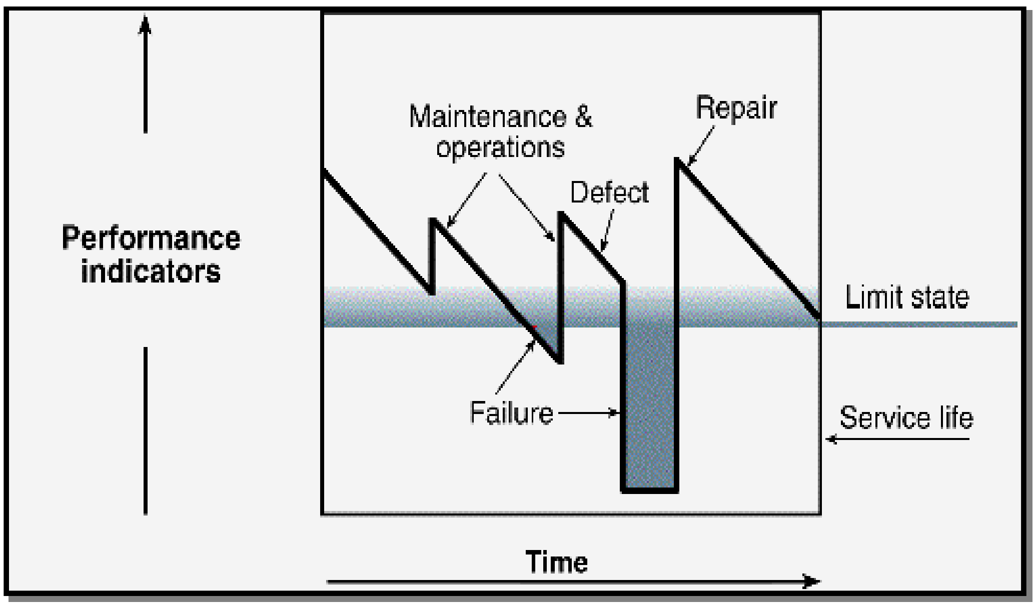
DEVELOPING DETERIORATION MODELS FOR NEBRASKA BRIDGES

Nebraska Department of Roads (NDOR)

Project Number: SPR-P1(11) M302



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FINAL REPORT

Principal Investigator

George Morcous

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12. Abstract

Nebraska Bridge Management System (NBMS) was developed in 1999 to assist in optimizing budget allocation for the maintenance, rehabilitation and replacement needs of highway bridges. This requires the prediction of bridge deterioration to calculate life-cycle costs. At the meantime, the approach adopted to predict the deterioration of bridge components is based on national average deterioration rates, which are one drop in the deck condition rating every eight years and one drop in the superstructure and substructure condition rating every ten years. This approach does not account for the impact of traffic volume, structure and material type, and environment impacts, in addition to being not specific to Nebraska bridges.

The objective of this project is to develop deterioration models for Nebraska bridges that are based on the condition ratings of bridge components (i.e. deck, superstructure, and substructure) obtained from bridge inspections since 1998 up to 2010. The impact of governing deterioration factors, such as structure type, deck type, wearing surface, deck protection, ADT, ADTT, and highway district, is considered in developing these models.

Recently, NDOR decided to adopt "Pontis", the BMS supported by the AASHTO, to avoid the frequent updates of NBMS, which is costly and time-consuming. Pontis requires the use of a specific type of deterioration models (i.e. transition probability matrices), which are not available for Nebraska bridges. Therefore, another objective of this project is to develop Pontis deterioration models using the inventory and condition data readily available in the NBMS database. Procedures for updating the developed model will be also presented.

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ABSTRACT

Nebraska Bridge Management System (NBMS) was developed in 1999 to assist in optimizing budget allocation for the maintenance, rehabilitation and replacement needs of highway bridges. This requires the prediction of bridge deterioration to calculate life-cycle costs. At the meantime, the approach adopted to predict the deterioration of bridge components is based on national average deterioration rates, which are one drop in the deck condition rating every eight years and one drop in the superstructure and substructure condition rating every ten years. This approach does not account for the impact of traffic volume, structure and material type, and environment impacts, in addition to being not specific to Nebraska bridges.

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ACRONYMS

AASHTO	American Association of State and Highway Transportation Officials
ADT	Average Daily Traffic
ADTT	Average Daily Truck Traffic
BISON	Bridge Inspection System of Nebraska
BLCCA	Bridge Life-Cycle Cost Analysis
BMS	Bridge Management System
FHWA	Federal Highway Administration
IMS	Infrastructure Management System
LCC	Life-Cycle Cost
MR&R	Maintenance, Rehabilitation, and Replacement
NBI	National Bridge Inventory
NBIS	National Bridge Inspection Standards
NBMS	Nebraska Bridge Management System
NDOR	Nebraska Department of Roads
PMS	Pavement Management System
TAC	Technical Advisors Committee
USDOT	United States Department of Transportation

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1 INTRODUCTION

1.1 PROBLEM STATEMENT

The life-cycle cost (LCC) assessment of highway bridges is a decision making approach that is based on the total cost accrued over the entire life of a bridge extending from its construction to its replacement or final demolition (USDOT 2002). During the service life of a bridge, different types of costs are incurred by both bridge owners and users. The owner costs (sometimes called "agency costs") represent construction cost, maintenance cost, and demolition cost. The users' costs represent the costs incurred due to the closure of a bridge for maintenance and the cost incurred due to traffic congestion, detours, accidents, and failures, besides the indirect costs of environment pollution due to idling of vehicles. Although an accurate estimation of these costs is quite difficult, the LCC is considered an efficient approach for comparing the long-term effects of different maintenance strategies and identifying the optimal ones (Hawk 2003). This is extremely important for most bridge owners due to limitations on the availability of funds required to fulfill even urgent maintenance needs.

Deterioration models are integral component of LCC assessment because maintenance cost and user costs are highly dependent on bridge condition that varies over the analysis period. The quality of LCC-based decisions depends primarily on the accuracy and efficiency of the deterioration models used to predict the time-dependent performance and remaining service life of highway bridges (AASHTO 1993). By definition a deterioration model is a link between a measure of bridge condition that assesses the extent and severity of damages, and a vector of explanatory variables that represent the factors affecting bridge deterioration such as age, material properties, applied loads, environmental conditions, etc. The literature on deterioration models of highway bridges comprises several approaches that can be categorized into deterministic, stochastic, and artificial intelligence approaches. For more information about these approaches along with the techniques used, please refer to Morcous et al. (2002).

Nebraska bridge management system (NBMS) was developed in 1999 to assist decision makers at Nebraska Department of Roads (NDOR) in optimizing the allocation of funds to the maintenance, rehabilitation and replacement (MR&R) of approximately 16,000 highway bridges across the State of Nebraska (NDOR 1999). This system includes: 1) Bridge Inspection System of Nebraska (BISON), which is a data collection system used by bridge inspectors (NDOR 2002a); 2) national average deterioration rates for service life prediction of bridge components; 3) pre-defined flowcharts for selecting optimal maintenance actions based on the current and predicted conditions; and 4) cost data and formulas for estimating the budget required to implement the selected actions. NBMS was developed based on the National Bridge Inspection Standards (NBIS) and National Bridge Inventory (NBI) data items. For more information about these items, please refer to bridge inspection manual and coding guide (NDOR 2002b).

The approach adopted in NBMS for MR&R decision making is mostly based on engineering judgment without adequate consideration of the LCC assessment of proposed actions. This may result in uneconomical decisions that are hard to justify. In addition, the deterioration rates used in predicting future condition of bridge components and determining the optimum year of specific actions are entirely based on national average rates that do not necessarily reflect actual deterioration rates of Nebraska bridges. This also may result in over-or under-estimating when the action is needed. Moreover, the formula adopted for cost estimate and the corresponding unit prices need to be updated to reflect the actual cost incurred by contractors in recent projects.

Therefore, Nebraska Department of Roads (NDOR) has recently adopted Pontis to establish a rational and systematic approach for MR&R decision making and avoid the frequent updates of NBMS, which is costly and time-consuming. Pontis is a bridge management system that assists transportation agencies in managing bridge inventories and making decisions about preservation and functional improvements for their structures. Pontis was first developed by the FHWA in 1986 and was administered by AASHTO since 1994. NDOR uses Pontis version 4.4 which was released in Jan. 2005 and is currently used by over 45 states (AASHTO 2005). Pontis stores inspection data at three different levels: 1) structure, such as bridge or culvert; 2) structure unit, such as span or frame; and 3) element, such as deck or girder. Element conditions are presented in Pontis using 1 to 5 rating system (with 1 being excellent condition) and four environments (benign, low, moderate, and severe). Pontis preservation module identifies the set of optimal MR&R policies at the network level using the LCC assessment approach. This module uses transition probability matrices for predicting the deterioration of bridge elements over a given analysis period. The transition probability matrices built in Pontis were entirely based on engineering judgment and does not reflect the actual bridge deterioration rates in any specific state. To ensure the reliability of the MR&R policies proposed by Pontis, accurate deterioration models that are specific to Nebraska bridges need to be developed, then these models will be used in either Pontis or any other LCC assessment tool (BLCCA software developed by Hawk 2003) to propose optimal MR&R strategies.

1.2 OBJECTIVE

The project represents the first phase of a multi-phase project that aims to optimizing MR&R decisions based on LCC assessment of bridge structures. The objective of this phase is twofold:

1. Develop deterioration models for different bridge components, namely deck, superstructure, and substructure, using the inventory and condition data currently available for Nebraska bridges. These models include those required by Pontis preservation module to determine the long-term MR&R policy that minimizes LCC.
2. Develop procedures for updating the developed models as new data becomes available.

1.3 REPORT ORGANIZATION

The report is organized as follows: Chapter 2 presents the data analysis required to determine the data set that can used in developing reliable and consistent deterioration models. Chapter 3 discusses the classification parameters used in data grouping for developing deterioration models. Chapter 4 presents the development of deterministic deterioration models for bridge deck, superstructure and substructure components considering the parameters presented in Chapter 3. Chapter 5 presents the development of stochastic deterioration models for bridge components using Markov chain approach to be used in Pontis analysis. Chapter 6 presents the procedures for updating the developed models as new data becomes available. Chapter 7 summarizes the research work and its main conclusions.

2 DATA ANALYSIS

2.1 INTRODUCTION

In the United States, condition ratings are used for standardized reporting of visual inspections of bridges. The Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation’s Bridges provides instructions for coding of condition rating for bridge structure (USDOT 1995). In this system, bridge elements have rating on a scale of 0 (failed condition) to 9 (excellent condition) and rate N assigned to not applicable cases. Table 2-1 shows the definition of condition ratings. Nebraska Department of Roads (NDOR) bridge inspection manual provides guidelines for inspection and condition rating of bridges (NDOR 2002b). The collected inspection data are updated using inspection software called Bridge Inspection System of Nebraska (BISON).

Table 2-1: Description of condition rating of bridge elements

State	Description
N	NOT APPLICABLE
9	EXCELLENT CONDITION
8	VERY GOOD CONDITION - no problems noted.
7	GOOD CONDITION - some minor problems.
6	SATISFACTORY CONDITION
5	FAIR CONDITION
4	POOR CONDITION
3	SERIOUS CONDITION
2	CRITICAL CONDITION
1	"IMMINENT" FAILURE CONDITION
0	FAILED CONDITION

There are 255 data items for bridges which categorized in three main data groups: Management items (BRI_MGT_ITEM), Inventory items (BRI_INV_ITEM), and Rating items (BRI_RAT_ITEM). There are 70 items for management, 106 for inventory and 79 items for rating item. Each item has specified number which has a specified definition in bridge inspection manual. For example, item BIR_INV_ITEM_029 represents average daily traffic and item BIR_RAT_ITEM_058 represents deck condition rating. Based on detailed discussions with

NDOR technical advisors committee (TAC), items shown in Table 2-2 have been selected for developing deterioration models. Description of each item will be explained in chapter 3.

Table 2-2: List of items selected for developing deterioration models

	Data Item	Item #
Inventory	Average Daily Traffic (ADT)	29
	% of Truck Traffic	109
	Deck Structure Type	107
	Material Type	43A
	Structure Type (Main)	43B
	Type of Wearing Surface	108A
	Deck Protection	108C
	Highway Agency District (Climatic Region)	2
	Functional Classification	26
	Year Built	27
	Year Reconstructed	106
	Structure Authority (Structure Number)	8
	Type of Service on Bridge	42A
Rating	Inspection Date	90
	Deck Condition Rating	58
	Superstructure Condition Rating	59
	Substructure Condition Rating	60

There are 15,568 bridges in the state of Nebraska according to the 2009 database of NDOR. Inspection data are available since year 1998 for each bridge. Extensive data filtering has been done on bridge inventory and inspection data for developing reliable and consistent deterioration models as presented in the following sections.

2.2. DATA FILTERING

In order to select reliable sets of data for developing deterioration models of bridge components, several filters have been applied to remove:

- not applicable and blank data
- duplicate data
- bridges with unrecorded major maintenance actions
- bridges with the same year built and year reconstructed

Each of these filters is described in more details in the following subsections.

2.2.1. Not Applicable and Blank Data

Data records with condition rating N “Not applicable” represent about 21% of all data according to 2010 inspection data. These records refer to culverts, which are not considered in this study. Tables 2-3 and 2-4 show the number of deck, superstructure and substructure components with different condition rating in years 1998 and 2010 respectively. Not applicable and blank data were removed from the database for developing deterioration models.

Table 2-3: Number of bridge components at different condition ratings - year 1998

Condition Rating	Deck	Superstructure	Substructure
0	21	18	18
1	4	5	5
2	5	10	13
3	85	170	279
4	652	1012	1087
5	3539	1644	1897
6	1894	2198	2327
7	2431	3208	3070
8	2677	3004	2700
9	1980	2044	1912
N	2691	2666	2671
Blank	58	58	58
Total	16037	16037	16037

Table 2-4: Number of bridge components at different condition ratings - year 2010

Condition Rating	Deck	Superstructure	Substructure
0	53	51	49
1	2	4	7
2	6	22	28
3	68	153	329
4	503	702	947
5	3679	1731	1799
6	1642	1784	1683
7	1987	2593	2684
8	3026	3263	3003
9	1435	2140	1913
N	3415	3373	3374
Blank	0	0	0
Total	15816	15816	15816

2.2.2. Duplicate Data

There are few duplicate records in the database. These records were removed for developing deterioration models. Table 2-5 shows the number of duplicate records in each inspection year from 1998 to 2010.

Table 2-5: Number of duplicate records in each inspection year

Year	1998	1999	2000	2001	2002	2003	2004	2005	2006	2008	2009	2010
All Records	16036	16347	16344	16062	16077	16092	16092	16092	16092	16092	16092	15816
Without Duplicate Management Records	15732	15706	15679	15634	15624	15625	15630	15629	15630	15608	15568	15550
Actual Structures comply with NBIS definition	15731	15690	15664	15634	15624	15625	15630	15629	15630	15608	15568	15568
Duplicate Data	304	641	665	428	453	467	462	463	462	484	524	266

2.2.3. Bridges with Unrecorded Major Maintenance Actions

Some bridges have undergone major maintenance actions that were not recorded in the year reconstructed, which results in erroneous data points in the condition versus age plots (outliers). In the absence of maintenance history, the age of bridge components is calculated based on year built while the condition corresponds to the condition of a relatively new component. Figures 2-1, 2-2 and 2-3 show the age of deck, superstructure and substructure in bridges versus condition rating at year 2010.

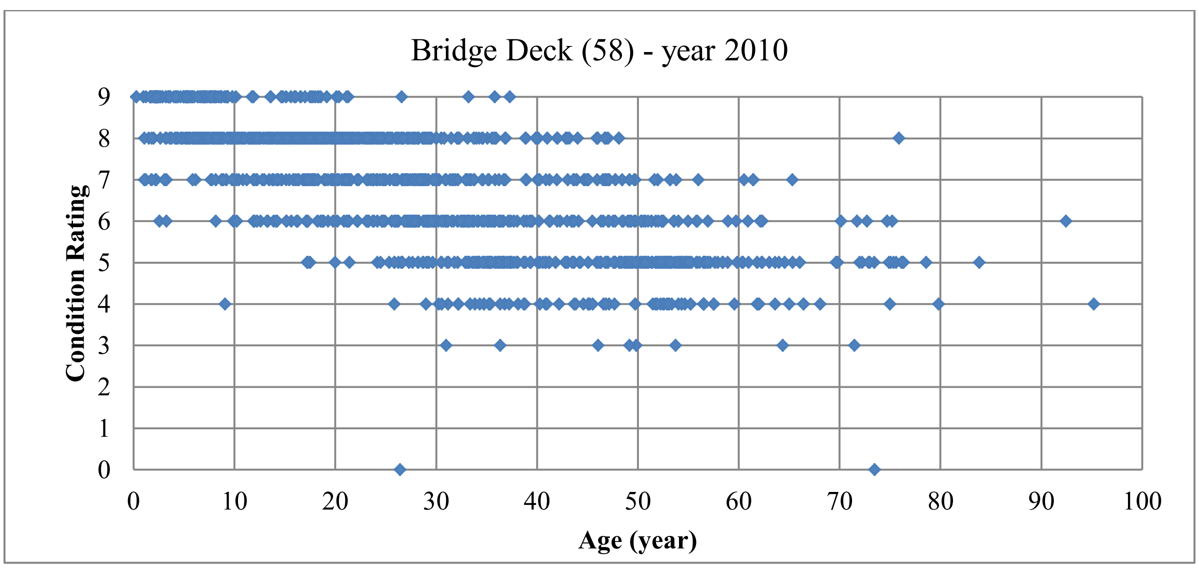


Figure 2-1: Age versus condition rating for bridge deck at year 2010

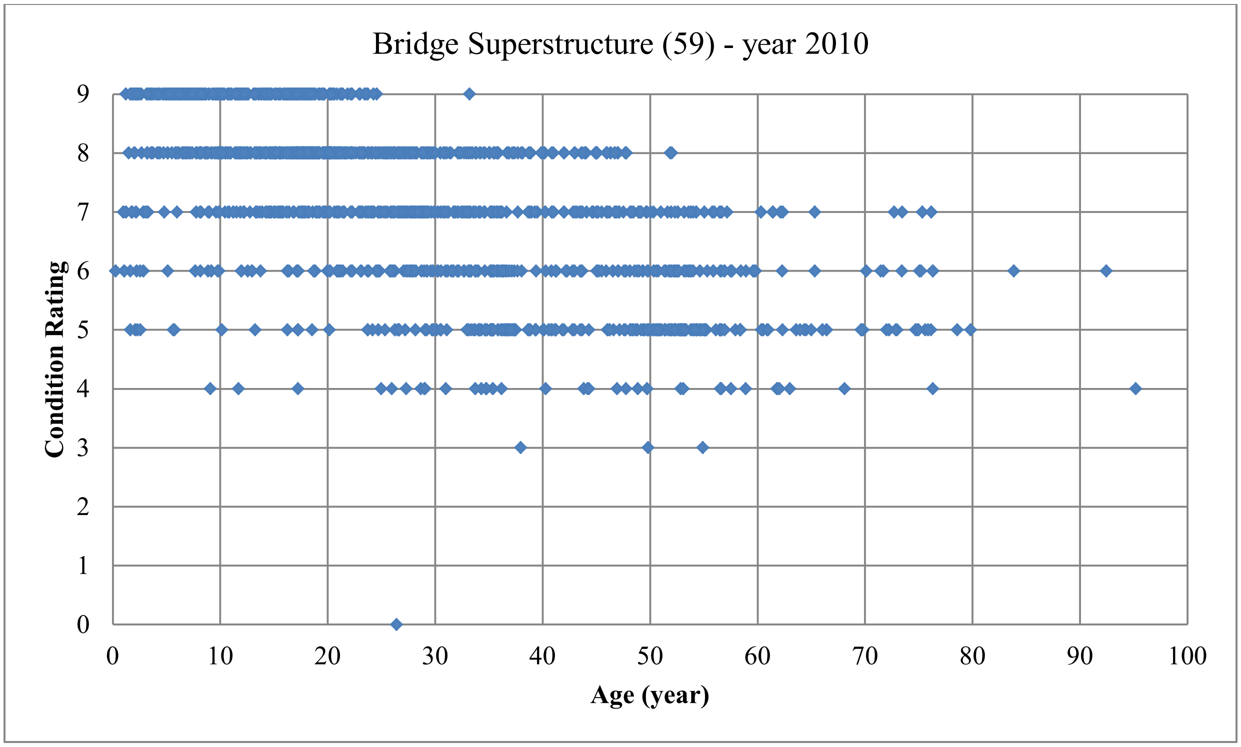


Figure 2-2: Age versus condition rating for bridge superstructure at year 2010

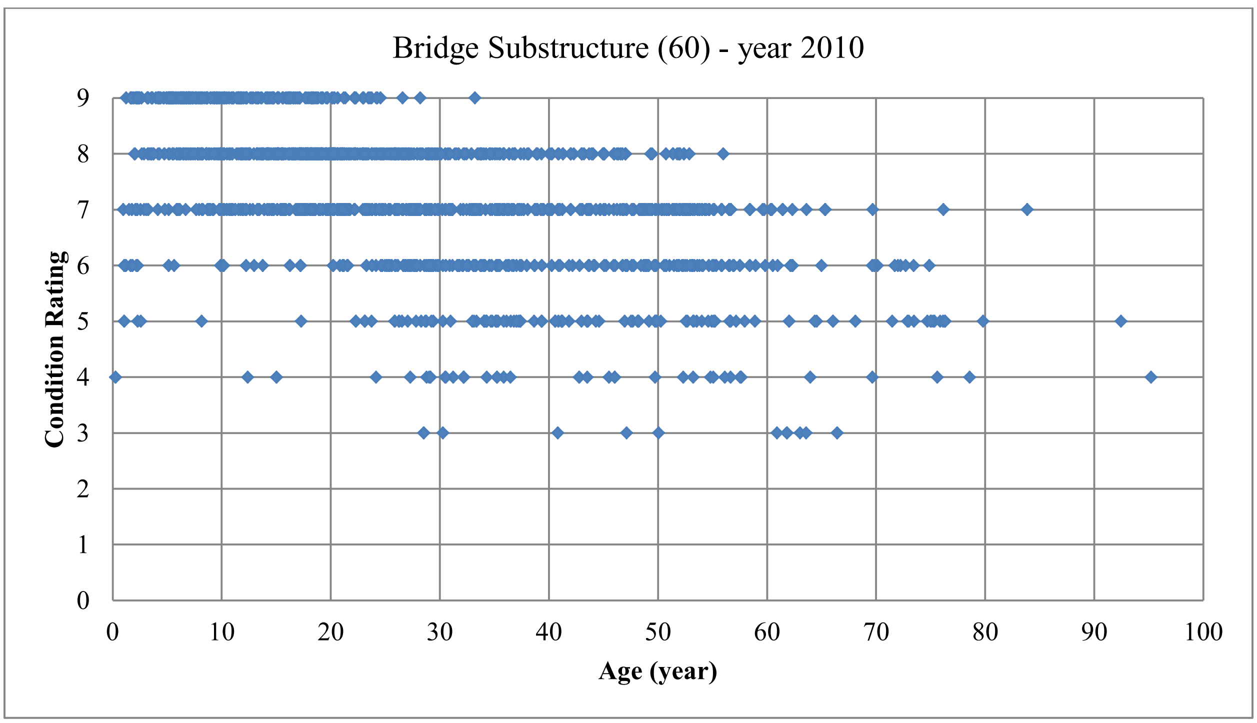


Figure 2-3: Age versus condition rating for bridge substructure at year 2010

Graphical representation of the data revealed that few data points with age less than 10 years and condition ratings of 4, 5 or 6 as well as data points with age 40 years or older and condition ratings of 9, 8, and 7. These data points are considered outliers. In order to partially address this issue, a limit on the maximum and minimum number age for each condition rating was imposed as follows:

- Condition rating 9 → age reconstructed less than 0 and more than 30 years
- Condition rating 8 → age reconstructed less than 0 and more than 40 years
- Condition rating 7 → age reconstructed less than 0 and more than 50 years
- Condition rating 6 → age reconstructed less than 10 and more than 60 years
- Condition rating 5 → age reconstructed less than 20 and more than 70 years
- Condition rating 4 → age reconstructed less than 30 and more than 80 years

2.2.4. Bridges with Same Year Built and Year Reconstructed

There are approximately 223 bridges that have same year of built and year reconstructed. They are all planned bridges and none of them is a real bridge. Filters were applied to identify such bridges. Inspection data corresponding to these bridges were removed from the database.

2.3. ANALYSIS PROCEDURE

To analyze bridge data, records from NDOR database were imported to Microsoft Excel. Records with not applicable and blank data, duplicate data, and same year built and year reconstructed were removed. Age built and age reconstructed of the bridges were calculated by subtracting year built (BIR_INV_ITEM027) and (BIR_RAT_ITEM090) year reconstructed (BIR_INV_ITEM106) from year of inspection (BIR_RAT_ITEM090) respectively. A limit on maximum and minimum age at each condition rating was imposed as mentioned in section 2.2.3. Step by step procedure for developing deterioration models for deck, superstructure and substructure will be explained in chapters 4 and 5.

3 CLASSIFICATION PARAMETERS

3.1 INTRODUCTION

Deterioration of bridge elements depend on several parameters related to bridge design, construction, geographical location and environment, and traffic volume, Therefore, it is important to classify bridges based on the values of these parameters so that homogenous and consistent data can be used in developing deterioration models with adequate accuracy. To achieve this goal, filtered data records are classified based on the following parameters that are discussed in more detail in the following subsections:

- Highway agency district
- Material type
- Structure type
- Deck structure type
- Functional classification
- Structure Authority
- Type of Service on bridges
- Type of deck wearing surface
- Deck protection
- Average daily traffic (ADT)
- Average daily truck traffic (ADTT)

3.2 HIGHWAY AGENCY DISTRICT

The highway agency district represents the district in which the bridge is located. There are eight districts in the state of Nebraska. These districts are described in item BIR_INV_RT_002B of the National Bridge Inventory (NBI) database. Figure 3-1 shows the district map of the state of Nebraska. Distribution of bridges in each district is shown in Figure 3-2 according to 2009 data. This figure clearly shows that districts 1, 3 and 4 have the highest numbers of bridges.

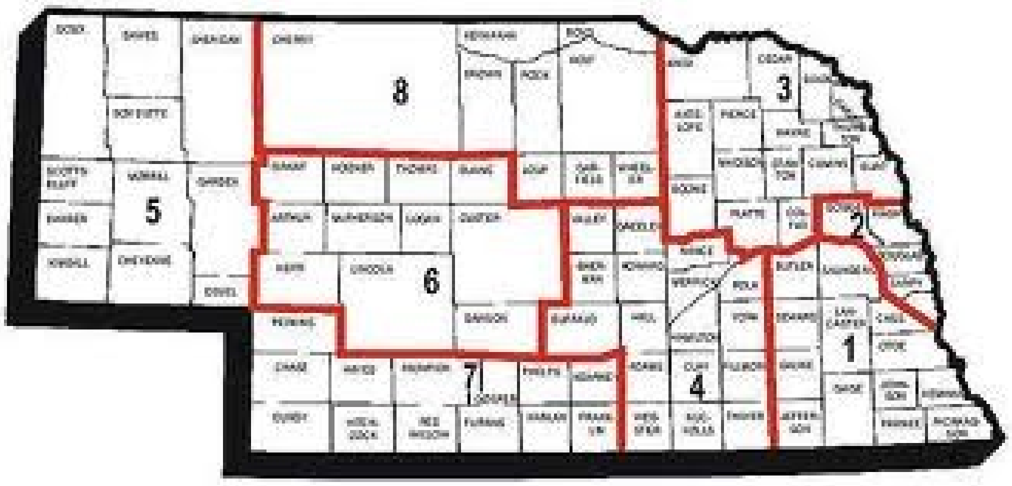


Figure 3-1: District map for state of Nebraska

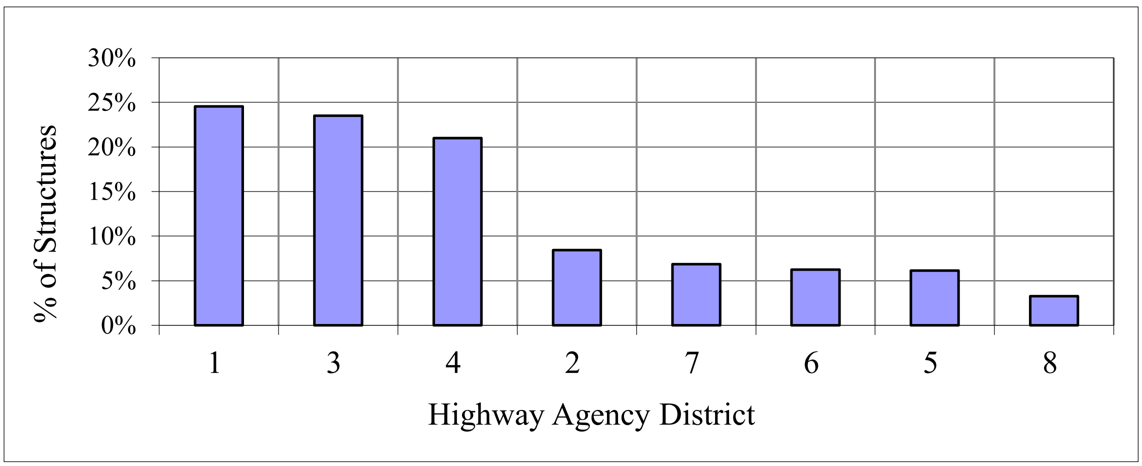


Figure 3-2: Distribution of bridges in each district – year 2009

3.3 MATERIAL TYPE

There are different types of materials used in bridge superstructure. Material type is presented in item BIR_INV_ITEM43A using a number from 0 to 9 as shown in Table 3-1. The table also shows the percentage of each material type in a descending order according to 2009 data. Figure 3-3 shows the percentages of using steel, reinforced concrete, prestressed concrete and wood in bridge superstructure. Post-tensioned concrete is coded as prestressed concrete. Figure 3-4 shows the type of support for bridge superstructure. This figure clearly indicates that most of bridges are simply supported.

Table 3-1: Distribution of material type in bridge superstructure - year 2009

Material Type (43A)	Frequency	Percentage
3- Steel	6995	45%
1- Concrete	3913	25%
7- Wood or Timber	1287	8%
5- Prestressed Concrete	1345	9%
2- Concrete Continuous	1250	8%
4- Steel Continuous	660	4%
6- Prestressed Concrete Continuous	110	1%
9- Aluminum, Wrought Iron, or Cast Iron	3	0%
0- Other	2	0%
8- Masonry	2	0%
Total	15568	100%

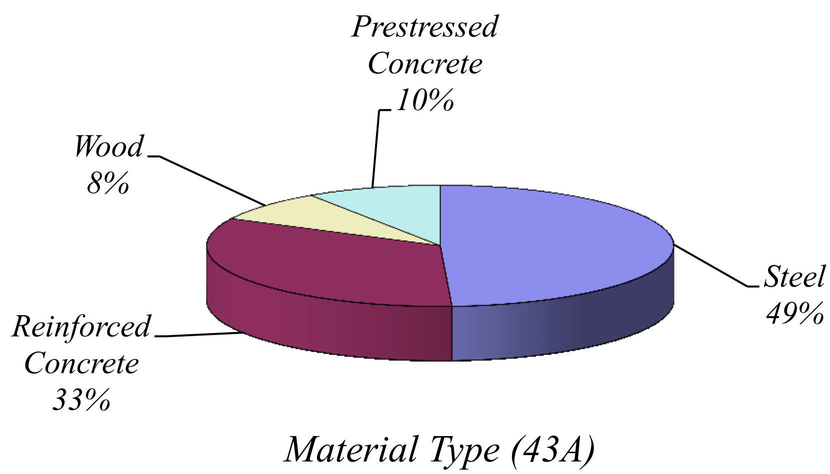


Figure 3-3: Distribution of material type in bridge superstructure – year 2009

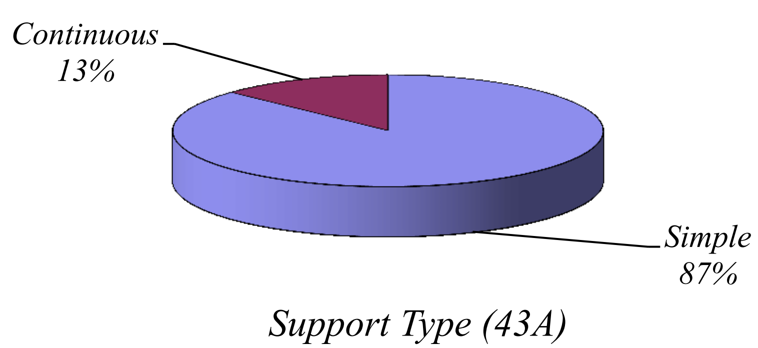


Figure 3-4: Type of superstructure support– year 2009

3.4 STRUCTURE TYPE

Type of structure represents the structural system of the bridge and is presented in item BIR_INV_ITEM43B. Type of structures has a numbers from 00 to 22 as described in Table 3-2 along with the percentages of structure type in descending order according to 2009 data.

Table 3-2: Distribution of structure type - year 2009

Structure Type (43B)	Frequency	Percentage
02- Stringer/Multi-Beam or Girder	8559	55%
19- Culvert	3232	21%
01- Slab	1458	9%
10- Truss-Thru	887	6%
04- Tee Beam	686	4%
03- Girder and Floor Beam System	484	3%
05- Box Beam or Girders - Multiple	34	0%
11- Arch - Deck	52	0%
22- Channel Beam	131	1%
07- Frame	17	0%
18- Tunnel	4	0%
09- Truss - Deck	3	0%
00- Other	9	0%
21- Segmental Box Girder	2	0%
06- Box Beam or Girders - Single or Spread	3	0%
12- Arch - Thru	3	0%
13- Suspension	1	0%
8- Orthotropic	0	0%
14- Stayed Girder	0	0%
15- Movable-Lift	0	0%
16- Movable-Bascule	0	0%
17- Movable-Swing	0	0%
20- Mixed Types	0	0%
Total	15568	100%

As shown in Table 3-2, stringer/multi-beam or girder has a highest percentage among all structure types. Culverts have are the second, but they have been removed from the database as deterioration models are being developed for bridges only. Figures 3-5 and 3-6 show the percentage of different structure types with and without culverts respectively.

