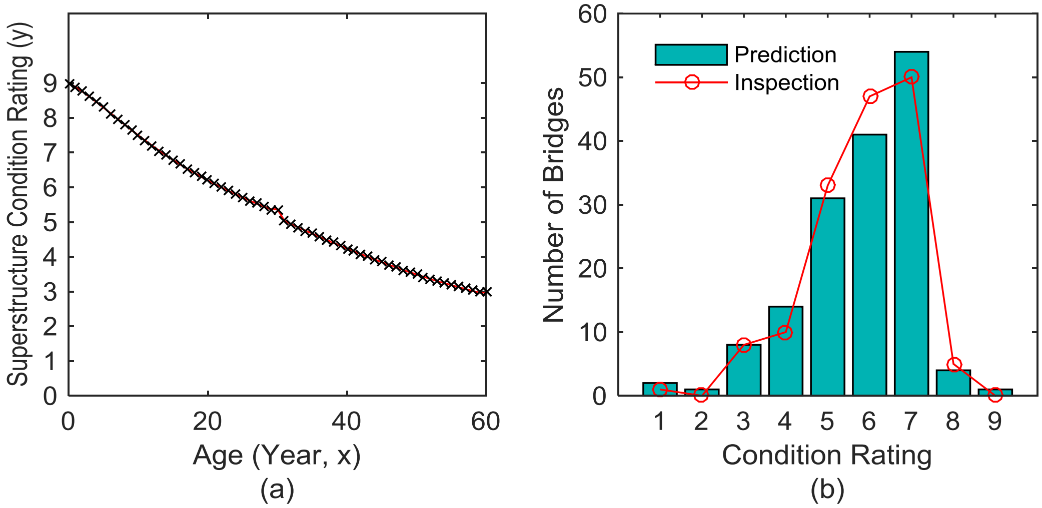


Figure 58. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for rest bridges

SUPERSTRUCTURE

Deterioration Model without Consideration of Explanatory Variables

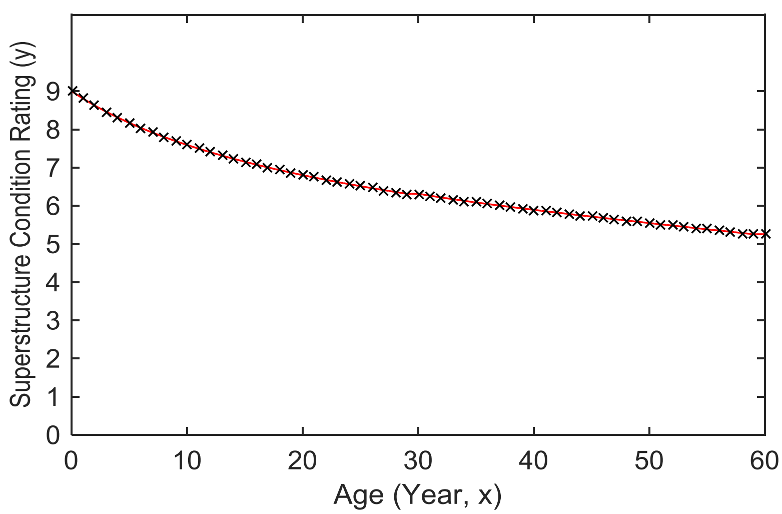


Figure 59. Graph. Deterioration model for superstructure element

A deterioration model for superstructure condition rating is developed using the entire inspection data in Figure 59. For this model two-transition probability matrices based on a 30 years interval (Table 40) is used. Similar to the deck condition rating model, the bridges less than 30 years old show faster deterioration at early ages and then become almost linear. This trend lasts for the bridges older than 30 years old. After 60 years, the condition rating for superstructure element, started with 9 (excellent condition) becomes little more than 5 (Fair Condition).

Table 40. Transition probability matrices for superstructcure element

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.8	0.2	0	0	0	0	0	0	0	0.7	0.3	0	0	0	0	0	0	0
8	0	0.89	0.11	0	0	0	0	0	0	0	0.8	0.2	0	0	0	0	0	0
7	0	0	0.93	0.07	0	0	0	0	0	0	0	0.95	0.05	0	0	0	0	0
6	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.97	0.03	0	0	0	0
5	0	0	0	0	0.98	0.02	0	0	0	0	0	0	0	0.97	0.03	0	0	0
4	0	0	0	0	0	0.96	0.04	0	0	0	0	0	0	0	0.96	0.04	0	0
3	0	0	0	0	0	0	0.99	0.01	0	0	0	0	0	0	0	0.98	0.02	0
2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.97	0.03
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Deterioration Models for Subsets Associated with Two Explanatory Variables

Based on the ranking system, the first two significant factors for the superstructure element condition rating are *Deck Structure Type* and *Bridge Roadway Width*. The minimum number of bridges within the subset is set to 50. The development of stochastic deterioration models for the superstructure element is conducted for the combination of [DST1 DST2 DST6 and DST8] and [BRW1, BRW2, BRW3, BRW4 and BRW5]. The remainder are combined together to develop a deterioration model for an extra set and total of 11 groups are generated.

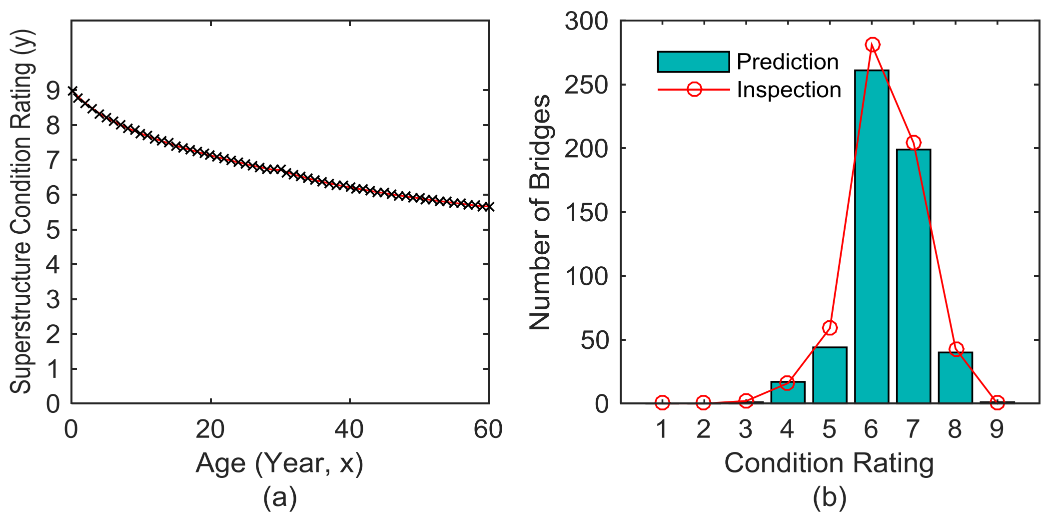


Figure 60. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for DST1 (Concrete Cast-in-Place) and BRW2 (5 – 10 m, 16.4– 32.8 ft) bridges

The first three deterioration models were developed for DST1 and BRW2 – BRW4 (Figure 60 ~ Figure 62). The number of inspection data for comparison are 9,534, 20,954, and 698 from 630, 1,248, and 59 bridges, respectively. Due to the small number of data focusing on the condition rating of 7 and 8, the deterioration model for DST1 and BRW4 decreases rapidly compared to others.

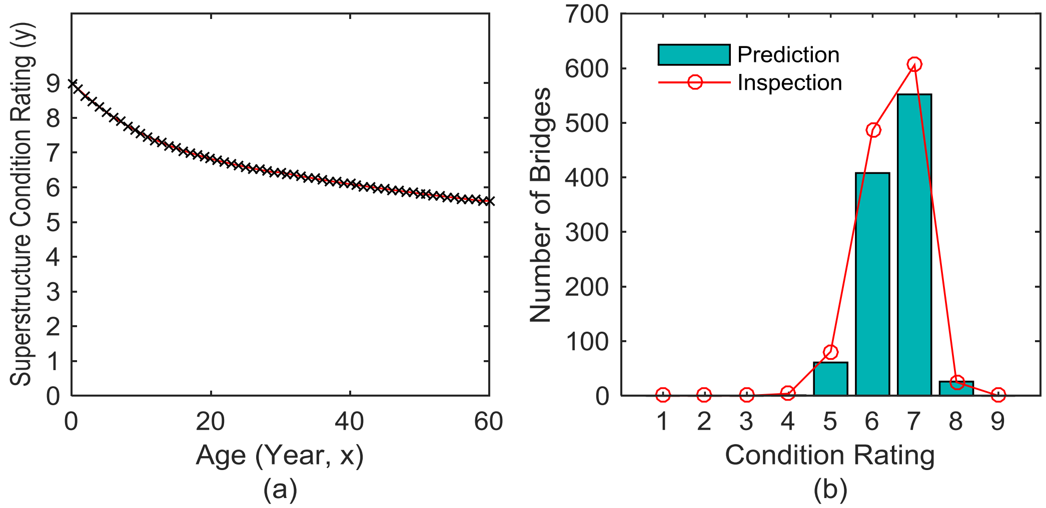


Figure 61. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for DST1 (Concrete Cast-in-Place) and BRW3 (10 – 15 m, 32.8 – 49.2 ft) bridges

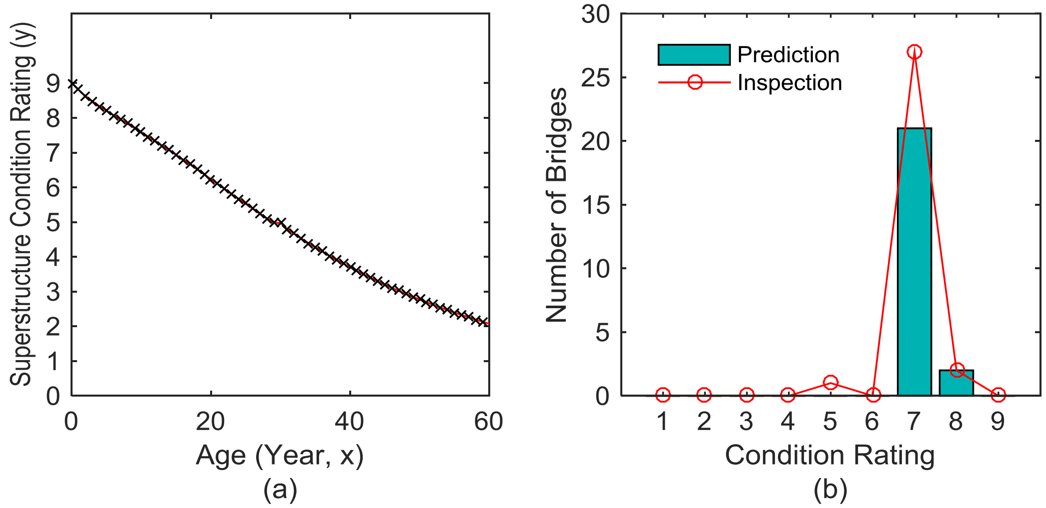


Figure 62. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for DST1 (Concrete Cast-in-Place) and BRW4 (15 – 20 m, 49.2 – 65.6 ft) bridges

The fourth deterioration model was developed for DST2 and BRW2 using 3,004 inspections data from 179 bridges (Figure 63).

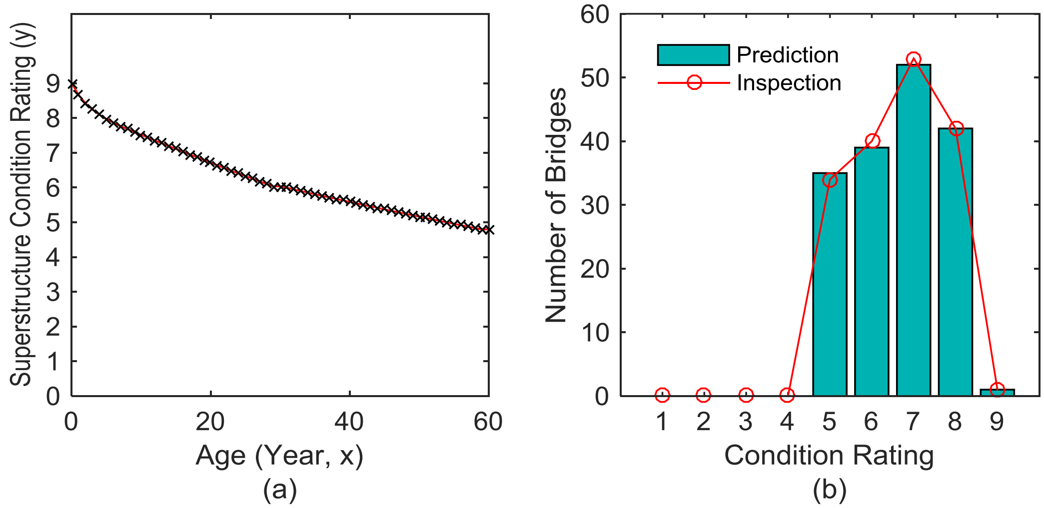


Figure 63. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for DST2 (Concrete Precast Panels) and BRW2 (5 – 10 m, 16.4– 32.8 ft) bridges

The fifth and sixth deterioration models were developed for [DST6 and BRW1] and [DST6 and BRW2] (Figure 64 and Figure 65) for which 688 and 1,574 inspection data from 72 and 105 bridges, respectively, were used. A faster deterioration is observed for the first 30 year period for the bridges belonging to BRW2 compared to BRW1 (i.e., wider bridges deteriorate faster).

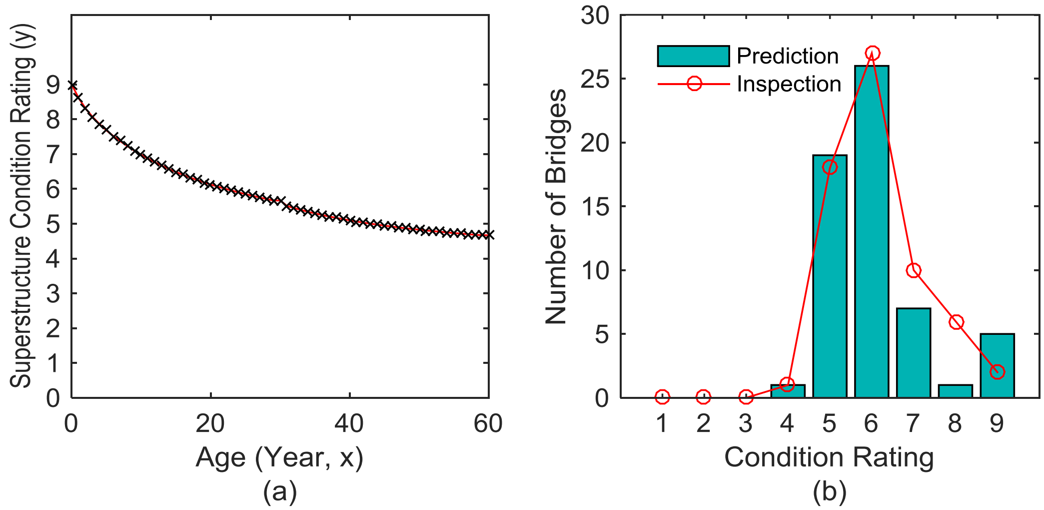


Figure 64. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for DST6 (Corrugated Steel) and BRW1 (0 – 5 m, 0– 16.4 ft)bridges

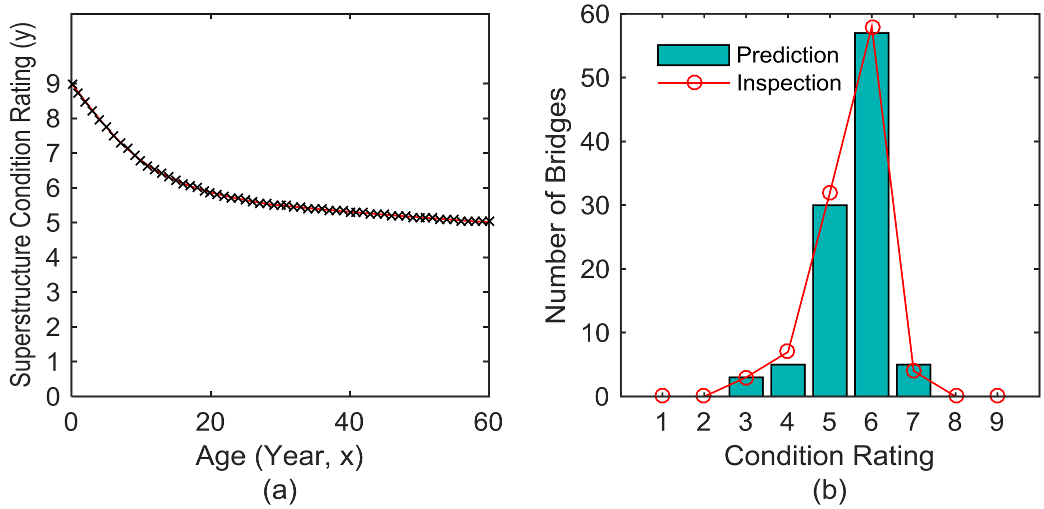


Figure 65. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for DST6 (Corrugated Steel) and BRW2 (5 – 10 m, 16.4– 32.8 ft) bridges

The seventh and eighth superstructure deterioration models were developed for [DST8 and BRW1] and [DST8 and BRW2] (Figure 66 and Figure 67), for which 1,675 and 1,383 inspection data from 156 and 98 bridges were used. The figures show that the bridges associated to BRW2 deteriorate faster than BRW1.