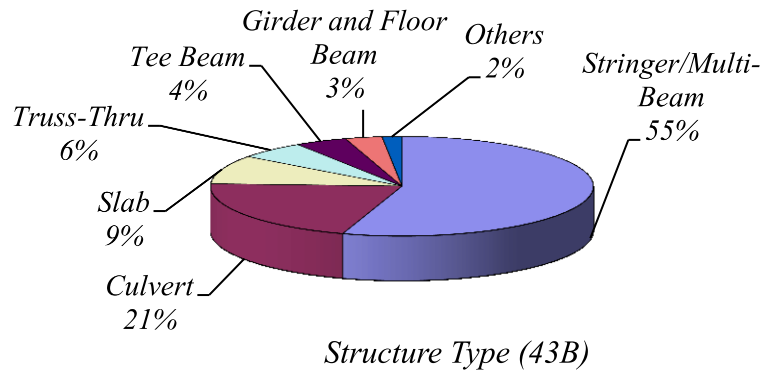


Figure 3-5: Distribution of structure type in highway structures (with culverts) – year 2009

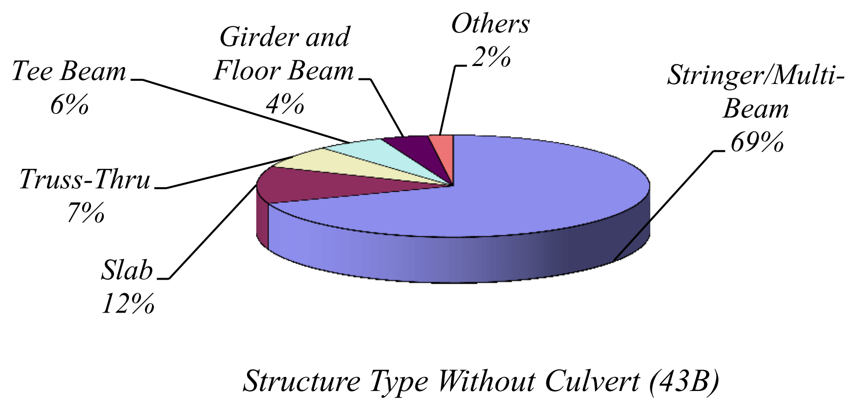


Figure 3-6: Distribution of structures type in highway structures (without culverts) – year 2009

3.5 DECK STRUCTURE TYPE

Cast-in-place concrete is the main type of deck in bridge structures. Deck structure types are described in item BIR_INV_ITEM107 using numbers from 1 to 9 as listed in Table 3-3. If more than one type of deck is used on the same bridge, the code of the most dominant type is reported. Code N is used for a back filled culvert or arch with the approach roadway section carried across the structure. Table 3-3 also shows the percentage of deck structure type in bridges according to

2009 data. Figure 3-7 presents the distribution of deck structures type in bridges excluding culverts.

Table 3-3: Distribution of deck structure type - year 2009

Deck Structure Type (107)	Frequency	Percentage
1- Concrete Cast-in-Place	7824	50%
8- Timber	2619	17%
N- Not Applicable	3243	21%
9- Other	1067	7%
2- Concrete Precast Panels	514	3%
6- Corrugated Steel	259	2%
7- Aluminum	13	0%
5- Steel Plate	16	0%
3- Open Grating	11	0%
4- Closed Grating	0	0%
Total	15568	100%

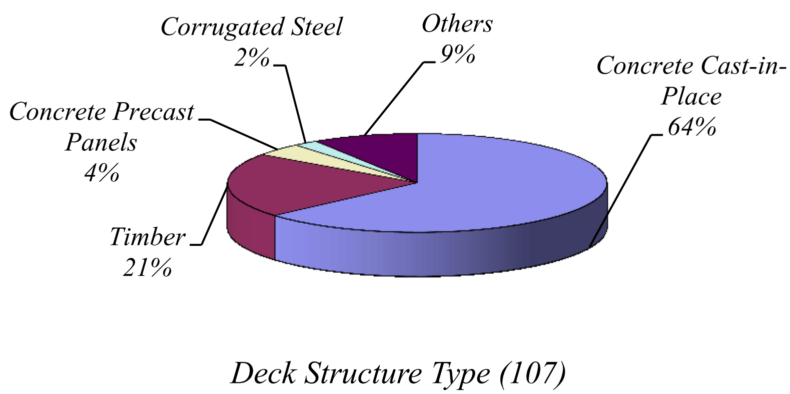


Figure 3-7: Distribution of deck structure type – year 2009

3.6 FUNCTIONAL CLASSIFICATION

Item BIR_INV_ITEM026 is assigned to the functional classification of the road on the bridge. Codes of functional classification are used for rural and urban areas. Rural areas have the following codes: 01, 02, and 06 to 09. Urban areas have the following codes: 11, 12, 14, 16, 17 and 19. Description of each code with their percentage of bridges according to 2009 data is listed in Table 3-4. Figures 3-8 and 3-9 show the distribution of bridge functional classification and whether it is located in rural or urban areas respectively.

Table 3-4: Functional classification of bridges - year 2009

Functional Classification (26)	Frequency	Percentage
09- Rural – Local	8733	56%
07- Rural - Major Collector	2377	15%
06- Rural - Minor Arterial	1291	8%
08- Rural - Minor Collector	1221	8%
02- Rural - Principal Arterial – Other	883	6%
14- Urban - Other Principal Arterial	262	2%
01- Rural - Principal Arterial – Interstate	217	1%
16- Urban - Minor Arterial	164	1%
19- Urban – Local	147	1%
11- Urban - Principal Arterial – Interstate	118	1%
17- Urban – Collector	101	1%
12- Urban - Principal Arterial Other Freeway or Expressway	54	0%
Total	15568	100%

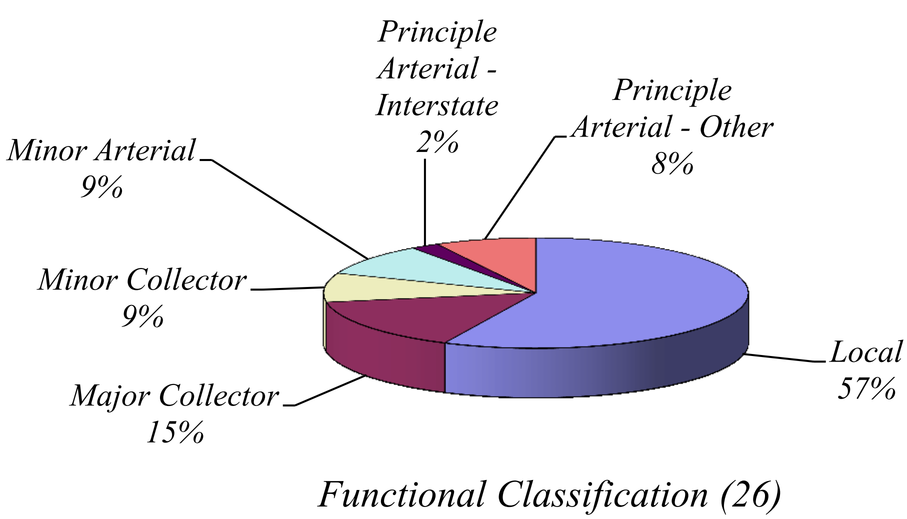


Figure 3-8: Functional classification of bridges – year 2009

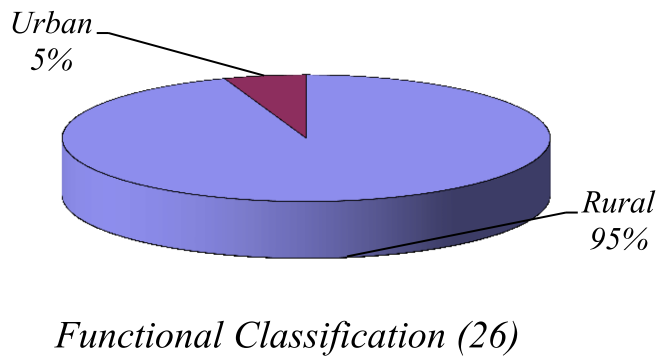


Figure 3-9: Distribution of bridges in rural and urban areas – year 2009

3.7 STRUCTURE AUTHORITY

This item (BRI_INV_ITEM008) defines whether the bridge is owned/administered by the city/county, state, federal government, or municipal government. This item assigns a different starting letter for each authority: “C” means city/county structure, “S” means state structure, “U” means urban structure, “M” means municipal structure and “F” means federal structure. Table 3-5 presents the number and percentage of different structure authorities in the state of Nebraska according to 2009 data. Figure 3-10 shows that city/county structures have the highest percentage of bridges, followed by state structures. State bridges have more reliable condition data than those of other bridges due to the more strict inspection requirements and procedures adopted by state inspectors. Therefore, deterioration models are developed for state bridges.

Table 3-5: Structure authority - year 2009

Structure Authority (8)	Frequency	Percentage
City/County Structure	11326	72.8%
State Structure	3549	22.8%
Urban Structure	467	3.0%
Municipal Structure	171	1.1%
Federal Structure	55	0.4%
Total	15568	100%

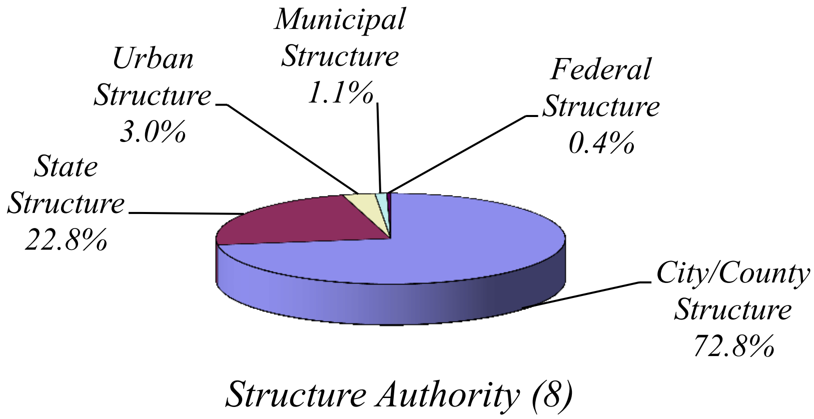


Figure 3-10: Structure authority of bridges – year 2009

3.8 TYPE OF SERVICE ON BRIDGE

This item describes the type of service on bridges. There are numbers 0 to 9 that explain service type. For example, number 1 belongs to highway and number 2 belongs to railroad. Item BRI_INV_ITEM42A is assigned to type of service on bridge. Table 3-6 shows the description of different types of service on bridges. Figure 3-11 illustrates the distribution of type of service according to 2009 data. Results show that highway bridges represent 96% of all bridges.

Table 3-6: Type of service on bridges - year 2009

Type of Service on (42A)	Frequency	Percentage
1- Highway	14984	96.2%
6- Overpass Structure at an Interchange or Second Level of	222	1.4%
5- Highway - Pedestrian	189	1.2%
2- Railroad	115	0.7%
3- Pedestrian/Bicycle	49	0.3%
0- Other	3	0.0%
7- Third Level Interchange	3	0.0%
4- Highway - Railroad	2	0.0%
9- Building or Plaza	1	0.0%
8- Fourth Level Interchange	0	0.0%
Total	15568	100%

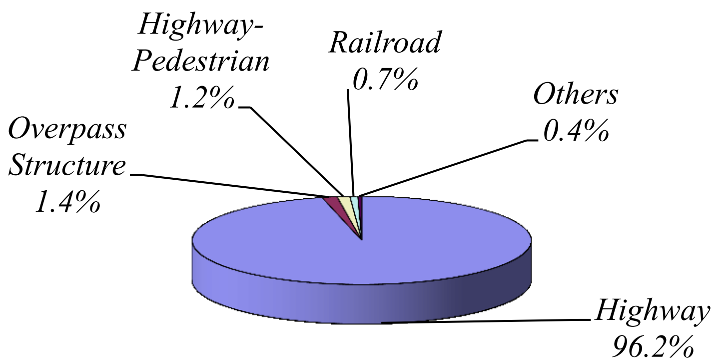


Figure 3-11: Type of service on bridges – year 2009

3.9 TYPE OF DECK WEARING SURFACE

There are different types of wearing surface used on bridge decks. These types are described in item BRI_INV_ITEM108A and listed in Table 3-7.

Table 3-7: Type of deck wearing surface - year 2009

Type of Wearing Surface (108A)	Frequency	Percentage
1- Concrete	7052	45.3%
N- Not Applicable	3204	20.6%
7- Timber	1973	12.7%
8- Gravel	1595	10.2%
9- Other	637	4.1%
6- Bituminous	596	3.8%
4- Low Slump Concrete	326	2.1%
2- Type 47BD-SF (Silica Fume)	76	0.5%
3- Latex Concrete	39	0.3%
0- None	65	0.4%
5- Epoxy Overlay	3	0.0%
Total	15568	100%

Figure 3-12 shows the distribution of different types of deck wearing surface according to 2009 data. Results clearly show that bare concrete decks without wearing surface are the most dominant type of bridge decks. Number 0 represents no wearing surface on bridge decks other than concrete ones, while N applies only to structures with no deck.

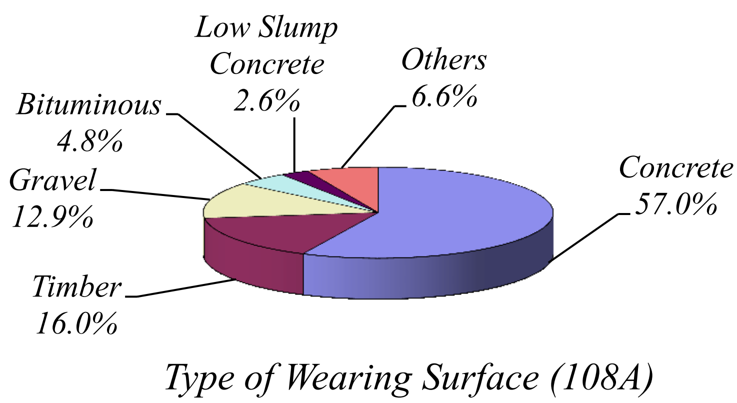


Figure 3-12: Distribution of type of deck wearing surface – year 2009

3.10 DECK PROTECTION

There are six different types of deck protection presented in item BIR_INV_ITEM108C. Table 3-8 lists these types and their percentages in descending order according to 2009 data. Figure 3-13 shows that more than 66% of bridges have no deck protection. Deck protection using epoxy coated reinforcing steel is the most dominant type of deck protection in recent years.

Table 3-8: Distribution of deck protection - year 2009

Deck Protection (108C)	Frequency	Percentage
0- None	10403	66.8%
N- Not Applicable	3257	20.9%
1- Epoxy Coated Reinforcing	1494	9.6%
8- Unknown	216	1.4%
2- Galvanized Reinforcing	160	1.0%
9- Other	18	0.1%
3- Other Coated Reinforcing	7	0.0%
4- Cathodes Protection	7	0.0%
7- Internally Sealed	4	0.0%
6- Polymer Impregnated	2	0.0%
Total	15568	100%

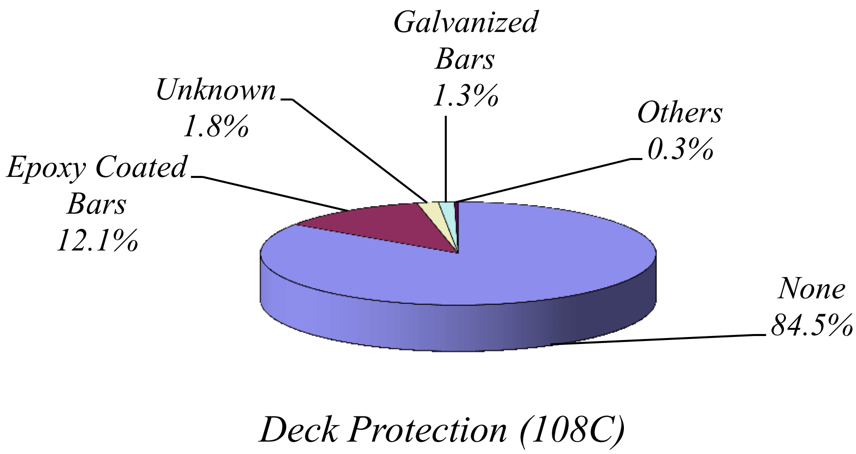


Figure 3-13 Distribution of deck protection – year 2009

3.11 AVERAGE DAILY TRAFFIC (ADT)

The average daily traffic (ADT) on highway bridges is described in item BRI_INV_ITEM029. Based on the 2007 AASHTO Load and Resistance Factor Rating (LRFR), the ADT can be categorized into four different levels as listed in Table 3-9. Figure 3-14 shows the frequency diagram of each of these four levels according to 2000 and 2009 data. This figure clearly shows that average daily traffic less than 100 has the highest frequency.

Table 3-9: Description of ADT Categories (Item 29) – AASHTO LRFR 2007

ADT Category
ADT < 100
100 ≤ ADT <1000
1000 ≤ ADT < 5000
ADT ≥ 5000

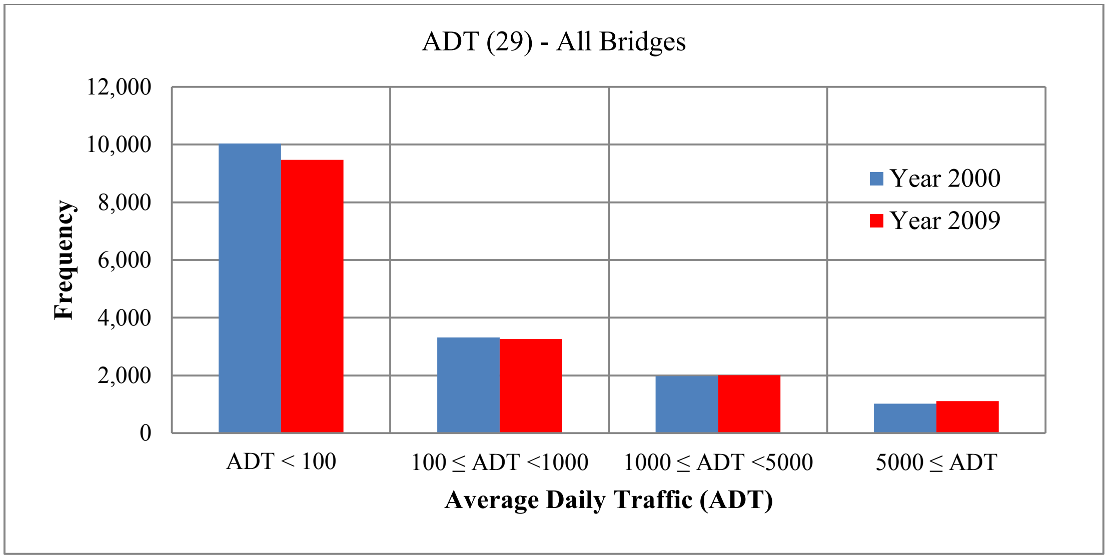


Figure 3-14: Average daily traffic (ADT) frequency diagram for all bridges – years 2000 and 2009

3.12. AVERAGE DAILY TRUCK TRAFFIC (ADTT)

Average Daily Truck Traffic (ADTT) is a percentage of item 29 (ADT) and described in item BRI_INV_ITEM109. Based on data analysis, the ADTT is categorized into three different levels as listed in Table 3-10. Figure 3-15 presents the frequency diagram of ADTT in all bridges according to 2000, 2005 and 2009 data. This figure clearly shows the highest percentage of ADTT is less than 100.

Table 3-10: Description of ADTT Categories (Item 109)

ADTT Category
ADTT < 100
100 ≤ ADTT <500
ADTT ≥ 500

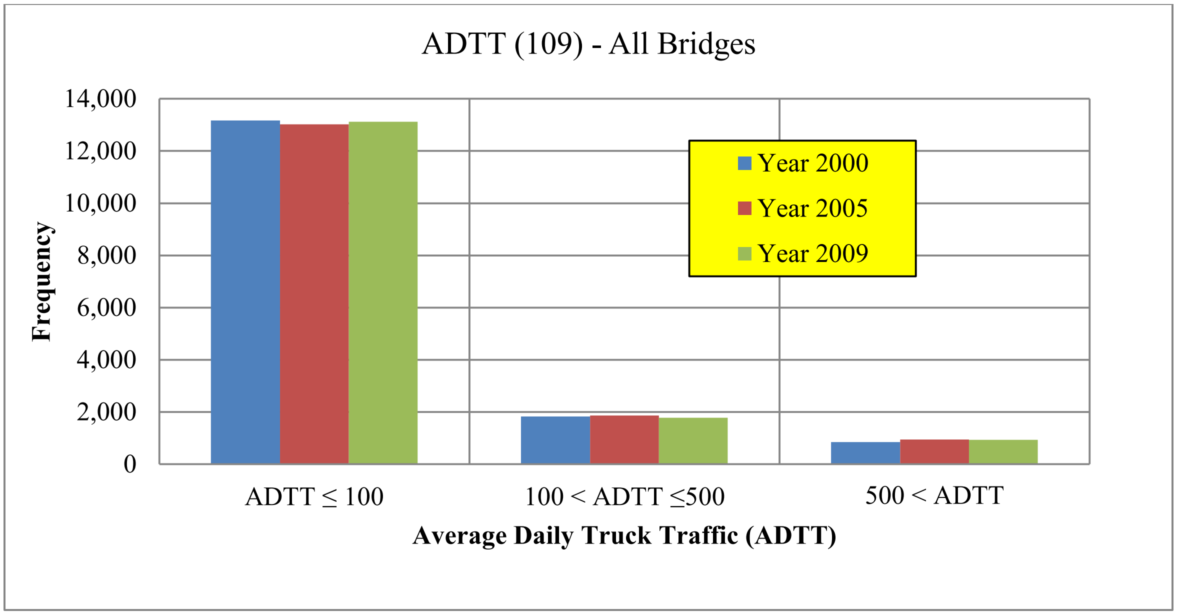


Figure 3-15: Average daily truck traffic (ADTT) frequency diagram for all bridges – years 2000, 2005 and 2009

4 DETERMINISTIC DETERIORATION MODELS

4.1 INTRODUCTION

Bridge deterioration is the process of decline in the condition of the bridge resulting from normal operating conditions (Abed-Al-Rahim and Johnston, 1995), excluding damage from such events as earthquakes, accidents, or fire. The deterioration process exhibits the complex phenomena of physical and chemical changes that occur in different bridge components. What makes the problem more complicated is that each element has its own unique deterioration rate (Thompson, 2001a). Accurately predicting the rate of deterioration for each bridge element is, therefore, crucial to the success of any BMS.

In the late 1980s, deterioration models for bridge components were introduced in order to predict the future condition of infrastructure assets as a function of their expected service condition. Deterioration models in Infrastructure Management Systems (IMSs) were first developed for Pavement Management Systems (PMSs). Deterioration models in PMS differ from those in BMS because of the differences in construction materials, structural functionality, and the types of loads carried. In addition, safety is more important in bridges than in pavements. Despite of the dissimilarities in the deterioration models for pavement and bridges, the approaches to developing pavement deterioration models for PMSs have been employed in the development of bridge deterioration models in BMSs.

Approaches for the calculation of deterioration rates for bridge elements can be classified into two broad categories: (i) Deterministic Approaches, and (ii) Stochastic Approaches. Deterministic models are dependent on a mathematical or statistical formula for the relationship between the factors affecting bridge deterioration and the measure of a bridge's condition. The output of such models is expressed by deterministic values (i.e., there are no probabilities involved) that represent the average predicted conditions. The models can be developed as using straight-line extrapolation, regression, and curve-fitting methods.

Straight-line extrapolation is the simplest condition-prediction model is based on straight-line extrapolation; this method can be used to predict the material condition rating (MCR) of a bridge given the assumption that traffic loading and maintenance history follow a straight line. The method requires only one condition measurement to be carried out after construction; an initial condition can be assumed at the time of construction and a second condition is determined at the time of the inspection. The straight-line extrapolation is used because of its simplicity (Shahin, 1994). Although this method is accurate enough for predicting short-term conditions, it is not accurate for long periods of time. In addition, the straight line method cannot predict the rate of deterioration of a relatively new bridge, or of a bridge that has undergone some repair or maintenance. Regression models are used to establish an empirical relationship between two or more variables: one dependent variable and one or more independent variables. Each variable is described in terms of its mean and variance (Shahin, 1994). In this chapter curve fitting are used for developing deterioration models for bridges deck, superstructure and substructure.

Stochastic approach treats the deterioration process as a stochastic. The state-of-the-art stochastic approach has been based on the Markov-chain theory. In the Markov-chain deterioration model, the performance level is specified as discrete states. The Markov-chain deterioration models will be explained in chapter 5.

4.2 DECK

Bridge decks are considered the most vulnerable element in a bridge. A harsh environment, an increase in traffic volume, and aging are the main reasons for rapid bridge deck deterioration. This section presents the development of deck deterioration models considering the impact of different parameters like: type of wearing surface, average daily traffic (ADT), average daily truck traffic (ADTT), highway agency district, and type of deck protection. Most of data analysis was conducted on state bridges because they have more reliable condition data.

4.2.1. Type of Deck Wearing Surface

There are different types of wearing surface used on bridge decks. These types are described in item 108A. Table 4-1 lists the description of item 108A. Wearing surface 1 (concrete) represents bare concrete deck. Other types of wearing surfaces, such as type 2 (silica fume), type 3 (latex concrete), and type 4 (low-slump concrete) are commonly used in Nebraska. Figure 4-1 shows the frequency diagram of wearing surface type for all bridges.

Table 4-1: Description of wearing surface type (Item 108A)

None	0
Concrete	1
Silica fume	2
Latex concrete	3
Low slump con.	4
Epoxy overlay	5
Bituminous	6
Timber	7
Gravel	8
Other	9
Not applicable	N

Thus, in developing deterioration model for deck wearing surface, three different cases are considered: original deck, re-deck and overlays. Original deck represents those decks which don't have year-reconstructed in database (item 106 equal to zero). Re-deck is those decks which have year-reconstructed (item 106 more than zero) and item 108A equal to 1. Overlays represent those decks which have year-reconstructed (item 106 more than zero) and item 108A equal to 2 (silica fume), 3 (latex concrete) or 4 (low slump concrete).

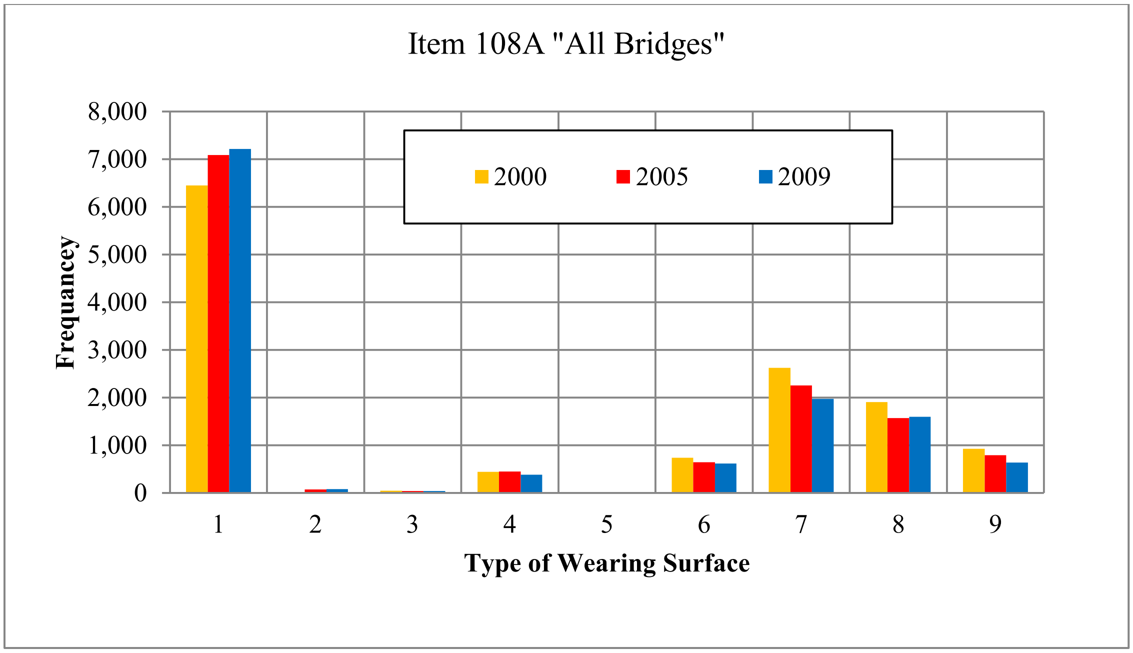


Figure 4-1: Frequency diagram of wearing surface type in all bridges - years 2000, 2005 and 2009

Figure 4-2 shows the frequency diagram of wearing surface type for state bridges only. These figures indicate that wearing surface type 1 (concrete) has the highest frequency in all bridges and state bridges. There is no bridge decks with wearing surface type 5 (epoxy overlay). There are few state bridge decks with wearing surface type 7 (timber) and 8 (gravel). No deterioration curves were developed for these decks due to inadequate data points. Figure 4-3 to 4-5 show deterioration curves for decks in bridges other than state bridges at years 2000, 2005 and 2009. These figures show that decks with wearing surface type 7 (timber) and type 8 (gravel) have almost similar deterioration rates.

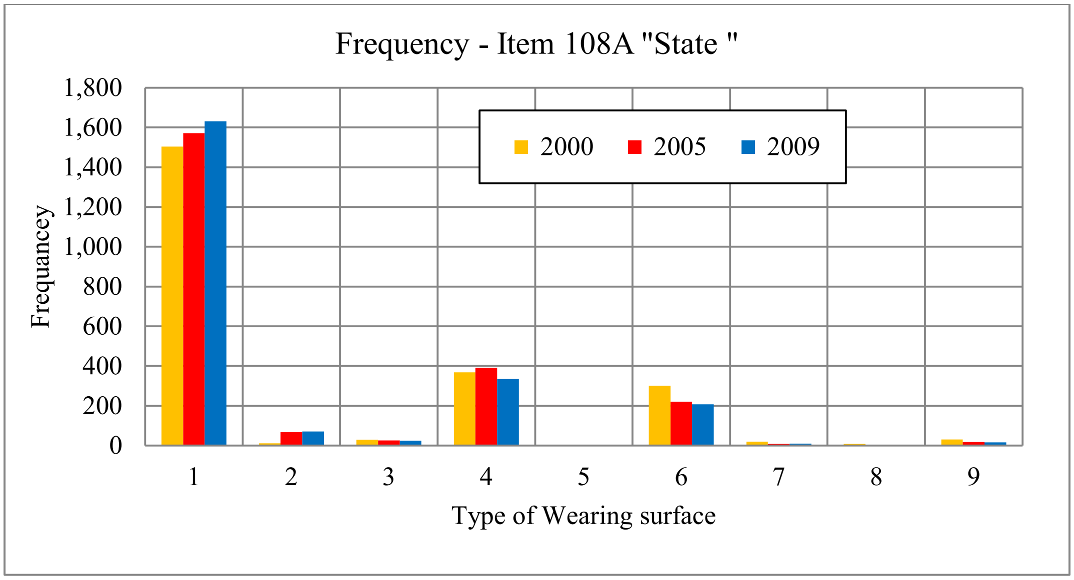


Figure 4-2: Frequency diagram for wearing surface type in state bridges - years 2000, 2005 and 2009

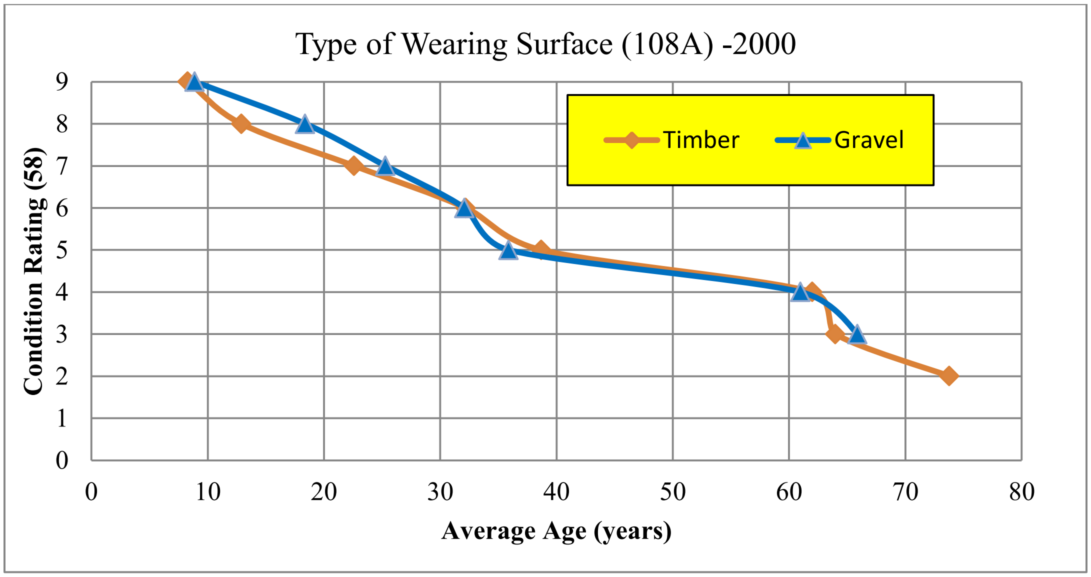


Figure 4-3: Deterioration curves for timber and gravel in bridges other than state bridges - year 2000

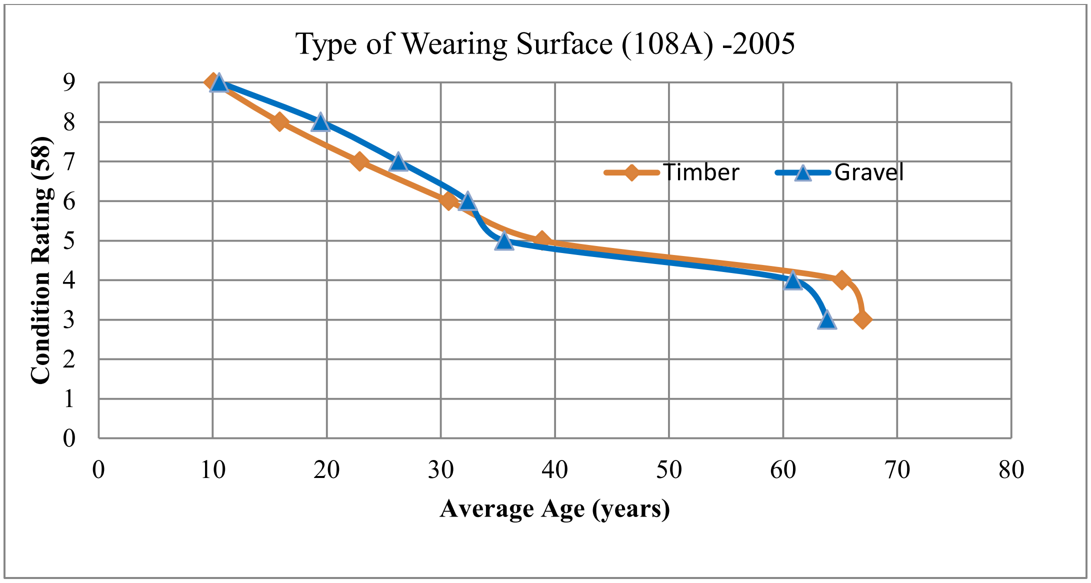


Figure 4-4: Deterioration curves for timber and gravel in bridges other than state bridges - year 2005

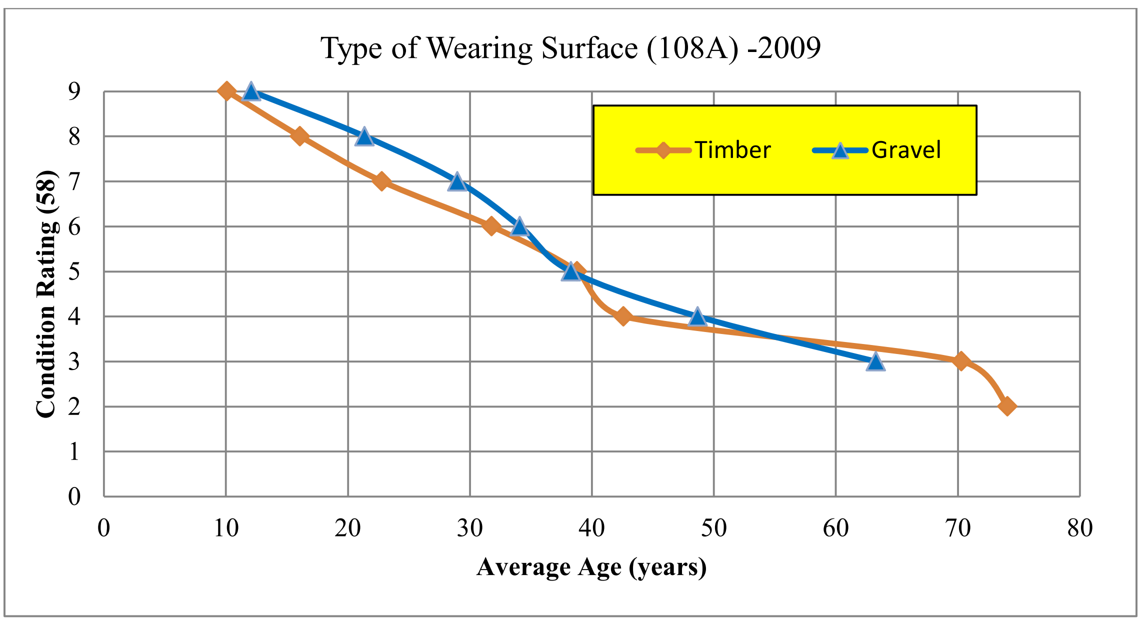


Figure 4-5: Deterioration curves for timber and gravel in bridges other than state bridges - year 2009

Figures 4-6 and 4-7 show the deck condition rating versus age diagram for decks with type 6 (bituminous wearing surface) in all bridges and state bridges in year 2009. This data cannot be used to develop deterioration curves as most of bridge decks with bituminous wearing surface are rated at condition 5.

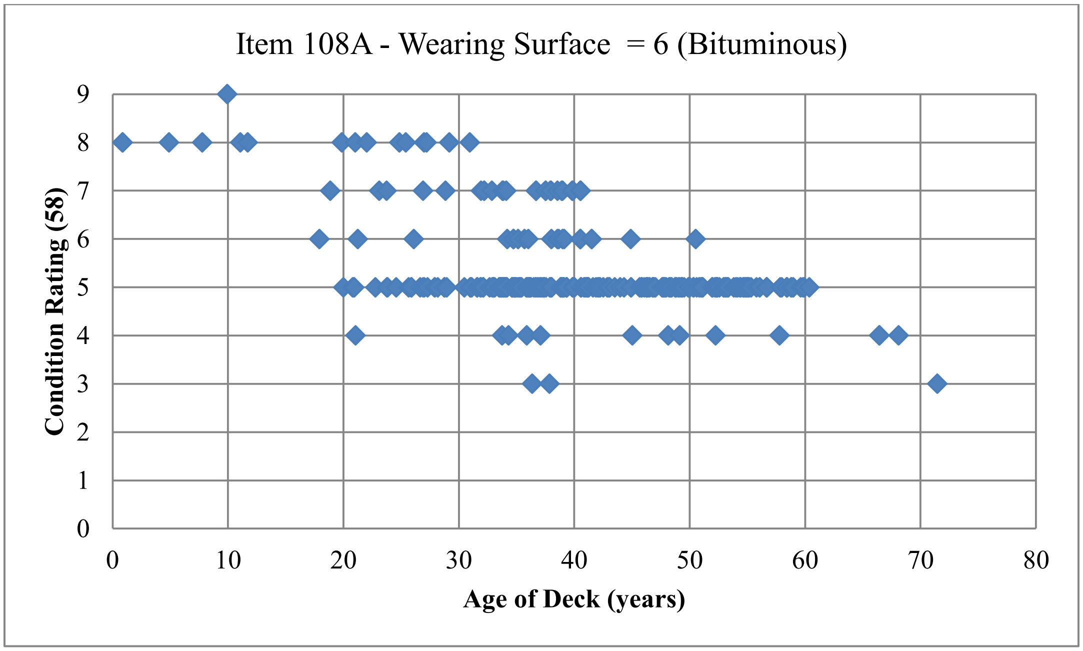


Figure 4-6: Condition rating of wearing surface type 6 (bituminous) for all bridges – year 2009

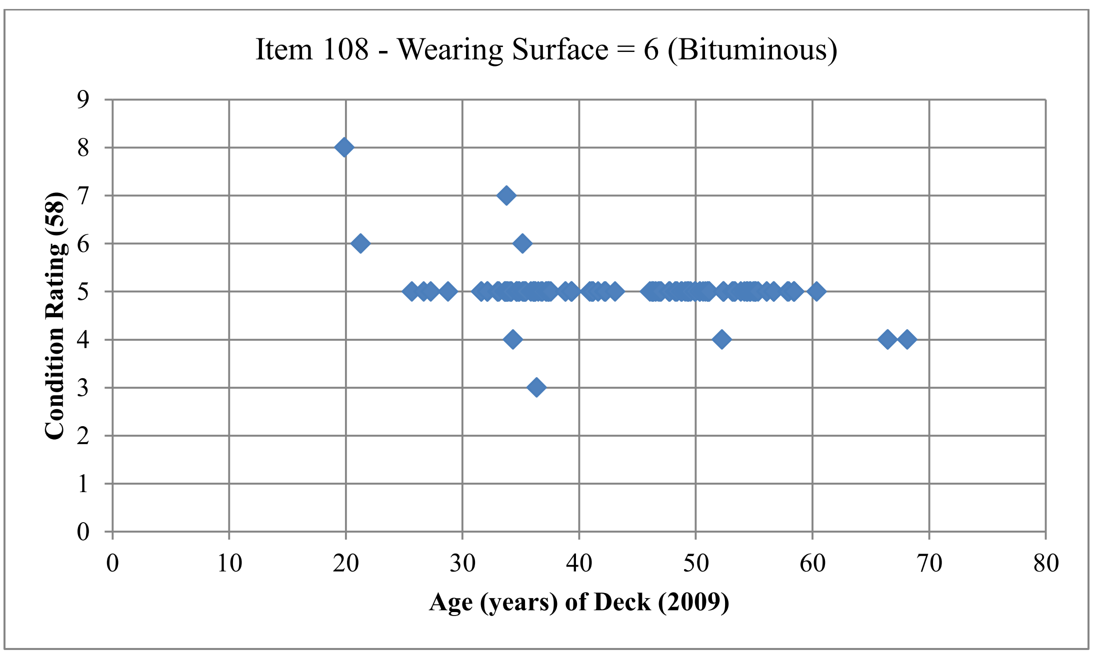


Figure 4-7: Condition rating of wearing surface type 6 (bituminous) for state bridges – year 2009

4.2.1.1. Original Deck

Original deck represents those bridge decks that don't have year reconstructed in database and item 108A equal to 1. Figure 4-8 shows original deck deterioration curve for state bridges at year 2000, 2005 and 2009.

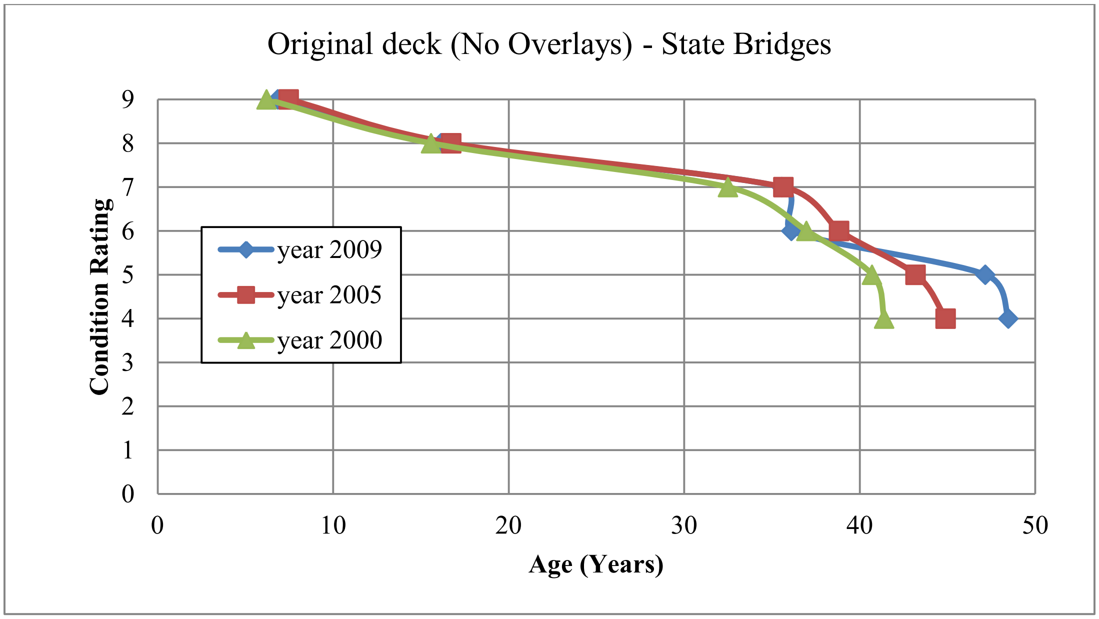


Figure 4-8: Original deck deterioration curve for state bridges – years 2000, 2005 and 2009

To develop reliable deterioration models for original bridge decks, all data from 1998 to 2010 were combined together. Duplicate data were eliminated and deterioration models were developed. Figure 4-9 shows the deterioration curves of bridge decks in state bridges. Dash line represents the national average deterioration rate which takes 8 years to drop from high to lower condition in bridge decks. This figure shows that original concrete decks have lower deterioration rate than national average.

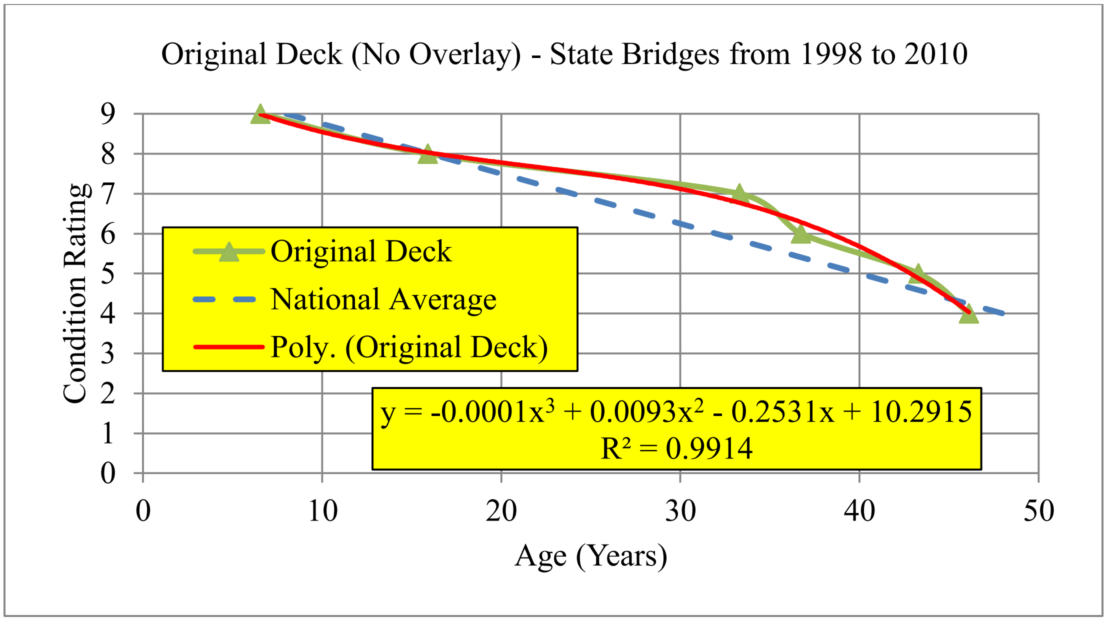


Figure 4-9: Original deck deterioration curve for state bridges

Equation 4-1shows the original deck deterioration formula for state bridges:

$$Y = -0.0001X^3+0.0093X^2-0.2531X+10.2915 \qquad \text{(Eq. 4-1)}$$

Where:

X= age (years) and

Y= condition rating of deck.

Table 4-2 listed the average transition period for original decks in state bridges at years 2000, 2005, 2009 and from 1998 to 2010.

Table 4-2: Transition period for original decks in state bridges

Original Deck	Condition Rating - State Bridges				
Transition Period (years)	9 ⟹ 8	8 ⟹ 7	7 ⟹ 6	6 ⟹ 5	5 ⟹ 4
2000	9.4	16.9	4.5	3.7	0.7
2005	9.3	18.9	3.2	4.4	1.7
2009	9.3	19.4	0.5	11.1	1.3
1998 to 2010	9.3	17.4	3.4	6.6	2.8

Figure 4-10 shows the average transition period for years 2000, 2005, 2009 and 1998 to 2010. This figure clearly shows that condition 8 to 7 with approximately 17.5 years has a maximum transition period.

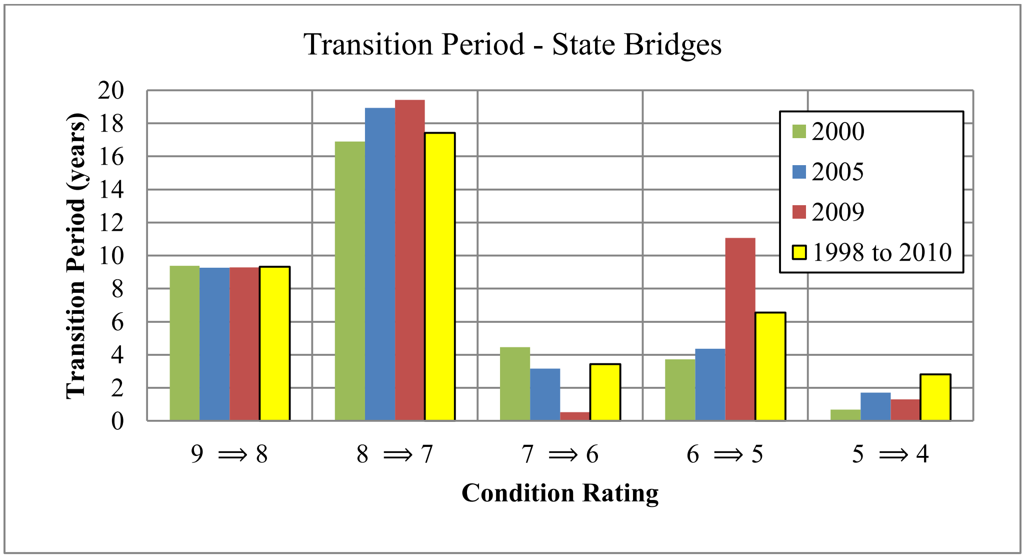


Figure 4-10: Original deck transition period in state bridges – years 2000, 2005, 2009 and from 1998 to 2010

4.2.1.2. Replacement deck

Replacement decks represent those bridge decks that have year reconstructed in database and item 108A equals to 1. Figure 4-11 shows deterioration curve for replacement decks in state bridges at years 2000, 2005 and 2009.

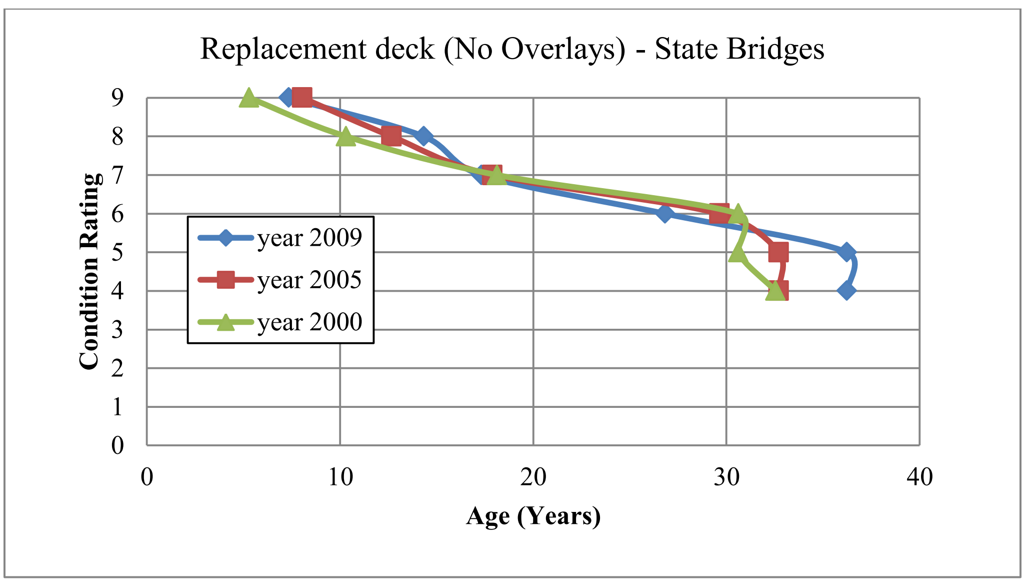


Figure 4-11: Replacement deck deterioration curve in state bridges – years 2000, 2005 and 2009

Figure 4-12 presents the replacement deck deterioration curve developed for state bridges using condition data from 1998 to 2010 and the power formula that best fits the data points.

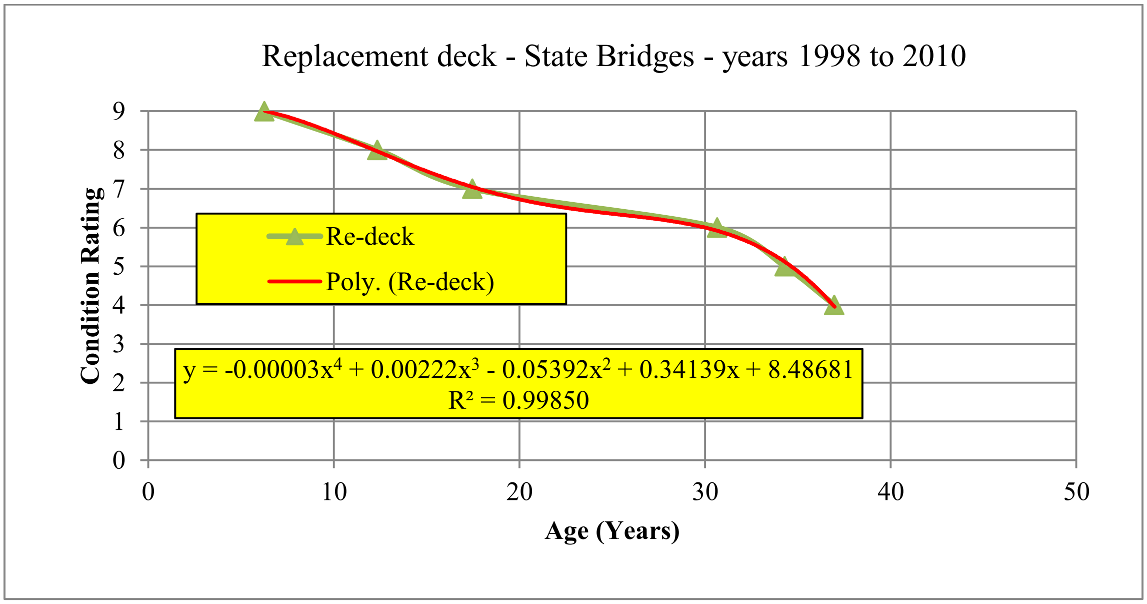


Figure 4-12: Replacement deck deterioration curve in state bridges

Table 4-3 listed the average transition period for replacement decks at years 2000, 2005, 2009 and from 1998 to 2010. Figure 4-13 shows replacement deck transition period for state bridges. This figure clearly shows that condition 7 to 6 with approximately 13 years has a maximum transition period.

Table 4-3: Transition period for replacement decks in state bridges

Re-deck	Condition Rating - State Bridges				
Transition Period (years)	$9 \Longrightarrow 8$	$8 \Longrightarrow 7$	$7 \Longrightarrow 6$	$6 \Longrightarrow 5$	$5 \Longrightarrow 4$
2000	5.0	7.8	12.5	0.0	1.9
2005	4.6	5.2	11.8	3.1	0.0
2009	7.0	3.0	9.5	9.4	0.0
1998 to 2010	6.1	5.1	13.2	3.6	2.7

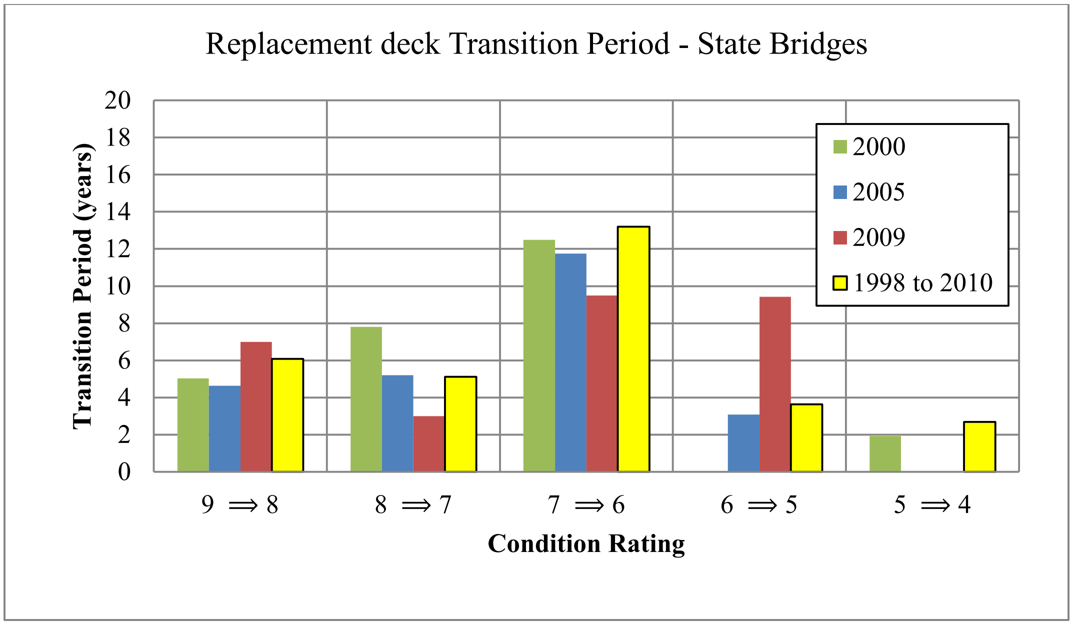


Figure 4-13: Replacement deck transition period diagram in state bridges – years 2000, 2005, 2009 and from 1998 to 2010.

Figure 4-14a presents the distribution of re-deck in each district. Figure 4-14b shows the distribution of duration to re-deck in state bridges at year 2009. This figure indicates that most of the state bridges have duration to re-deck between 25 to 40 years. Therefore, three main groups were considered: duration to re-deck less than 25 years, more than 25 years and less than 40 years, and duration to re-deck more than 40 years.

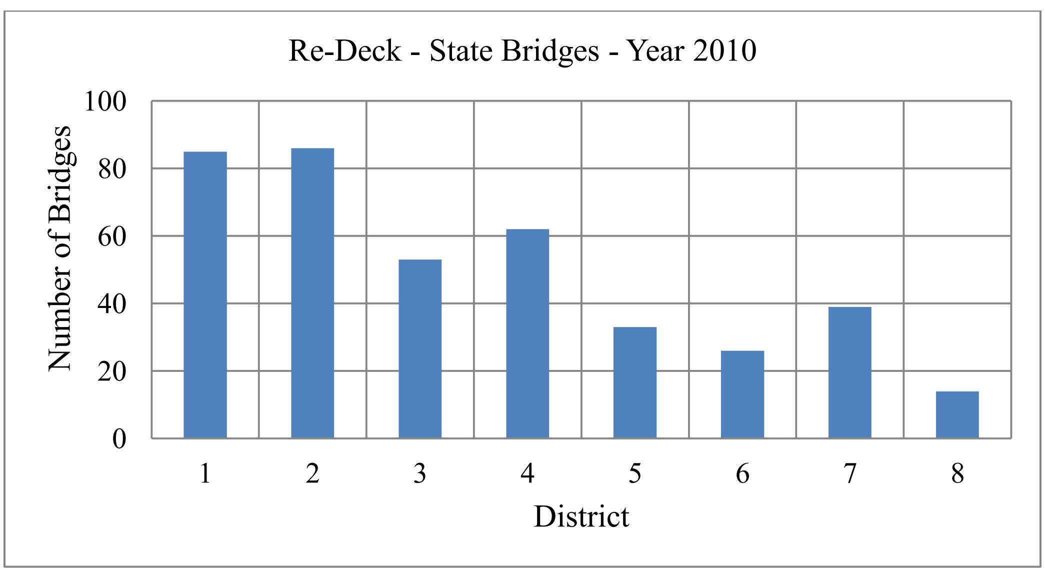


Figure 4-14a: Histogram of distribution of re-deck in districts – year 2010

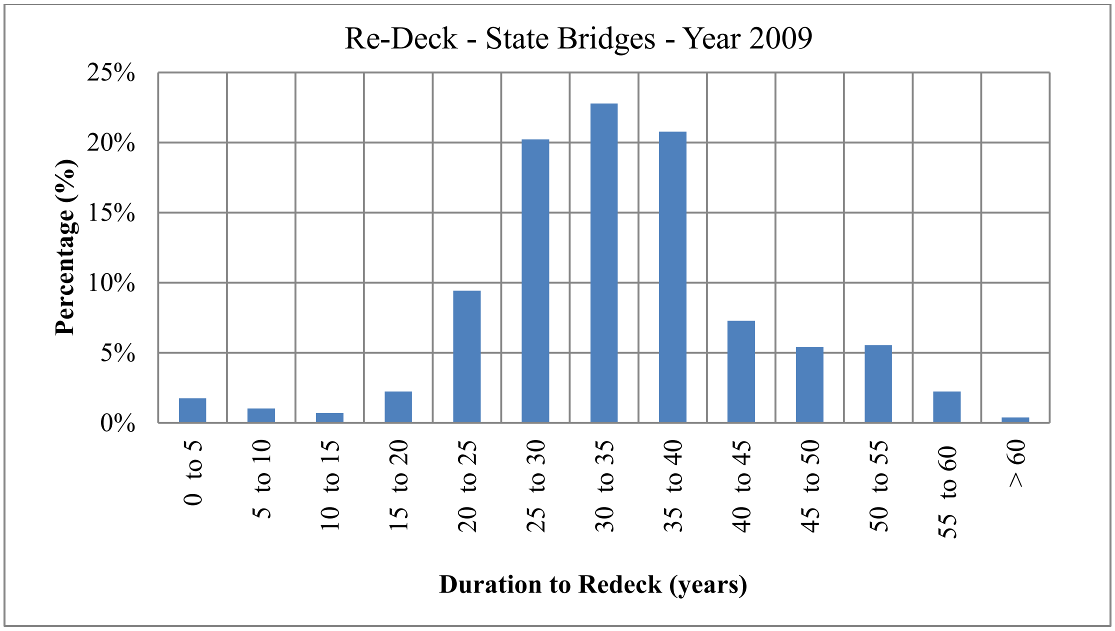


Figure 4-14b: Histogram of state bridges for different durations to re-deck – year 2009

Figure 4-15 to 4-18 show the deterioration curves for those three groups at years 2000, 2005, 2009 and from 1998 to 2010, respectively.