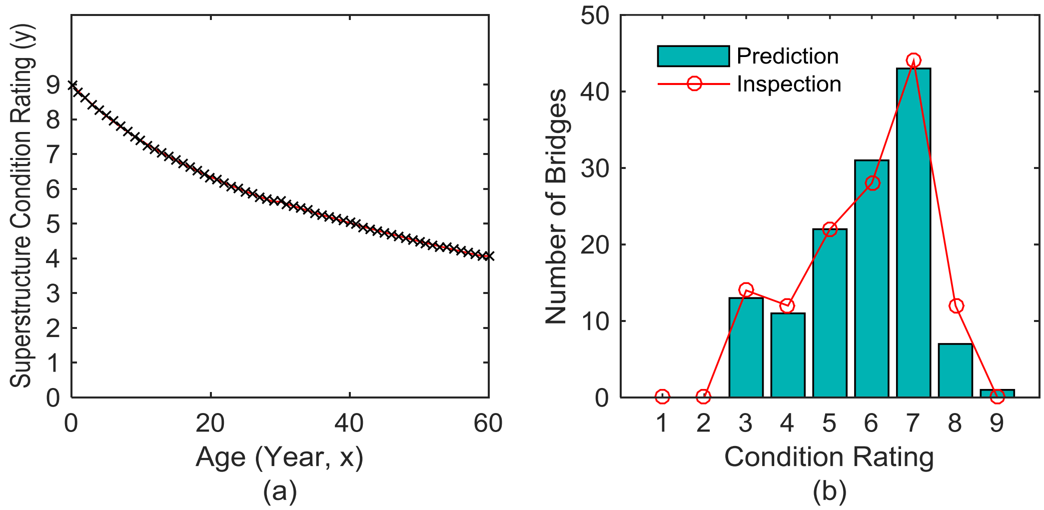


Figure 66. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for DST8 (Wood/Timber) and BRW1 (0 – 5 m, 0 ft – 16.4 ft) bridges

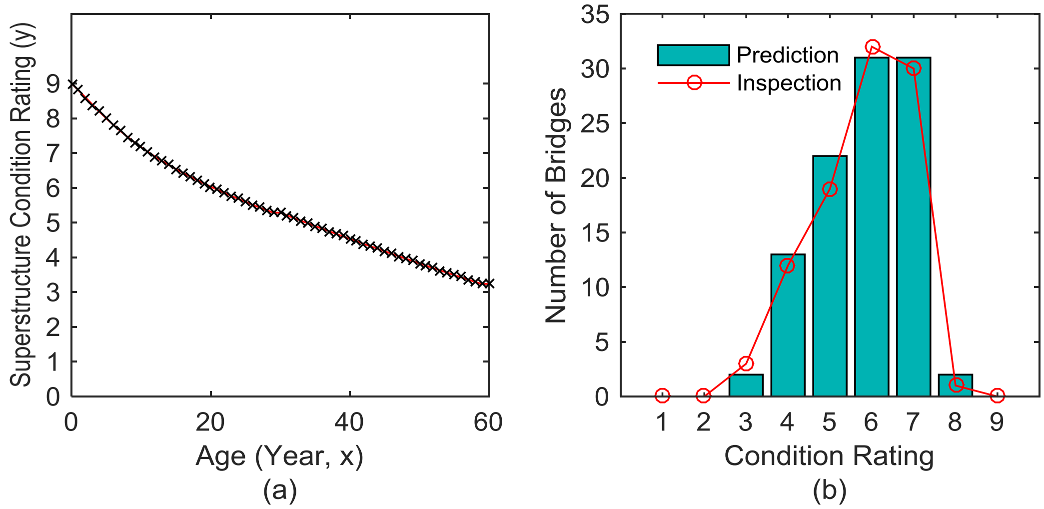


Figure 67. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for DST8 (Wood/Timber) and BRW2 (5 – 10 m, 16.4 ft – 32.8 ft)bridges

The ninth deterioration model was developed for DST1 and [BRW1 or BRW5] (Figure 68), for which 844 bridge inspections from 74 bridges were used. These subsets include many relatively new bridges with condition ratings of 9.

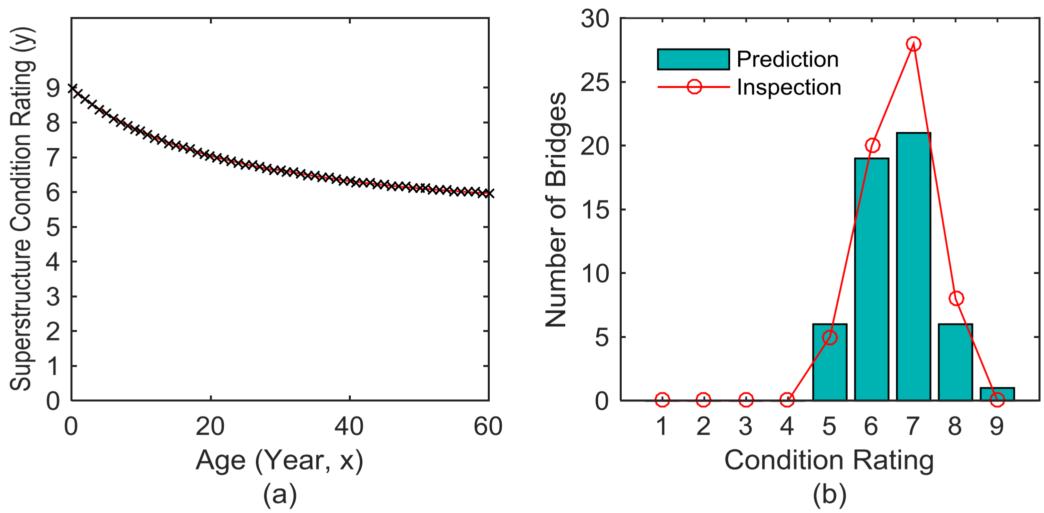


Figure 68. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for DST1 (Concrete Cast-in-Place) and BRW1 (0 – 5 m, 0 ft – 16.4 ft), BRW5 (20 m, 65.5 ft) bridges

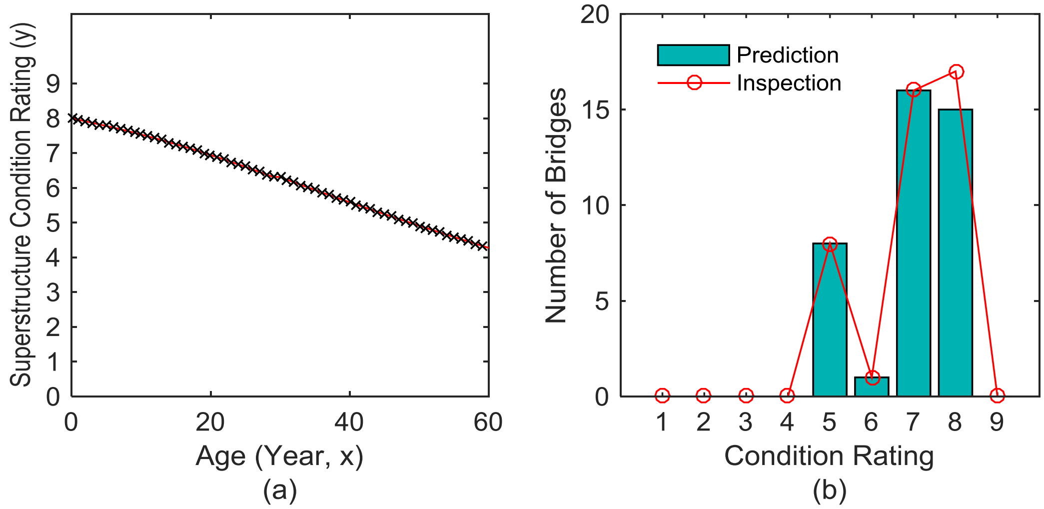


Figure 69. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for DST2 (Concrete Precast Panels) and BRW1, BRW3 – BRW5 bridges

The tenth deterioration model was developed for the DST2 and [BRW1, BRW3, BRW4, or BRW5] (Figure 69), for which 689 inspection data from 50 bridges were used. The 11th deterioration model was developed for the remainder of the bridges not belonging to the other datasets due to lack of data (Figure 70). For this final dataset only 136 inspection data from 11 bridges were used. Using only 11 bridges in this set causes issues with the prediction (see Figure 70b) and the abrupt change in slope at the 30-year zone is very sharp.

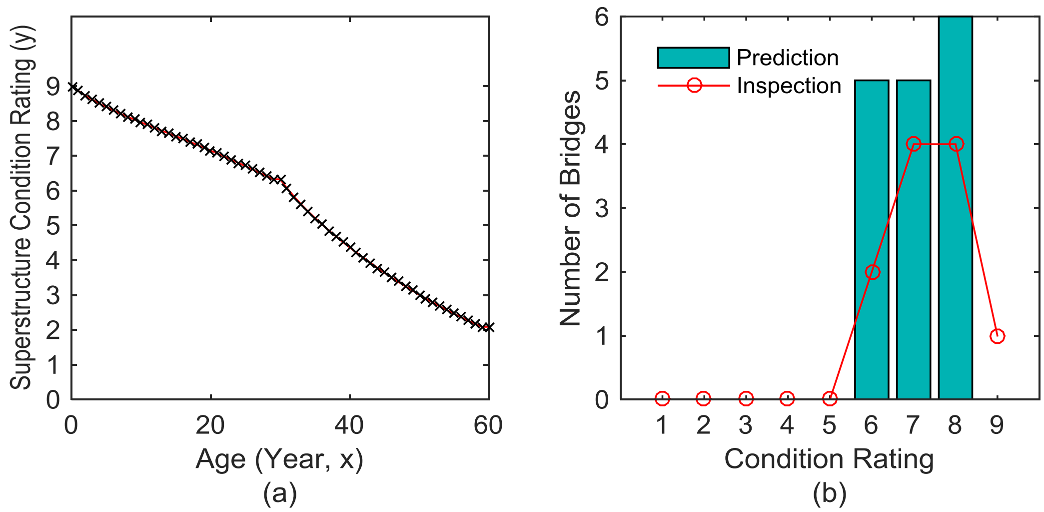


Figure 70. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for rest bridges

SUBSTRUCTURE

Deterioration Model without Consideration of Explanatory Variables

The deterioration model for substructure element is developed using entire inspection data (Figure 71), for which two transition probability matrices based on 30 years interval (Table 41) is used. Similar to deck element model, the bridges less than 30 years old show that the faster deterioration at the early age and become nearly linear.

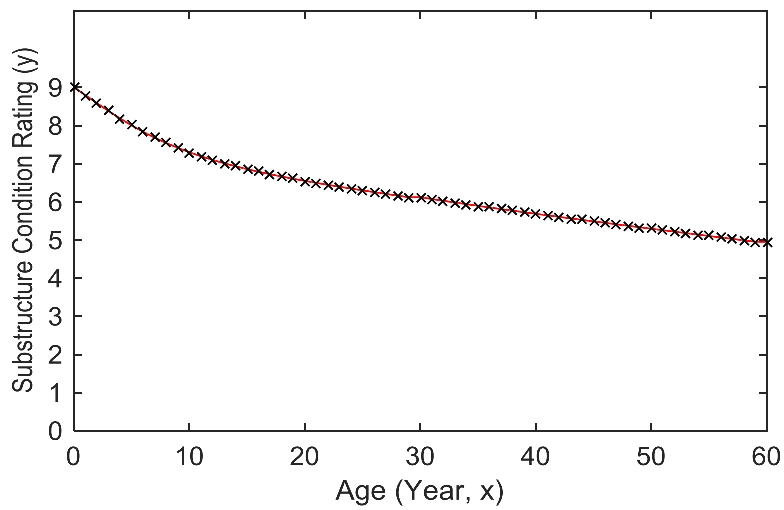


Figure 71. Graph. Deterioration model for substructure element

Table 41. Transition probability matrices for substructure element

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.8	0.2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
8	0	0.77	0.23	0	0	0	0	0	0	0	0.74	0.26	0	0	0	0	0	0
7	0	0	0.95	0.05	0	0	0	0	0	0	0	0.94	0.06	0	0	0	0	0
6	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.97	0.03	0	0	0	0
5	0	0	0	0	0.96	0.04	0	0	0	0	0	0	0	0.97	0.03	0	0	0
4	0	0	0	0	0	0.94	0.06	0	0	0	0	0	0	0	0.96	0.04	0	0
3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.97	0.03	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Deterioration Models for Subsets Associated with Two Explanatory Variables

Based on the ranking system, the first two significant factors for the deck element condition rating are *Type of Wearing Surface* and *Design Load*. The minimum number of bridge inventory in a subset is set to 50 so that the development of stochastic deterioration models is mostly conducted for the combination of [WS3: Latex Concrete/Similar; WS6: Bituminous; WS0: None] and [DL5: MS18; DL6: MS 18+Mod; DL0: Other/Unknown]. The remainder are combined together to develop a deterioration model for an extra set and total of ten groups are generated.

The first and second deterioration models were developed for [WS3 and DL5] and [WS3 and DL6] (Figure 72 and Figure 73), for which 2,421 and 7,079 inspection data from 141 and 428 bridges were used, respectively. These two models are similar shape but WS3-DL5 shows slightly faster decrease than WS3-DL6. Although the total number of inspections seems relatively large, no bridges in the subset had an inspection with condition ratings of 8 or 9.

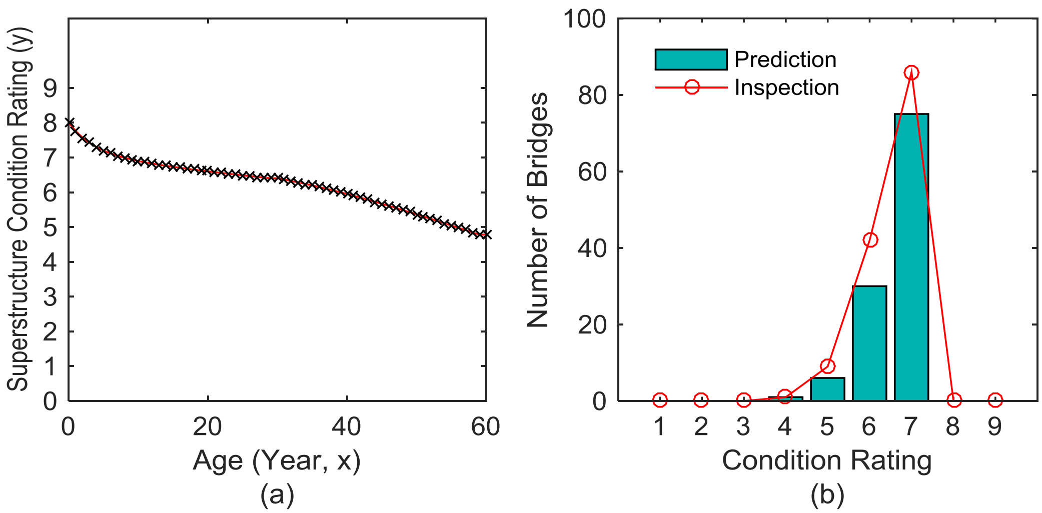


Figure 72. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS3 (Latex Concrete/Similar) and DL5 (MS 18) bridges

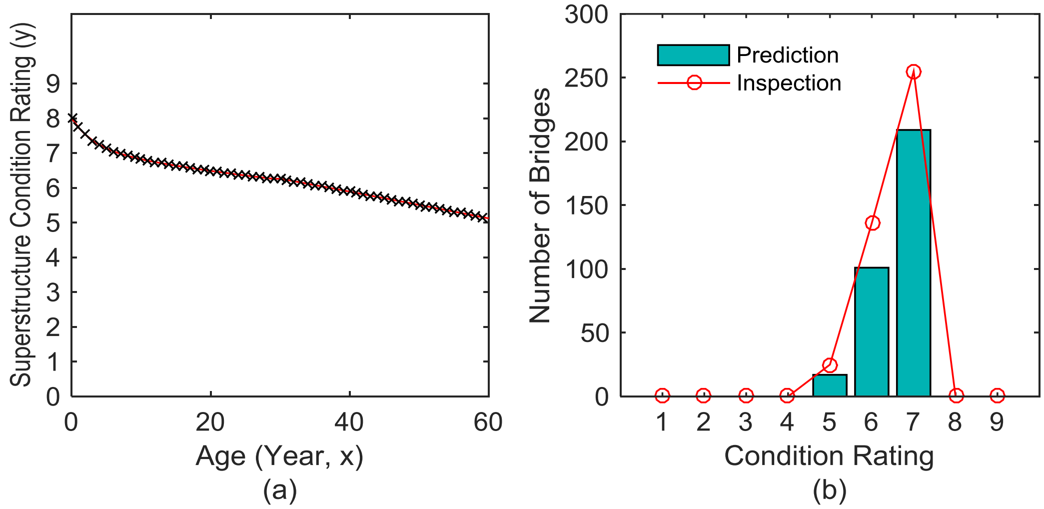


Figure 73. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS3 (Latex Concrete/Similar) and DL6 (MS 18+Mod) bridges

The next four deterioration models were developed for [WS6 and DL2], [WS6 and DL5], [WS6 and DL6], and [WS6 and DL0] (Figure 74, Figure 75, Figure 76, and Figure 77), for which 995, 3,126, 4,134, and 1,598 inspection data from 61, 213, 211, and 125 bridges were used, respectively. There did seem to be an issue with an insufficient number of inspections, as observed by the abrupt change in slope at the 30-year zone for [WS6 and DL2] in Figure 74.

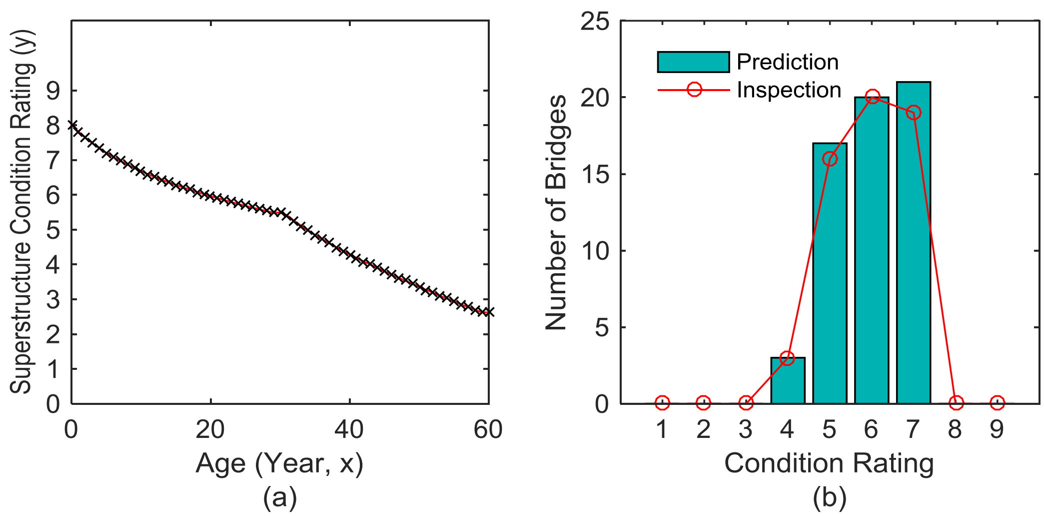


Figure 74. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS6 (Bituminous) and DL2 (M 13.5) bridges

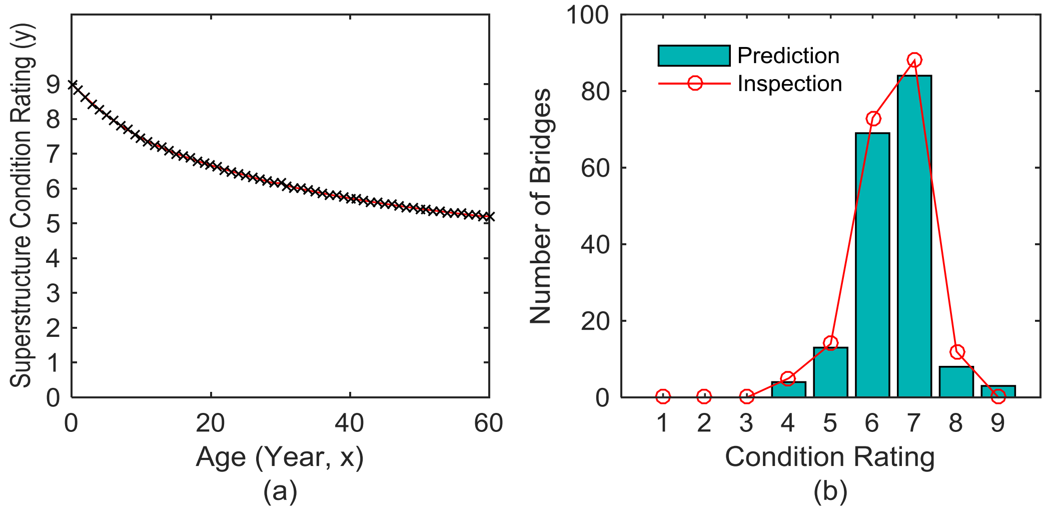


Figure 75. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS6 (Bituminous) and DL5 (MS 18) bridges

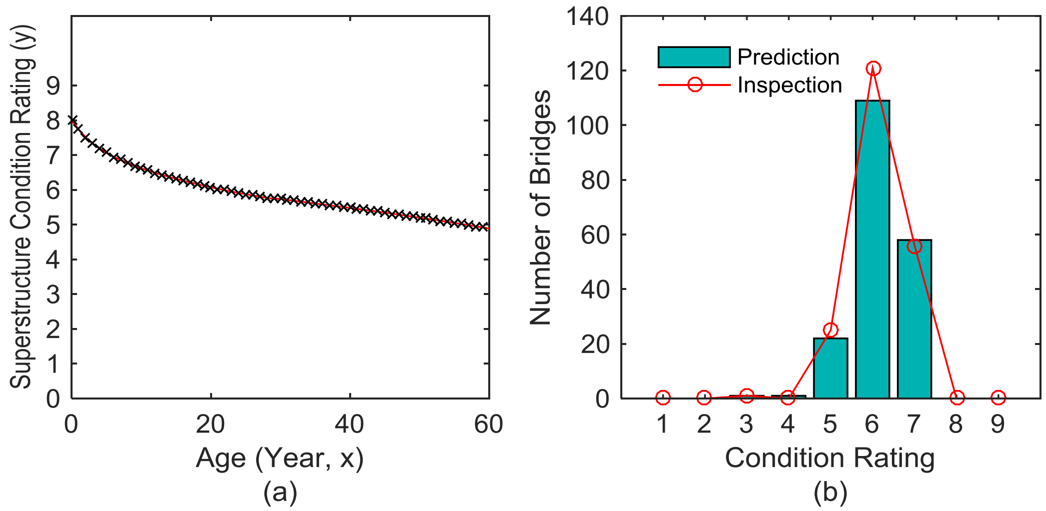


Figure 76. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS6 (Bituminous) and DL6 (MS 18+Mod) bridges

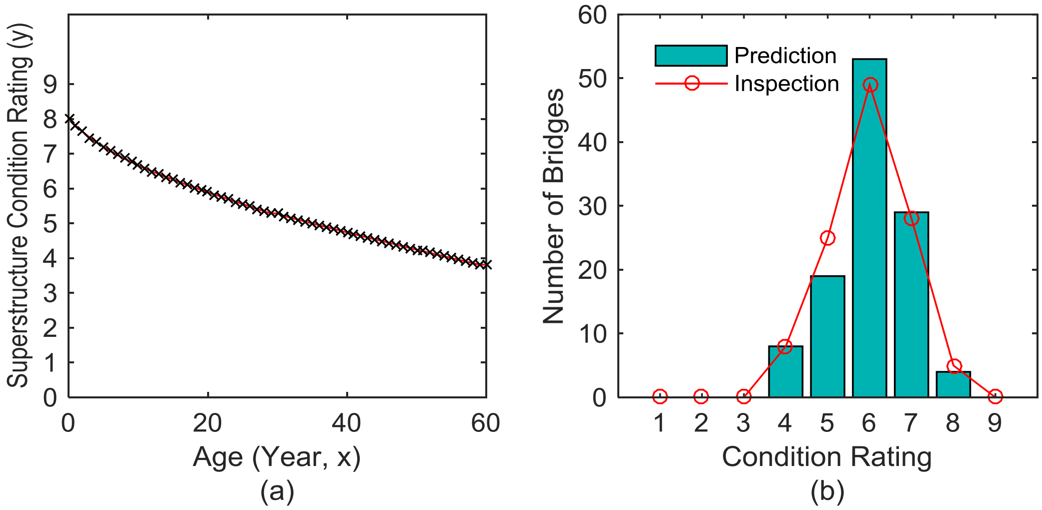


Figure 77. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS6 (Bituminous) and DL0 (Other/Unknown) bridges

The seventh deterioration model is developed for [WS7 and DL0] (Figure 78), for which 765 bridge inspections from 73 bridges were used. The deterioration model is almost linear but the decrease of condition rating from 8 to 7 is fast compared to others.

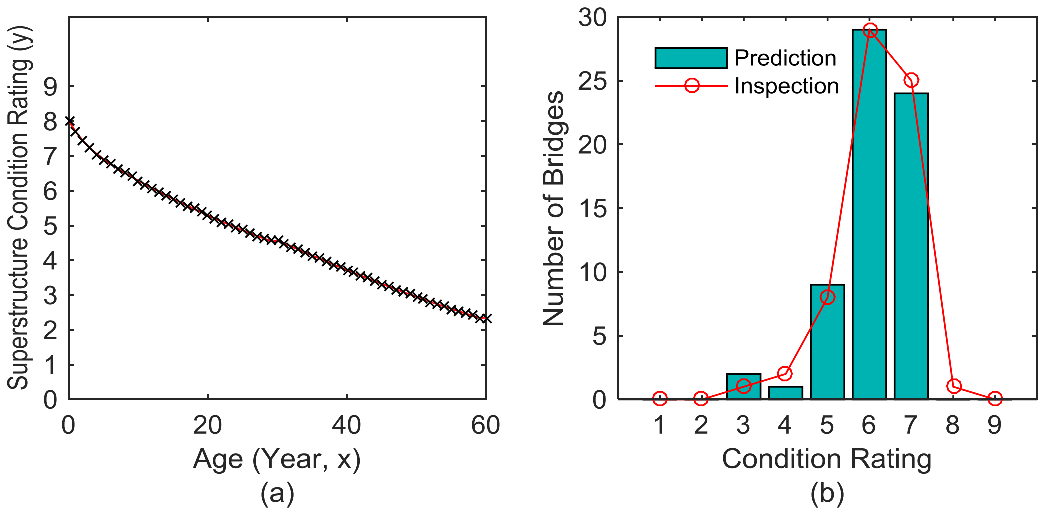


Figure 78. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS7 (Wood/Timber) and DL0 (Other/Unknown) bridges

The eighth deterioration model was developed for [WS8 and DL0], for which 977 bridge inspections from 67 bridges were used.

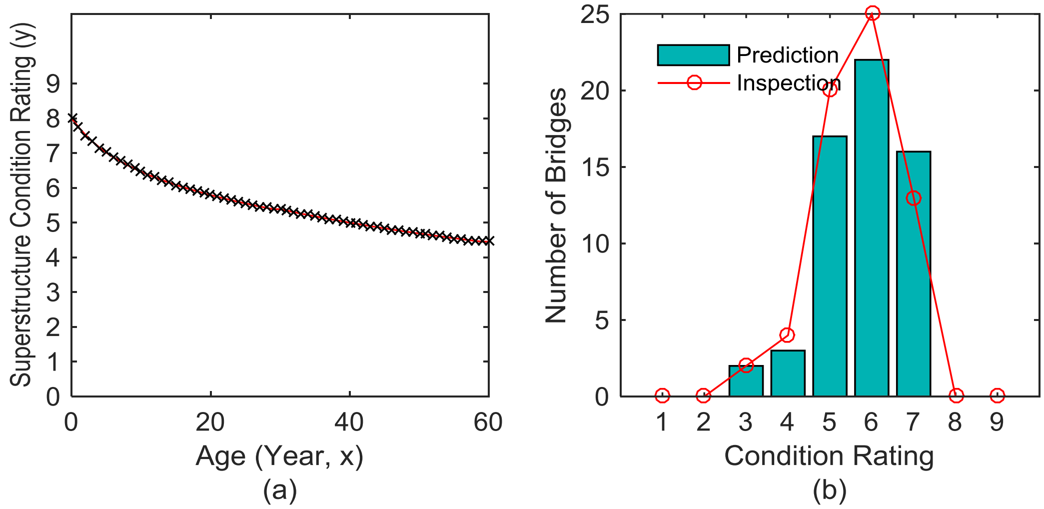


Figure 79. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS8 (Gravel) and DL0 (Other/Unknown) bridges

The ninth to 12th deterioration models were developed for [WS0 and DL5], [WS0 and DL6], [WS0 and DL9], and [WS0 and DL0] (Figure 80, Figure 81, Figure 82, and Figure 83), for which 9,735, 2,055, 1,274, 1,790 inspection data from 529, 149, 136, and 120 bridges were used. The lack of data points are observed for [WS0 and DL9], where the zoning technique cannot predict any condition rating after 30 years.

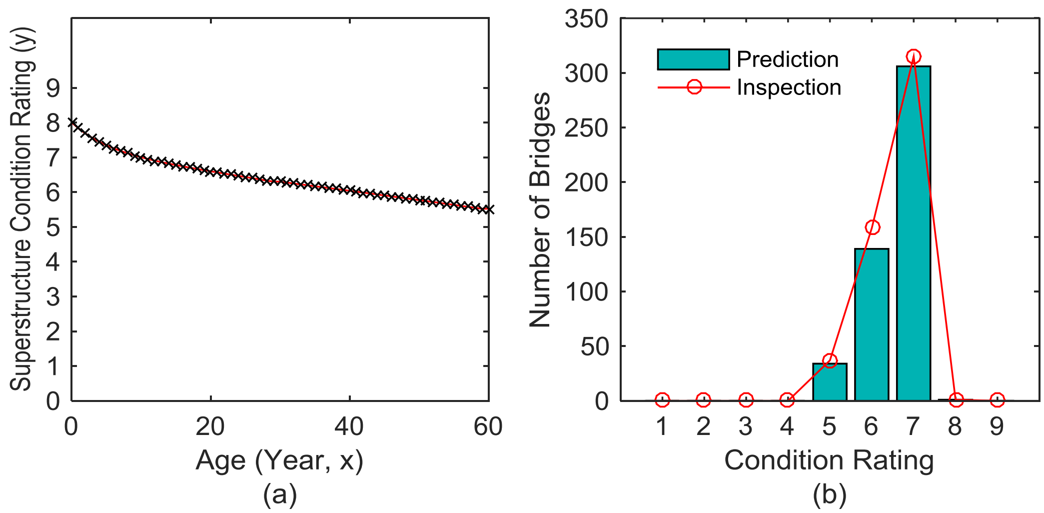


Figure 80. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS0 (None) and DL5 (MS 18) bridges

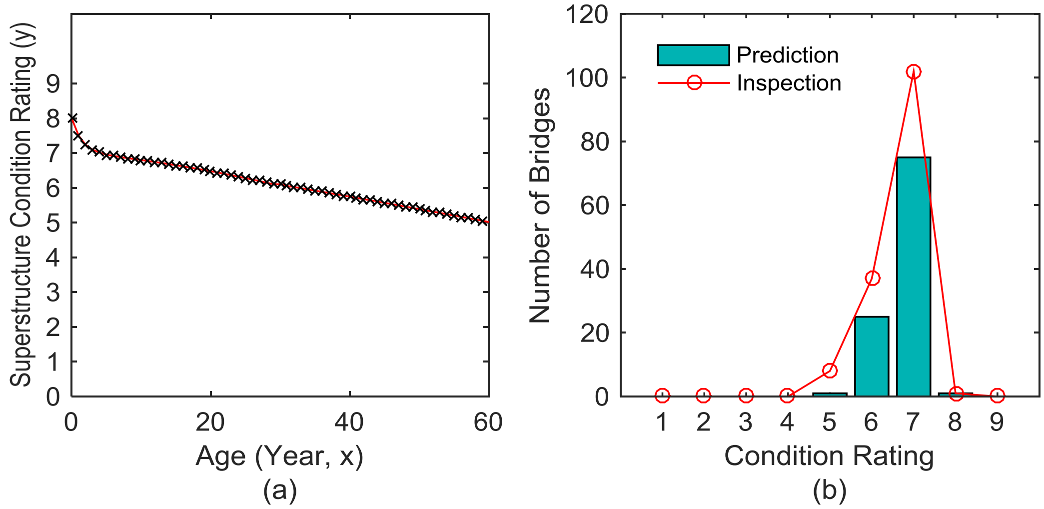


Figure 81. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS0 (None) and DL6 (MS 18+Mod) bridges

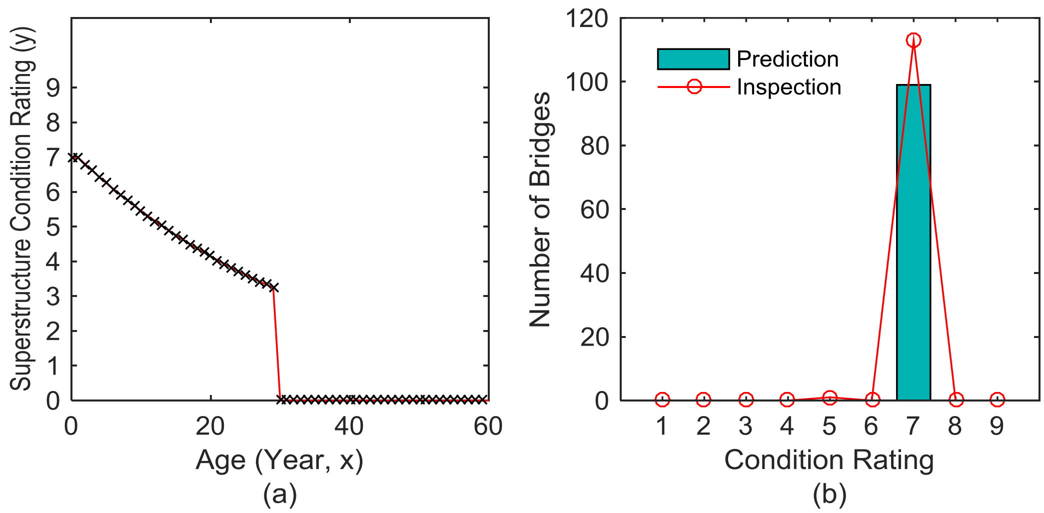


Figure 82. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS0 (None) and DL9 (MS 22.5) bridges