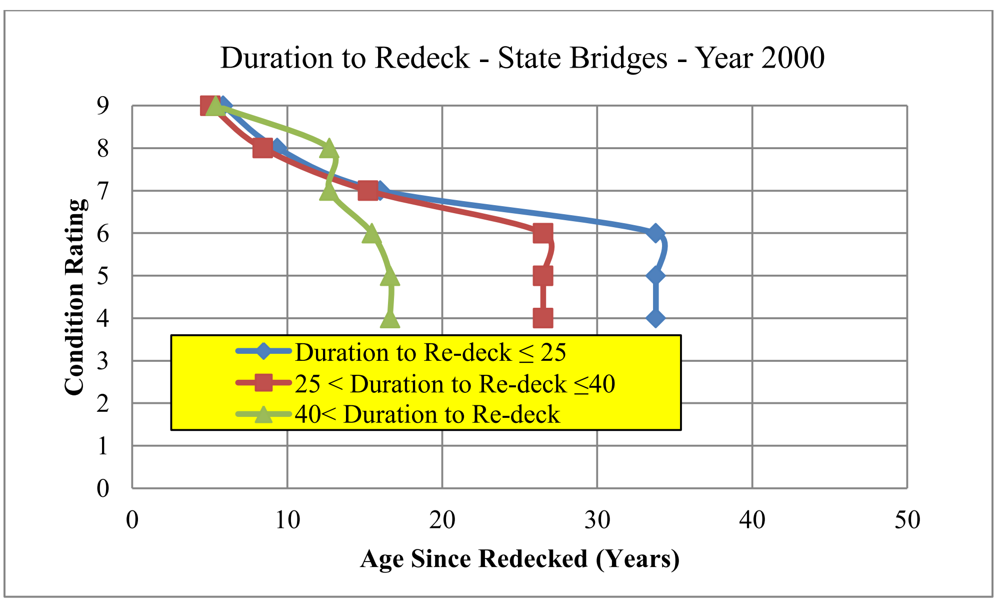


Figure 4-15: Deterioration curves of state bridge deck based on duration to re-deck - year 2000

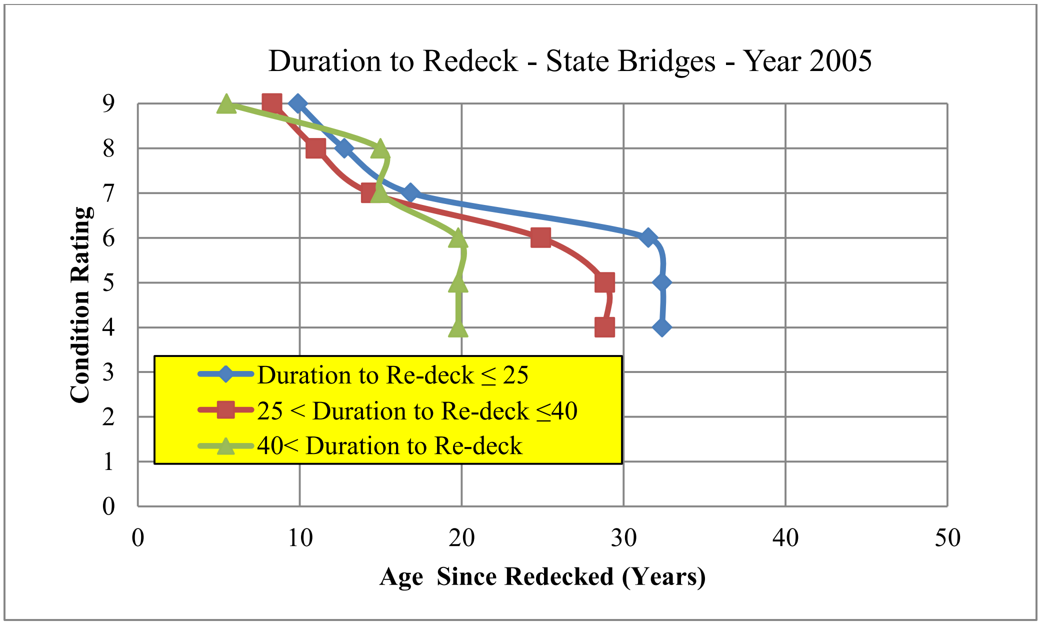


Figure 4-16: Deterioration curves od state bridge decks based on duration to re-deck for year 2005

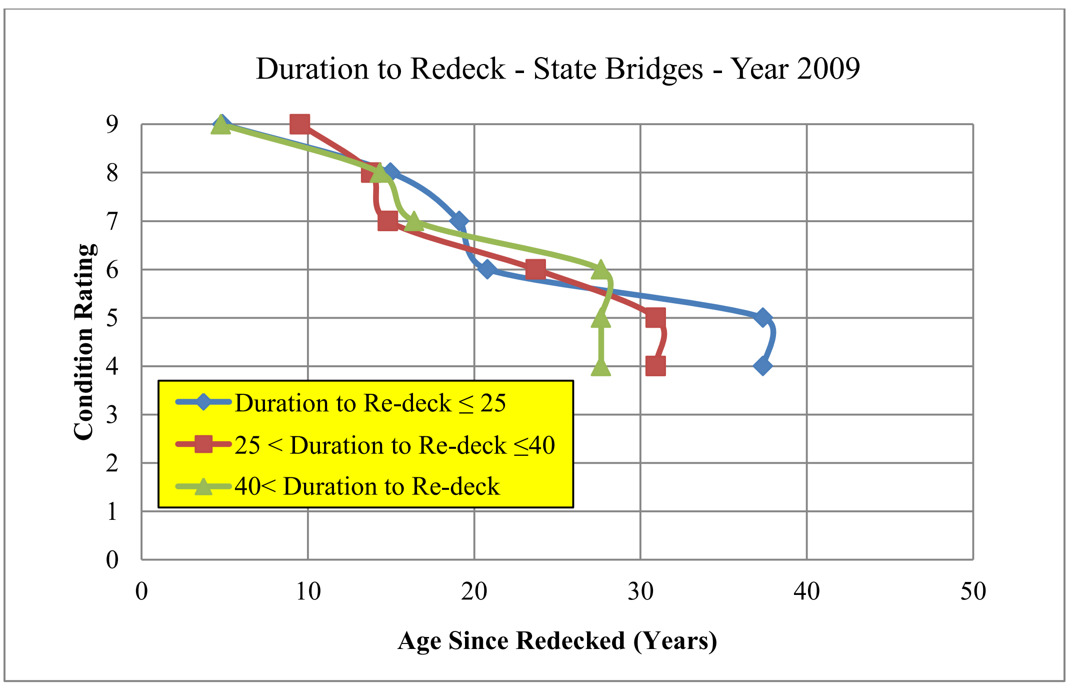


Figure 4-17: Deterioration curves of state bridge decks based on duration to re-deck for year 2009

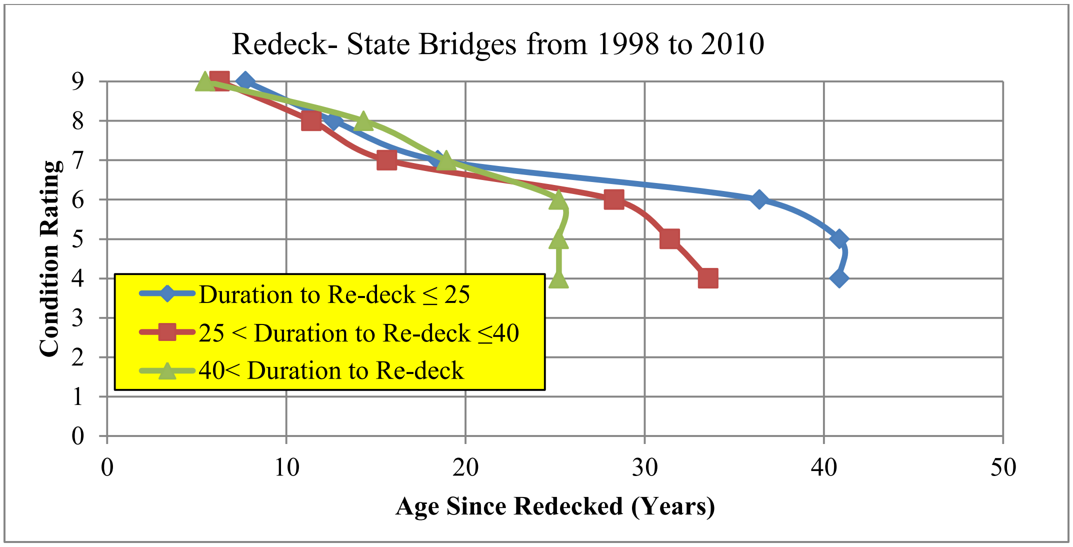


Figure 4-18: Deterioration curves of state bridge decks based on duration to re-deck from year 1998 to 2010

4.2.1.3. Overlays

There are three main types of deck overlay in state bridges: silica fume, latex concrete and low slump concrete. Overlays represent those decks which have year reconstructed (item 106 more than zero) and item 108A equal to 2 (silica fume), 3 (latex concrete) or 4 (low slump concrete). Histogram of duration to overlay in state bridges was developed as shown in Figure 4-19. This figure clearly shows that most of the state bridges have duration to overlay between 15 to 35 years.

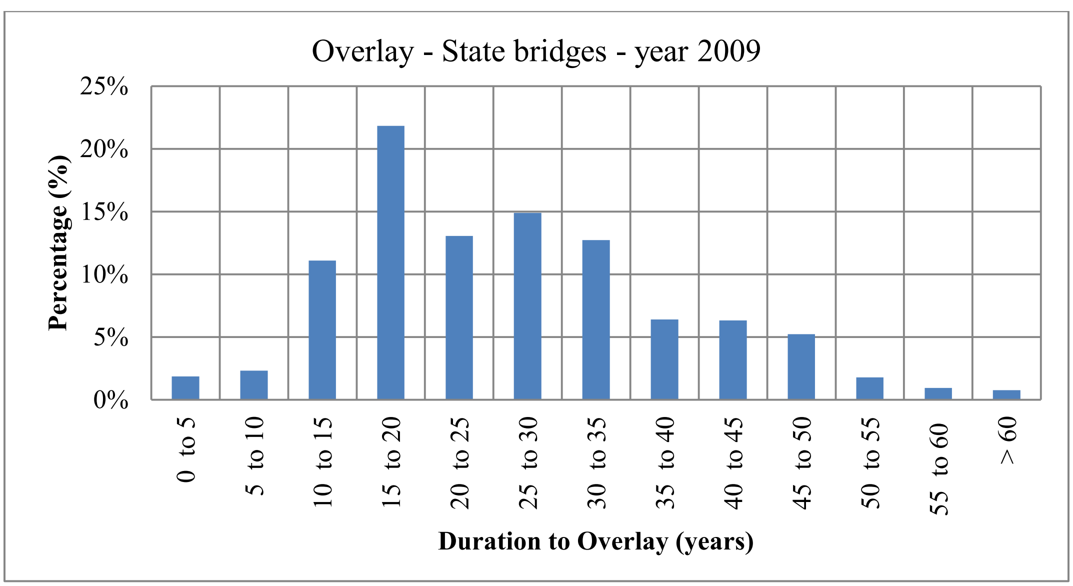


Figure 4-19: Overlays histogram of state bridges– year 2009

Based on duration to overlay histogram, deterioration curves were developed for three different categories: duration to overlay less than 15 years, more than 15 years and less than 35 years, and duration to overlay more than 35 years. Figures 4-20, 4-21, 4-22 and 4-23 show the deterioration curves for those three groups at years 2000, 2005, 2009 and from 1998 to 2010, respectively.

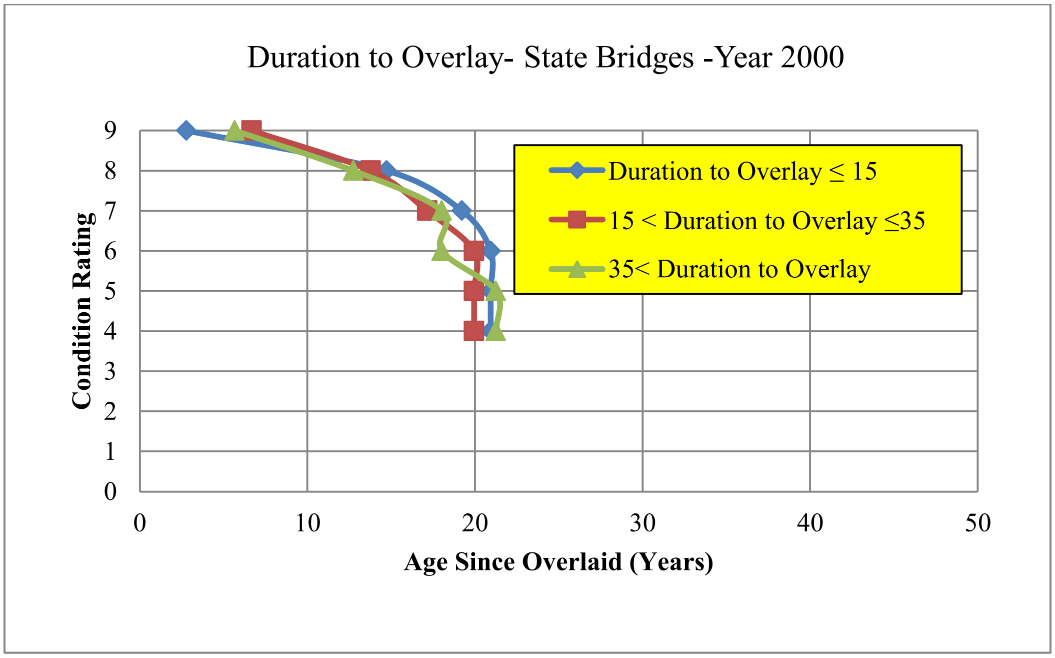


Figure 4-20: Deterioration curves of overlays based on duration to overlay - year 2000

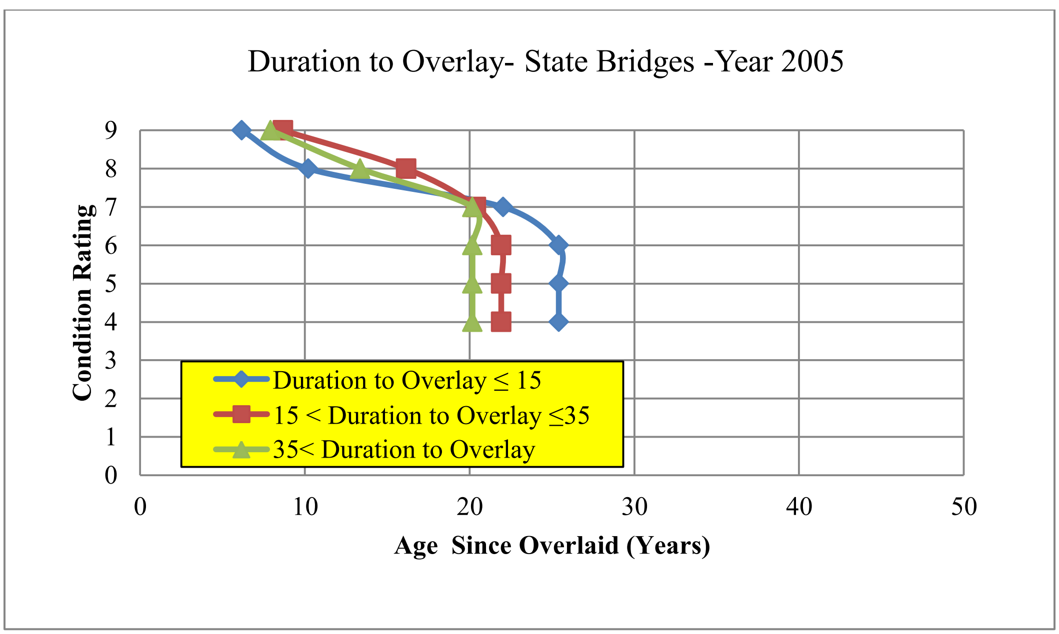


Figure 4-21: Deterioration curves of overlays based on duration to overlay - year 2005

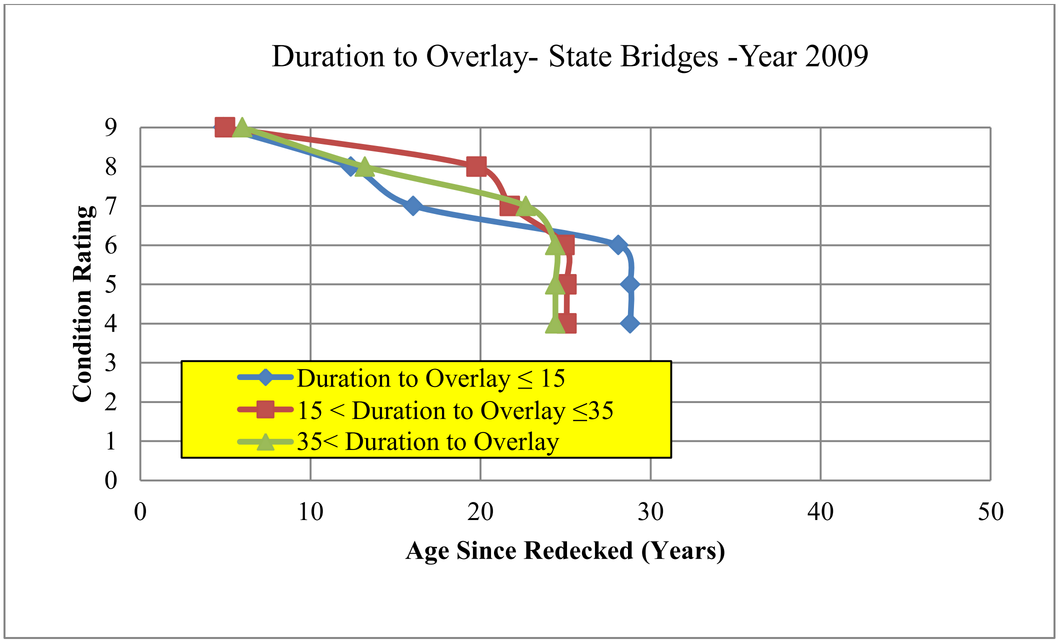


Figure 4-22: Deterioration curves of overlays based on duration to overlay - year 2009

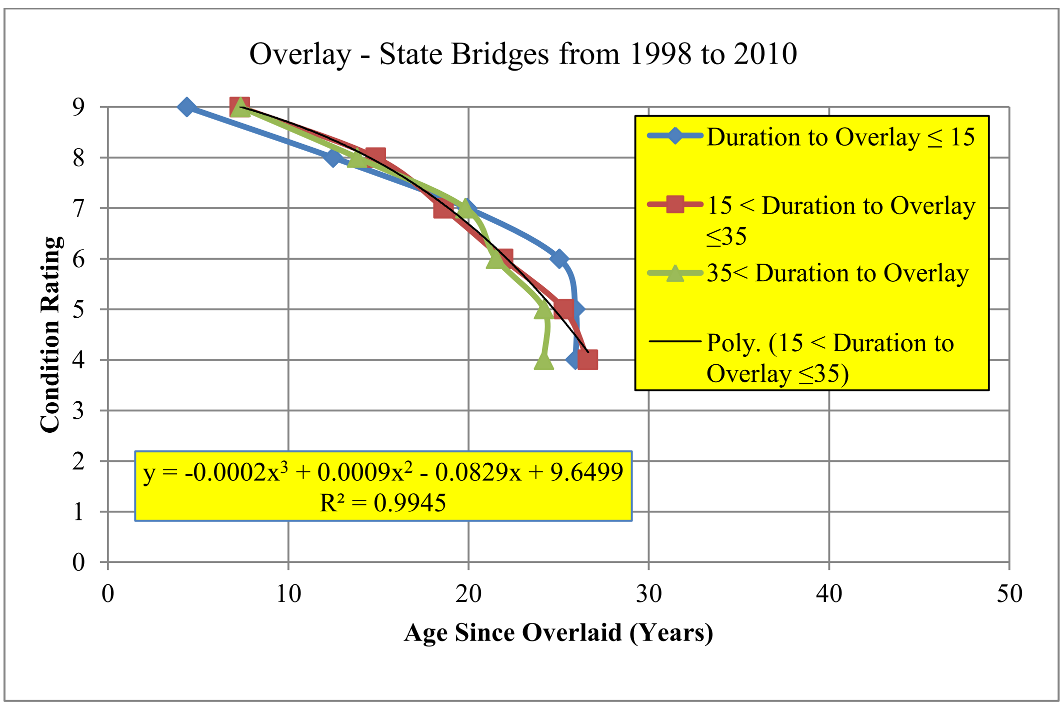


Figure 4-23: Deterioration curves of overlays based on duration to overlay - years 1998 to 2010

Table 4-4 listed the average transition period for overlays at years 2000, 2005, 2009 and from 1998 to 2010. Figure 4-24 shows overlays transition period for state bridges. This figure clearly shows that condition 9 to 8 with approximately 7 years has a maximum transition period.

Table 4-4: Transition period of overlays in state bridges

Overlays	Condition Rating - State Bridges				
Transition Period (years)	9 ⟹ 8	8 ⟹ 7	7 ⟹ 6	6 ⟹ 5	5 ⟹ 4
2000	7.1	3.4	2.8	0.0	0.0
2005	7.5	4.2	1.5	0.0	0.0
2009	14.8	2.0	3.2	0.1	0.0
1998 to 2010	7.5	3.8	3.3	3.4	1.3

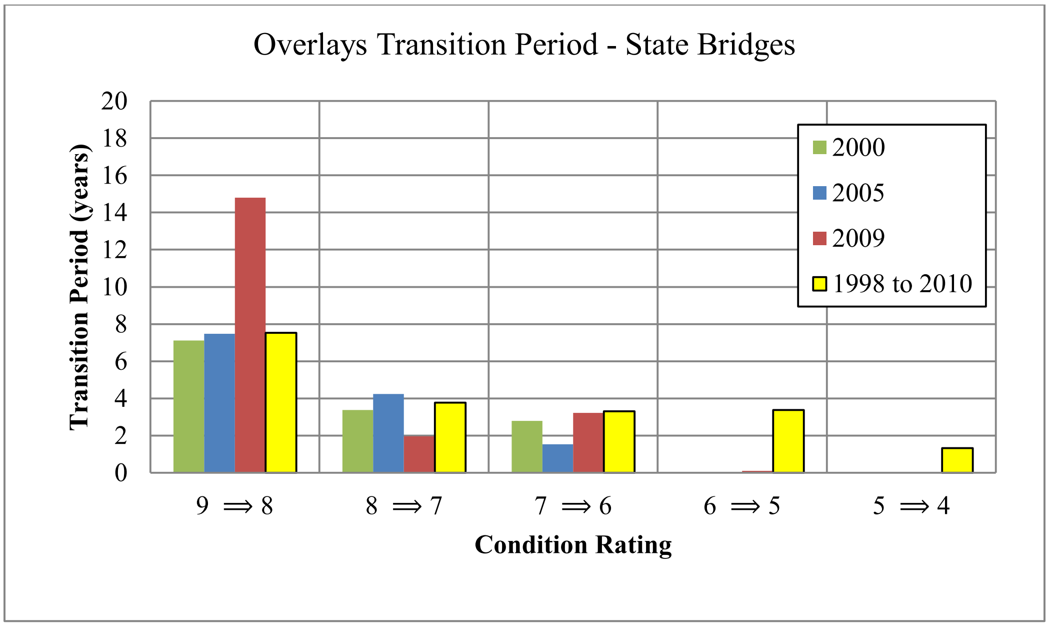


Figure 4-24: Overlays transition period in state bridges – years 2000, 2005, 2009 and from 1998 to 2010.

4.2.1.3.1. Silica Fume

Silica fume is one of the materials used recently as a wearing surface on bridge decks. According to 2009 data, there are 70 state bridges with silica fume overlay on their decks. Figure 4-25 presents the histogram of bridge decks which have been overlaid by silica fume. This figure clearly shows that most of the state bridges overlaid by silica fume have duration to overlay between 25 to 45 years. Figure 4-26 shows the age histogram of silica fume overlay at year 2009.

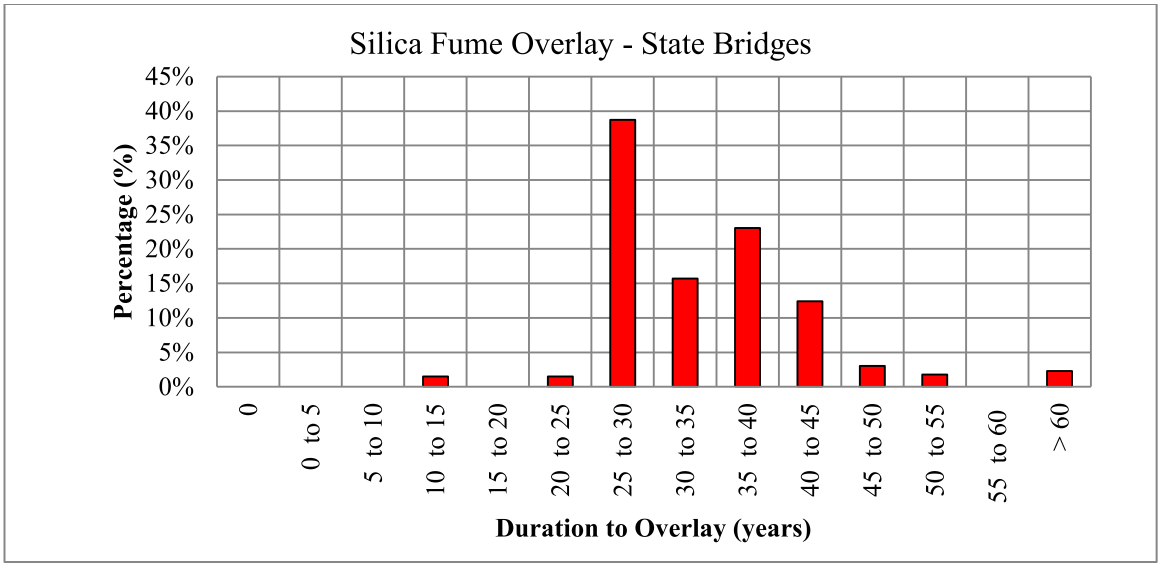


Figure 4-25: Duration to overlay histogram of silica fume overlay – year 2009

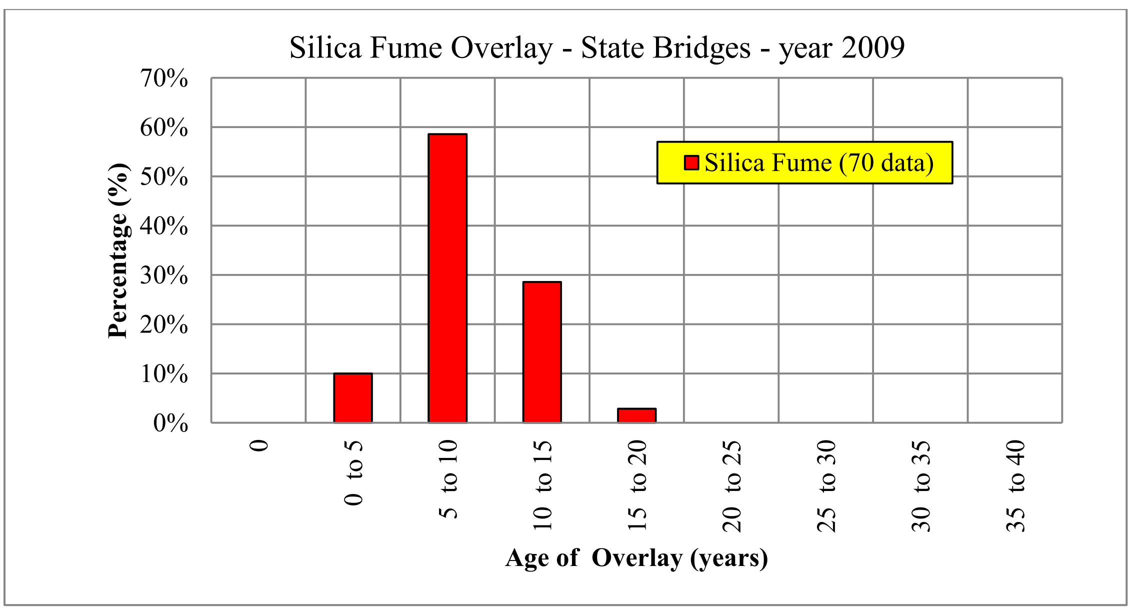


Figure 4-26: Age histogram of silica fume overlay – year 2009

Figure 4-26 indicates that silica fume overlay is used as a new wearing surface for decks recently as it has an age between 5 to 15 years. Therefore, there is not enough data for developing deterioration model for this type of overlay.

4.2.1.3.2. Latex Concrete

There are few state bridges (27 bridges) which have been overlaid with latex concrete. Figure 4-27 presents the duration to overlay histogram for decks with latex concrete wearing surface. This figure indicates that most of the state bridges overlaid with latex concrete had duration to overlay between 10 to 15 years. Figure 4-28 presents the age histogram of latex concrete overlay in year 2009. This figure clearly shows that latex concrete overlay is one of the old materials used in bridge decks as wearing surface and has an age between 30 to 35 years. However, deterioration curve was not developed for latex concrete overlay due to the small number of data points.

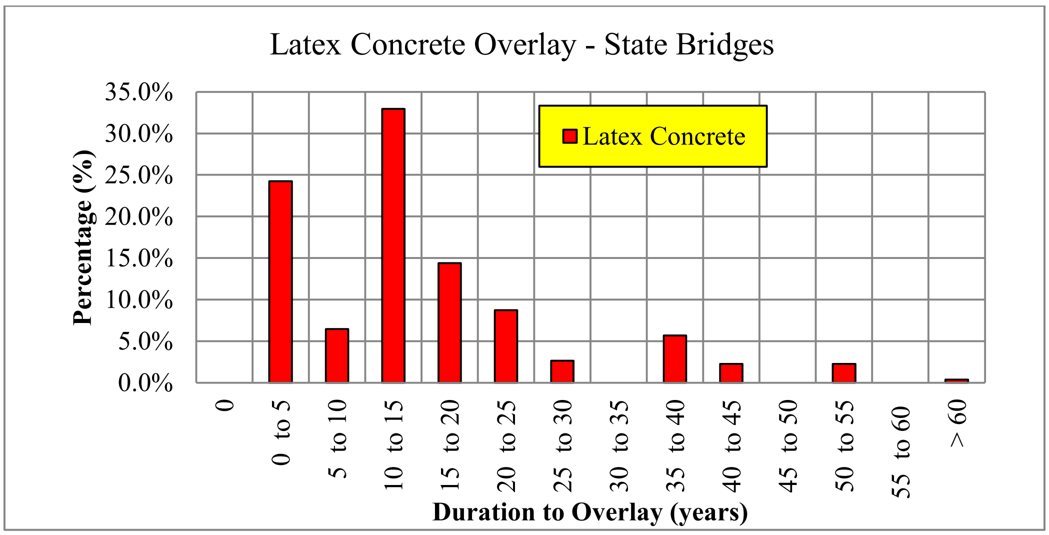


Figure 4-27: Bridge decks overlaid by latex concrete – year 2009

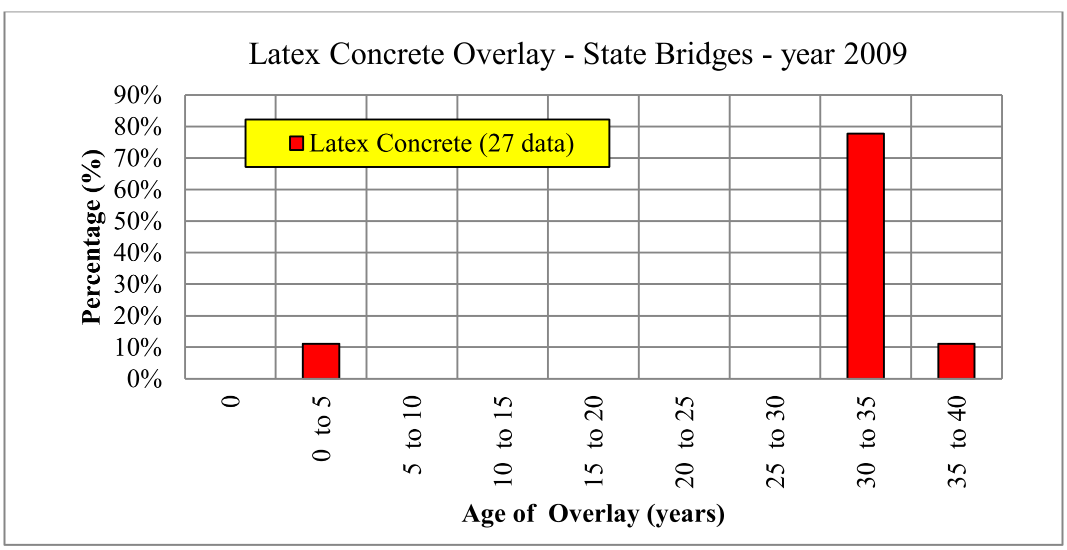


Figure 4-28: Latex concrete age histogram – year 2009

4.2.1.3.3. Low Slump Concrete

There are 338 state bridges at year 2009 which have low slump concrete wearing surface. Figure 4-29 presents the histogram of bridge decks with low slump concrete wearing surface. This figure shows that most of the state bridges overlaid with low slump concrete had duration to overlay between 15 to 35 years. Figure 4-30 shows the age histogram of low slump concrete overlay in year 2009. This figure shows low slump concrete overlay has an age between 15 to 35 years. Figure 4-31 shows deterioration curve of low-slump concrete overlay in state bridges.

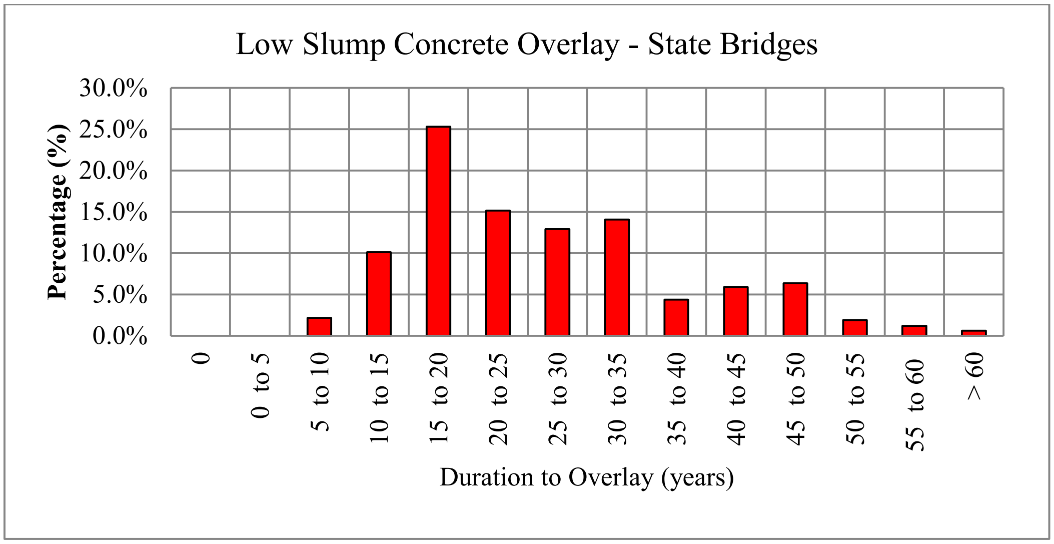


Figure 4-29: Bridge decks overlaid by low slump concrete – year 2009

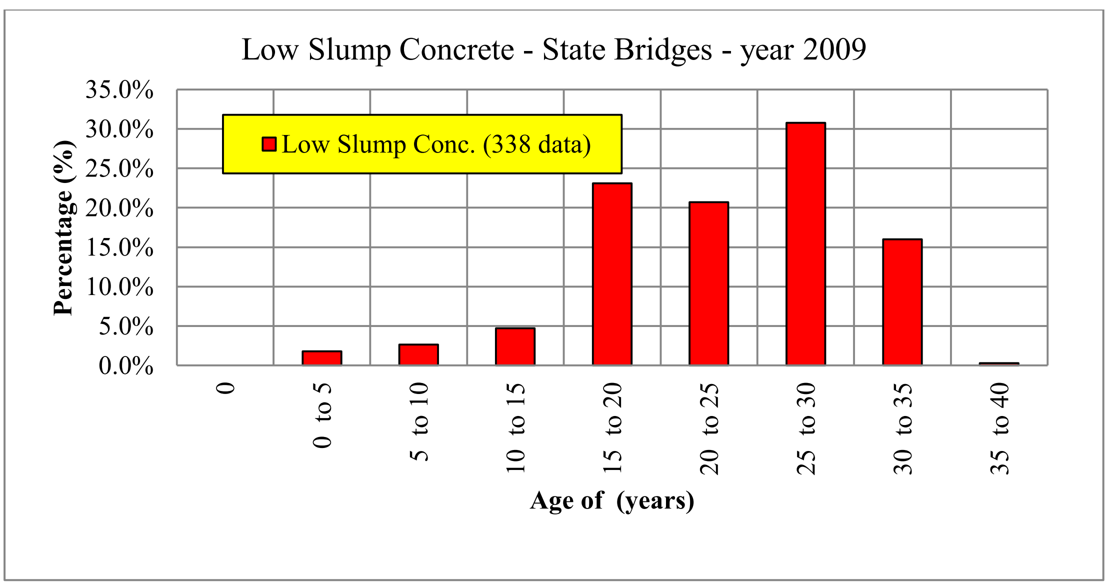


Figure 4-30: Low slump concrete age histogram – year 2009

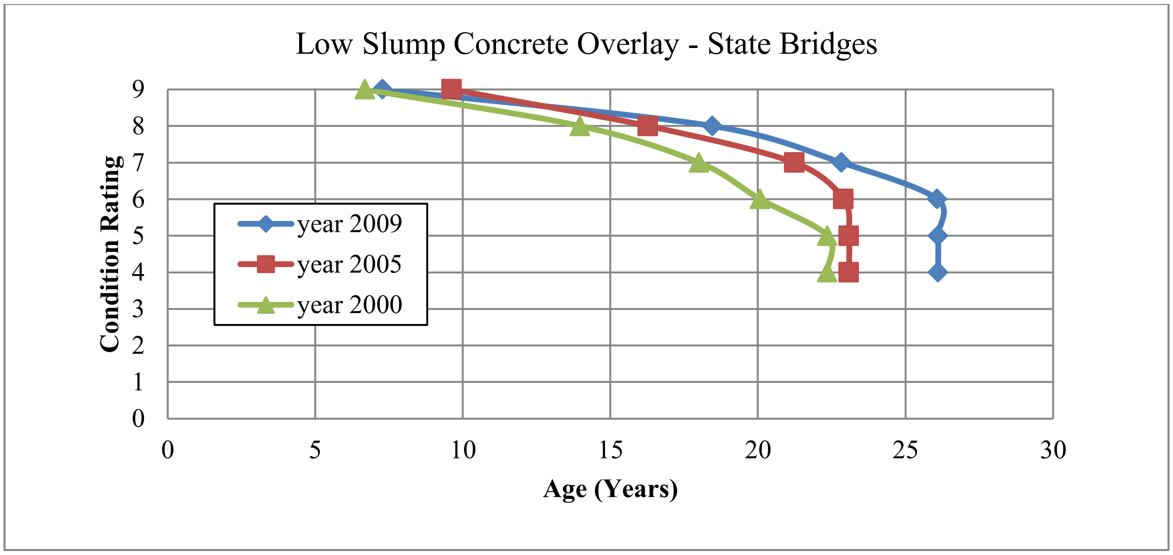


Figure 4-31: Deterioration curve of low slump concrete overlay in state bridge decks – years 2000, 2005 and 2009

Figure 4-32 shows the deterioration curve of low slump concrete overlay in state bridge decks using condition data from 1998 to 2010 and the power formula that best fits the condition data. For comparison, deterioration curve for original deck also plotted in this figure. This figure clearly shows that deterioration rate for low-slump concrete overlay is significantly higher than that of original concrete deck.