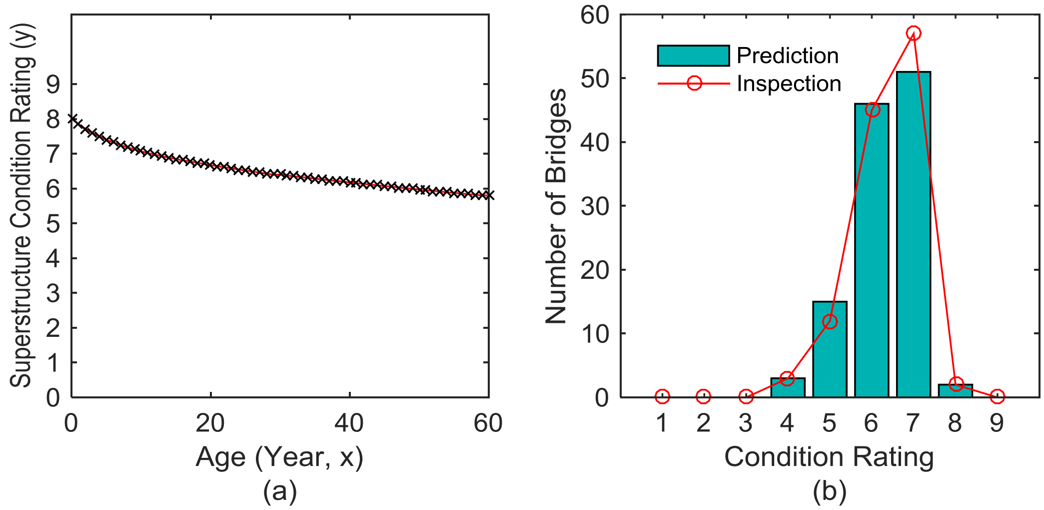
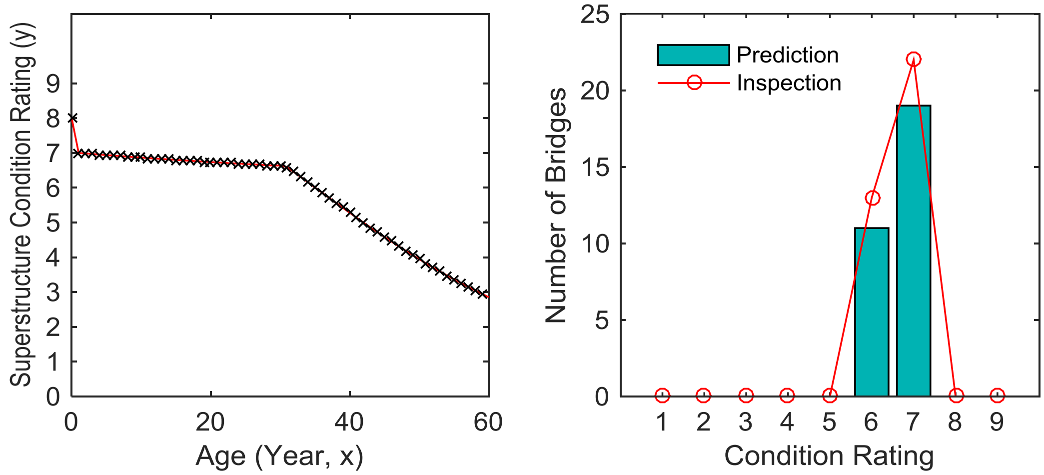


Figure 83. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS0 (None) and DL0 (Other/Unknown) bridges

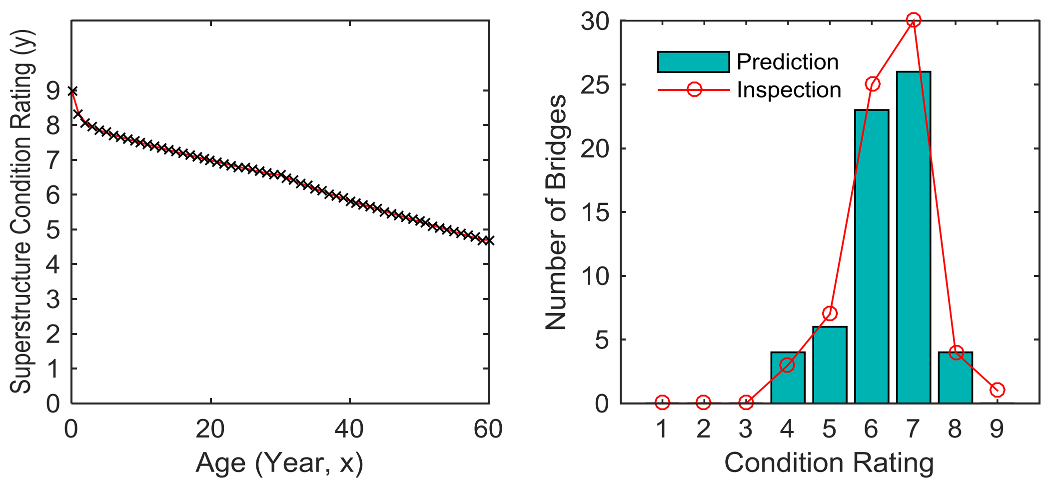
The 13th deterioration model was developed for WS5 and all remaining DLs (Figure 84), for which 890 inspection data from 55 bridges were used.



(a) (b)

Figure 84. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS5 (Epoxy Overlay) and DL0 – DL9 (all) bridges

The 14th deterioration model was developed for WS6 and [DL1, DL3, DL4, DL7, DL8, or DL9] (Figure 85), for which 1,064 inspection data from 73 bridges were used.



(a) (b)

Figure 85. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS6 (Bituminous) and DL1 (M 9), DL3 (MS 13.5), DL4 (M 18), and DL9 (MS 22.5) bridges

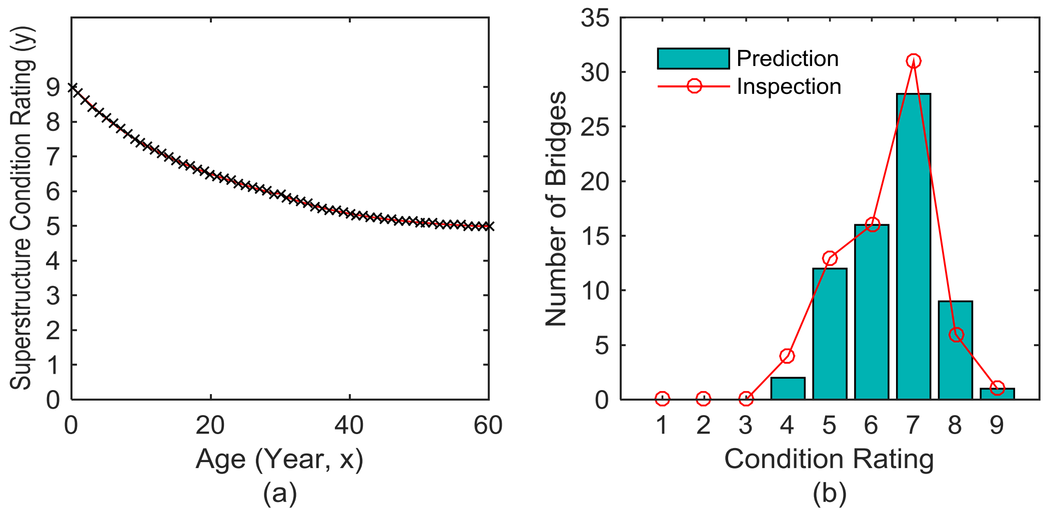


Figure 86. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS8 (Gravel) and DL1 – DL9 (all except DL0) bridges

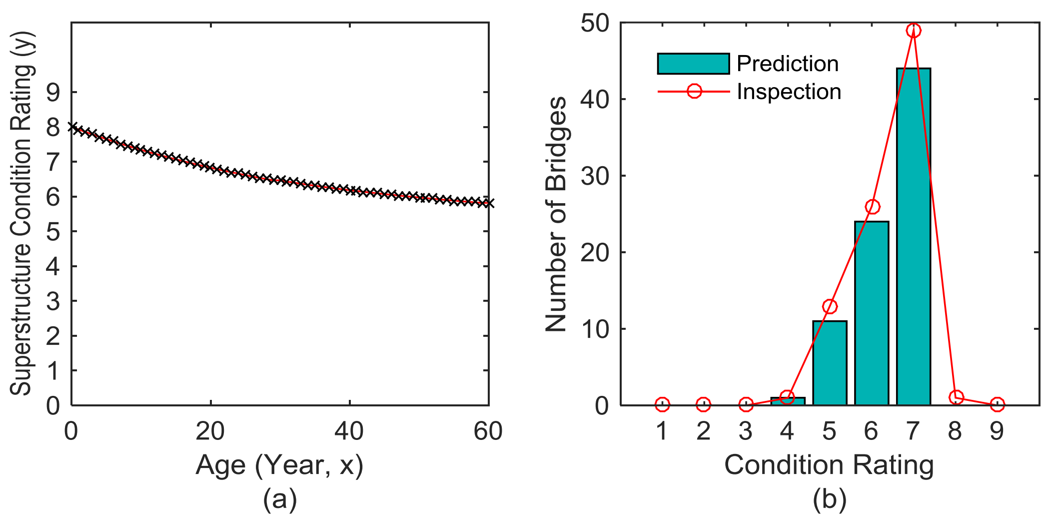


Figure 87. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for WS0 (None) and DL1 - DL4 (M 9 - M 18) bridges

The 15th deterioration model was developed for WS8 and all DLs except DL0 (Figure 86), for which 1,054 inspection data from 79 bridges were used. The 16th deterioration model was developed for WS0 and [DL1, DL2, DL3, DL4, DL7, or DL8] (Figure 87), for which 1,334 inspection data from 97 bridges were used. The last deterioration model was developed for the rest of the bridges (Figure 88), for which 1,319 inspection data from 130 bridges were used.

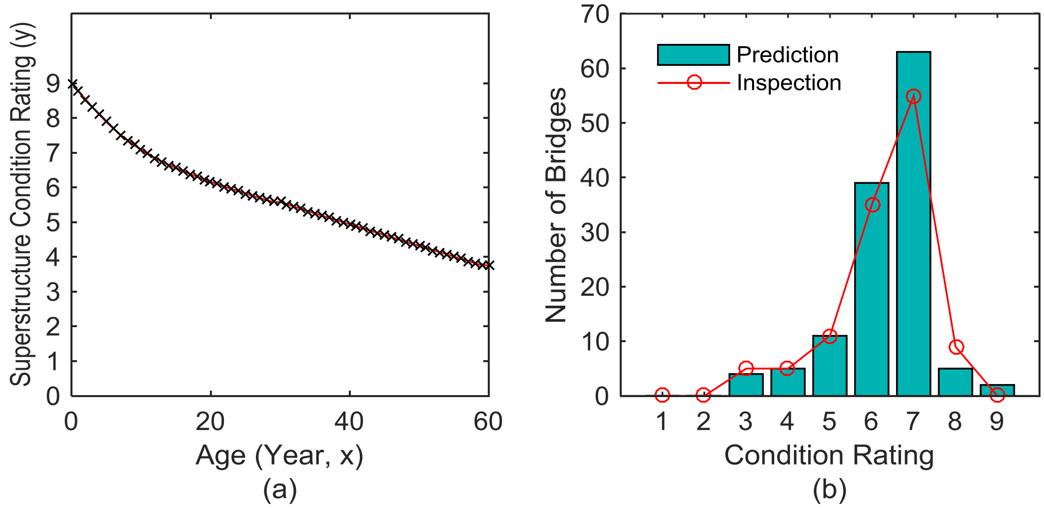


Figure 88. Graph. (a) Deterioration model and (b) comparison between prediction and inspection result in terms of number of bridges versus condition rating for rest bridges

CHAPTER 7 CONCLUSIONS

Both deterministic and stochastic deterioration models were developed for the prediction of deck, superstructure, and substructure components of Wyoming bridges. A method for the unbiased selection of explanatory variables is utilized using LASSO amongst the NBI inspection data. The cross validation optimizes the number of explanatory variables, which fits the regression model with the minimized subset of inspection data. The 27 NBI data and Average Temperature, Precipitation, Elevation information is was investigated for the estimation of deck, superstructure, and substructure condition ratings. According to the sequential order of significance, deterministic deterioration models for the first five explanatory variables are developed when an individual index possesses more than 10 percent of total population.

Stochastic deterioration models were developed for each subset. Stochastic models using Markov Chains are considered standard practice in the bridge management field. In order to leverage the large amount of accumulated data from WYDOT, two deterioration models were developed for each subset: one for the first 30 years and one for 30+ years.

The following conclusions can be made from this investigation:

- LASSO regression, a form of penalized linear regression, can remove human influence from the selection of explanatory variables. LASSO identified [Type of Wearing Surface, Structure Length, Functional Classification of Inventory Route, and Average Daily Traffic] for deck condition rating. Superstructure condition rating was found to have [Deck Structure Type, Bridge Roadway Width (Curb to Curb), Functional Classification of Inventory Route, and Length of Maximum Span] as most important. Substructure condition rating was found to have [Type of Wearing Surface, Design Load, Bridge Roadway Width (Curb to Curb), and Functional Classification of Inventory Route] as most important.

- While deterministic and stochastic models can be made for various subsets, bridge managers should be careful about implementing models developed from small datasets, and engineering judgment should be applied. The models developed based on the entire deck, superstructure or substructure data sets should be considered for use in these situations.

Implementing and updating these deterioration models is of utmost importance to WYDOT bridge managers. For this reason, the Appendix contains routine instructions for updating the models. The bridge models developed in this report can be used in the current WYDOT bridge management system to manage their current inventory. The models can also be implemented in any program capable of solving a power function or matrix analysis using the methodologies, mathematics and matrices presented in Chapter 5 and Chapter 6. Note that these models are not meant to predict the condition rating of a single bridge, but of a group of bridges for planning, effort allocation, and management purposes.

Future research should focus on conversion of element level inspection data into more accurate or meaningful (to WYDOT) condition ratings. It was evident that within the available data, the current conversion method was producing condition ratings typically within the middle of the range. Furthermore, due to WYDOT's relatively small inventory, future research could look into statistical methods that could enhance the predictive ability of current methods, or develop completely new methods for small bridge inventories. Techniques that hold promise are logistic regression, other autoregressive models (of which Markov Chains are a subset) and fuzzy sets.

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APPENDIX

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PROGRAM CODES

Matlab® (© 1994-2016 The MathWorks, Inc) is used to develop stochastic deterioration models with the consideration of two explanatory variables. This code is designed to simplify the process to access the future inspection data and to develop deterioration models consistently. In order to operate the actual code, Matlab® compiler 8.5 (exactly same version) (© 1994-2016 The MathWorks, Inc) has to be installed. The code is designed to read 'ascii code' text file and its name should be 'WYxxxx.txt' where the 'xxxx' is the year of inspection.

Three codes are developed which are: 1) Load_NBI_DATA_WYDOT.m, 2) DTR_MODEL_WYDOT.m, and 3) DTR_Plotting.m. 'Load_NBI_DATA_WYDOT.m' is aimed to load the inspection data from 1991 to the one that the user can access. It creates a big data file named "RAW_DATA.mat' which includes all inspection data, condition ratings, and the geometry and climate information. 'DTR_MODEL_WYDOT.m' is the main code to develop deterioration models. Based on the ranking system for explanatory variables, this code splits the bridge data into multiple subsets which are tossed to the sub-routine code 'DTR_Plotting.m.' The percentage prediction method is used to estimate the transition probability matrix and zoning technique with 30 years interval is utilized. The deterioration model is developed for each subset and the followings are the specific code.

Load_NBI_DATA_WYDOT.m

- Lines 1 – 6: The number of strings to recognize all inspection items in a line of inspection data is coded. The definition of items and their length is described by Weseman (1995).
- Line 8: 'FOR' loop to load the ascii file from 1992 to 2014 inspection data. 23 indicates the number of years for the historical data.
- Lines 55 – 58: 'ie' defines a vector of indices including candidate variables, condition rating, and year reconstructed. The item, year reconstructed, is used to replace year built and to update the age of bridge when the inspection year is newer than year reconstructed.
- Line 60: 'ic' defines the deck, superstructure, and substructure condition rating indices assigned for 'ic.


```
1  index_l = [  3; 15;  1;  1;  1;  5;  1;  2;  3;  5; 24;  1; 18; 25;  4;  7;  1; 10;  2;  8;
2              9;  3;  1;  2;  2;  2;  4;  2;  2;  6;  4;  1;  4;  1;  2;  1;  1;  1;  1;  1;
3              1;  1;  4;  5;  1;  1;  1;  1;  2;  1;  2;  3;  4;  3;  5;  6;  3;  3;  4;  4;
4              4;  1;  4;  1;  3;  3;  1;  1;  1;  1;  1;  1;  3;  1;  3;  1;  1;  1;  1;  1;
5              1;  2;  1;  6;  4;  2;  3;  3;  3;  4;  4;  4;  6;  6;  6;  4;  3;  2; 15;  1;
6              1;  1;  1;  1;  1;  4;  1;  1;  1;  1;  2;  1;  1;  1;  1;  6;  4;  4;];
7
```

```
for i = 23:-1:1
    eval(['bdg_insp = dataread("file", "WY' num2str(i+1991) '.txt", "%s", "delimiter", "\n");']);

    if i == 23
        for j = 1:size(bdg_insp,1)
            indv_bdg = bdg_insp{j};
            bdg_name{j,1} = indv_bdg(4:18);
            n = j;
            m = 0;
            for k = 1:length(index_l)
                bdg{j,k,i} = indv_bdg(m+1:m+index_l(k));
                m = m + index_l(k);
            end
        end
    else
        for j = 1:size(bdg_insp,1)
            indv_bdg = bdg_insp{j};
            bdg_nt = indv_bdg(4:18);
            k = 1;
            while k <= n
                bdg_comp = bdg_name{k,1};
                if bdg_nt == bdg_comp
                    m = 0;
                    for k2 = 1:length(index_l)
                        bdg{k,k2,i} = indv_bdg(m+1:m+index_l(k2));
                        m = m + index_l(k2);
                    end
                    break;
                else
                    if k < n
                        k = k+1;
                    else
                        bdg_name{n+1} = bdg_nt;
                        n = n+1;
                        m = 0;
                        for k2 = 1:length(index_l)
                            bdg{n,k2,i} = indv_bdg(m+1:m+index_l(k2));
                            m = m + index_l(k2);
                        end
                        break;
                    end
                end
            end
        end
    end
```

```
end

ie = [   4;   8;  17;  24;  26;  27;  28;  29;  30;  32;
        35;  46;  47;  48;  49;  52;  54;  55;  56;  59;
        60; 107; 108; 109; 110; 111; 112;  67;  68;  69;
        106]';
Bdg_Candidate = zeros(size(bdg,1),length(ie)+3,size(bdg,3));
ic = [28 29 30];

%% Mapping precipitation, average temperature, and elevation

load Precip
load TempAvg
load Elev

LongLeftLimit = -(111 + 5/48);
LongRightLimit = -(103 + 47/48);
LatMinLimit = 40 + 15/16;
LatMaxLimit = 45 + 1/16;
LatLongIncrement = 1/120;

for i = 1:size(bdg,3)
    for k = 1:size(bdg,1)
        for j = 1:length(ie)
            Bdg_Candidate(k,j,i) = str2double(bdg{k,ie(j),i});
            if ie(j) == 54 || ie(j) == 55 || ie(j) == 56 || ie(j) == 59 || ie(j) == 60
                Bdg_Candidate(k,j,i) = Bdg_Candidate(k,j,i)/10;
            elseif ie(j) == 111
                Bdg_Candidate(k,j,i) = Bdg_Candidate(k,j,i)/100;
            end
        end

        LatitudeRaw = str2double(bdg{k,20,i});
        LongitudeRaw = str2double(bdg{k,21,i});

        r = floor(LatitudeRaw/10^6);
        s = floor((LatitudeRaw-r*10^6)/10^4);
        t = (LatitudeRaw-r*10^6-s*10^4)/10^2;
        LatitudeRaw = r + s/60 + t/3600;

        r = floor(LongitudeRaw/10^6);
        s = floor((LongitudeRaw-r*10^6)/10^4);
        t = (LongitudeRaw-r*10^6-s*10^4)/10^2;
        LongitudeRaw = -(r + s/60 + t/3600);

        Bdg_Candidate(k,j+1,i)                                                    =
```

```
interp2((LongLeftLimit:LatLongIncrement:LongRightLimit),(LatMinLimit:LatLongIncrement:LatMaxLimit),Precip,LongitudeRaw,(LatMaxLimit + LatMinLimit - LatitudeRaw))./1000;
    Bdg_Candidate(k,j+2,i) = interp2((LongLeftLimit:LatLongIncrement:LongRightLimit),(LatMinLimit:LatLongIncrement:LatMaxLimit),TempAvg,LongitudeRaw,(LatMaxLimit + LatMinLimit - LatitudeRaw));
    Bdg_Candidate(k,j+3,i) = interp2((LongLeftLimit:LatLongIncrement:LongRightLimit),(LatMinLimit:LatLongIncrement:LatMaxLimit),Elev,LongitudeRaw,(LatMaxLimit + LatMinLimit - LatitudeRaw))./1000;
  end
end

save RAW_DATA Bdg_Candidate
```

DTR_MODEL_WYDOT.m

- Lines 5 - 31: the candidate variable information is described with item index (assigned index for analysis).

- Lines 33 -35: the condition rating information is described with item index (assigned index for analysis). The assigned index will be disappeared when splitting condition ratings as separate data.

- Line 47: ‘Year Reconstructed’ is described with item index (assigned index).

- Lines 39 – 40: latitude and longitude information with item index.

- Lines 41 – 43: precipitation, average temperature, and altitude are described with (assigned index for analysis).

- Lines 86 – 114: specific indices for candidate variable and the type of data are defined. The value for type is the interval to discretize the continuous inspection data when it is not unity. When it is unity, the program recognizes the candidate variable can use all defined indices.

- Line 117: ‘cond_index’ denotes the target element to develop deterioration models such that 1) deck, 2) superstructure, and 3) substructure.

- Line 118: ‘year’ denotes the last year of the archived inspection data.

- Lines 140 – 142: ‘ci1_set’, ‘ci2_set’, and ‘ci3_set’ are the result of raking system to select explanatory variables for deck, superstructure, and substructure elements.

```
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clear;
close all;
clc

%   4(01): Route Signing Prefix
%   8(02): Highway Agency Distric
%  17(03): Base Highway Network
%  24(04): Maintenance Responsibility
%  26(05): Functional Classification of Inventory Route
%  27(06): Year Built
%  28(07): Lanes on the Structure
%  29(08): Lanes under the Structure
%  30(09): Average Daily Traffic
%  32(10): Design Load
%  35(11): Skew
%  46(12): Type of Service on Bridge
%  47(13): Type of Service under Bridge
%  48(14): Kind of Material and/or Design
%  49(15): Type of Design and/or Construction
%  52(16): Number of Spans in Main Unit
%  54(17): Inventory Route, Total Horizontal Clearance
%  55(18): Length of Maximum Span
%  56(19): Structure Length
%  59(20): Bridge Roadway Width (Curb to Curb)
%  60(21): Deck Width (Out to Out)
% 107(22): Deck Structure Type
% 108(23): Type of Wearing Surface
% 109(24): Type of Membrane
% 110(25): Deck Protection
% 111(26): Average Daily Truck Traffic
% 112(27): Designated National Network

%  67(28): Deck Condition
%  68(29): Superstructure Condition
%  69(30): Substructure Condition

% 106(31): Reconstruction Year

%  20(XX): Latitude
%  21(XX): Logitude
% Brg(29) Precipitation
% Brg(30) Average Temperature
% Brg(31) Elevation

load RAW_DATA
```

```
% Candidate variable amongst all nbi data %
ie = [   4;   8;  17;  24;  26;  27;  28;  29;  30;  32;
        35;  46;  47;  48;  49;  52;  54;  55;  56;  59;
        60; 107; 108; 109; 110; 111; 112;  67;  68;  69;
       106]';

ic = [28 29 30];

Brd = Bdg_Candidate;
Bcd = Bdg_Candidate(:,ic,:);
Brd(:,ic,:) = [];

% Replacing year built to reconstructed year and Converting year built into
% age
yb = zeros(size(Brd,1),size(Brd,3));
for i = 1:size(Brd,1)
    for j = 1:size(Brd,3)
        yb(i,j) = Brd(i,6,j);
        if Brd(i,28,j) > yb(i,j) && Brd(i,28,j) <= 1991+j
            yb(i,j) = Brd(i,28,j);
        end
    end
end

% Deterioration simplification %
dtr = nan(size(Bcd,1),3,size(Bcd,3)-1);
for i = 1:3
    for j = 1:size(Bcd,3)-1
        for k = 1:size(Bcd,1)
            dt = Bcd(k,i,j) - Bcd(k,i,j+1);
            if dt >= 1 && Bcd(k,i,j) >= 2
                dtr(k,i,j) = 1;
            elseif dt == 0 && Bcd(k,i,j) >= 1
                dtr(k,i,j) = 0;
            end
        end
    end
end

% Canditdate variable information %
var_info.var01.index = (1:5);                    var_info.var01.type = 1;
var_info.var02.index = (1:8);                    var_info.var02.type = 1;
var_info.var03.index = [0 1];                    var_info.var03.type = 1;
var_info.var04.index = [1 2 3 4 62 66];          var_info.var04.type = 1;
var_info.var05.index = [1 2 6 7 8 9 11 12 14 16 17 19]; var_info.var05.type = 1;
var_info.var07.index = (1:5);                    var_info.var07.type = 1;
```

```
var_info.var08.index = (0:6);                    var_info.var08.type = 1;
var_info.var09.index = (1:5);                    var_info.var09.type = 5000;
var_info.var10.index = [1 2 3 4 5 6 7 8 9 0];        var_info.var10.type = 1;
var_info.var11.index = (1:5);                    var_info.var11.type = 15;
var_info.var12.index = [1 2 3 4 5 6 7 8 9 0];        var_info.var12.type = 1;
var_info.var13.index = [1 2 3 4 5 6 7 8 9 0];        var_info.var13.type = 1;
var_info.var14.index = [1 2 3 4 5 6 7 8 9 0];        var_info.var14.type = 1;
var_info.var15.index = [1 2 3 4 5 6 7 9 10 22];       var_info.var15.type = 1;
var_info.var16.index = (1:9);                    var_info.var16.type = 2;
var_info.var17.index = (1:6);                    var_info.var17.type = 5;
var_info.var18.index = (1:5);                    var_info.var18.type = 20;
var_info.var19.index = (1:5);                    var_info.var19.type = 50;
var_info.var20.index = (1:6);                    var_info.var20.type = 5;
var_info.var21.index = (1:6);                    var_info.var21.type = 5;
var_info.var22.index = (1:9);                    var_info.var22.type = 1;
var_info.var23.index = [1 2 3 4 5 6 7 8 9 0];        var_info.var23.type = 1;
var_info.var24.index = [1 2 3 8 9 0];              var_info.var24.type = 1;
var_info.var25.index = [1 2 3 4 6 7 8 9 0];          var_info.var25.type = 1;
var_info.var26.index = (1:5);                    var_info.var26.type = 0.1;
var_info.var27.index = [0 1];                    var_info.var27.type = 1;
var_info.var29.index = (1:6);                    var_info.var29.type = 0.2;
var_info.var30.index = (0:5);                    var_info.var30.type = 2;
var_info.var31.index = (1:7);                    var_info.var31.type = 0.5;

%% 2014 Inspection Data %%
cond_index = 1;
year = 2014;
ay = year - 1991;

brd = zeros(size(Brd,1)*size(Brd,3),size(Brd,2));
bcd = zeros(size(Bcd,1)*size(Bcd,3),size(Bcd,2));
dtr_bln = nan(size(dtr,1)*size(dtr,3),size(dtr,2));
age = nan(size(yb,1)*size(yb,2),1);
yb_i = zeros(length(age),1);

for i = 1:size(Bcd,3)
    brd((i-1)*size(Brd,1)+1:i*size(Brd,1),:) = Brd(:,:,i);
    bcd((i-1)*size(Bcd,1)+1:i*size(Bcd,1),:) = Bcd(:,:,i);
    if i ~= size(Bcd,3)
        dtr_bln((i-1)*size(dtr,1)+1:i*size(dtr,1),:) = dtr(:,:,i);
    end
    age((i-1)*size(yb,1)+1:i*size(yb,1),1) = i+1991 - yb(:,i);
    yb_i((i-1)*size(yb,1)+1:i*size(yb,1),1) = i;
end

dtr_bln = [dtr_bln; 10*ones(size(Bcd,1),size(Bcd,2))];
```

```
est_cnd = (1:size(bcd,1))';

ci1_set = [23 19 5 9 7 2 30 11 4 10 16 29 8 21 22 14 27 18 24 26 31 15 25 13 12];
ci2_set = [22 20 5 18 15 19 4 25 30 12 14 24 29 16 1 23 7 8 11 27 2 13 31];
ci3_set = [23 10 20 5 26 30 1 24 11 12 13 2 4 14 29 8 16 19 22 15 25];

for k = 2:2

    eval(['exp_var_set = ci' num2str(cond_index) '_set(1:k);']);
    age_t = age;
    brd_t = brd(:,exp_var_set);
    bcd_t = bcd(:,cond_index);
    dtr_bln_t = dtr_bln(:,cond_index);
    b_index = (1:size(bcd,1))';
    yb_it = yb_i;

    if k == 1
        sub_info.index = 10^10;
        sub_info.age = age_t;
        sub_info.cr = bcd_t;
        sub_info.dtr = dtr_bln_t;
        sub_info.b_index = b_index;
        sub_info.yb_it = yb_it;
        sub_info.cond_index = cond_index;
        [trans_mc, br_index, apdt] = DTR_Plotting(sub_info);
        for lbi = 1:size(br_index,1)
            est_cnd(br_index(lbi,1),2) = br_index(lbi,2);
        end
    end
    final = [];

    m = length(exp_var_set);
    list_n = 1;
    min_bdg = 50;
    min_dtr = 200;


    for i = 1:length(exp_var_set(1:m))
        eval(['temp_var= var_info.var' num2str(exp_var_set(i),'%02d') ';']);
        int_tmp = temp_var.type;
        if int_tmp ~= 1
            brd_t(:,i) = floor(brd_t(:,i)/int_tmp) + 1;
            for j = 1:size(brd_t,1)
                if brd_t(j,i) > max(temp_var.index)
                        brd_t(j,i) = max(temp_var.index);
                end
```

```
            end
        end
    end

    while m >= length(exp_var_set)-1 && m > 0
        lt = zeros(1,m);
        for i = 1:length(exp_var_set(1:m))
            eval(['lt(i) = length(var_info.var' num2str(exp_var_set(i),'%02d') '.index);']);
        end

        total_c = prod(lt);
        n = length(lt);

        list_var = zeros(total_c,n);
        int_var = 1;
        while n > 0
            eval(['temp_l = var_info.var' num2str(exp_var_set(n),'%02d') '.index;']);
            total_c = total_c / length(temp_l);
            for i = 1:total_c
                for j = 1:length(temp_l)
                    list_var((i-1)*length(temp_l)*int_var+(j-1)*int_var+1:(i-1)*length(temp_l)*int_var+j*int_var,n) = temp_l(j);
                end
            end
            int_var = int_var*length(temp_l);
            n = n-1;
        end

        bdg_cls = nan(size(brd_t,1),1);
        for i = 1:size(brd_t,1)
            for j = 1:size(list_var,1)
                if norm(list_var(j,:) - brd_t(i,1:m)) == 0
                    bdg_cls(i) = j;
                end
            end
        end

        eval(['temp_l = var_info.var' num2str(exp_var_set(m),'%02d') '.index;']);

        for i = 1:size(list_var,1)/length(temp_l)
            rb_cmplt = 0;
            for j = 1:length(temp_l)
                tar_index = bdg_cls == (i-1)*length(temp_l)+j;

                if sum(tar_index) >= min_dtr && sum(yb_it(tar_index) == 23) >= min_bdg
                    eval(['final.var' num2str(list_n,'%02d') '.cond_index = cond_index;']);
```

```
                eval(['final.var' num2str(list_n,'%02d') '.index = list_var((i-1)*length(temp_l)+j,:);']);
                eval(['final.var' num2str(list_n,'%02d') '.num_bdg = sum(yb_it(tar_index) == 23);']);
                eval(['final.var' num2str(list_n,'%02d') '.age = age_t(tar_index,:);']);
                eval(['final.var' num2str(list_n,'%02d') '.cr = bcd_t(tar_index,:);']);
                eval(['final.var' num2str(list_n,'%02d') '.dtr = dtr_bln_t(tar_index,:);']);
                eval(['final.var' num2str(list_n,'%02d') '.b_index = b_index(tar_index,1);']);
                eval(['final.var' num2str(list_n,'%02d') '.yb_it = yb_it(tar_index);']);

                eval(['sub_info = final.var' num2str(list_n,'%02d') ';']);
                [trans_mc, br_index, apdt] = DTR_Plotting(sub_info);
                eval(['final.var' num2str(list_n,'%02d') '.trans_mc = trans_mc;']);

                eval(['output = final.var' num2str(list_n,'%02d') ';']);
                output = rmfield(output,'age');
                output = rmfield(output,'cr');
                output = rmfield(output,'dtr');
                output = rmfield(output,'b_index');
                output = rmfield(output,'yb_it');

                struct2csv(output,'output.csv');
                files = dir('output.csv');
                eval(['movefile(files.name, sprintf("output' num2str(list_n,'%02d') '.csv","f"));']);

                for lbi = 1:size(br_index,1)
                    est_cnd(br_index(lbi,1),k+2) = br_index(lbi,2);
                end

                age_t(tar_index,:) = [];
                bcd_t(tar_index,:) = [];
                brd_t(tar_index,:) = [];
                dtr_bln_t(tar_index,:) = [];
                b_index(tar_index) = [];
                yb_it(tar_index) = [];
                bdg_cls(tar_index) = [];

                list_n = list_n + 1;
                rb_cmplt = 1;
            else
                list_var((i-1)*length(temp_l)+j,m) = 10^10;
                bdg_cls(tar_index) = 10^10;
            end
        end
```

```
        if m == 1
            tar_index = bdg_cls == 10^10;

            [~,l_ind] = max(list_var((i-1)*length(temp_l)+1:i*length(temp_l),m));

            eval(['final.var' num2str(list_n,'%02d') '.cond_index = cond_index;']);
            eval(['final.var' num2str(list_n,'%02d') '.index = list_var((i-1)*length(temp_l)+l_ind(1),:);']);
            eval(['final.var' num2str(list_n,'%02d') '.num_bdg = sum(yb_it(tar_index) == 23);']);
            eval(['final.var' num2str(list_n,'%02d') '.age = age_t(tar_index,:);']);
            eval(['final.var' num2str(list_n,'%02d') '.cr = bcd_t(tar_index,:);']);
            eval(['final.var' num2str(list_n,'%02d') '.dtr = dtr_bln_t(tar_index,:);']);
            eval(['final.var' num2str(list_n,'%02d') '.b_index = est_cnd(tar_index,1);']);
            eval(['final.var' num2str(list_n,'%02d') '.yb_it = yb_it(tar_index);']);

            eval(['sub_info = final.var' num2str(list_n,'%02d') ';']);

            [trans_mc, br_index, apdt] = DTR_Plotting(sub_info);
            eval(['final.var' num2str(list_n,'%02d') '.trans_mc = trans_mc;']);

            eval(['output = final.var' num2str(list_n,'%02d') ';']);
            output = rmfield(output,'age');
            output = rmfield(output,'cr');
            output = rmfield(output,'dtr');
            output = rmfield(output,'b_index');
            output = rmfield(output,'yb_it');

            struct2csv(output,'output.csv');
            files = dir('output.csv');
            eval(['movefile(files.name, sprintf(''output' num2str(list_n,'%02d') '.csv'',''f''));']);

            for lbi = 1:size(br_index,1)
                est_cnd(br_index(lbi,1),k+2) = br_index(lbi,2);
            end

            age_t(tar_index,:) = [];
            bcd_t(tar_index,:) = [];
            brd_t(tar_index,:) = [];
            dtr_bln_t(tar_index,:) = [];
            b_index(tar_index) = [];
            yb_it(tar_index) = [];
            bdg_cls(tar_index) = [];

            list_n = list_n + 1;
```

```
        end

    end
    m = m - 1;
  end

  num_tree = structfun(@numel,final);

end
```