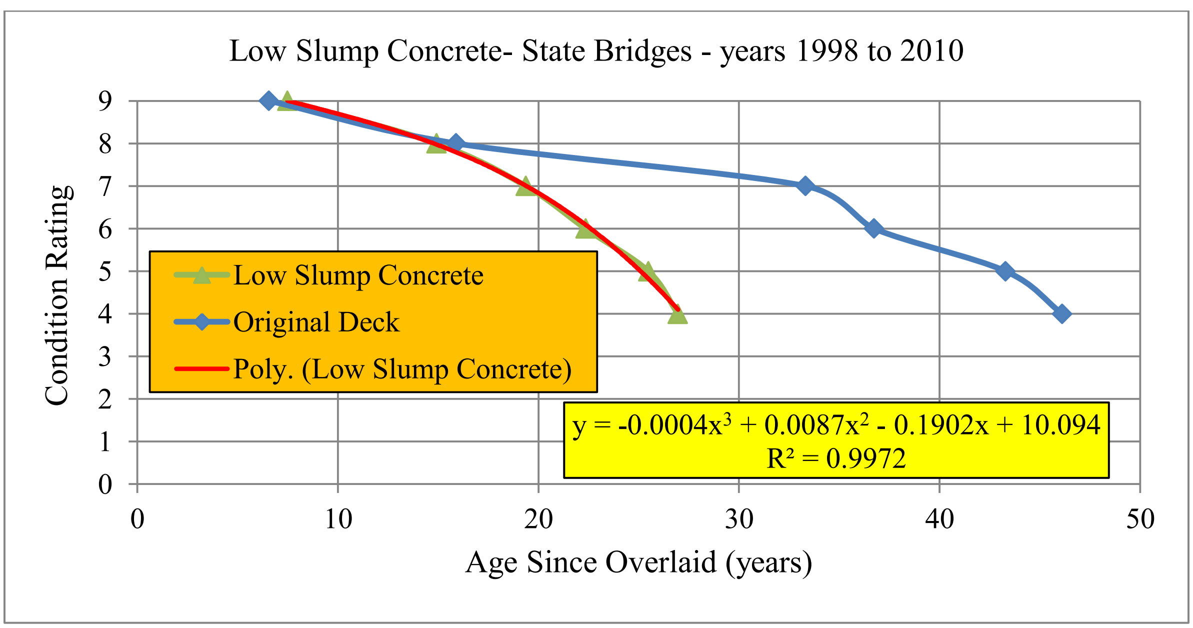


Figure 4-32: Deterioration curve of low slump concrete overlay

Table 4-5 and figure 4-33 show the average transition period of low-slump concrete overlay for years 2000, 2005, 2009 and 1998 to 2010. Results show that condition 9 to 8 has an average transition period with approximately 7.5 years.

Table 4-5: Transition period of low slump concrete overlay on state bridge decks.

Low Slump Concrete	Condition Rating - State Bridges				
Transition Period (years)	9 ⟹ 8	8 ⟹ 7	7 ⟹ 6	6 ⟹ 5	5 ⟹ 4
2000	7.3	4.0	2.1	2.3	0.0
2005	6.7	5.0	1.7	0.2	0.0
2009	11.2	4.4	3.2	0.0	0.0
1998 to 2010	7.4	4.4	3.0	3.1	1.5

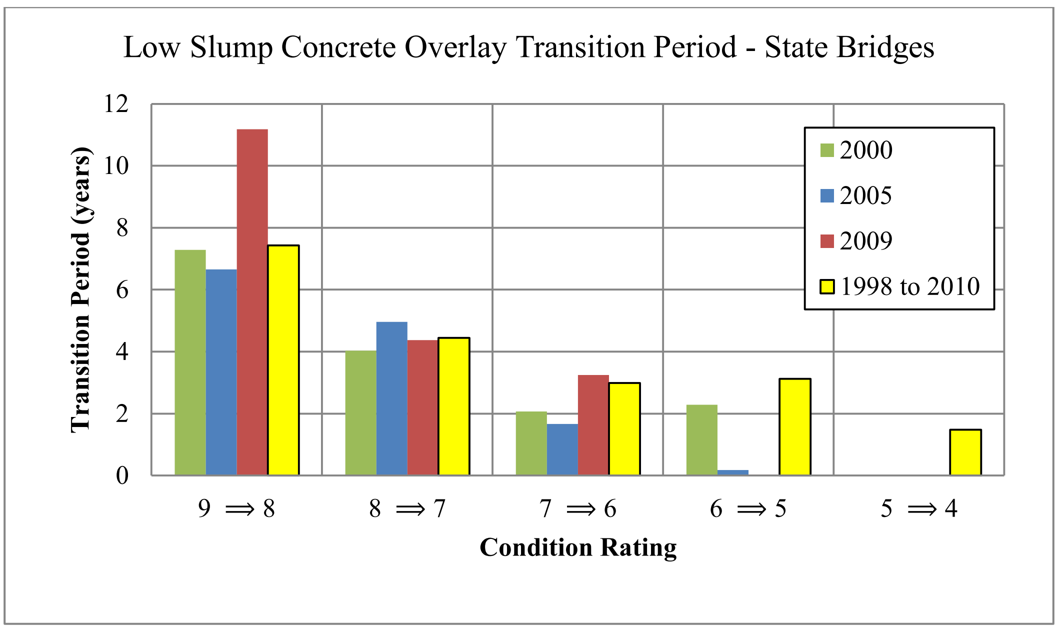


Figure 4-33: Transition period histogram of low slump concrete overlay on state bridge decks – years 2000, 2005, 2009 and from 1998 to 2010

4.2.2. Traffic on Deck

Traffic volume significantly influences the rate of deterioration of bridge decks. In this section, impact of traffic volume on state bridge decks is presented. There are two parameters related to traffic volume in database: average daily traffic (ADT) and average daily truck traffic (ADTT). ADTT is a percentage of ADT.

4.2.2.1. Average Daily Traffic (ADT)

ADT on highway bridges is described in item BRI_INV_ITEM029 of the National Bridge Inventory (NBI) database. Based on AASHTO Load and Resistance Factor Rating 2007 (LRFR), the ADT was categorized into the four different levels listed in Table 3-9. Figure 4-34 shows the frequency diagram of ADT in state bridges at years 2000, 2005 and 2009. Same plot for all bridges is shown in Figure 3-14. This figure clearly shows that ADT more than 100 and less than 500 has a highest frequency in state bridges. However, ADT less than 100 had a highest frequency in all bridges.

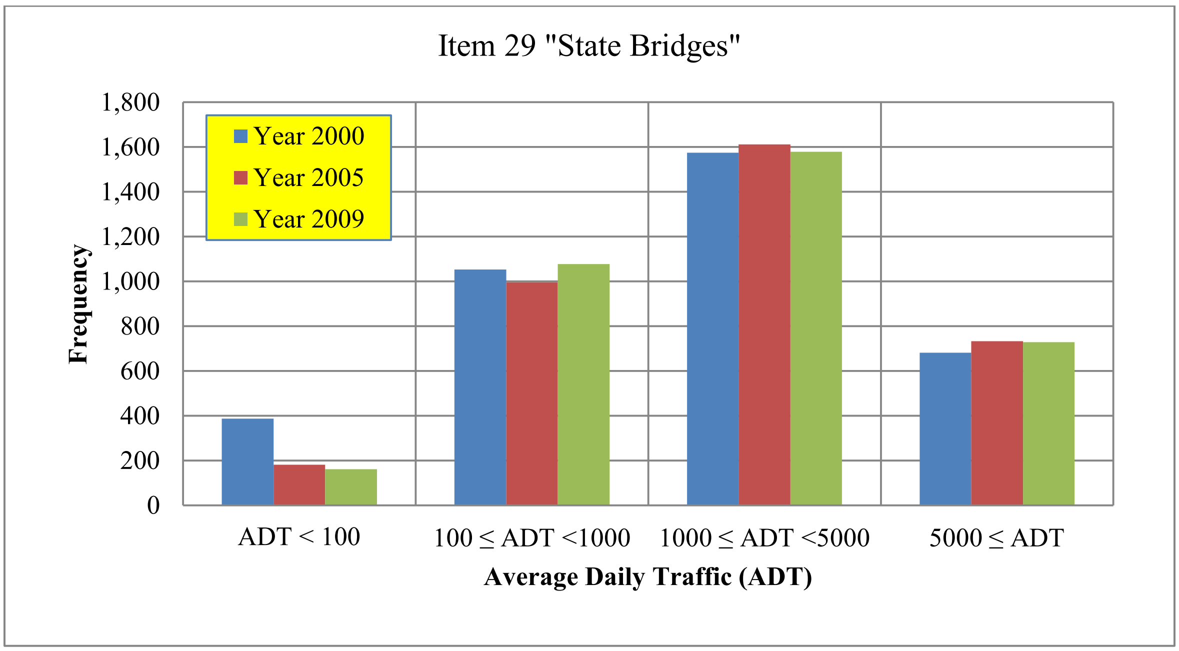


Figure 4-34: Frequency diagram of ADT in state bridges – years 2000, 2005 and 2009

Figures 4-35, 4-36 and 4-37 show the deterioration curves of state bridge decks with different levels of traffic at years 2000, 2005, and 2009. These figures indicate that decks with lower traffic volumes have better condition than those with higher traffic volume. Figures 4-38, 4-39 and 4-40 show the average transition period for state bridge decks with different traffic volumes at years 2000, 2005 and 2009. These figures indicate that bridges with low traffic volume have a longest average transition period in most cases.

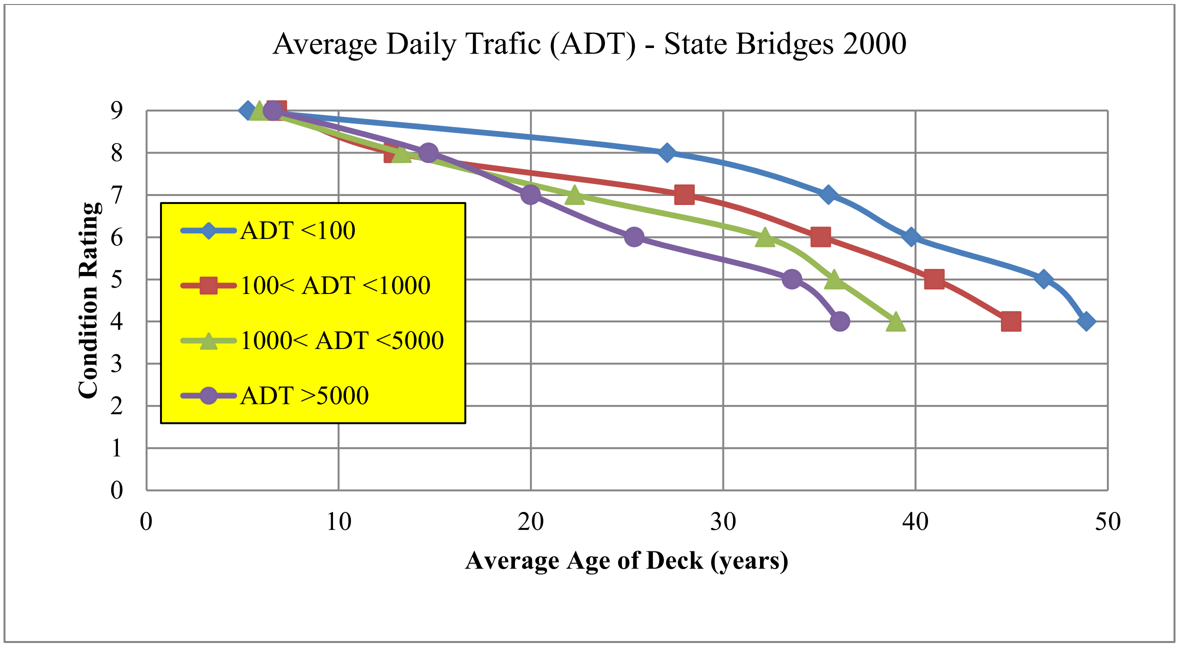


Figure 4-35: Deterioration curves of state bridge decks with different ADT- year 2000

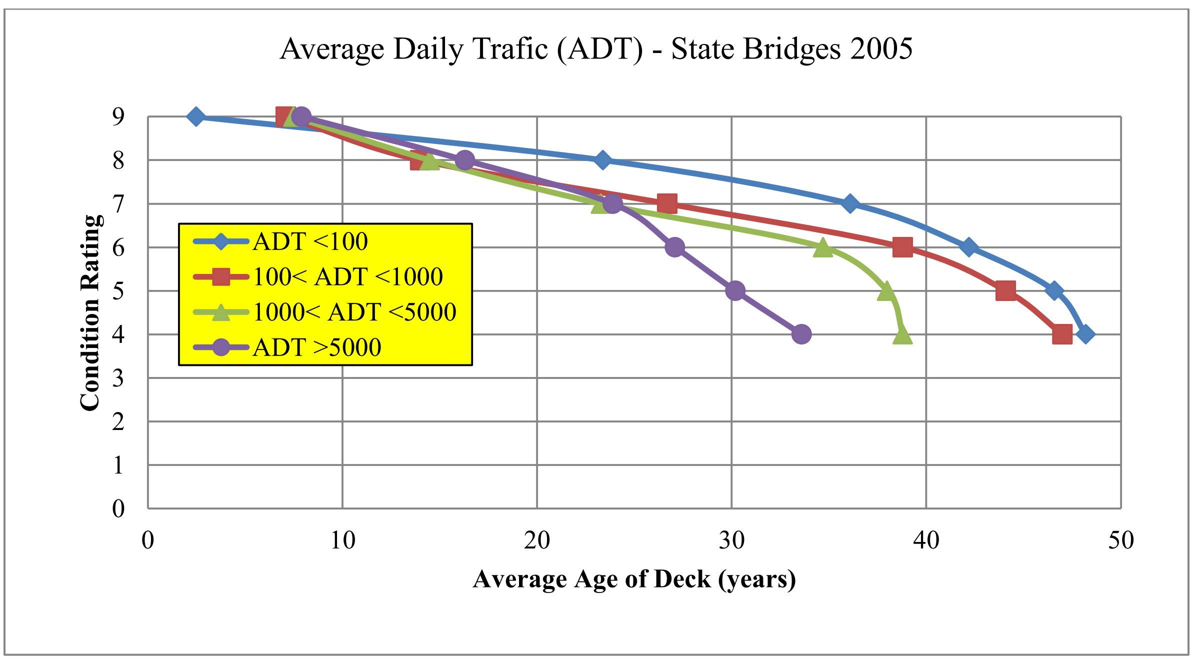


Figure 4-36: Deterioration curves of state bridge decks with different ADT - year 2005

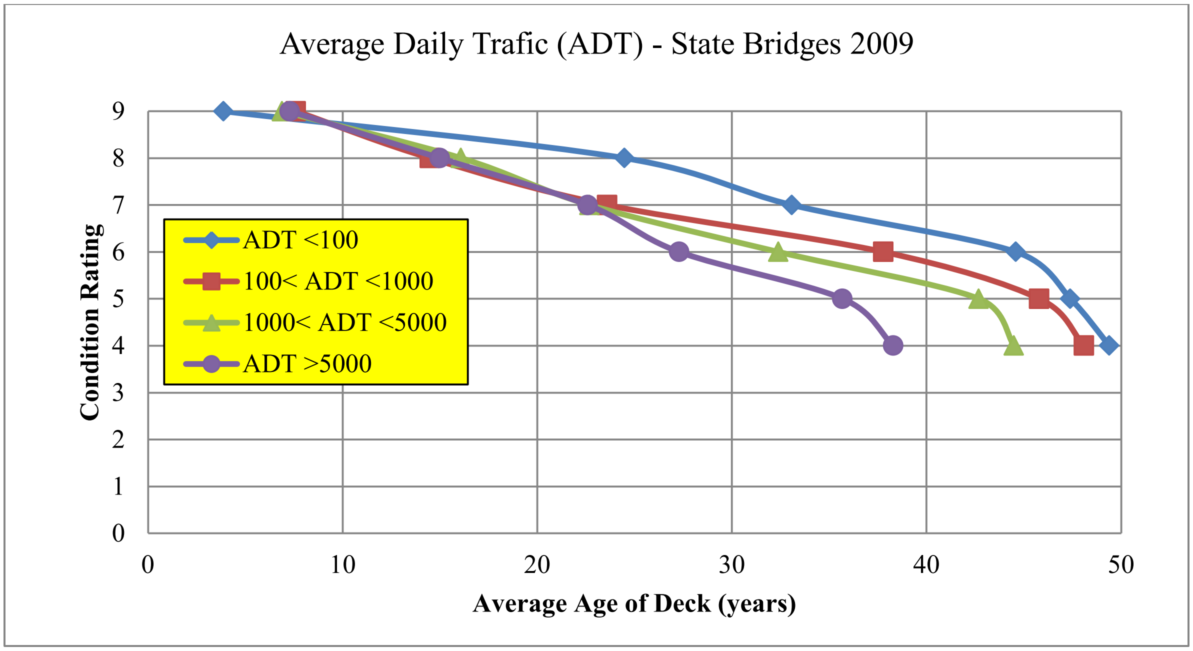


Figure 4-37: Deterioration curves of state bridge decks with different ADT- year 2009

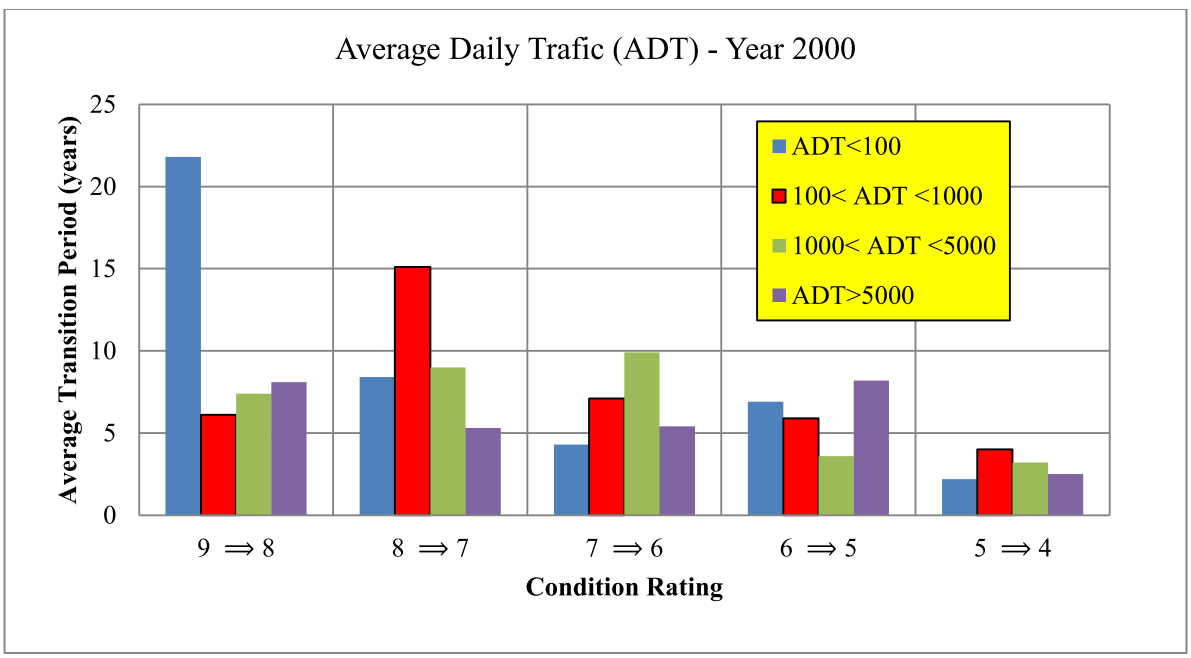


Figure 4-38: Average transition period of state bridge decks with different ADT – year 2000

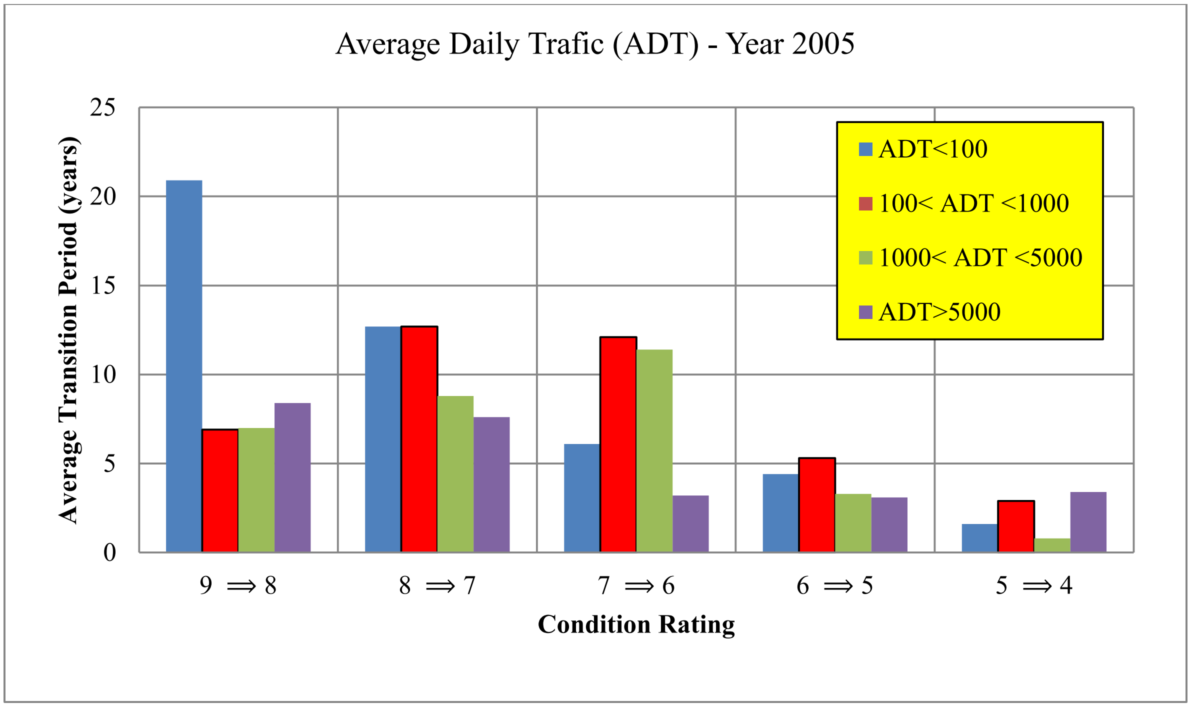


Figure 4-39: Average transition period of state bridge decks with different ADT – year 2005

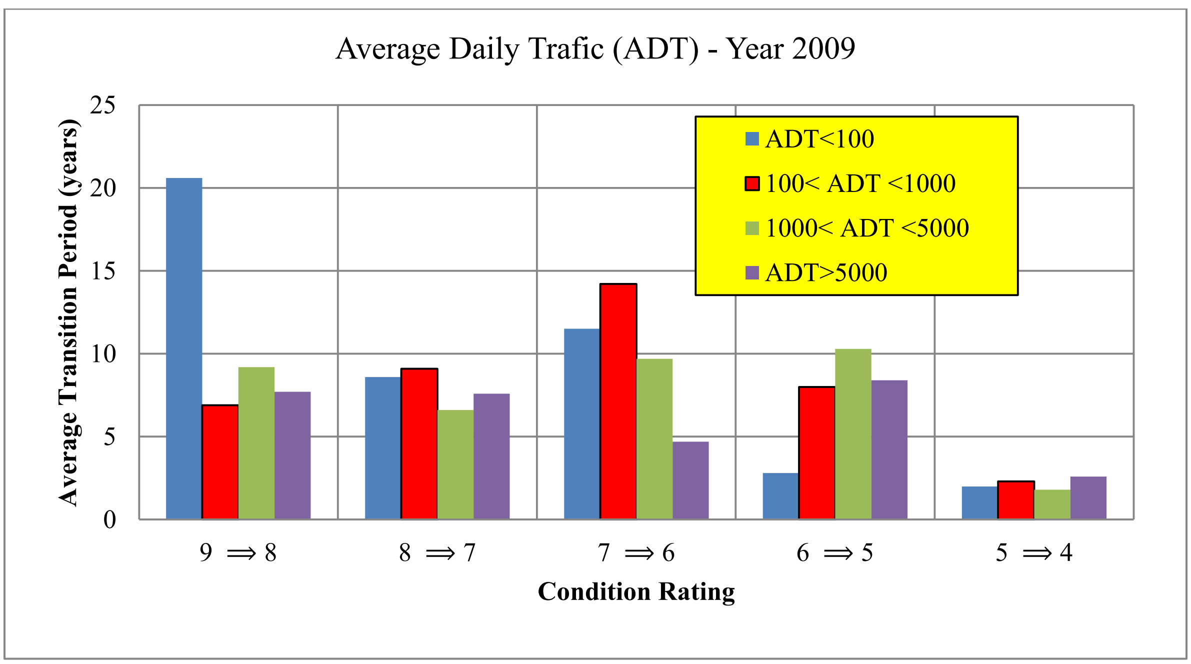


Figure 4-40: Average transition period of state bridge decks with different ADT – year 2009

4.2.2.2. Average Daily Truck Traffic (ADTT)

ADTT is a percentage of item 29 (ADT). Based on data analysis, the ADTT was categorized into three different levels of traffic which was listed in Table 3-10. Figure 4-41 shows the frequency diagram of ADTT in state bridges with bare concrete decks. Results show that bridges with ADTT more than 100 and less than 500 has a highest frequency; and bridges ADTT less than 100 have a higher frequency than those with ADTT more than 500.

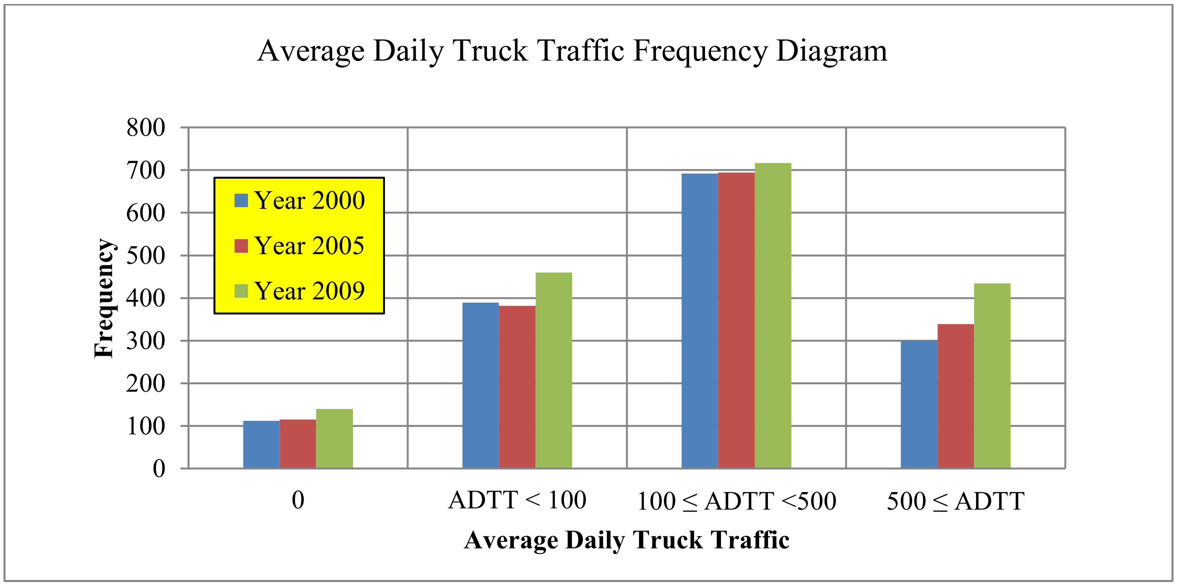


Figure 4-41: ADTT frequency diagram in state bridges

All state bridges with ADTT = 0 were eliminated in developing Figures 4-42, 4-43 and 4-44, which show the deterioration curves of concrete decks in state bridges with different levels of ADTT in years 2000, 2005, and 2009. These figures indicate that decks with lower ADTT have better condition than those with higher ADTT. There aren't enough data at condition 5 for ADTT more than 500 and this cause a significant difference between average age of bridge decks at condition 6 and 5. Figures 4-45, 4-46 and 4-47 present the deterioration curve of concrete decks in state bridges developed using the condition data from year 1998 to 2010 with ADTT less than 100, more than 100 and less than 500, and more than 500 respectively.