DTR_Plotting.m

- Line 9: ‘max_yb’ is identical to the total number of inspection years since 1992.
- Line 12: ‘dyear’ is the interval in year for zoning technique.

```
    Copyright State of Wyoming, Wyoming Department of Transportation, and Utah State University. Licensed under PGLv2 open-source license.

1   function [trans_t, br_index, apdt] = DTR_Plotting(var_info)
2
3   age = var_info.age;
4   con_dat = var_info.cr;
5   dtr = var_info.dtr;
6   br_index = var_info.b_index;
7   gr_num = zeros(size(age,1),1);
8   yb_it = var_info.yb_it;
9   max_yb = 23;
10  cond_index = var_info.cond_index;
11
12  dyear = 30;
13  for j = 1:size(age,1)
14      gr_num(j,1) = floor(age(j,1)/dyear);
15  end
16
17  for i = length(age):-1:1
18      if isnan(age(i,1)) || isnan(con_dat(i,1)) || con_dat(i,1) == 0 || isnan(dtr(i,1)) || yb_it(i) == max_yb
19          age(i) = [];
20          con_dat(i) = [];
21          dtr(i) = [];
22          br_index(i) = [];
23          gr_num(i) = [];
24          yb_it(i) = [];
25      end
```

```
end

for i = 1:9
    t_in = con_dat == i;
    if sum(t_in) < 2 || sum(t_in) == sum(dtr(t_in)) || sum(dtr(t_in)) == 0;
        age(t_in) = [];
        con_dat(t_in) = [];
        dtr(t_in) = [];
        br_index(t_in) = [];
        gr_num(t_in) = [];
        yb_it(t_in) = [];
    end
end

num_trans = nanmax(gr_num) + 1;

input_data = zeros(1,6);
en = 1;
trans_t = zeros(9*num_trans,9);

for j = 1:size(age,1)
    if gr_num(j,1) >= 0 && gr_num(j,1) <= num_trans-1 && isnan(dtr(j,1)) == 0 && dtr(j,1) ~= 10
        if dtr(j,1) == 1 && con_dat(j,1) >= 2
            a = 9*gr_num(j,1)+10-con_dat(j,1);
            b = 11-con_dat(j,1);
            trans_t(a,b) = trans_t(a,b) + 1;
            input_data(en,:) = [ gr_num(j,1) con_dat(j,1) age(j,1) 1 br_index(j,1) yb_it(j)];
            en = en+1;
        elseif con_dat(j,1) >= 1 && dtr(j,1) == 0
            a = 9*gr_num(j,1)+10-con_dat(j,1);
            b = 10-con_dat(j,1);
            trans_t(a,b) = trans_t(a,b) + 1;
            input_data(en,:) = [gr_num(j,1) con_dat(j,1) age(j,1) 0 br_index(j,1) yb_it(j)];
            en = en+1;
        end
    end
end

ap = zeros(size(input_data,1),2);

yl = 60;
cv_change = zeros(yl,1);
con_init = zeros(1,9);
init_index = 1;
while sum(trans_t(init_index,:)) == 0
```

```
    init_index = init_index + 1;
end
init_index = rem(init_index,9);
con_init(init_index) = 1;

for i = 1:num_trans

    tar_index = input_data(:,1) == i-1;
    idt = input_data(tar_index,2:3);
    dtr = input_data(tar_index,4);
    bu_dtr = input_data(tar_index,5);
    yb_t = input_data(tar_index,6);

    trans_mc = trans_t((i-1)*9+1:i*9,:);

    for j = 1:9
        if sum(trans_mc(j,:)) ~= 0
            trans_mc(j,:) = trans_mc(j,:) / sum(trans_mc(j,:));
        end
    end
    trans_mc(9,9) = 1;

    for j = 1:dyear

        cv = con_init*trans_mc^(j-1);
        cv_change((i-1)*dyear+j) = cv*(9:-1:1)';
    end
    con_init = cv;

    apdt = zeros(length(dtr),2);
    apdt(:,1) = idt(:,1) - dtr;
    prediction_t = trans_mc*(9:-1:1)';
    for j = 1:length(dtr)
        apdt(j,2) = prediction_t(10 - idt(j,1));
    end

    if i == 1
        ini_ap = 1;
    else
        ini_ap = end_ap + 1;
    end
    ap(ini_ap:size(apdt,1)+ini_ap-1,:) = apdt;

    end_ap = length(dtr);

    trans_t((i-1)*9+1:i*9,:) =  trans_mc;
```

```
    for j = 1:9
        est_tar_index = idt(:,1) == j;
        con_vec = zeros(1,9);
        con_vec(10-j) = 1;
        up_index = bu_dtr(est_tar_index);

        for k = 1:length(up_index)
            [~, temp_i] = sort( abs(br_index(:,1) - up_index(k)), 'ascend');
            br_index(temp_i(1) ,2) = con_vec*trans_mc*(9:-1:1)';
        end

    end
end

yb_index1 = input_data(:,6) == max(yb_it)-1;
yb_index2 = input_data(:,6) == max(yb_it);
hist_ap = zeros(9,2);

for i = 1:9
    hist_ap(i,1) = sum(input_data(yb_index2,2) == i);
    hist_ap(i,2) = sum(round(br_index(yb_index1,2)) == i);
end

f = figure; set(f,'position',[100 100 500 300]);


hold on; grid off; box on;
set(gca,'fontname','arial','fontsize',11)

cf = fit((0:length(cv_change)-1)',cv_change,'linearinterp');
dx = 0.01;
x = (-50:dx:100)';
y = cf(x);

hold on;

plot(x,y,'r');


plot((0:length(cv_change)-
1),cv_change,'linestyle','none','marker','x','markeredgecolor','k','MarkerSize',5);

set(gca,'ytick',(0:9));
axis([0 60 0 11]);
xlabel(sprintf('Age (Year, x) '));
if cond_index == 1
```

```
    ylabel('Deck Condition Rating (y)');
elseif cond_index == 2
    ylabel(sprintf('\\fontname{arial narrow}Superstructure Condition Rating (y)'));
elseif cond_index == 3
    ylabel(sprintf('\\fontname{arial narrow}Substructure Condition Rating (y)'));
end
```

RESULT OF TRANSITION PROBABILITY MATRIX

For the stochastic deterioration model, the prediction of condition rating can be obtained by multiplying transition probability matrix to initial condition rating vector. The program creates output files for each subset with the extension of ‘csv.’ It contains the following information:

- cond_index: 1 for deck, 2 for superstructure, and 3 for substructure.
- index: indices for explanatory variables.
- num_bdg: number of bridges belonging to the corresponding subset.
- trans_mc: two or three transition probability matrices depending on the bridge ages. The first (9×9) matrix is for the bridges less than 30 years and the next (9×9) is for the bridges between 30 and 60 years.

The first two transition matrices for each subset are tabulated in the following section.

Deck element

Table 42. Transition probability matrices for bridges belonging to WS3 (Latex Concrete/Similar) and SL1 (0 – 50 m)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.53	0.47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.79	0.21	0	0	0	0	0	0	0	0.67	0.33	0	0	0	0	0	0
7	0	0	0.92	0.08	0	0	0	0	0	0	0	0.88	0.12	0	0	0	0	0
6	0	0	0	0.93	0.07	0	0	0	0	0	0	0	0.93	0.07	0	0	0	0
5	0	0	0	0	0.95	0.05	0	0	0	0	0	0	0	0.93	0.07	0	0	0
4	0	0	0	0	0	0.88	0.12	0	0	0	0	0	0	0	0.93	0.07	0	0
3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.95	0.05	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 43. Transition probability matrices for bridges belonging to WS3 (Latex Concrete/Similar) and SL2 (50 – 100 m)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.78	0.22	0	0	0	0	0	0	0	0.75	0.25	0	0	0	0	0	0
7	0	0	0.92	0.08	0	0	0	0	0	0	0	0.87	0.13	0	0	0	0	0
6	0	0	0	0.91	0.09	0	0	0	0	0	0	0	0.9	0.1	0	0	0	0
5	0	0	0	0	0.9	0.1	0	0	0	0	0	0	0	0.92	0.08	0	0	0
4	0	0	0	0	0	0.89	0.11	0	0	0	0	0	0	0	0.92	0.08	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.92	0.08	0
2	0	0	0	0	0	0	0	0.67	0.33	0	0	0	0	0	0	0	1	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 44. Transition probability matrices for bridges belonging to WS6 (Bituminous) and SL1 (0 – 50 m)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.85	0.15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.81	0.19	0	0	0	0	0	0	0	0.77	0.23	0	0	0	0	0	0
7	0	0	0.94	0.06	0	0	0	0	0	0	0	0.92	0.08	0	0	0	0	0
6	0	0	0	0.95	0.05	0	0	0	0	0	0	0	0.95	0.05	0	0	0	0
5	0	0	0	0	0.99	0.01	0	0	0	0	0	0	0	0.95	0.05	0	0	0
4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.96	0.04	0	0
3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 45. Transition probability matrices for bridges belonging to WS7 (Wood/Timber) and SL1 (0 – 50 m)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.45	0.55	0	0	0	0	0	0	0	0.5	0.5	0	0	0	0	0	0	0
8	0	0.81	0.19	0	0	0	0	0	0	0	0.66	0.34	0	0	0	0	0	0
7	0	0	0.87	0.13	0	0	0	0	0	0	0	0.88	0.12	0	0	0	0	0
6	0	0	0	0.9	0.1	0	0	0	0	0	0	0	0.93	0.07	0	0	0	0
5	0	0	0	0	0.92	0.08	0	0	0	0	0	0	0	0.9	0.1	0	0	0
4	0	0	0	0	0	0.8	0.2	0	0	0	0	0	0	0	0.92	0.08	0	0
3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.93	0.07
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 46. Transition probability matrices for bridges belonging to WS8 (Gravel) and SL1 (0 – 50 m)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.86	0.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.8	0.2	0	0	0	0	0	0	0	0.76	0.24	0	0	0	0	0	0
7	0	0	0.93	0.07	0	0	0	0	0	0	0	0.9	0.1	0	0	0	0	0
6	0	0	0	0.95	0.05	0	0	0	0	0	0	0	0.94	0.06	0	0	0	0
5	0	0	0	0	0.94	0.06	0	0	0	0	0	0	0	0.91	0.09	0	0	0
4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 47. Transition probability matrices for bridges belonging to WS0 (None) and SL1 (0 – 50 m)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.67	0.33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.86	0.14	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
7	0	0	0.93	0.07	0	0	0	0	0	0	0	0.87	0.13	0	0	0	0	0
6	0	0	0	0.96	0.04	0	0	0	0	0	0	0	0.94	0.06	0	0	0	0
5	0	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.96	0.04	0	0	0
4	0	0	0	0	0	0.95	0.05	0	0	0	0	0	0	0	0.95	0.05	0	0
3	0	0	0	0	0	0	0.96	0.04	0	0	0	0	0	0	0	0.92	0.08	0
2	0	0	0	0	0	0	0	0.96	0.04	0	0	0	0	0	0	0	0.99	0.01
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 48. Transition probability matrices for bridges belonging to WS0 (None) and SL2 (50 – 100 m)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.89	0.11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0.91	0.09	0	0	0	0	0	0	0	0.89	0.11	0	0	0	0	0
6	0	0	0	0.95	0.05	0	0	0	0	0	0	0	0.93	0.07	0	0	0	0
5	0	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.95	0.05	0	0	0
4	0	0	0	0	0	0.96	0.04	0	0	0	0	0	0	0	0.94	0.06	0	0
3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.96	0.04	0
2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.6	0.4
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 49. Transition probability matrices for bridges belonging to WS5 (Epoxy Overlay) and SL1 – SL5

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.5	0.5	0	0	0	0	0	0	0	0.88	0.13	0	0	0	0	0	0
7	0	0	0.92	0.08	0	0	0	0	0	0	0	0.88	0.12	0	0	0	0	0
6	0	0	0	0.95	0.05	0	0	0	0	0	0	0	0.9	0.1	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0	0	0.9	0.1	0	0	0
4	0	0	0	0	0	0.86	0.14	0	0	0	0	0	0	0	0.82	0.18	0	0
3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.67	0.33	0
2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 50. Transition probability matrices for bridges belonging to WS0 (None) and SL3 – SL5 (100 m ~)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.88	0.13	0	0	0	0	0	0	0	0.88	0.13	0	0	0	0	0	0
7	0	0	0.89	0.11	0	0	0	0	0	0	0	0.85	0.15	0	0	0	0	0
6	0	0	0	0.93	0.07	0	0	0	0	0	0	0	0.93	0.07	0	0	0	0
5	0	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.93	0.07	0	0	0
4	0	0	0	0	0	0.88	0.13	0	0	0	0	0	0	0	0.95	0.05	0	0
3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 51. Transition probability matrices for bridges belonging not to previous nine subsets

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.88	0.12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.75	0.25	0	0	0	0	0	0	0	0.72	0.28	0	0	0	0	0	0
7	0	0	0.82	0.18	0	0	0	0	0	0	0	0.85	0.15	0	0	0	0	0
6	0	0	0	0.93	0.07	0	0	0	0	0	0	0	0.91	0.09	0	0	0	0
5	0	0	0	0	0.93	0.07	0	0	0	0	0	0	0	0.93	0.07	0	0	0
4	0	0	0	0	0	0.96	0.04	0	0	0	0	0	0	0	0.89	0.11	0	0
3	0	0	0	0	0	0	0.9	0.1	0	0	0	0	0	0	0	0.89	0.11	0
2	0	0	0	0	0	0	0	0.85	0.15	0	0	0	0	0	0	0	1	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Superstructure Element