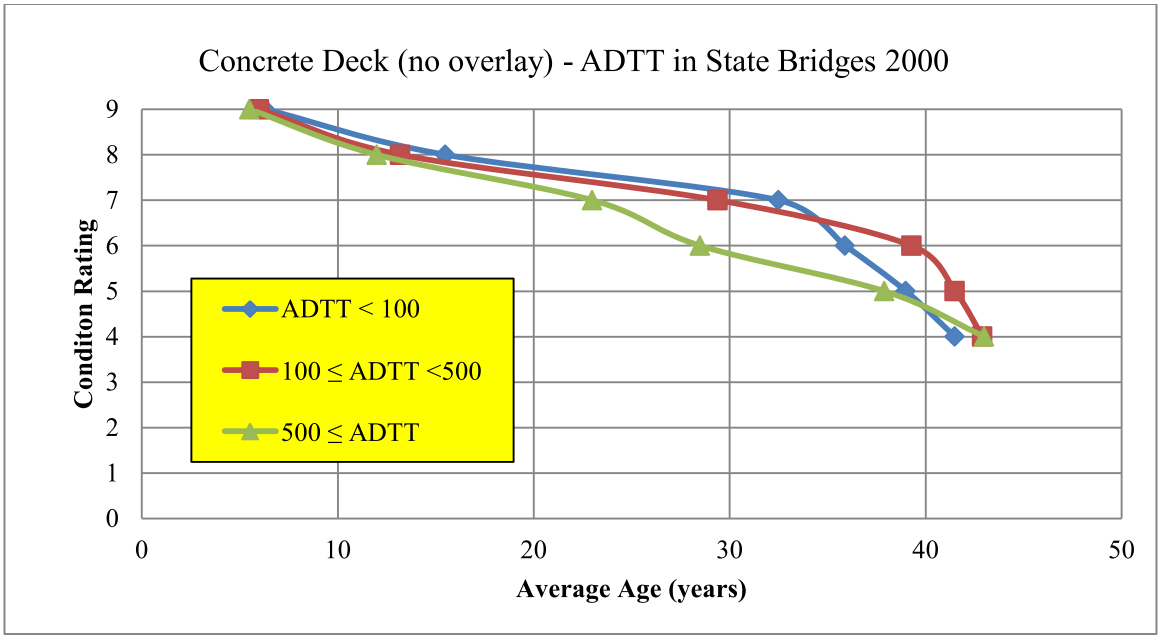


Figure 4-42: Deterioration curves of state bridge decks with different ADTT - year 2000

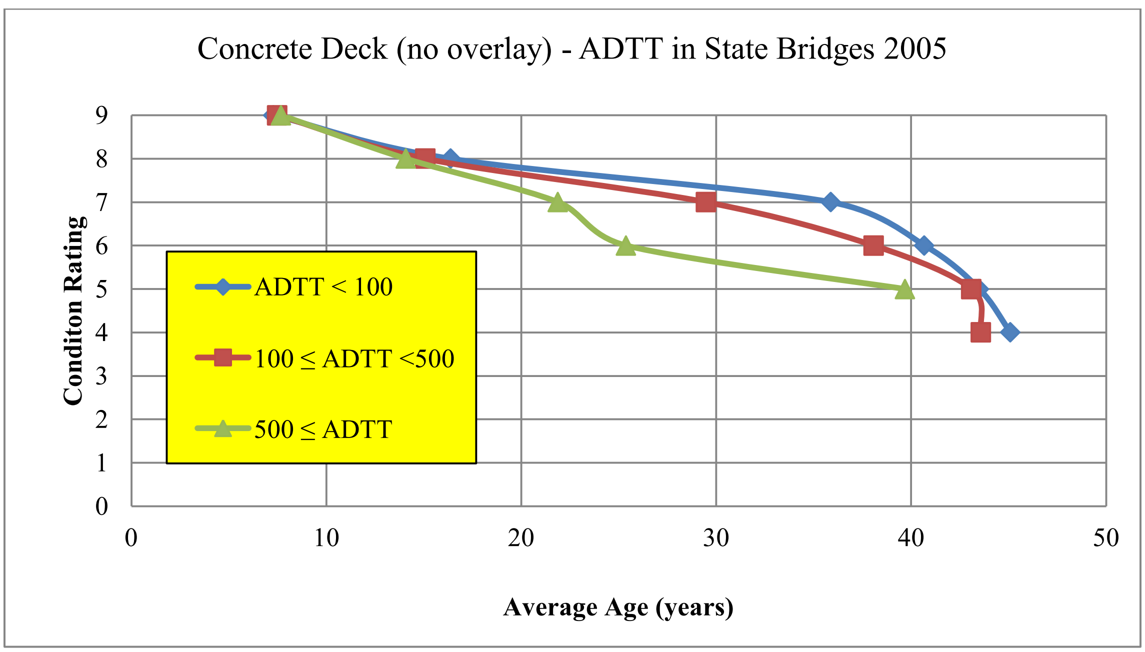


Figure 4-43: Deterioration curves of state bridge decks with different ADTT - year 2005

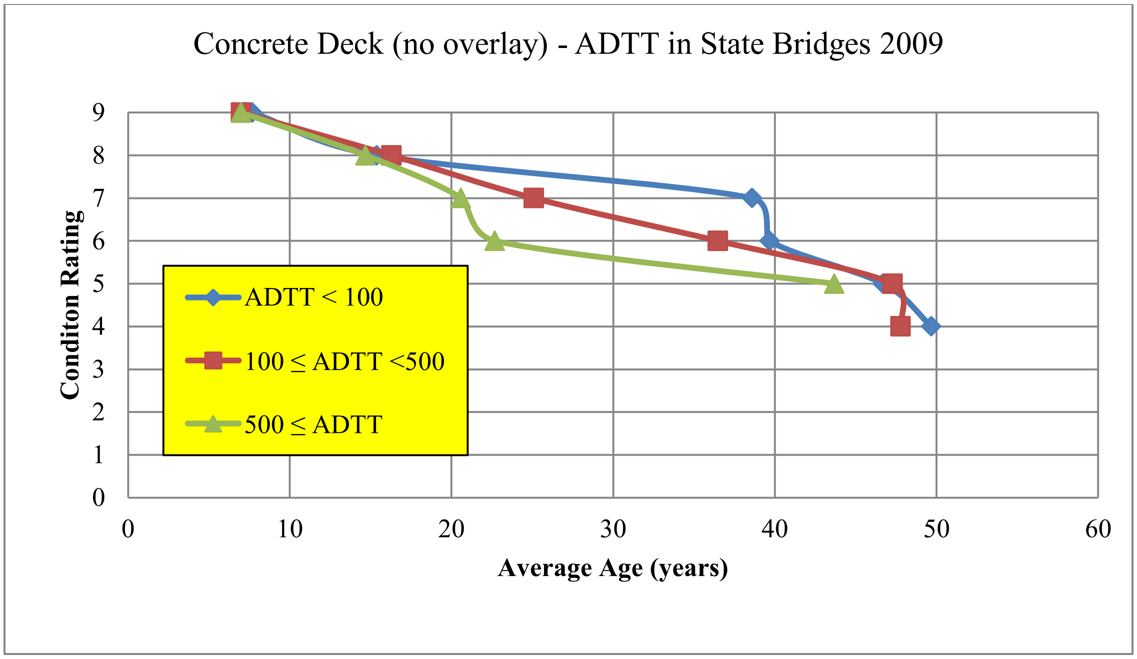


Figure 4-44: Deterioration curves of state bridge decks with different ADTT - year 2009

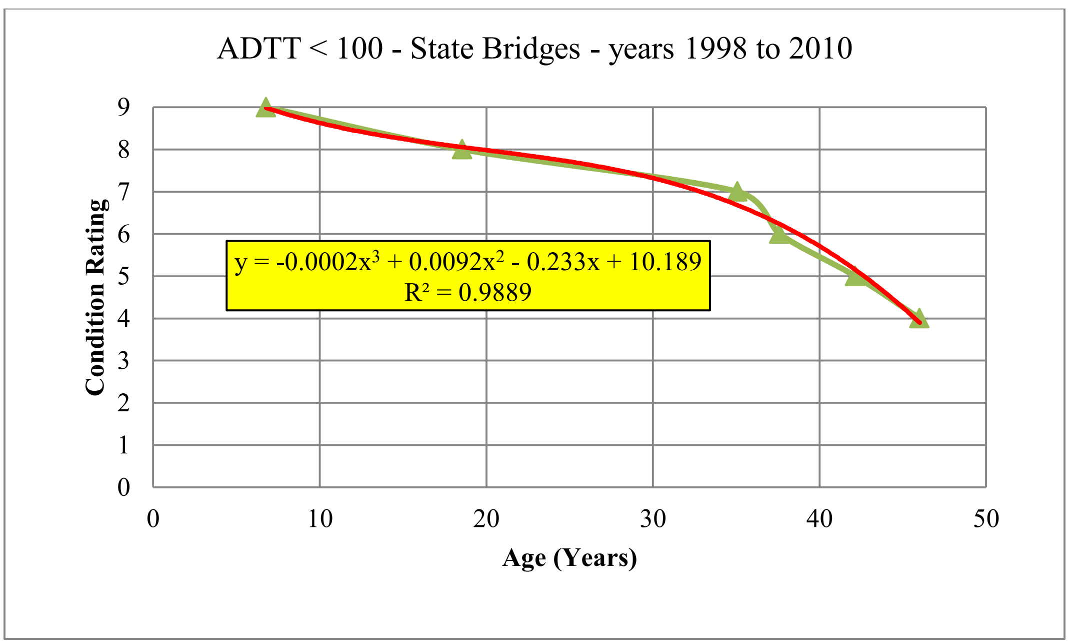


Figure 4-45: Deterioration curve of state bridge decks with ADTT < 100

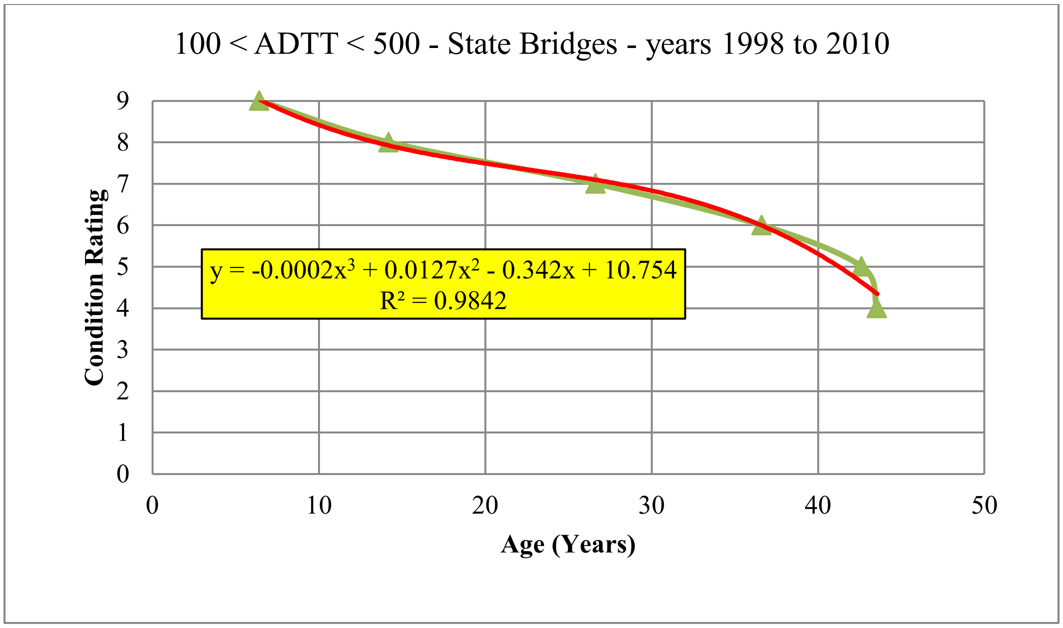


Figure 4-46: Deterioration curve of state bridge decks with 100 < ADTT < 500

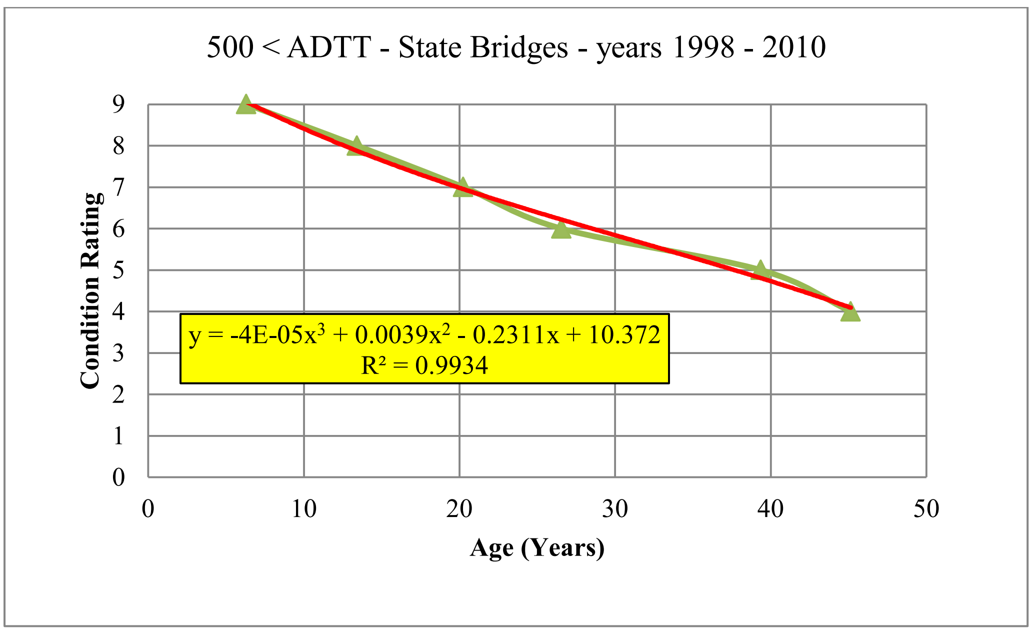


Figure 4-47: Deterioration curve of state bridge decks with ADTT > 500

Tables 4-6, 4-7 and 4-8 list the transition period calculated for ADTT less than 100, more than 100 and less than 500, and more than 500. These data are plotted in Figures 4-48, 4-49 and 4-50 for comparison purposes. Also, all transition periods calculated from condition data from 1998 to 2010 were plotted all together in Figure 4-51.

Table 4-6: Transition period for state bridge decks with ADTT < 100

ADTT < 100	Condition Rating - State Bridges				
Transition Period (years)	$9 \Rightarrow 8$	$8 \Rightarrow 7$	$7 \Rightarrow 6$	$6 \Rightarrow 5$	$5 \Rightarrow 4$
2000	7.7	23.2	1.1	7.0	3.0
2005	9.1	19.5	4.8	2.8	1.6
2009	9.2	17.0	3.4	3.1	2.5
1998 to 2010	11.8	16.5	2.5	4.6	3.9

Table 4-7: Transition period for state bridge decks with 100 < ADTT < 500

100 ≤ ADTT <500	Condition Rating - State Bridges				
Transition Period (years)	$9 \Rightarrow 8$	$8 \Rightarrow 7$	$7 \Rightarrow 6$	$6 \Rightarrow 5$	$5 \Rightarrow 4$
2000	7.2	16.2	9.9	2.2	1.4
2005	7.6	14.4	8.6	5.0	0.5
2009	9.3	8.8	11.4	10.8	0.5
1998 to 2010	7.8	12.4	10.0	6.0	0.9

Table 4-8: Transition period for state bridge decks with ADTT > 500

500 ≤ ADTT	Condition Rating - State Bridges				
Transition Period (years)	$9 \Rightarrow 8$	$8 \Rightarrow 7$	$7 \Rightarrow 6$	$6 \Rightarrow 5$	$5 \Rightarrow 4$
2000	6.5	11.0	5.5	9.4	5.1
2005	6.4	7.8	3.5	14.3	0
2009	7.7	5.9	2.1	21.0	0
1998 to 2010	7.1	6.8	6.3	12.8	5.8

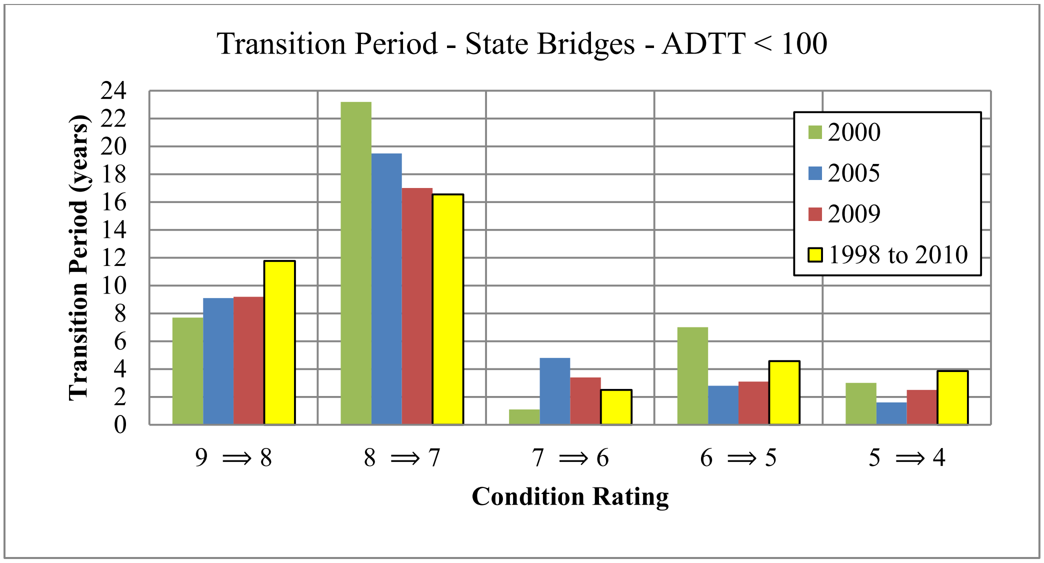


Figure 4-48: Transition period for state bridge decks with ADTT < 100

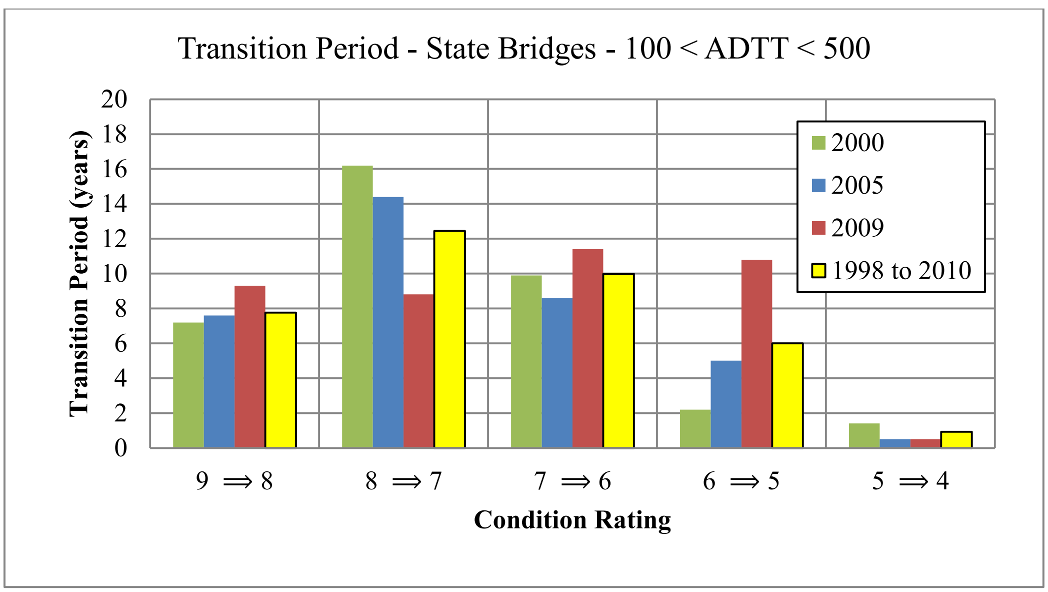


Figure 4-49: Transition period for state bridge decks with 100 < ADTT < 500

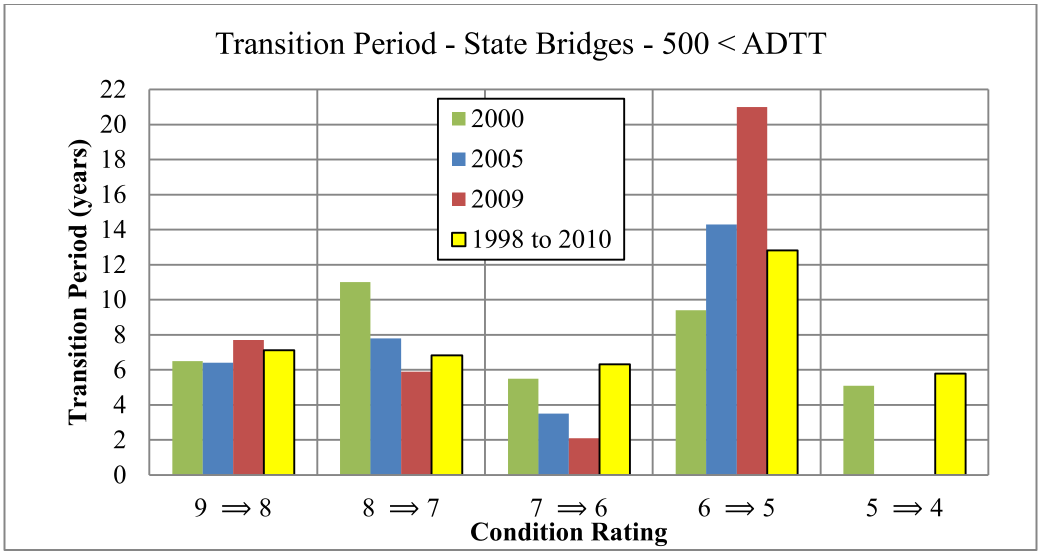


Figure 4-50: Transition period for state bridge decks with ADTT > 500

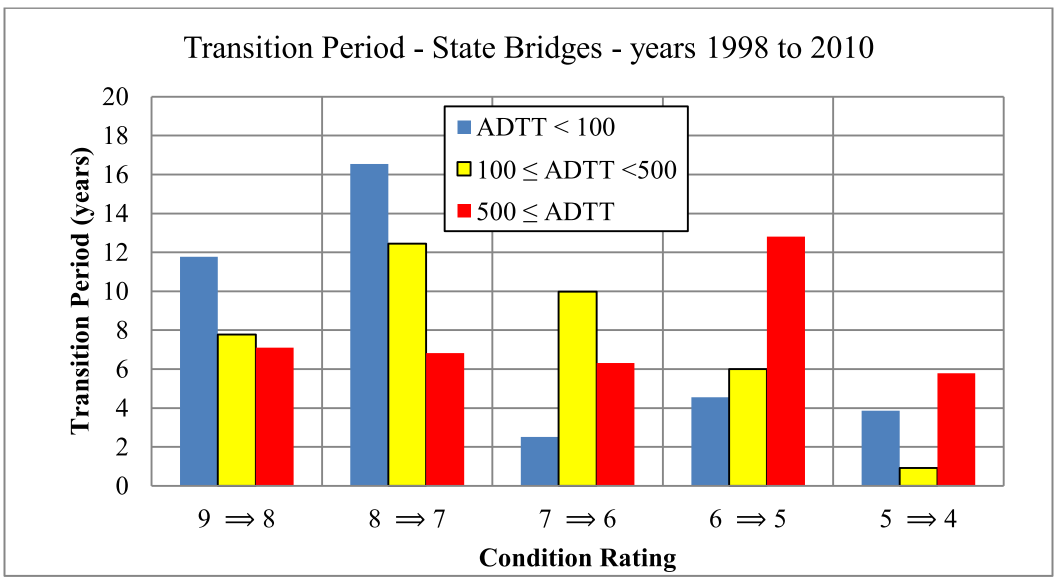
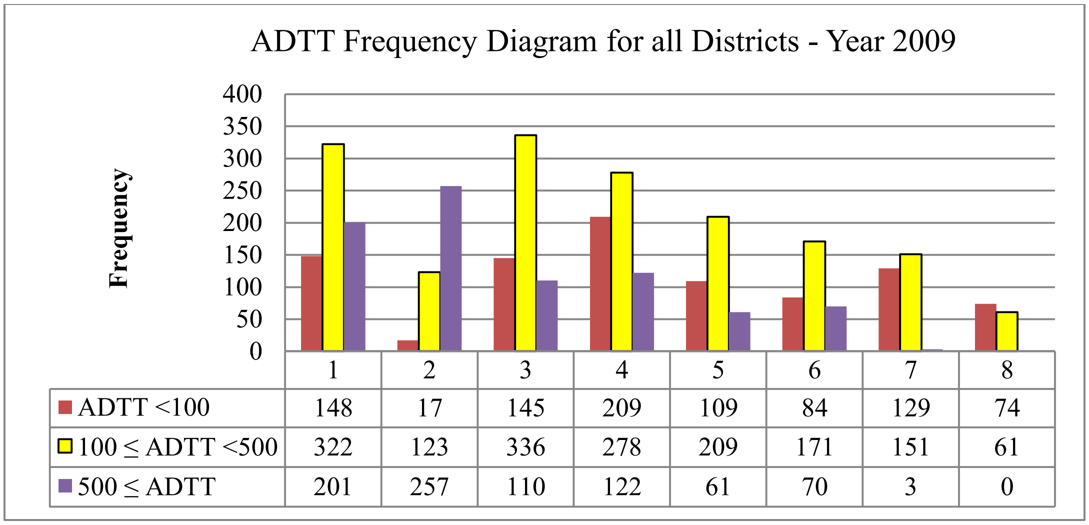


Figure 4-51: Transition period for state bridge decks with different ADTT

4.2.3. Highway Agency District

The eight districts of the state of Nebraska are described in section 3.2. Figure 4-52 shows the frequency diagram of ADTT in each district for state bridges in year 2009. This figure shows that district 2 has the highest frequency of ADTT more than 500. Following district 2, district 1 has a higher frequency than other districts. For ADTT more than 100 and less than 500, districts 3 and 1 have the highest frequency.



	1	2	3	4	5	6	7	8
ADTT <100	148	17	145	209	109	84	129	74
100 ≤ ADTT <500	322	123	336	278	209	171	151	61
500 ≤ ADTT	201	257	110	122	61	70	3	0

Figure 4-52: ADTT frequency diagram for districts 1 to 8 in state bridges - year 2009

The other conclusion from this figure is that most of state bridges are in districts 1, 2, 3 and 4 (about two thirds), therefore, deterioration models are developed for concrete decks in two categories: a) districts 1, 2, 3 and 4; and b) districts 5, 6, 7 and 8. Figures 4-53 and 4-54 show the deterioration curves and transition period for districts 1, 2, 3 and 4. These figures clearly show the deterioration rate for bridge decks in district 2 is higher than other districts due to the higher ADTT. Thus, deterioration curves for districts 1, 3 and 4 is shown in Figure 4-55 separately from those in district 2, which is shown in Figure 4-56.

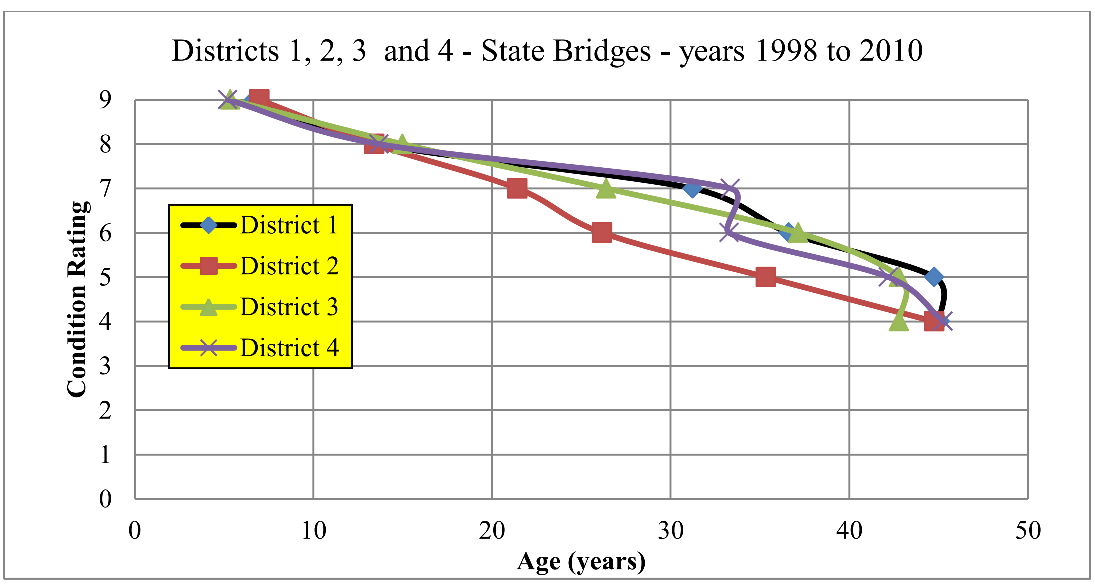


Figure 4-53: Deterioration curves of decks in districts 1, 2, 3 and 4 – years 1998 to 2010

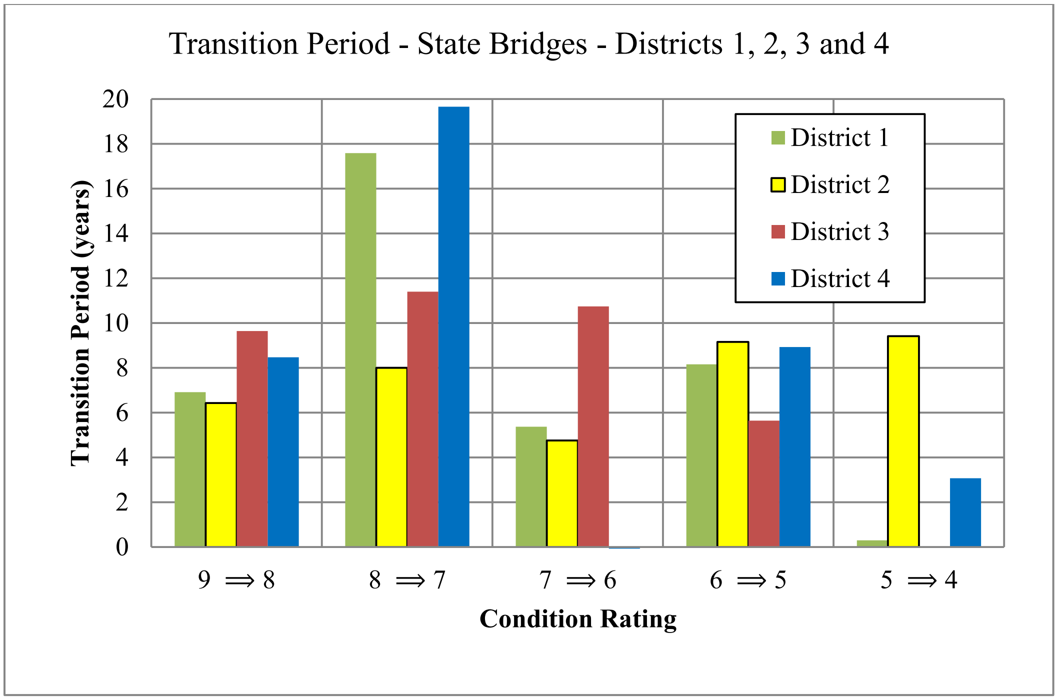


Figure 4-54: Transition periods of decks in districts 1, 2, 3 and 4 – years 1998 to 2010

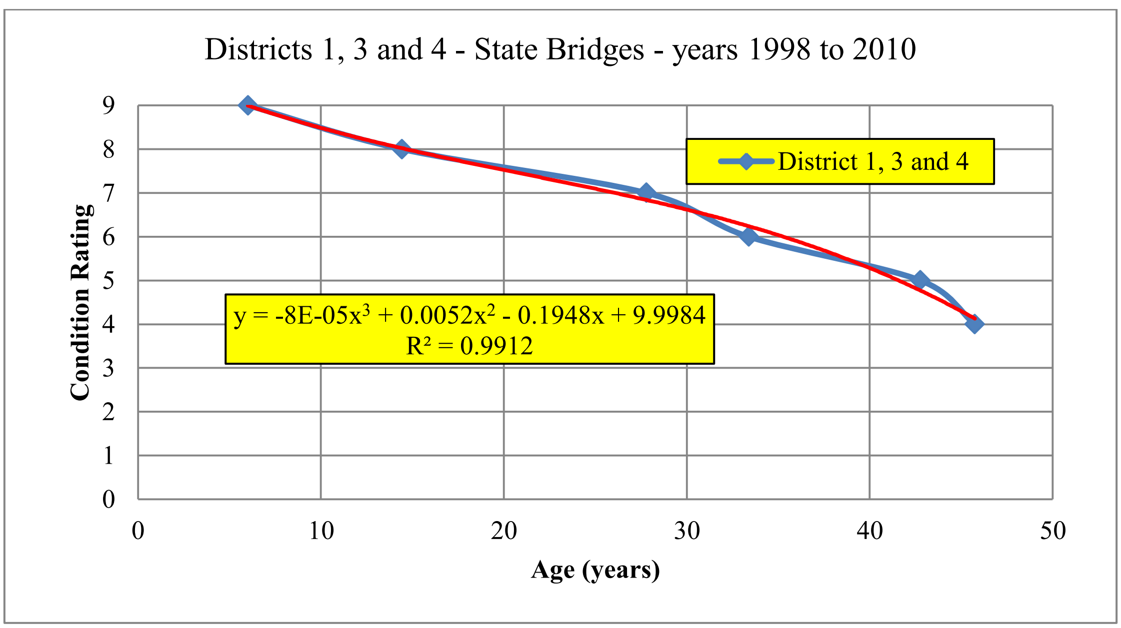


Figure 4-55: Deterioration curves of decks in districts 1, 3 and 4 – years 1998 to 2010

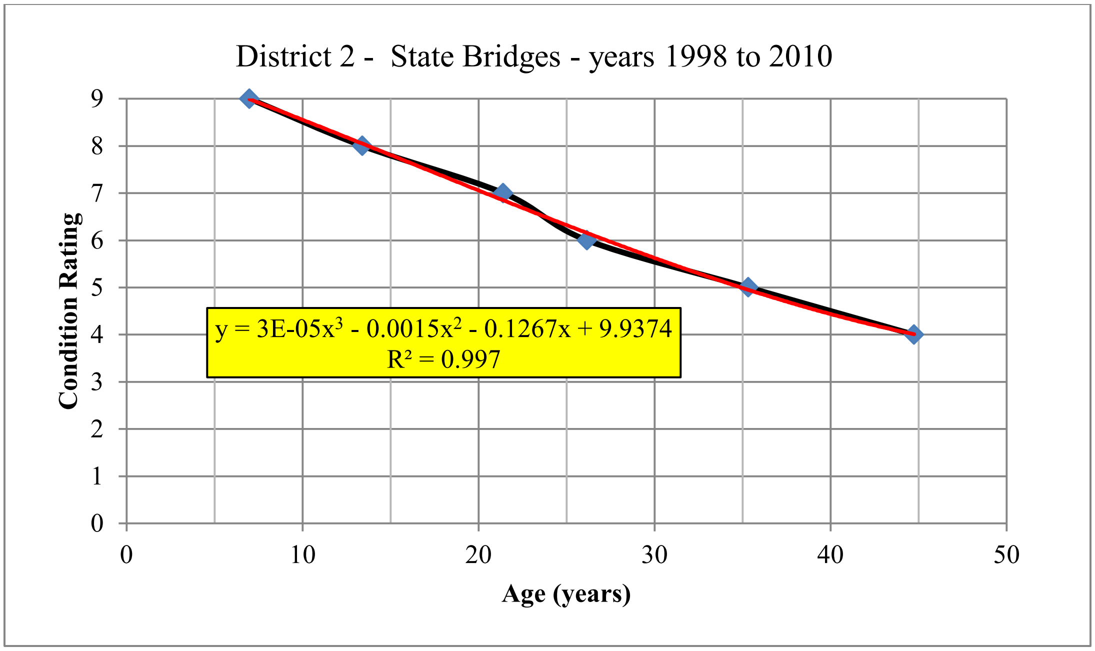


Figure 4-56: Deterioration curve of decks in district 2– years 1998 to 2010

Figures 4-57 and 4-58 show the deterioration curves and transition periods of decks in districts 5, 6, 7 and 8. These figures show that deterioration curves for all districts are almost the same with the exception of at conditions 5 and 4. Therefore, all data for these districts are combined together and a deterioration curve is developed as shown in Figure 4-59.

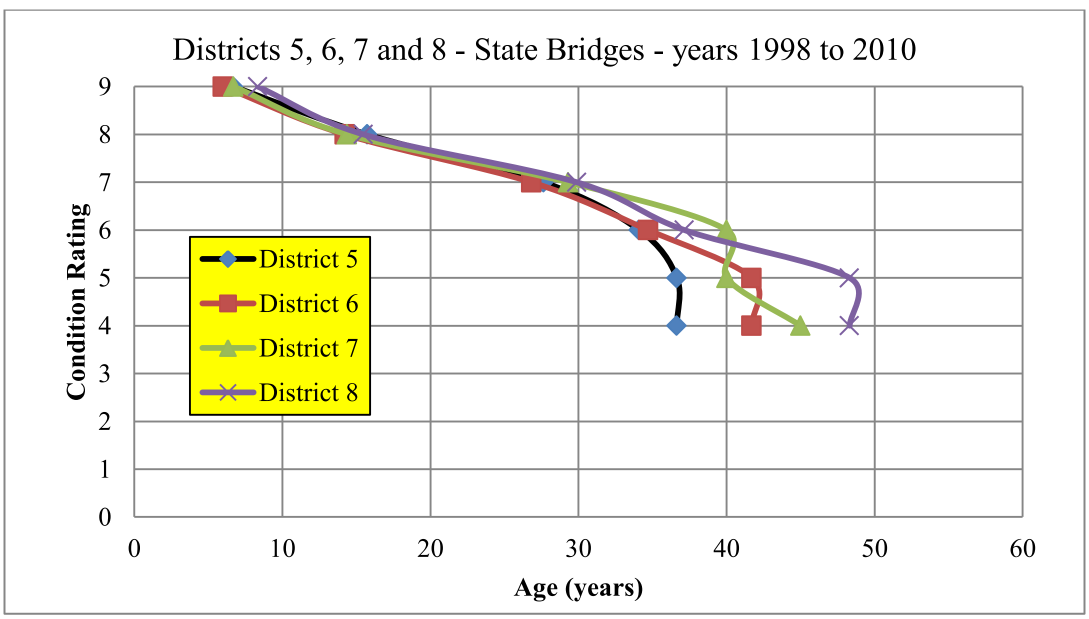


Figure 4-57: Deterioration curves of decks in districts 5, 6, 7 and 8 – years 1998 to 2010

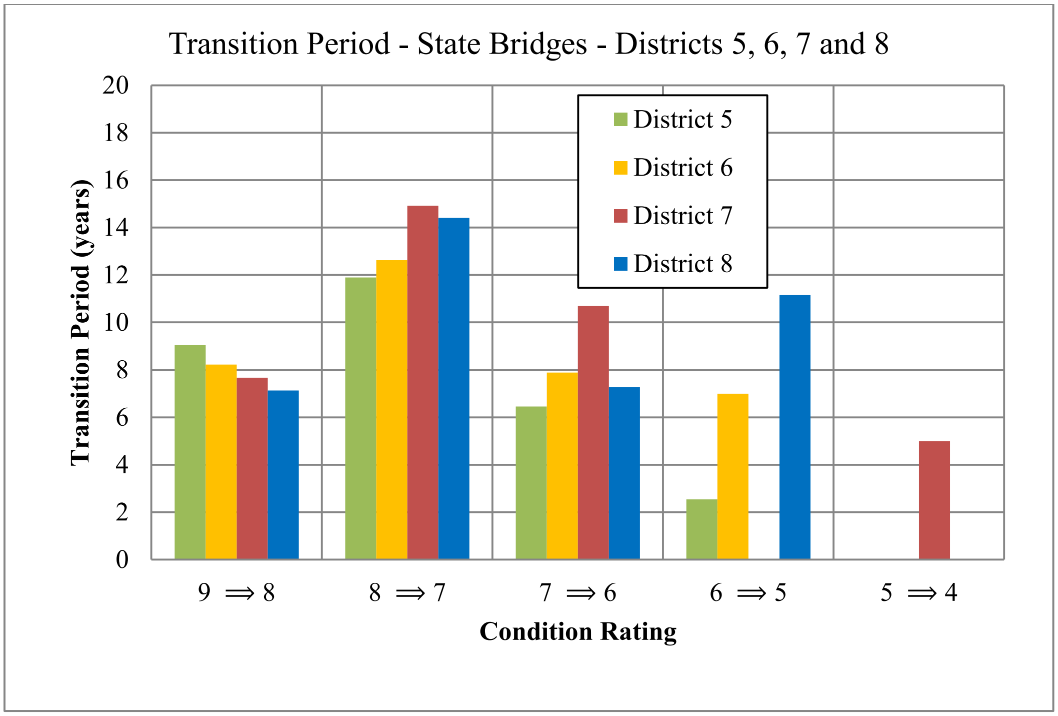


Figure 4-58: Transition period of decks in districts 5, 6, 7 and 8 – years 1998 to 2010

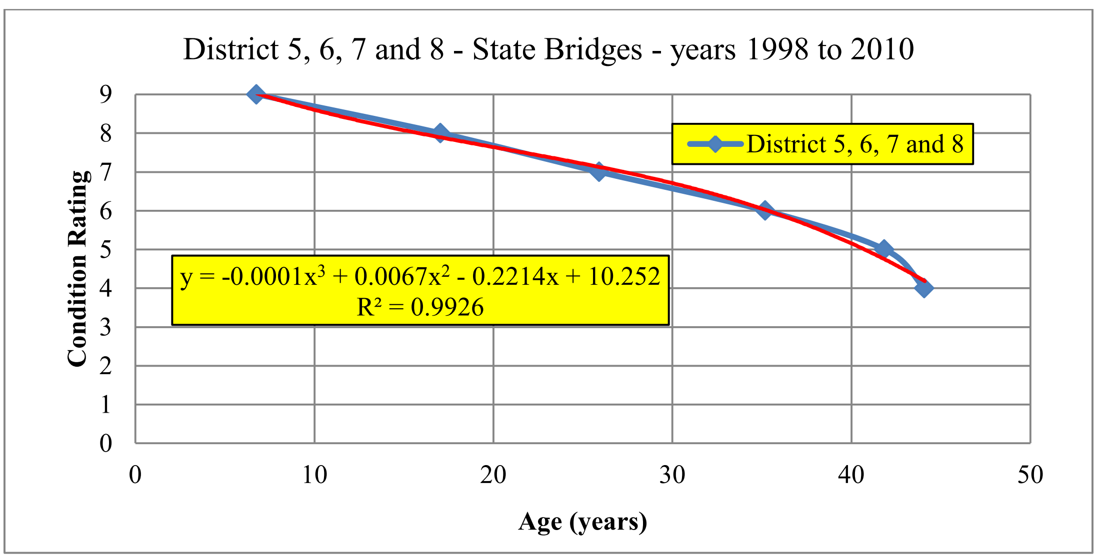


Figure 4-59: Deterioration curve of decks in districts 5, 6, 7 and 8 combined

4.2.4. DECK PROTECTION

Deterioration models are developed for decks with epoxy coated reinforcing (ECR) and with black rebar (BR), without protection, in state bridges. Figure 4-60 shows the percentage of state bridges with ECR and BR at year 2010. This figure clearly shows more than 70% of bridge decks have epoxy coated reinforcing.

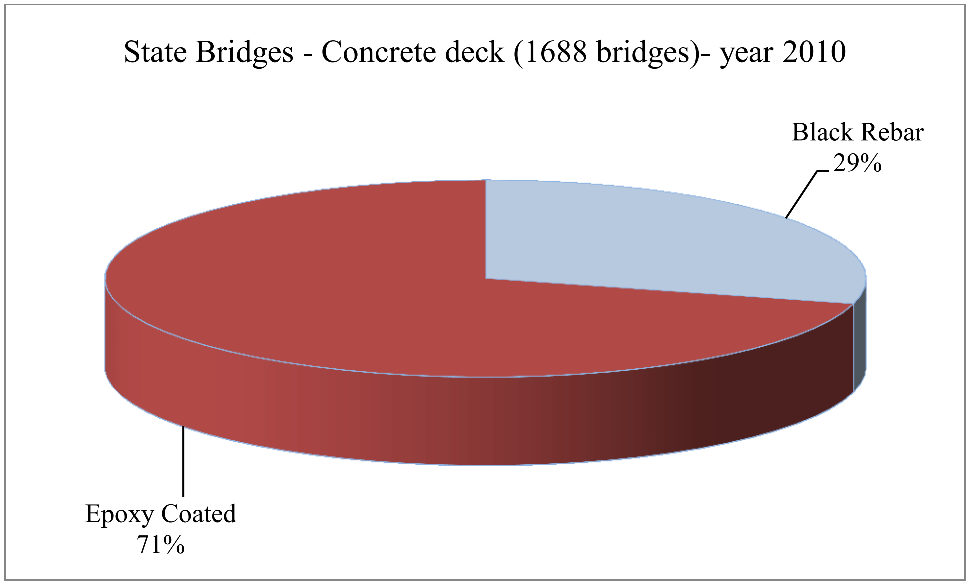
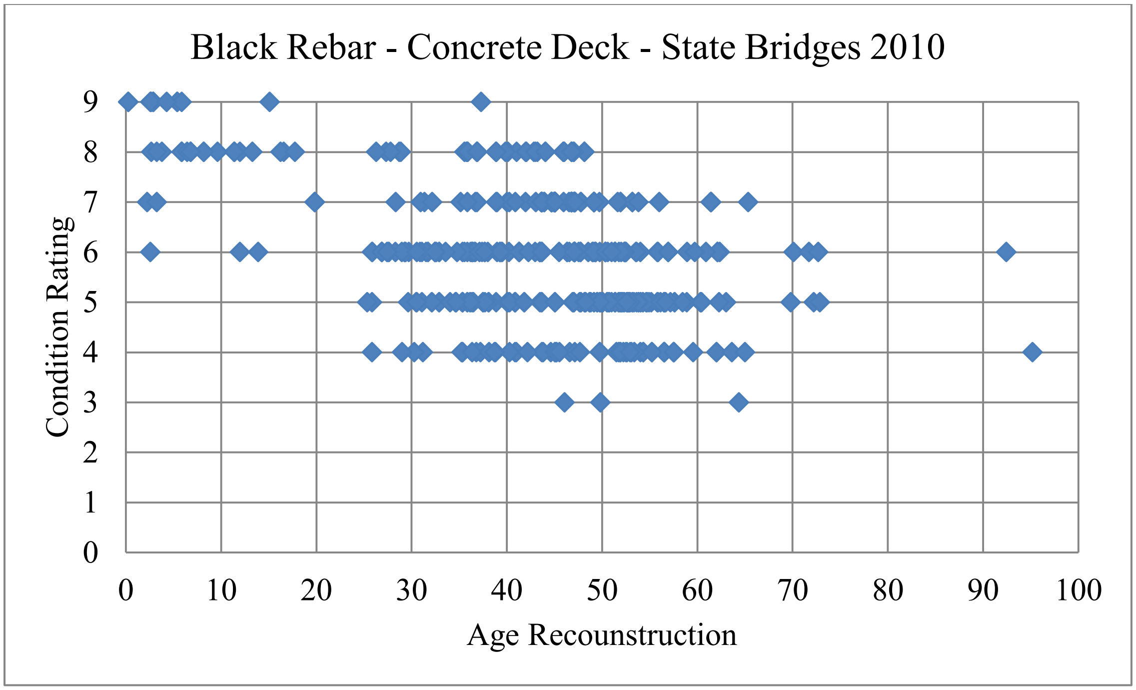
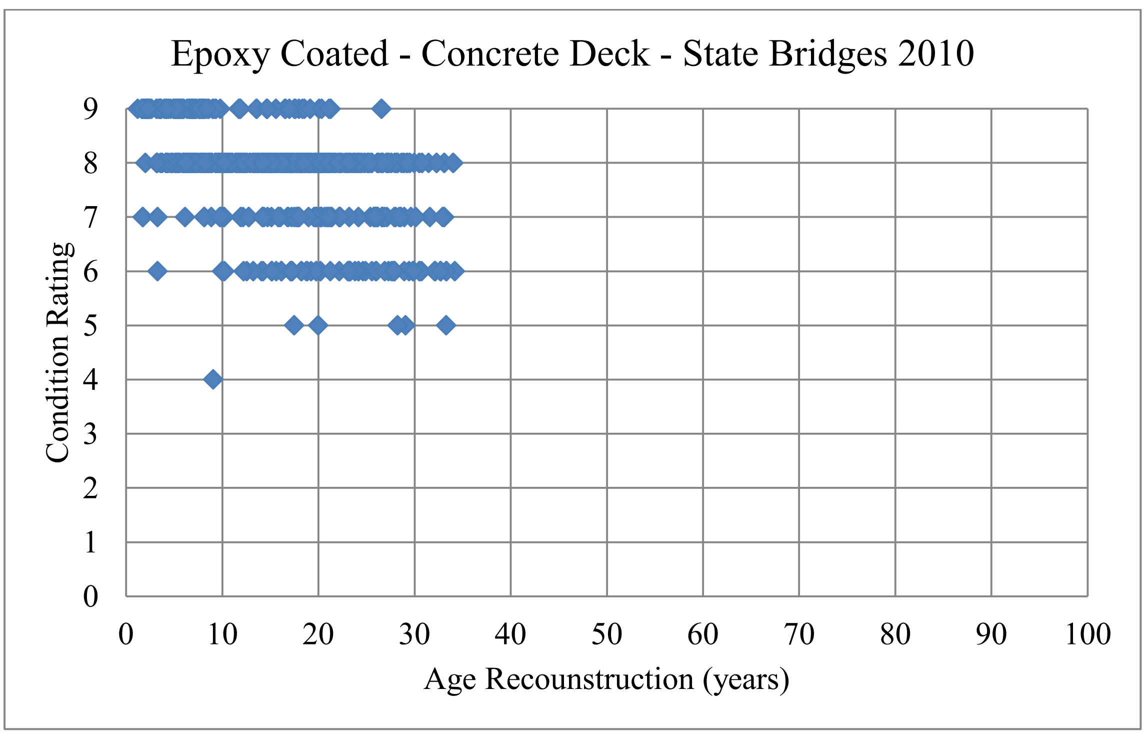


Figure 4-60: Deck with epoxy coated reinforcing and without protection (with black rebar) in state bridges – year 2010

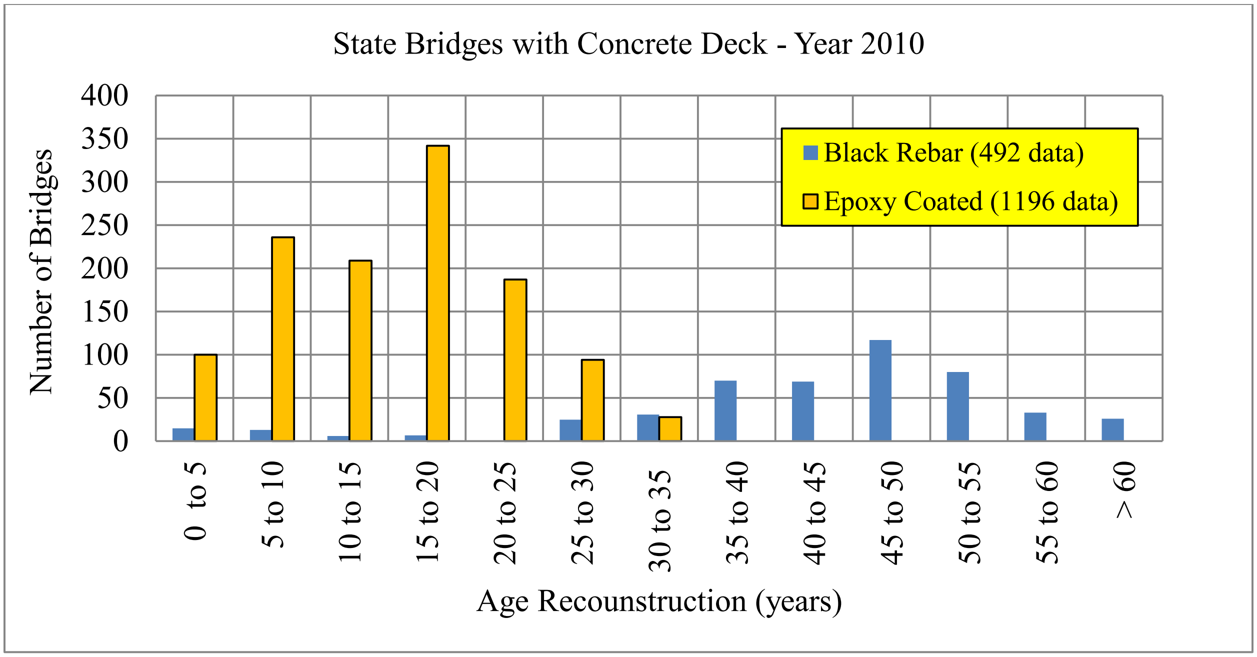
Figures 4-61 and 4-62 are plotted age reconstruction versus condition rating for decks with ECR and BR at year 2010. These figure show that age reconstruction for decks with ECR is different than those decks with BR. For better comparison, Histogram of age reconstruction for decks with ECR and BR in state bridges was developed as shown in Figure 4-66. This figure clearly shows that decks with ECR have age reconstruction between 5 to 25 years. However decks with BR have age reconstruction between 35 to 55 years which is completely different than deck with BR. Thus developing deterioration curves for ECR and BR decks with different age reconstruction is not realistic and it needs to be investigated with probabilistic method. Comparison between deck with ECR and BR using Markov approach will be presented in next chapter.



Figures 4-61: Age reconstruction versus condition rating for decks with BR - year 2010



Figures 4-62: Age reconstruction versus condition rating for decks with ECR - year 2010



Figures 4-63: Histogram of age reconstruction for decks with ECR and BR - year 2010

4.3 SUPERSTRUCTURE

The bridge superstructure consists of that portion of the bridge above the bearings. Same as decks, a harsh environment, high traffic volume, and aging are the main reasons for rapid bridge superstructure deterioration. Main material types of bridges are steel, concrete and prestressed concrete (section 3.3.). There are 782 steel, 775 prestressed concrete, and 110 concrete bridge superstructure according to 2009 data. Figure 4-64 presents the condition distribution of bridge superstructure for each material type. This figure clearly shows that most of steel and prestressed concrete superstructure has condition ratings 9, 8 and 7, while most concrete superstructure has condition ratings 5 and 6. To deal with superstructure deterioration, two main types of superstructure are considered in state bridges: steel and prestressed concrete superstructures.

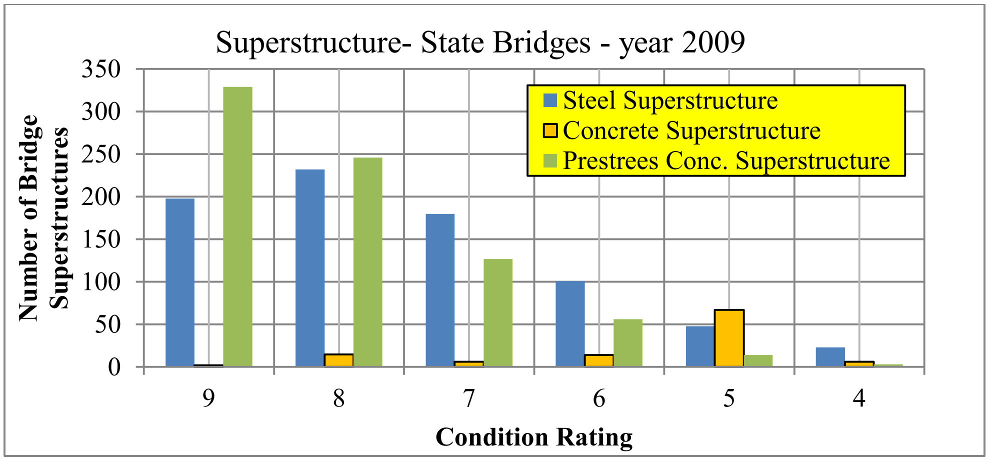


Figure 4-64: Superstructure distribution by condition rating and material type – year 2008

Bridge superstructure is described in item BRI_RAT_ITEM059 of the National Bridge Inventory (NBI) database. Steel and prestressed concrete materials are described in item 43A section 3.3 (numbers 3 and 5 respectively). In this section, deterioration models are developed for steel and prestressed concrete superstructures. Figure 4-65, 4-66 and 4-67 show deterioration curves at years 2000, 2005 and 2009 for steel and prestressed concrete. To obtain better results, all data from years 1998 to 2010 for superstructure were combined together. Deterioration curves for all data are shown in Figure 4-68. These figures clearly show that steel and prestressed concrete superstructure have similar deterioration rates from condition 9 to 7. There is no enough data for prestressed concrete superstructure at condition 6 or less.

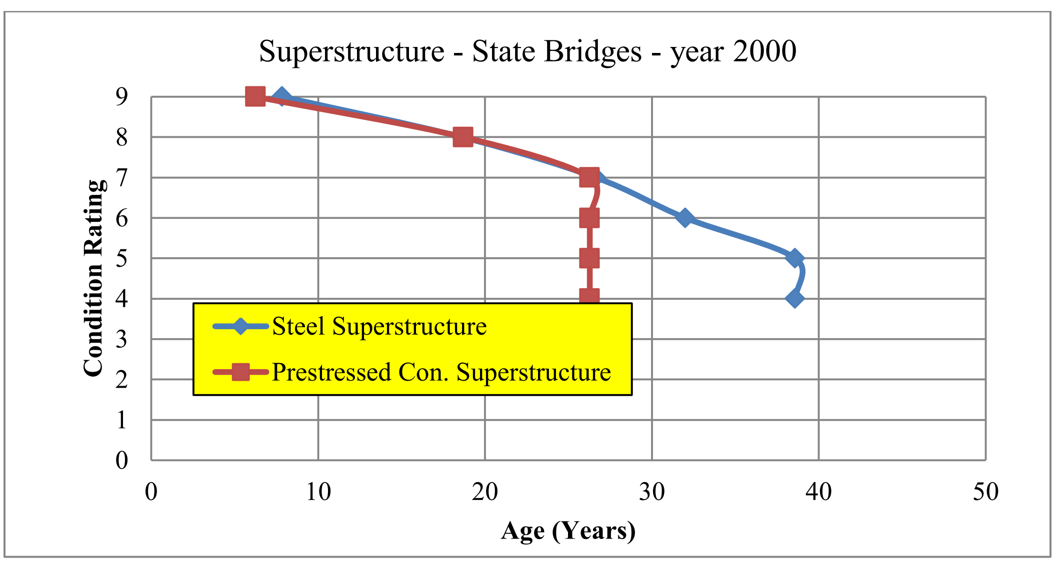


Figure 4-65: Deterioration curves of steel and prestressed concrete superstructure – year 2000

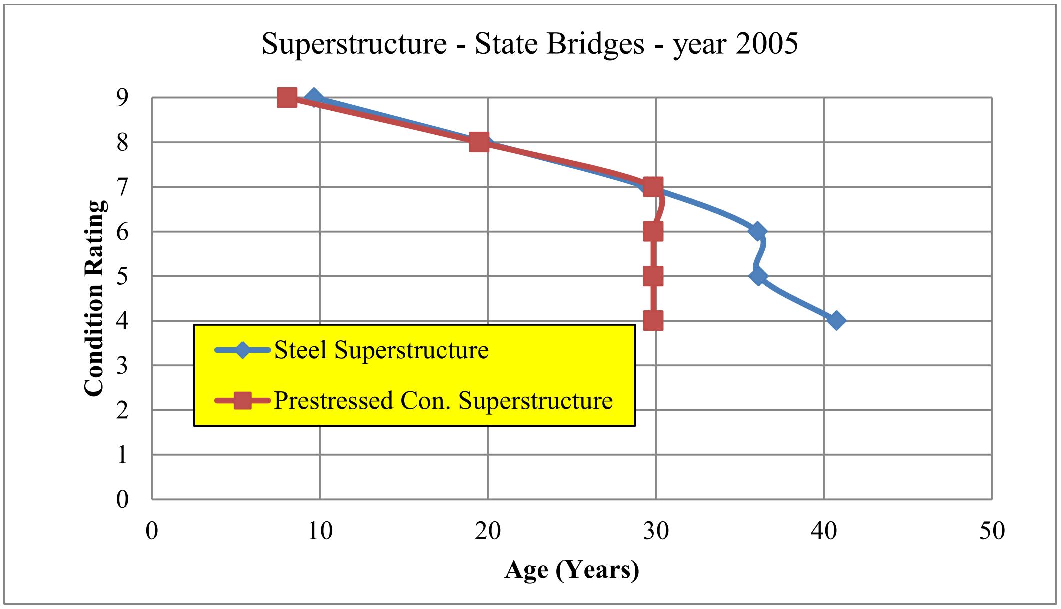


Figure 4-66: Deterioration curves of steel and prestressed concrete superstructure – year 2005

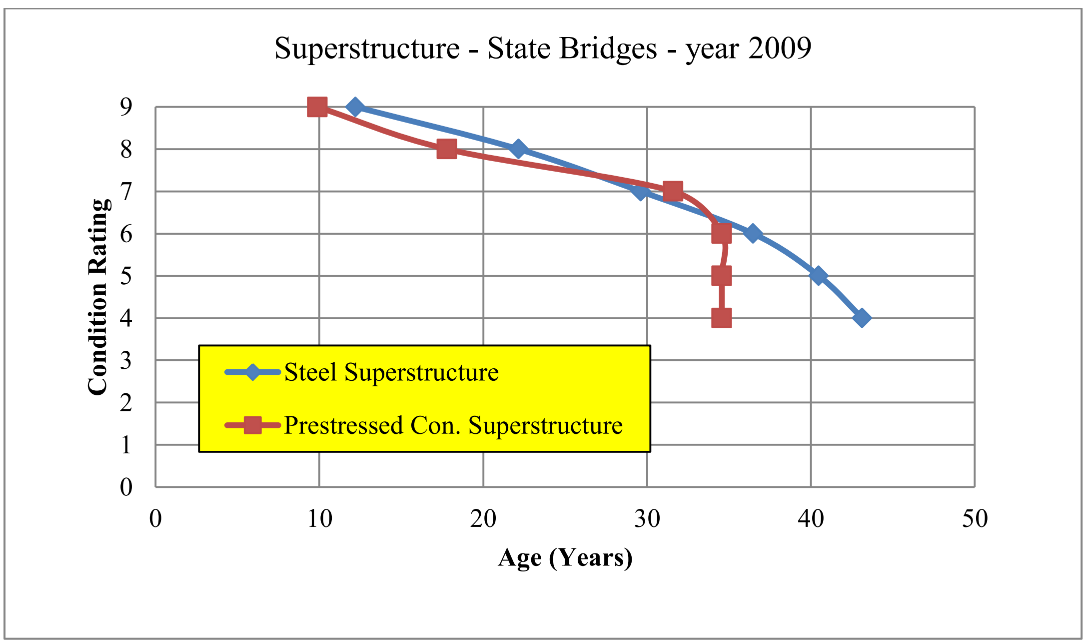


Figure 4-67: Deterioration curves of steel and prestressed concrete superstructure – year 2009

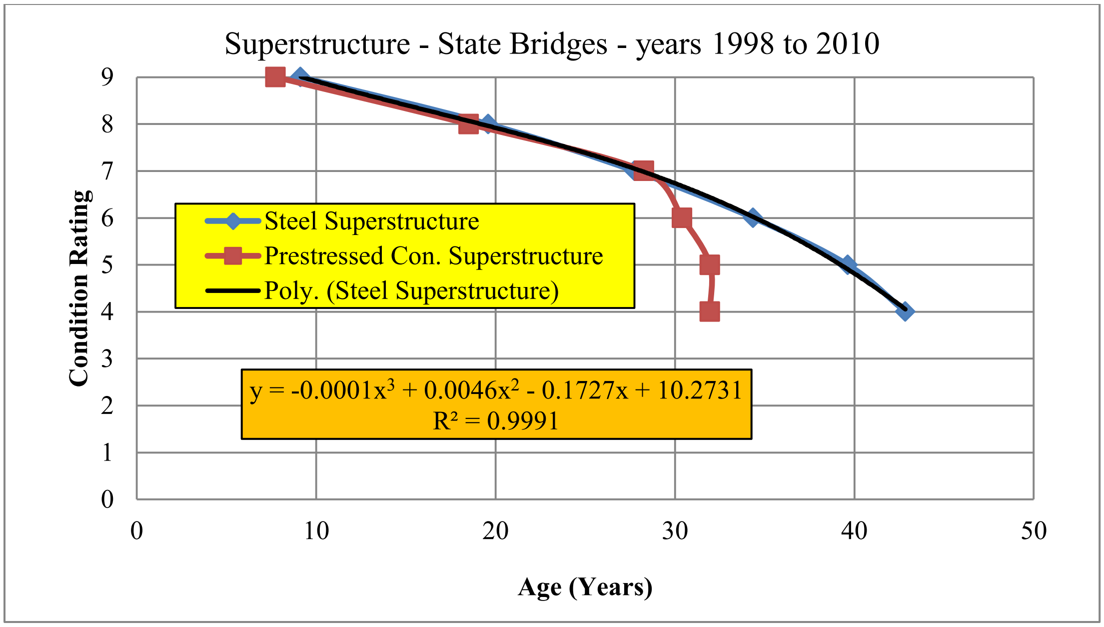


Figure 4-68: Deterioration curves of steel and prestressed concrete superstructure – years 1998 to 2010

Tables 4-11 and 4-12 list the transition period of steel and prestressed concrete superstructure in state bridges. Data from these tables are plotted in Figures 4-69 and 4-70.

Table 4-11: Transition period of steel superstructure in state bridges

Steel Superstructure	Condition Rating - State Bridges				
Transition Period (years)	9 ⟹ 8	8 ⟹ 7	7 ⟹ 6	6 ⟹ 5	5 ⟹ 4
2000	10.8	8.0	5.4	6.6	0.0
2005	10.1	9.7	6.5	0.1	4.6
2009	9.9	7.5	6.9	4.0	2.7
1998 to 2010	10.5	8.2	6.6	5.3	3.2

Table 4-12: Transition period of prestressed concrete superstructure in state bridges

Prestressed Concrete	Condition Rating - State Bridges				
Transition Period (years)	9 ⟹ 8	8 ⟹ 7	7 ⟹ 6	6 ⟹ 5	5 ⟹ 4
2000	12.5	7.6	0.0	0.0	0.0
2005	11.4	10.4	0.0	0.0	0.0
2009	7.9	13.8	3.0	0.0	0.0
1998 to 2010	10.8	9.8	2.1	1.5	0.0

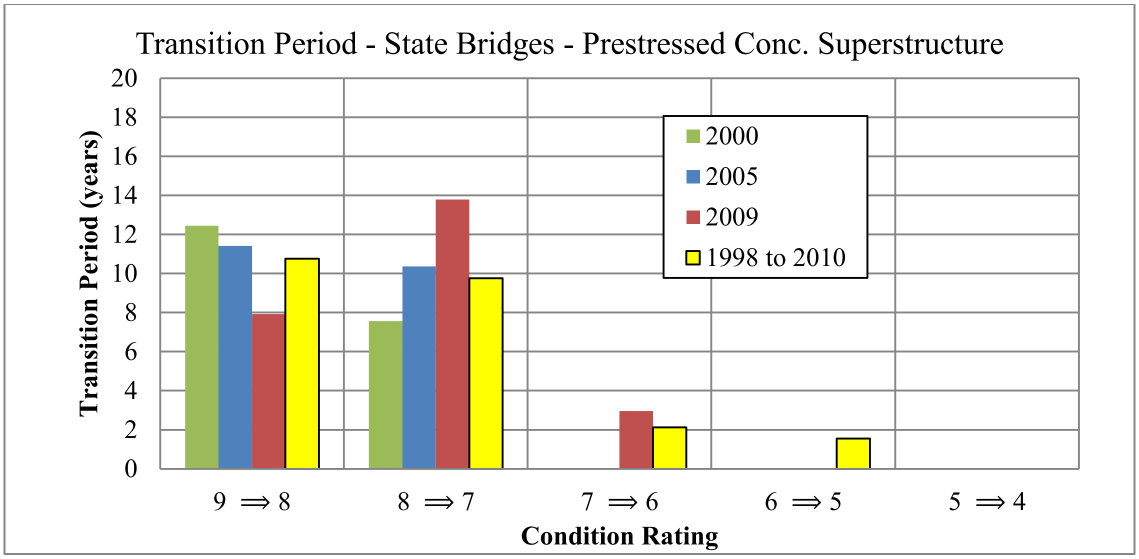


Figure 4-69: Transition period of prestressed concrete superstructure in state bridges

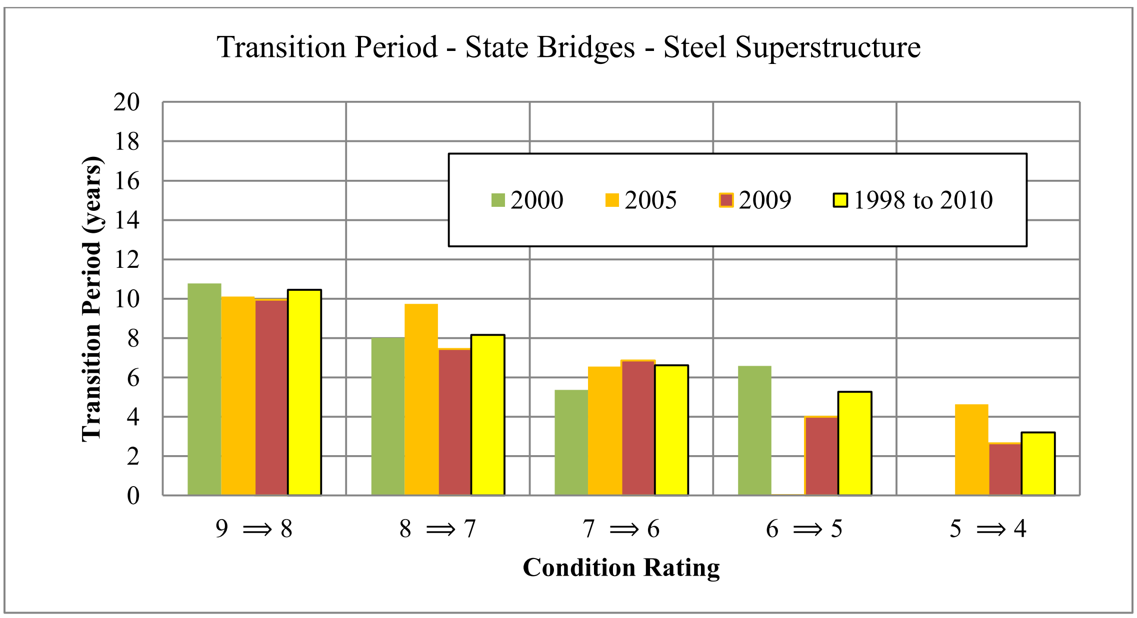


Figure 4-70: Transition period of steel superstructure in state bridges

For better comparison, average transition period for all data since 1998 to 2010 is plotted in Figure 4-71. This figure shows that prestressed concrete superstructure has a slightly better condition than steel superstructure from condition 9 to 7.