Table 52. Transition probability matrices for bridges belonging to DST1 (Concrete Cast-in-Place) and BRW2 (5 – 10 m, 16.4 ft – 32.8 ft)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.8	0.2	0	0	0	0	0	0	0	0.73	0.27	0	0	0	0	0	0	0
8	0	0.94	0.06	0	0	0	0	0	0	0	0.8	0.2	0	0	0	0	0	0
7	0	0	0.94	0.06	0	0	0	0	0	0	0	0.95	0.05	0	0	0	0	0
6	0	0	0	0.99	0.01	0	0	0	0	0	0	0	0.98	0.02	0	0	0	0
5	0	0	0	0	0.99	0.01	0	0	0	0	0	0	0	0.98	0.02	0	0	0
4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 53. Transition probability matrices for bridges belonging to DST1 (Concrete Cast-in-Place) and BRW3 (10 – 15 m, 32.8 ft – 49.2 ft)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.81	0.19	0	0	0	0	0	0	0	0.67	0.33	0	0	0	0	0	0	0
8	0	0.86	0.14	0	0	0	0	0	0	0	0.78	0.22	0	0	0	0	0	0
7	0	0	0.95	0.05	0	0	0	0	0	0	0	0.96	0.04	0	0	0	0	0
6	0	0	0	0.99	0.01	0	0	0	0	0	0	0	0.98	0.02	0	0	0	0
5	0	0	0	0	0.99	0.01	0	0	0	0	0	0	0	0.98	0.02	0	0	0
4	0	0	0	0	0	0.92	0.08	0	0	0	0	0	0	0	1	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 54. Transition probability matrices for bridges belonging to DST1 (Concrete Cast-in-Place) and BRW4 (15 – 20 m, 49.2 ft – 65.6 ft)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.8	0.2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
8	0	0.93	0.07	0	0	0	0	0	0	0	0.67	0.33	0	0	0	0	0	0
7	0	0	0.97	0.03	0	0	0	0	0	0	0	0.97	0.03	0	0	0	0	0
6	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0.67	0.33	0	0	0
4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 55. Transition probability matrices for bridges belonging to DST2 (Concrete Precast Panels) and BRW2 (5 – 10 m, 16.4 ft – 32.8 ft)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.67	0.33	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
8	0	0.94	0.06	0	0	0	0	0	0	0	0.94	0.06	0	0	0	0	0	0
7	0	0	0.87	0.13	0	0	0	0	0	0	0	0.98	0.02	0	0	0	0	0
6	0	0	0	0.93	0.07	0	0	0	0	0	0	0	0.97	0.03	0	0	0	0
5	0	0	0	0	0.99	0.01	0	0	0	0	0	0	0	0.99	0.01	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 56. Transition probability matrices for bridges belonging to DST6 (Corrugated Steel) and BRW1 (0 – 5 m, 0 ft – 16.4 ft)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.61	0.39	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.84	0.16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0.86	0.14	0	0	0	0	0	0	0	0.83	0.17	0	0	0	0	0
6	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.92	0.08	0	0	0	0
5	0	0	0	0	0.99	0.01	0	0	0	0	0	0	0	0.99	0.01	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 57. Transition probability matrices for bridges belonging to DST6 (Corrugated Steel) and BRW2 (5 – 10 m, 16.4 ft – 32.8 ft)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.74	0.26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.75	0.25	0	0	0	0	0	0	0	0.7	0.3	0	0	0	0	0	0
7	0	0	0.78	0.22	0	0	0	0	0	0	0	0.67	0.33	0	0	0	0	0
6	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.99	0.01	0	0	0	0
5	0	0	0	0	0.98	0.02	0	0	0	0	0	0	0	0.98	0.02	0	0	0
4	0	0	0	0	0	0.95	0.05	0	0	0	0	0	0	0	1	0	0	0
3	0	0	0	0	0	0	0.88	0.13	0	0	0	0	0	0	0	0.96	0.04	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 58. Transition probability matrices for bridges belonging to DST8 (Wood/Timber) and BRW1 (0 – 5 m, 0 ft – 16.4 ft)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.79	0.21	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
8	0	0.86	0.14	0	0	0	0	0	0	0	0.85	0.15	0	0	0	0	0	0
7	0	0	0.89	0.11	0	0	0	0	0	0	0	0.89	0.11	0	0	0	0	0
6	0	0	0	0.93	0.07	0	0	0	0	0	0	0	0.94	0.06	0	0	0	0
5	0	0	0	0	0.94	0.06	0	0	0	0	0	0	0	0.95	0.05	0	0	0
4	0	0	0	0	0	0.93	0.07	0	0	0	0	0	0	0	0.93	0.07	0	0
3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.98	0.02	0
2	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.91	0.09
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 59. Transition probability matrices for bridges belonging to DST8 (Wood/Timber) and BRW2 (5 – 10 m, 16.4 ft – 32.8 ft)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.8	0.2	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
8	0	0.77	0.23	0	0	0	0	0	0	0	0.82	0.18	0	0	0	0	0	0
7	0	0	0.89	0.11	0	0	0	0	0	0	0	0.89	0.11	0	0	0	0	0
6	0	0	0	0.93	0.07	0	0	0	0	0	0	0	0.92	0.08	0	0	0	0
5	0	0	0	0	0.91	0.09	0	0	0	0	0	0	0	0.94	0.06	0	0	0
4	0	0	0	0	0	0.94	0.06	0	0	0	0	0	0	0	0.93	0.07	0	0
3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.97	0.03	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 60. Transition probability matrices for bridges belonging to DST1 (Concrete Cast-in-Place) and BRW1 (0 – 5 m, 0 ft – 16.4 ft), BRW5 (+ 20 m, 65.6 ft)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.82	0.18	0	0	0	0	0	0	0	0.79	0.21	0	0	0	0	0	0	0
8	0	0.91	0.09	0	0	0	0	0	0	0	0.93	0.07	0	0	0	0	0	0
7	0	0	0.95	0.05	0	0	0	0	0	0	0	0.94	0.06	0	0	0	0	0
6	0	0	0	0.99	0.01	0	0	0	0	0	0	0	0.99	0.01	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 61. Transition probability matrices for bridges belonging to DST2 (Concrete Precast Panels) and BRW1, BRW3 - BRW5

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.96	0.04	0	0	0	0	0	0	0	0.92	0.08	0	0	0	0	0	0
7	0	0	0.95	0.05	0	0	0	0	0	0	0	0.97	0.03	0	0	0	0	0
6	0	0	0	0.85	0.15	0	0	0	0	0	0	0	0.83	0.17	0	0	0	0
5	0	0	0	0	0.98	0.03	0	0	0	0	0	0	0	0.98	0.02	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 62. Transition probability matrices for bridges belonging not to previous ten subsets

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.86	0.14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.95	0.05	0	0	0	0	0	0	0	0.78	0.22	0	0	0	0	0	0
7	0	0	0.91	0.09	0	0	0	0	0	0	0	0.95	0.05	0	0	0	0	0
6	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.91	0.09	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Substructure Element

Table 63. Transition probability matrices for bridges belonging to WS3 (Latex Concrete/Similar) and DL5 (MS 18)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.76	0.24	0	0	0	0	0	0	0	0.6	0.4	0	0	0	0	0	0
7	0	0	0.97	0.03	0	0	0	0	0	0	0	0.96	0.04	0	0	0	0	0
6	0	0	0	0.98	0.02	0	0	0	0	0	0	0	0.97	0.03	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0	0	0.92	0.08	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.92	0.08	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 64. Transition probability matrices for bridges belonging to WS3 (Latex Concrete/Similar) and DL6 (MS 18+Mod)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.73	0.27	0	0	0	0	0	0	0	0.61	0.39	0	0	0	0	0	0
7	0	0	0.96	0.04	0	0	0	0	0	0	0	0.95	0.05	0	0	0	0	0
6	0	0	0	0.98	0.02	0	0	0	0	0	0	0	0.98	0.02	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0	0	0.99	0.01	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 65. Transition probability matrices for bridges belonging to WS6 (Bituminous) and DL2 (M 13.5)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.81	0.19	0	0	0	0	0	0	0	0.74	0.26	0	0	0	0	0	0
7	0	0	0.9	0.1	0	0	0	0	0	0	0	0.92	0.08	0	0	0	0	0
6	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.93	0.07	0	0	0	0
5	0	0	0	0	0.83	0.17	0	0	0	0	0	0	0	0.96	0.04	0	0	0
4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.89	0.11	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 66. Transition probability matrices for bridges belonging to WS6 (Bituminous) and DL5 (MS 18)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.81	0.19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.83	0.17	0	0	0	0	0	0	0	0.75	0.25	0	0	0	0	0	0
7	0	0	0.95	0.05	0	0	0	0	0	0	0	0.93	0.07	0	0	0	0	0
6	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.97	0.03	0	0	0	0
5	0	0	0	0	0.96	0.04	0	0	0	0	0	0	0	0.98	0.02	0	0	0
4	0	0	0	0	0	0.85	0.15	0	0	0	0	0	0	0	1	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 67. Transition probability matrices for bridges belonging to WS6 (Bituminous) and DL6 (MS 18+Mod)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.73	0.27	0	0	0	0	0	0	0	0.7	0.3	0	0	0	0	0	0
7	0	0	0.93	0.07	0	0	0	0	0	0	0	0.9	0.1	0	0	0	0	0
6	0	0	0	0.95	0.05	0	0	0	0	0	0	0	0.99	0.01	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0	0	0.98	0.02	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.94	0.06	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.83	0.17	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 68. Transition probability matrices for bridges belonging to WS6 (Bituminous) and DL0 (Other/Unknown)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.8	0.2	0	0	0	0	0	0	0	0.79	0.21	0	0	0	0	0	0
7	0	0	0.91	0.09	0	0	0	0	0	0	0	0.88	0.12	0	0	0	0	0
6	0	0	0	0.94	0.06	0	0	0	0	0	0	0	0.95	0.05	0	0	0	0
5	0	0	0	0	0.98	0.02	0	0	0	0	0	0	0	0.95	0.05	0	0	0
4	0	0	0	0	0	0.84	0.16	0	0	0	0	0	0	0	0.98	0.02	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 69. Transition probability matrices for bridges belonging to WS7 (Wood/Timber) and DL0 (Other/Unknown)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.69	0.31	0	0	0	0	0	0	0	0.67	0.33	0	0	0	0	0	0
7	0	0	0.89	0.11	0	0	0	0	0	0	0	0.9	0.1	0	0	0	0	0
6	0	0	0	0.9	0.1	0	0	0	0	0	0	0	0.91	0.09	0	0	0	0
5	0	0	0	0	0.9	0.1	0	0	0	0	0	0	0	0.95	0.05	0	0	0
4	0	0	0	0	0	0.93	0.07	0	0	0	0	0	0	0	0.9	0.1	0	0
3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.96	0.04	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 70. Transition probability matrices for bridges belonging to WS8 (Gravel) and DL0 (Other/Unknown)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.74	0.26	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
7	0	0	0.89	0.11	0	0	0	0	0	0	0	0.89	0.11	0	0	0	0	0
6	0	0	0	0.95	0.05	0	0	0	0	0	0	0	0.94	0.06	0	0	0	0
5	0	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.97	0.03	0	0	0
4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.98	0.02	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 71. Transition probability matrices for bridges belonging to WS0 (None) and DL5 (MS18)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.83	0.17	0	0	0	0	0	0	0	0.87	0.13	0	0	0	0	0	0
7	0	0	0.97	0.03	0	0	0	0	0	0	0	0.97	0.03	0	0	0	0	0
6	0	0	0	0.98	0.02	0	0	0	0	0	0	0	0.98	0.02	0	0	0	0
5	0	0	0	0	0.98	0.02	0	0	0	0	0	0	0	0.99	0.01	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 72. Transition probability matrices for bridges belonging to WS0 (None) and DL6 (MS 18+Mod)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.5	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0.98	0.02	0	0	0	0	0	0	0	0.97	0.03	0	0	0	0	0
6	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.97	0.03	0	0	0	0
5	0	0	0	0	0.96	0.04	0	0	0	0	0	0	0	0.99	0.01	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 73. Transition probability matrices for bridges belonging to WS0 (None) and DL9 (MS 22.5)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	No bridge exist!								
8	0	0	0	0	0	0	0	0	0									
7	0	0	0.97	0.03	0	0	0	0	0									
6	0	0	0	0	0	0	0	0	0									
5	0	0	0	0	0.86	0.14	0	0	0									
4	0	0	0	0	0	0	0	0	0									
3	0	0	0	0	0	0	0	0	0									
2	0	0	0	0	0	0	0	0	0									
1	0	0	0	0	0	0	0	0	1									

Table 74. Transition probability matrices for bridges belonging to WS0 (None) and DL0 (Other/Unknown)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.85	0.15	0	0	0	0	0	0	0	0.92	0.08	0	0	0	0	0	0
7	0	0	0.98	0.02	0	0	0	0	0	0	0	0.97	0.03	0	0	0	0	0
6	0	0	0	0.97	0.03	0	0	0	0	0	0	0	0.98	0.02	0	0	0	0
5	0	0	0	0	0.95	0.05	0	0	0	0	0	0	0	0.99	0.01	0	0	0
4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 75. Transition probability matrices for bridges belonging to WS5 (Epoxy Overlay) and DL0 – DL9 (all)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	1	0	0	0	0	0	0	0	0.88	0.13	0	0	0	0	0	0
7	0	0	0.98	0.02	0	0	0	0	0	0	0	0.96	0.04	0	0	0	0	0
6	0	0	0	1	0	0	0	0	0	0	0	0	0.95	0.05	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 76. Transition probability matrices for bridges belonging to WS6 (Bituminous) and DL1 (M 9), DL3 (MS 13.5), DL4 (M 18), and DL9 (MS 22.5)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.33	0.67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.93	0.07	0	0	0	0	0	0	0	0.8	0.2	0	0	0	0	0	0
7	0	0	0.96	0.04	0	0	0	0	0	0	0	0.91	0.09	0	0	0	0	0
6	0	0	0	0.95	0.05	0	0	0	0	0	0	0	0.97	0.03	0	0	0	0
5	0	0	0	0	0.95	0.05	0	0	0	0	0	0	0	0.95	0.05	0	0	0
4	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.96	0.04	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 77. Transition probability matrices for bridges belonging to WS8 (Gravel) and DL1 – DL9 (all except DL0)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.81	0.19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.81	0.19	0	0	0	0	0	0	0	0.76	0.24	0	0	0	0	0	0
7	0	0	0.93	0.07	0	0	0	0	0	0	0	0.93	0.07	0	0	0	0	0
6	0	0	0	0.95	0.05	0	0	0	0	0	0	0	0.87	0.13	0	0	0	0
5	0	0	0	0	0.98	0.02	0	0	0	0	0	0	0	1	0	0	0	0
4	0	0	0	0	0	0.89	0.11	0	0	0	0	0	0	0	1	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 78. Transition probability matrices for bridges belonging to WS0 (None) and DL1 – DL4 (M 9 – M 18)

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.93	0.07	0	0	0	0	0	0	0	0.88	0.13	0	0	0	0	0	0
7	0	0	0.95	0.05	0	0	0	0	0	0	0	0.97	0.03	0	0	0	0	0
6	0	0	0	0.98	0.02	0	0	0	0	0	0	0	0.97	0.03	0	0	0	0
5	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

Table 79. Transition probability matrices for bridges belonging not to previous 16 subsets

CR	Age less than 30 years									Age between 30 and 60 years								
	9	8	7	6	5	4	3	2	1	9	8	7	6	5	4	3	2	1
9	0.77	0.23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0.75	0.25	0	0	0	0	0	0	0	0.75	0.25	0	0	0	0	0	0
7	0	0	0.91	0.09	0	0	0	0	0	0	0	0.89	0.11	0	0	0	0	0
6	0	0	0	0.96	0.04	0	0	0	0	0	0	0	0.96	0.04	0	0	0	0
5	0	0	0	0	0.9	0.1	0	0	0	0	0	0	0	0.94	0.06	0	0	0
4	0	0	0	0	0	0.9	0.1	0	0	0	0	0	0	0	0.94	0.06	0	0
3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0.94	0.06	0
2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1

GUIDELINES TO RUN CODES

- Step 1: Download and install Matlab Runtime ver. 8.5 (© 1994-2016 The MathWorks, Inc.) from http://www.mathworks.com/products/compiler/mcr/.

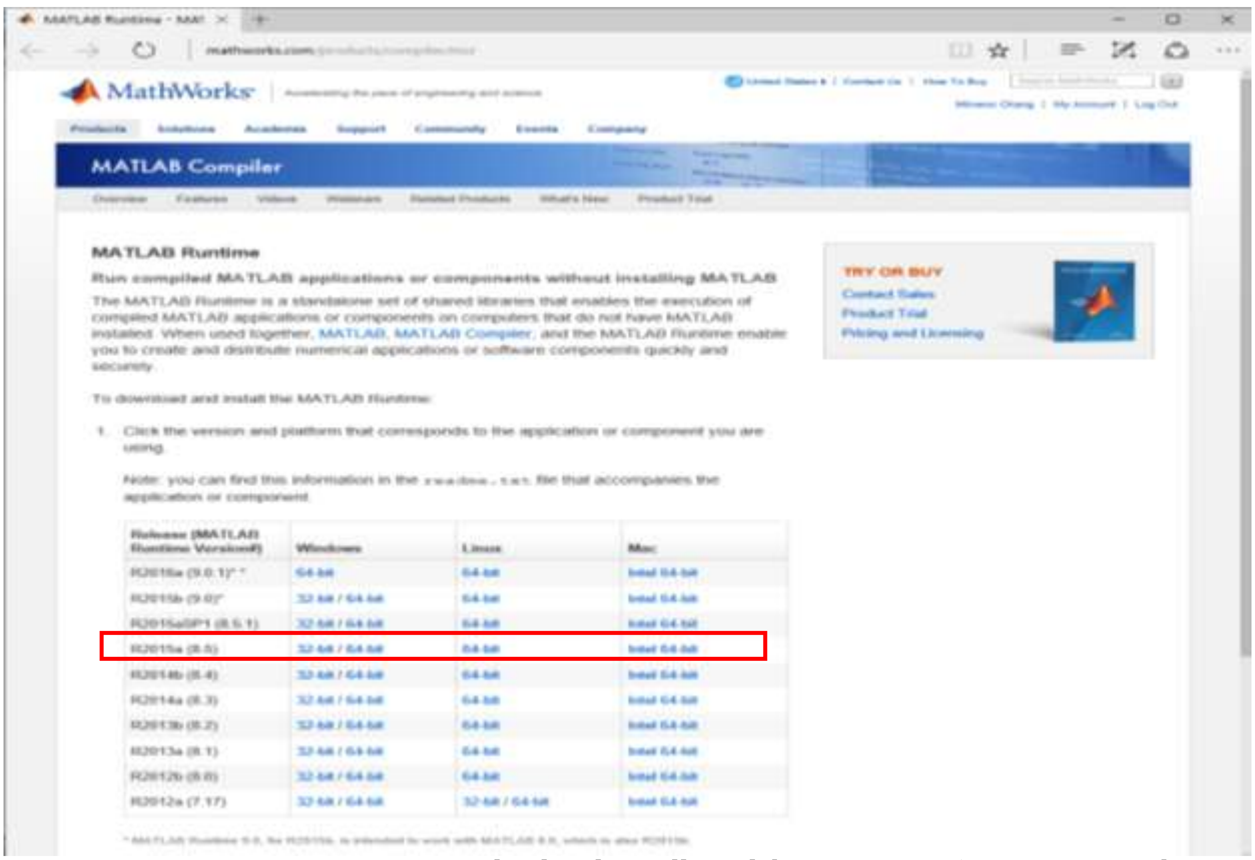


Figure 89. Screen Capture. Download and install Matlab runtime 8.5 (© 1994-2016 The MathWorks, Inc.)

- Step 2: Update codes for the users/ experiment and create executable files. If necessary, the user can create her/his own executable file. In the command window, type ‘deploytool’ and select ‘application compiler’, then the compiler toolbox pops up (Figure A-81). Specify the following information: 1) select the code, 2) insert the basic information, 3) locate all associated files (the program automatically detects subroutines), and 4) click the package button and process to create executable file.

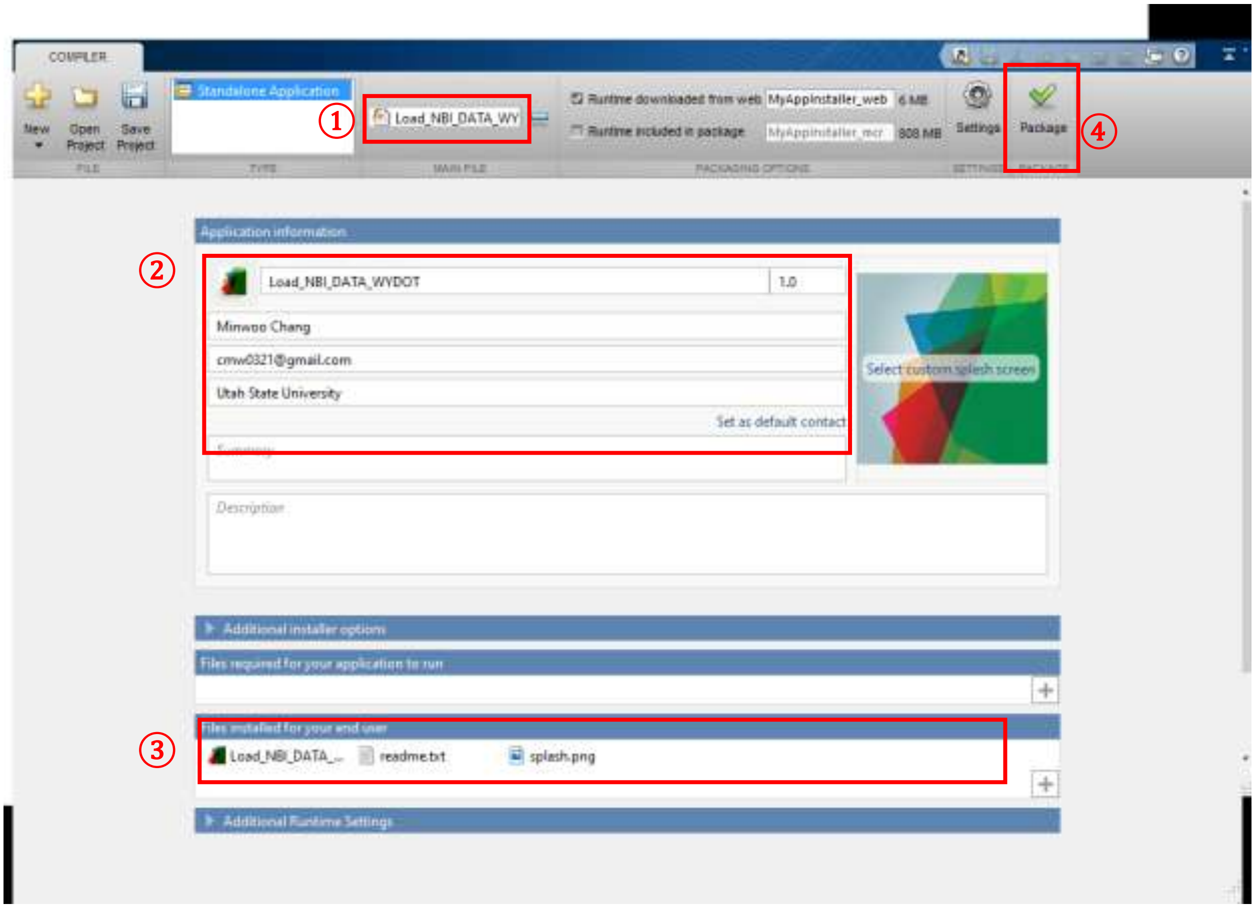


Figure 90. Screen Capture. Compiler to create executable files for ‘Load_NBI_DATA_WYDOT.exe’ and ‘DTR_MODEL_WYDOT.exe’

- Step 3: Place all files in the same folder and run ‘Load_NBI_DATA_WYDOT.exe’ which creates ‘RAW_DATA.mat’ for the development of deterioration models. It is the only required step when the user attempts to create first data file or update the contents.

- Step 4: Run ‘DTR_MODEL_WYDOT.exe’ when the ‘RAW_DATA.mat’ file is created.

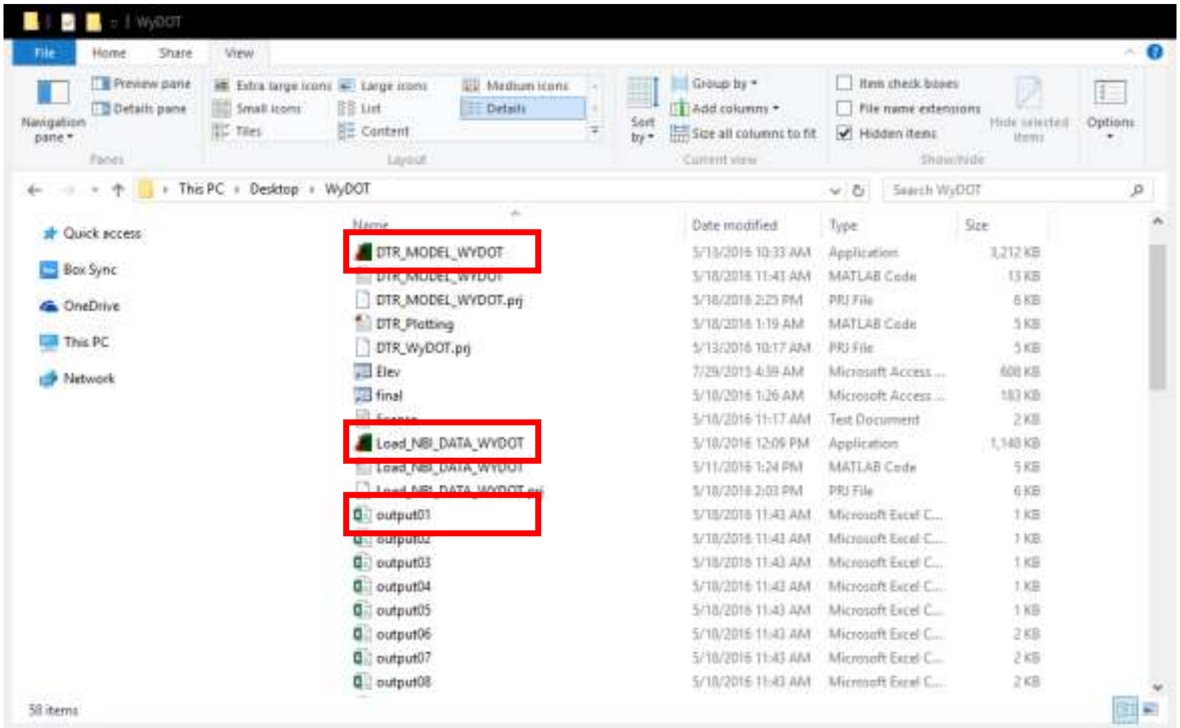


Figure 91. Screen Capture. Run executable files to develop deterioration models

- Step 5: Run ‘DTR_MODEL_WYDOT.exe’ when the ‘RAW_DATA.mat’ file is created.

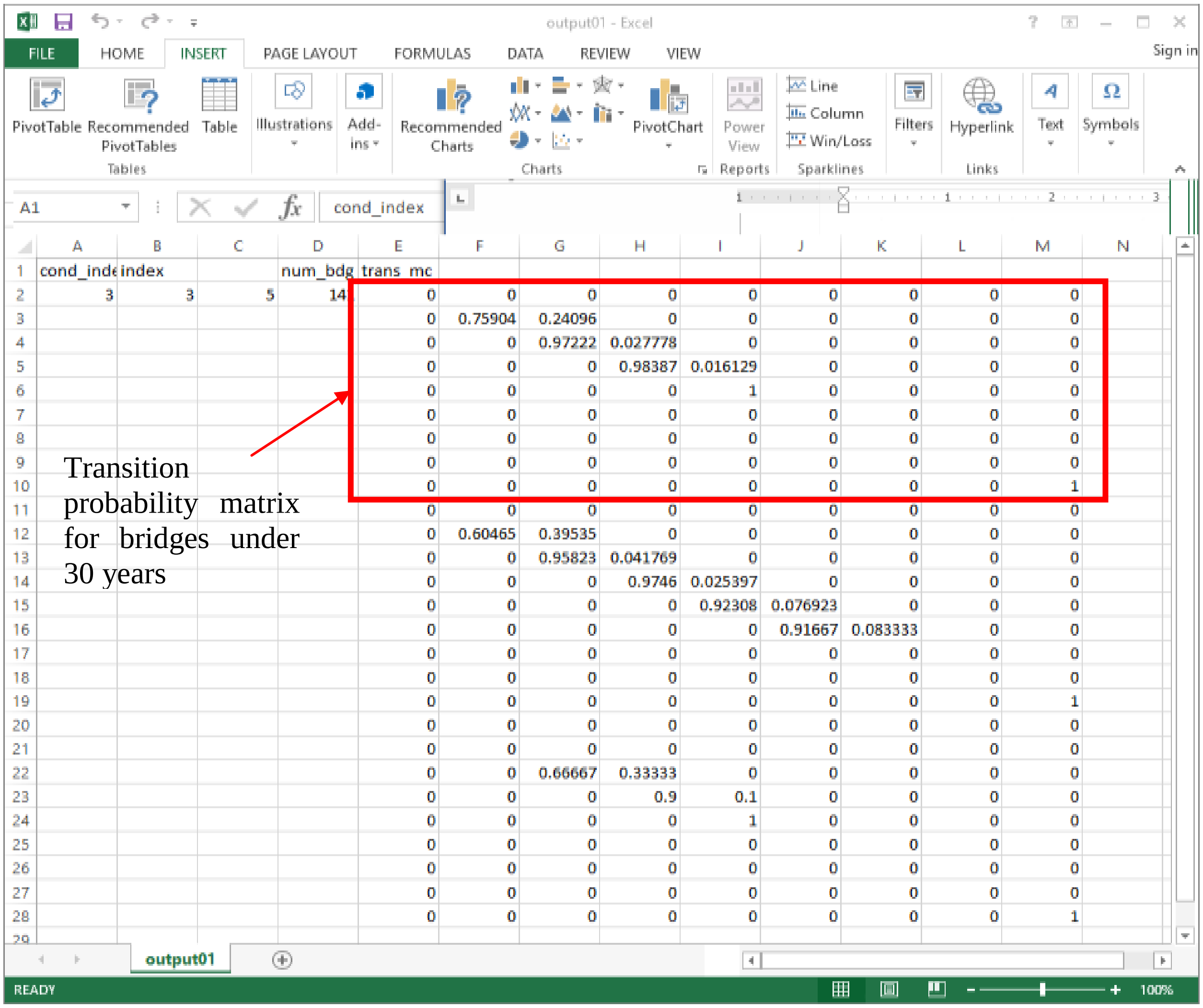
- Step 6: Check the output files.

The first column indicates what element is considered for the development of deterioration model. The possible indices are [1, 2, 3] for [deck, superstructure, substructure].

The next two columns are the specific indices for two explanatory variables. Table 80 ~ Table 82 are the specification of indices for explanatory variables when deck, superstructure, and substructure deterioration models are considered, respectively.

The fourth column explains the number of bridges in the corresponding subset.

The rest of the output shows the deterioration models for every thirty years. For example, the nine rows are transition probability matrix for bridges under thirty years old. The number of matrices varies from one to three, but mostly two or three are generated.



	A	B	C	D	E	F	G	H	I	J	K	L	M
1	cond_inde	index		num_bdg	trans_mc								
2	3	3	5	14	0	0	0	0	0	0	0	0	0
3					0	0.75904	0.24096	0	0	0	0	0	0
4					0	0	0.97222	0.027778	0	0	0	0	0
5					0	0	0	0.98387	0.016129	0	0	0	0
6					0	0	0	0	1	0	0	0	0
7					0	0	0	0	0	0	0	0	0
8					0	0	0	0	0	0	0	0	0
9					0	0	0	0	0	0	0	0	0
10					0	0	0	0	0	0	0	0	1
11					0	0	0	0	0	0	0	0	0
12					0	0.60465	0.39535	0	0	0	0	0	0
13					0	0	0.95823	0.041769	0	0	0	0	0
14					0	0	0	0.9746	0.025397	0	0	0	0
15					0	0	0	0	0.92308	0.076923	0	0	0
16					0	0	0	0	0	0.91667	0.083333	0	0
17					0	0	0	0	0	0	0	0	0
18					0	0	0	0	0	0	0	0	0
19					0	0	0	0	0	0	0	0	1
20					0	0	0	0	0	0	0	0	0
21					0	0	0	0	0	0	0	0	0
22					0	0	0.66667	0.33333	0	0	0	0	0
23					0	0	0	0.9	0.1	0	0	0	0
24					0	0	0	0	1	0	0	0	0
25					0	0	0	0	0	0	0	0	0
26					0	0	0	0	0	0	0	0	0
27					0	0	0	0	0	0	0	0	0
28					0	0	0	0	0	0	0	0	1

Figure 92. Screen Capture. Output file example

Table 80. Specific description for the indices when deterioration model for deck element is developed

Type of Wearing Surface		Structure Length	
Index	Description	Index	Description
1	Monolithic Concrete	1	0 – 50 (*m*)
2	Integral Concrete	2	50 – 100 (*m*)
3	Latex Concrete/Similar	3	100 – 150 (*m*)
4	Low Slump Concrete	4	150 – 200 (*m*)
5	Epoxy Overlay	5	200 – (*m*)
6	Bituminous		
7	Wood/Timber		
8	Gravel		
9	Other		
0	None		

Table 81. Specific description for the indices when deterioration model for superstructure element is developed

Deck Structure Type		Bridge Roadway Width (Curb-to-Curb)	
Index	Description	Index	Description
1	Concrete Cast-in-Place	1	0 – 5 (*m*)
2	Concrete Precast Panels	2	5 – 10 (*m*)
3	Open Grating	3	10 – 15 (*m*)
4	Closed Grating	4	15 – 20 (*m*)
5	Steel Plate	5	20 – 25 (*m*)
6	Corrugated Steel	6	25 – (*m*)
7	Aluminum		
8	Wood/Timber		
9	Other		

Table 82. Specific description for the indices when deterioration model for substructure element is developed

Type of Wearing Surface		Design Load	
Index	Description	Index	Description
1	Monolithic Concrete	1	M 9
2	Integral Concrete	2	M 13.5
3	Latex Concrete/Similar	3	MS 13.5
4	Low Slump Concrete	4	M 18
5	Epoxy Overlay	5	MS 18
6	Bituminous	6	MS 18+Mod
7	Wood/Timber	7	Pedestrian
8	Gravel	8	Railroad
9	Other	9	MS 22.5
0	None	0	Other/Unknown

GUIDELINES TO INSERT NEW DATA

NBI inspection data is written by WYDOT in ascii code and is available to the general public from http://www.fhwa.dot.gov/bridge/nbi/ascii.cfm. The inspection data is archived from 1992 and the most recent inspection data is 2015 as of May 31, 2016. Additional data has been obtained from WYDOT directly. If the user want to insert new data into the program, download the inspection data for Wyoming and save it into the folder where the program is located. For example, assume that the user wants to insert 2015 inspection data. The 'Load_NBI_DATA_WYDOT.m' should be modified at lines 8 and 11 such that the number '23' becomes'24'. In the line 118 of 'DTR_MODEL_WYDOT.m', the variable 'year' should be '2015' instead of '2014'. In the same manner, the line 8 of 'DTR_Plotting.m', the variable 'max_yb' should be '24' instead of '23'. Then, the user can create executable files using 'deploytool' and develop new deterioration models reflecting 2015 inspection data.