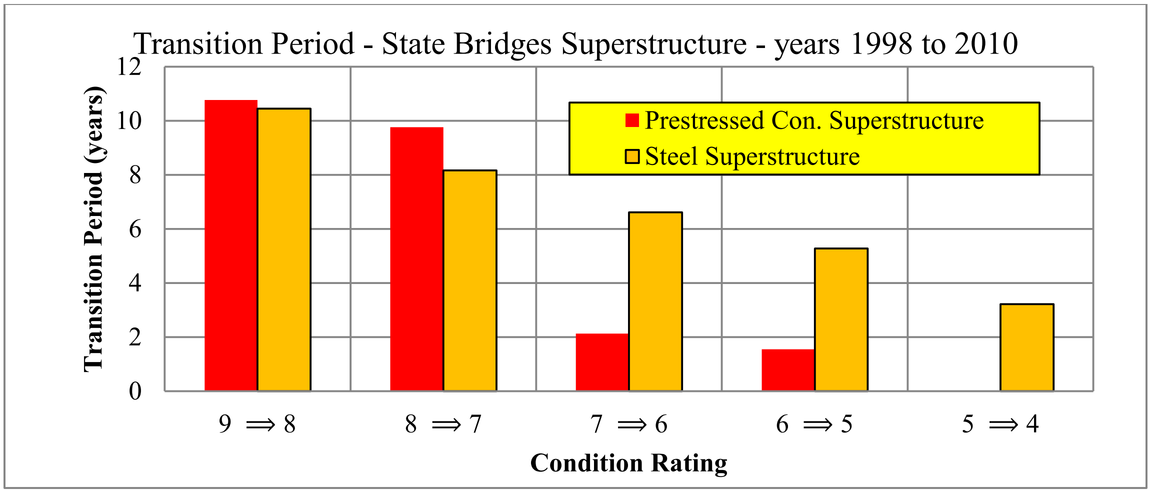


Figure 4-71: Transition period of steel and prestressed concrete superstructure in state bridges – years 1998 to 2010

4.4. SUBSTRUCTURE

The bridge superstructure consists of that portion of the bridge below the bearings. Bridge substructure is described in item BRI_RAT_ITEM060. State bridges have a more reliable data in database, therefore data analysis implemented on state bridges. Figures 4-72 shows deterioration curve at years 2000, 2005 and 2009.

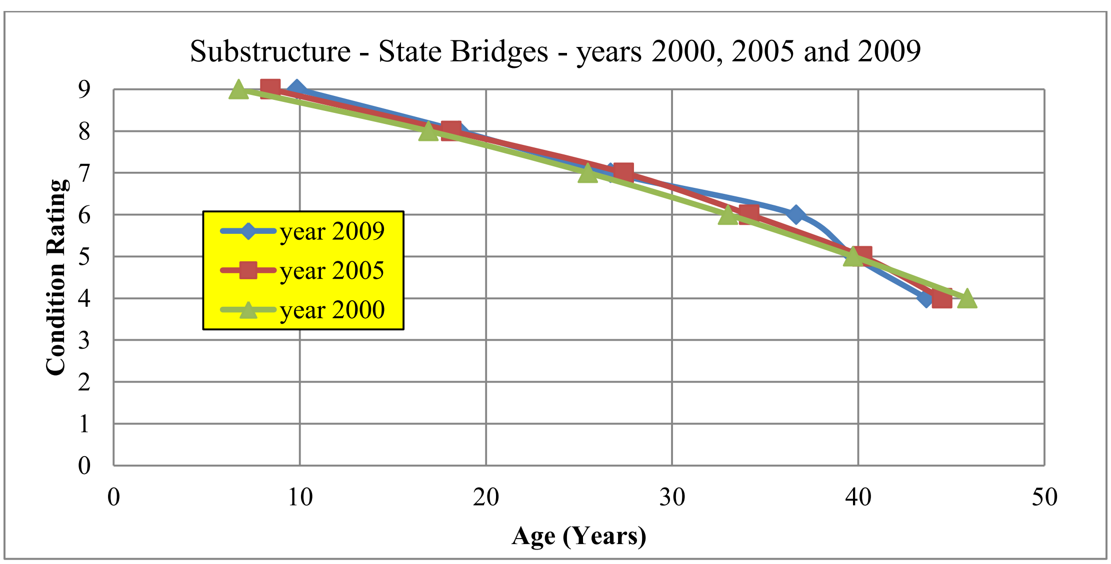


Figure 4-72: Deterioration model of substructure – years 2000, 2005 and 2009

To obtain the better results, all data from year 1998 to 2010 for substructure combined together. Deterioration curves for all data are shown in Figure 4-73.

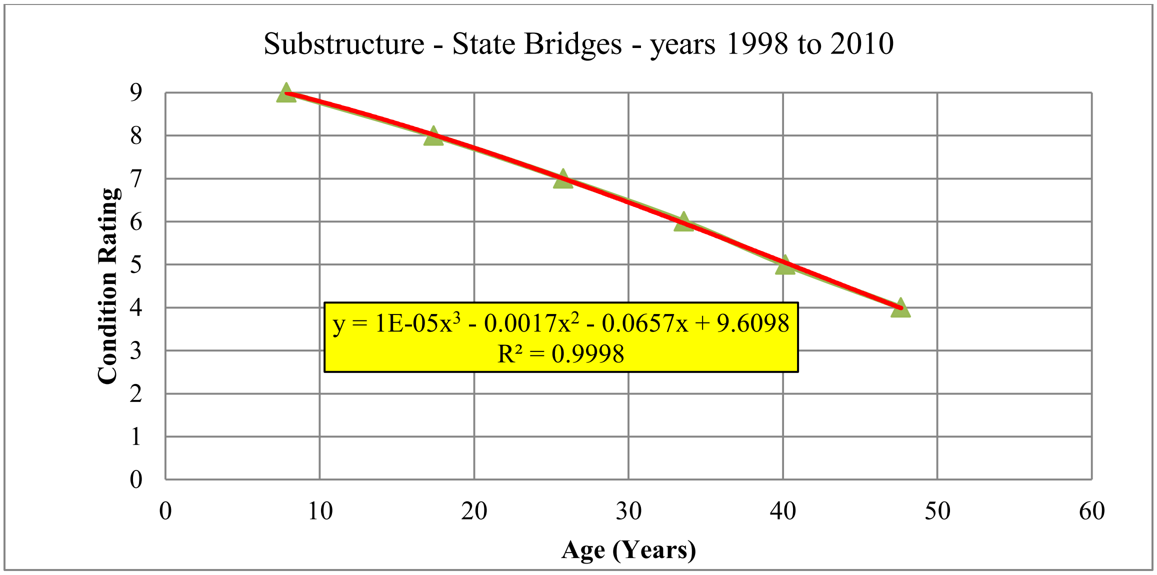


Figure 4-73: Deterioration model of substructure - years 1998 to 2010

In order to compare the deterioration of superstructure and substructure with national average, deterioration curves are plotted in the same Figure 4-74. Dash line represents the national average deterioration rate which takes 10 years to drop from high to lower condition for superstructure and substructure. This figure shows that superstructure has similar deterioration curve as substructure. However bridge superstructure and substructure components are lower than national average.

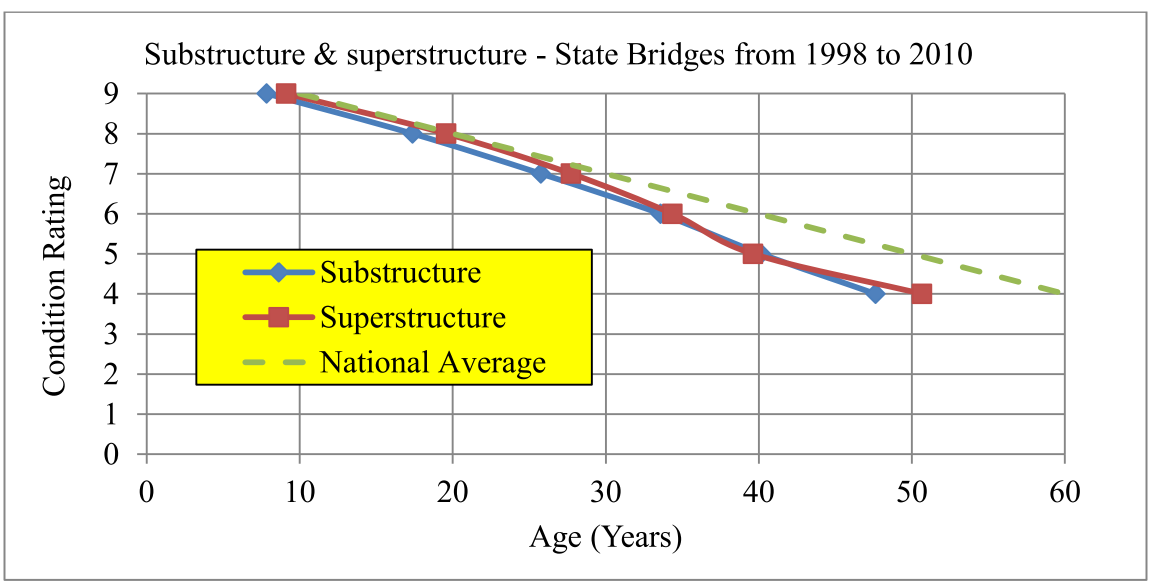


Figure 4-74: Deterioration model of substructure and superstructure - years 1998 to 2010

Table 4-13 lists average transition period for substructure at years 2000, 2005, 2009 and from 1998 to 2010. Data from table 4-13 are plotted in Figure 4-75. Results show that average transition period from condition 9 to 8 is about 9 years and from condition 8 to 7 and 7 to 6 are approximately 8 years.

Table 4-13: Transition period of substructure – years 2000, 2005, 2009 and 1998 to 2010

Substructure	Condition Rating - State Bridges				
Transition Period (years)	9 ⟹ 8	8 ⟹ 7	7 ⟹ 6	6 ⟹ 5	5 ⟹ 4
2000	10.2	8.6	7.5	6.7	6.1
2005	9.7	9.3	6.7	6.1	4.3
2009	8.7	8.1	10.0	3.1	3.9
1998 to 2010	9.5	8.4	7.8	6.6	7.5

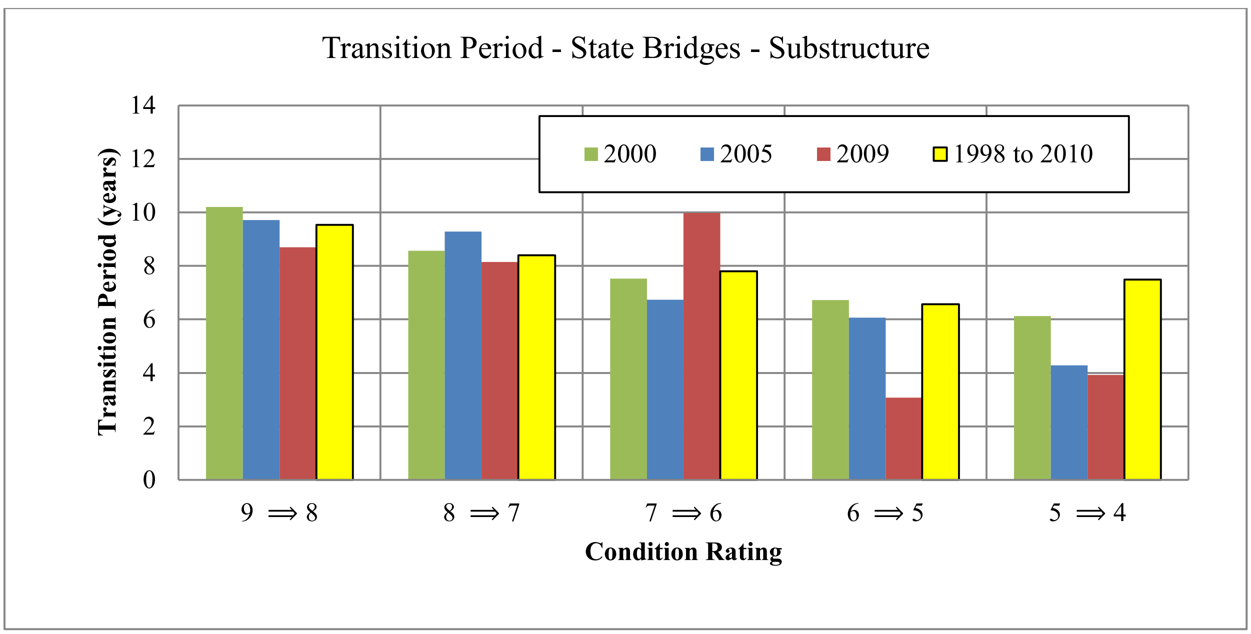


Figure 4-75: Transition period of substructure in state bridges

5 STOCASTIC DETERIORATION MODELS

5.1 INTRODUCTION

The theory of stochastic processes is being increasingly used in several applications in engineering and applied sciences. This theory has contributed significantly to the field of modeling infrastructure deterioration because of the high uncertainty and randomness involved in the deterioration process. The most commonly used stochastic technique for infrastructure deterioration is the Markov decision process (MDP). MDP is one of the most popular stochastic techniques obtained from operation research. This process has been used to develop stochastic deterioration models for different infrastructure facilities. Stochastic models treat the facility deterioration process as one or more random variables that capture the uncertainty and randomness of this process. These models can be classified either as state-based or time-based models (Mauch and Madanat, 2001). In state-based models, known as Markov chains, deterioration models are based on the concept of defining states in terms of facility condition ratings and obtaining the probabilities of the facility condition changing from one state to another in a discrete time given a set of explanatory variables, such as climate, traffic, structure type, etc. (Morcous, 2006). In time-based models, the duration that a facility remains at a particular state (condition rating) is modeled as a random variable using Weibull-based probability density functions to characterize the deterioration process, given its dependence on the same set of explanatory variables described above (Mishalani and Madanat, 2002; DeLisle et al., 2004).

In this chapter the condition data of Nebraska bridges is used to develop state-based stochastic deterioration models. The nine bridge condition ratings (from 9 to 1) can be defined as nine Markovian states with each condition rating corresponding to one of the nine states. For example, condition rating 9 is defined as State 1; rating 8 as State 2, and so on. Without repair or rehabilitation, the bridge condition rating should decrease with increase in bridge age. Therefore, there is a probability, $p_{i,j}$, of a bridge element transiting from one condition state, say i, to a lower condition state, j, during one inspection cycle. By knowing this probability for each of the condition states, the transition probability matrix P, can be developed as shown below:

$$P = \begin{bmatrix} p_{1,1} & p_{1,2} & \cdots\cdots & p_{1,n} \\ p_{2,1} & p_{2,2} & \cdots\cdots & p_{2,n} \\ . & . & \cdots\cdots & . \\ . & . & \cdots\cdots & . \\ p_{n,1} & p_{n,2} & \cdots\cdots & p_{n,n} \end{bmatrix} \tag{5-1}$$

In Eq. (5-1), *n* is the number of condition states. If the initial condition vector *P(0)* that describes the present condition of a bridge component is known, the future condition vector *P(t)* at any number of transition periods *(t)* can be obtained as follows:

$$P(t) = P(0) * P^t \tag{5-2}$$

Transition probabilities are obtained either from accumulated condition data or by using an expert judgment elicitation procedure, which requires the participation of several experienced bridge engineers. The outcomes of this elicitation procedure are manipulated to generate transition probability matrices for those agencies with inadequate condition data. A statistical updating of these probabilities can be undertaken when a statistically significant number of consistent and complete sets of condition data become available over the years. Two methods are commonly used to generate transition probability matrices from the condition data: regression-based optimization method and percentage prediction method. The regression-based optimization method estimates transition probabilities by solving the non-linear optimization problem that minimizes the sum of absolute differences between the regression curve that best fits the condition data and the conditions predicted using the Markov-chain model. The objective function and the constraints of this optimization problem can be formulated as follows (Butt et al. 1987):

$$\begin{aligned} &\text{Minimize } \sum_{t=1}^{N} \left| C(t) - E(t) \right| \\ &\text{Subject to: } 0 \le p_{ij} \le 1 \qquad \text{for} \quad i, j = 1,2,.....,n \\ &\qquad \sum_{i=1}^{n} p_{ij} = 1 \end{aligned} \tag{5-3}$$

where N = total number of transition periods,

$C(t)$ = facility condition at transition period number t based on the regression curve,

$E(t)$ = expected value of facility condition at transition period number t based on Markov-chains, which is calculated as follows:

$$E(t) = P(t)\, S \tag{5-4}$$

where, S = vector of condition states.

Since the regression model used in this method is affected significantly by any prior maintenance actions, whose records may not be readily available in many BMS databases, the percentage prediction method is commonly used. In this method, the probability $p_{i,j}$ is estimated using the following equation (Jiang et al. 1988):

$$p_{i,j} = n_{i,j} / n_i \tag{5-5}$$

where, $n_{i,j}$ = number of transitions from state i to state j within a given time period,

n_i = total number of bridges in state i before the transition.

The use of this method requires at least two consecutive condition records without any maintenance interventions, for a large number of bridge components at different condition states in order to generate reliable transition probabilities, which is the case of NBMS. Therefore, the percentage prediction method was used in this chapter to develop Markov-chains for bridge deck, superstructure, and substructure components as presented in the following subsections.

5.2. ENVIRONMENTAL CATEGORIES

Average daily traffic (ADT) and average daily truck traffic (ADTT) are considered the main parameters to define the environmental categories for bridge component deterioration in general, and bridge deck in particular (Morcous, et al. 2003). These environmental categories are classified into: low environment, moderate environment and severe environment. Low environment represents those with ADT less than 100 and ADTT less than 1000. Moderate environment represents those with ADT more than 1000 but less than 5000, and ADTT more than 100 but less than 500. Severe environment represents those with ADT more than 5000 and ADTT more than 500. Those environmental categories were defined to mimic the ones adopted by Pontis for modeling the deterioration of bridge elements.

In order to relate those environmental categories with highway districts in the state of Nebraska, several figures were plotted to graphically represent the distribution of bridges in all eight districts for different volumes of ADT and ADTT. Figures 5-1 and 5-2 show the distribution of state bridges in each district for ADT < 1000 and ADTT <100 (low environment) according 2009 data, respectively. These figures show that district 4 has a highest percentage of bridges.

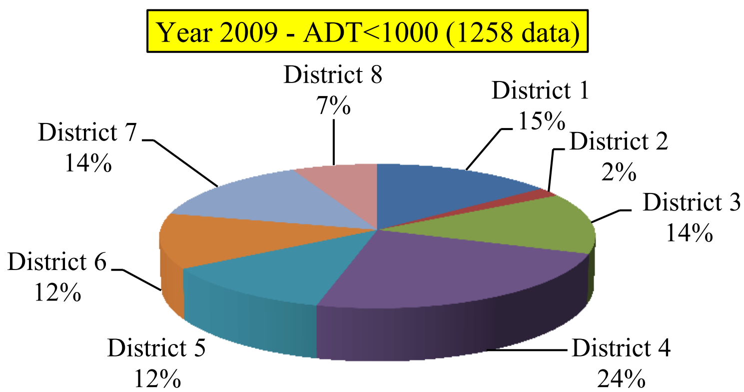


Figure 5-1: Distribution of state bridges in districts with ADT<1000 – year 2009

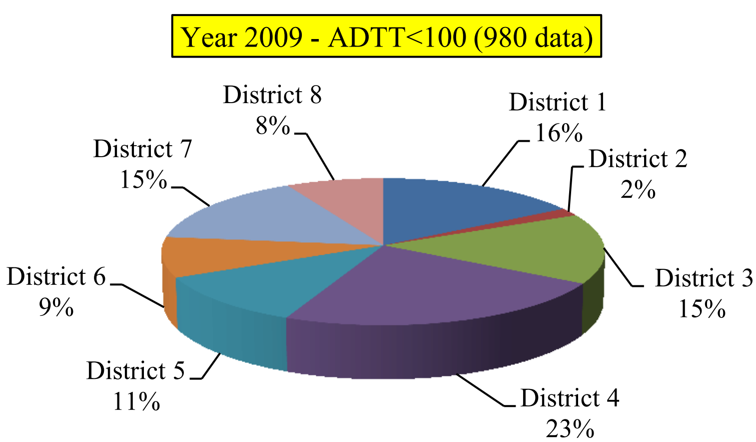


Figure 5-2: Distribution of state bridges in districts with ADTT<100 – year 2009

Figures 5-3 and 5-4 present the distribution of state bridges in districts with 1000 < ADT < 5000 and 100 < ADTT < 500 (moderate environment). These figures clearly show that district 1 and 3 have a highest percentage of bridges.

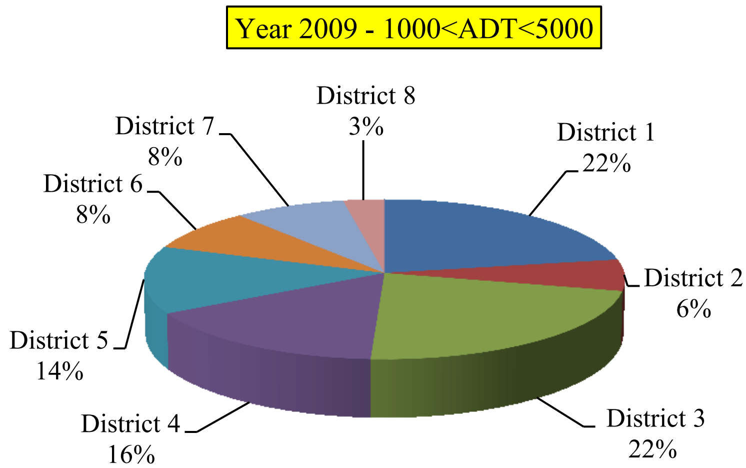


Figure 5-3: Distribution of state bridges in districts with 1000<ADT<5000 – Year 2009

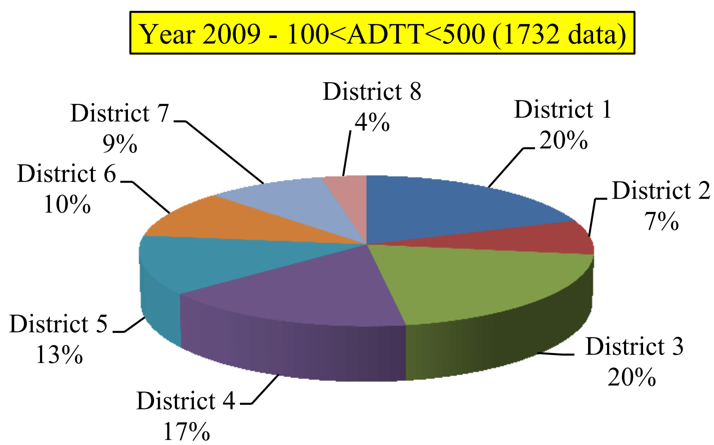


Figure 5-4: Distribution of state bridges in districts with 100<ADTT<500 – Year 2009

Distributions of state bridges in districts with ADT > 5000 and ADTT > 500 (severe environment) are shown in Figures 5-5 and 5-6, respectively. These figures show that district 2 has a highest percentage of bridges.

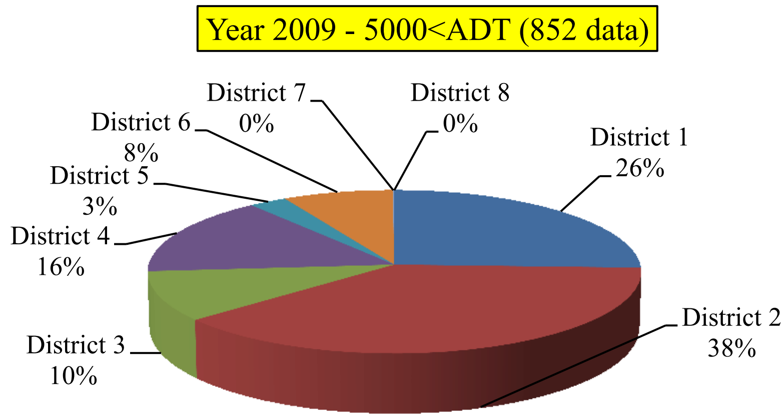


Figure 5-5: Distribution of bridges in districts with 5000 < ADT – Year 2009

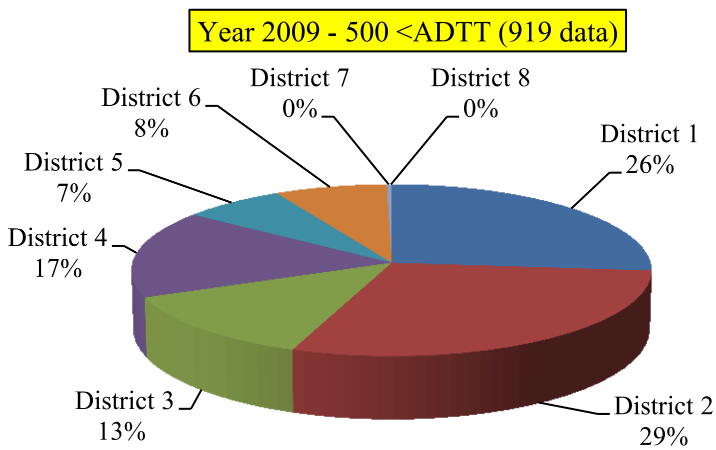


Figure 5-6: Distribution of bridges in districts with 500<ADTT – Year 2009

5.3. CONCRETE BRIDGE DECKS

Original concrete decks in state bridges are selected for developing stochastic deterioration models because they are considered the most dominant type of bridge decks. The condition data of original concrete decks represent the results of the detailed visual inspections carried out approximately every two years. According to the National Bridge Inspection Standards (NBIS), transition probability matrices for low, moderate, and severe environments are derived from the NBMS data of years 1998 to 2010. Tables 5-1, 5-2 and 5-3 show the developed transition probability matrices for concrete decks in state bridges with low, moderate, and severe environments respectively. Tables 5-4, 5-5 and 5-6 listed the conversion transition probability matrices in PONTIS format (5 by 5 matrix) for concrete decks in state bridges with low, moderate, and severe environments respectively.

Table 5-1: Transition probability matrix for low environment category (NBI)

Condition	9	8	7	6	5	4	3	2	1
9	0.70	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0	0.89	0.11	0.00	0.00	0.00	0.00	0.00	0.00
7	0	0	0.87	0.13	0.00	0.01	0.00	0.00	0.00
6	0	0	0	0.87	0.13	0.00	0.00	0.00	0.00
5	0	0	0	0	0.91	0.09	0.00	0.00	0.00
4	0	0	0	0	0	0.97	0.03	0.00	0.00
3	0	0	0	0	0	0	0.91	0.09	0.00
2	0	0	0	0	0	0	0	0.98	0.02
1	0	0	0	0	0	0	0	0	1.00

Table 5-2: Transition probability matrix for moderate environment category (NBI)

Condition	9	8	7	6	5	4	3	2	1
9	0.68	0.32	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.93	0.07	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.76	0.24	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.79	0.21	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.87	0.13	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.91	0.09	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.89	0.11	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.94	0.06
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

Table 5-3: Transition probability matrix for severe environment category (NBI)

Condition	9	8	7	6	5	4	3	2	1
9	0.66	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.90	0.10	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.68	0.32	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.77	0.23	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.73	0.27	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.70	0.30	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.10	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.99	0.01
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

Table 5-4: Transition probability matrix for low environment category (PONTIS format)

Condition	1	2	3	4	5
1	0.91	0.09	0.00	0.00	0.00
2	0.00	0.96	0.04	0.00	0.00
3	0.00	0.00	0.96	0.04	0.00
4	0.00	0.00	0.00	0.95	0.05
5	0.00	0.00	0.00	0.00	1.00

Table 5-5: Transition probability matrix for moderate environment category (PONTIS format)

Condition	1	2	3	4	5
1	0.91	0.09	0.00	0.00	0.00
2	0.00	0.96	0.05	0.00	0.00
3	0.00	0.00	0.91	0.09	0.00
4	0.00	0.00	0.00	0.88	0.12
5	0.00	0.00	0.00	0.00	1.00

Table 5-6: Transition probability matrix for severe environment category (PONTIS format)

Condition	1	2	3	4	5
1	0.90	0.10	0.00	0.00	0.00
2	0.00	0.95	0.06	0.00	0.00
3	0.00	0.00	0.73	0.27	0.00
4	0.00	0.00	0.00	0.71	0.29
5	0.00	0.00	0.00	0.00	1.00

The probabilities shown in Tables 5-1 to 5-6 represent the change of bridge deck condition under normal operating conditions in the state of Nebraska. To demonstrate the differences among the three environmental categories with respect to the predicted performance and service life of concrete bridge decks, the transition probability matrices shown in tables 5-1 to 5-6 are used to develop the deterioration curves shown in Fig. 5-7 and Fig. 5-8.

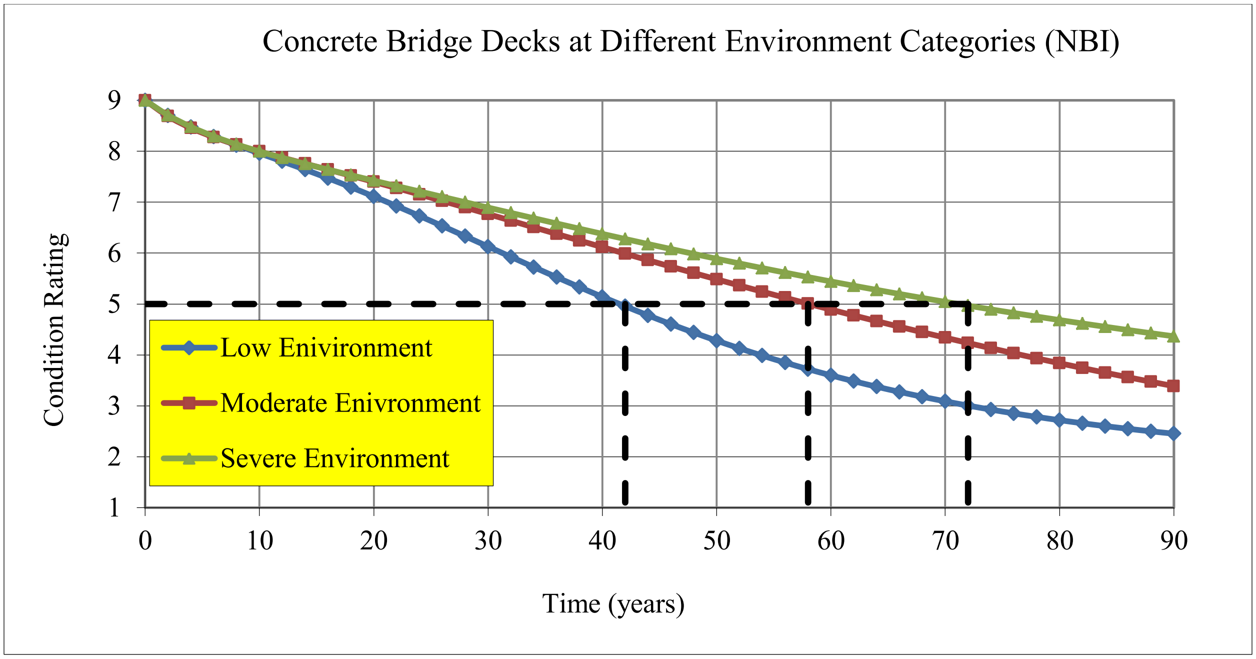


Figure 5-7: Deterioration curves of concrete bridge decks at different environments

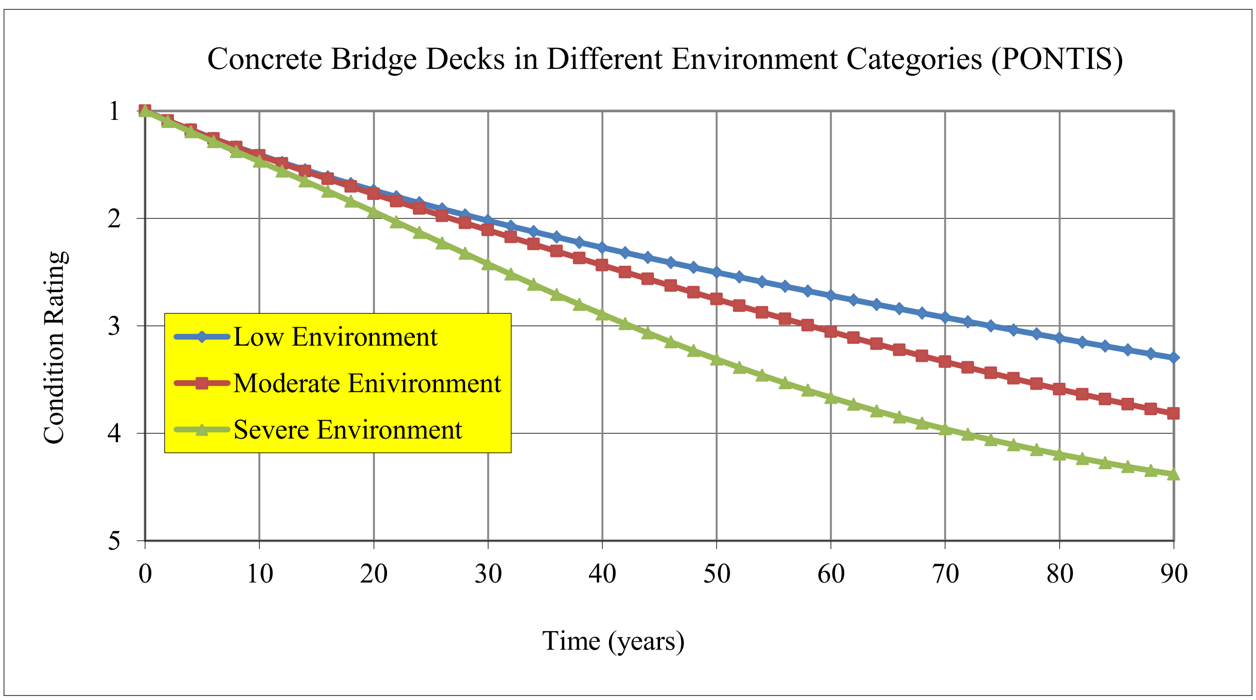


Figure 5-8: Deterioration curves of concrete bridge decks at different environments (PONTIS format)

Each of these curves represents the relationship between the average condition rating of concrete bridge decks and their age for a specific environmental category. From condition 9 to condition 7 there is no significant difference between deck deterioration in the different environmental categories. If the condition 5 (fair condition) is adopted as the minimum acceptable deck condition, the predicted average service live of bridge decks in low, moderate, and severe environments are 72, 58, and 42 years, respectively. This significant variation in the service life of bridge decks illustrates the considerable impact of the environment on the performance of bridge decks.

5.4. DECK PROTECTION

Figure 5-9 shows the number of bridge decks with ECR and BR in each condition rating at year 2010. This figure clearly shows that most of state bridges with ECR have condition 8. Tables 5-7 and 5-8 show the developed transition probability matrices for concrete decks in state bridges with ECR and BR.

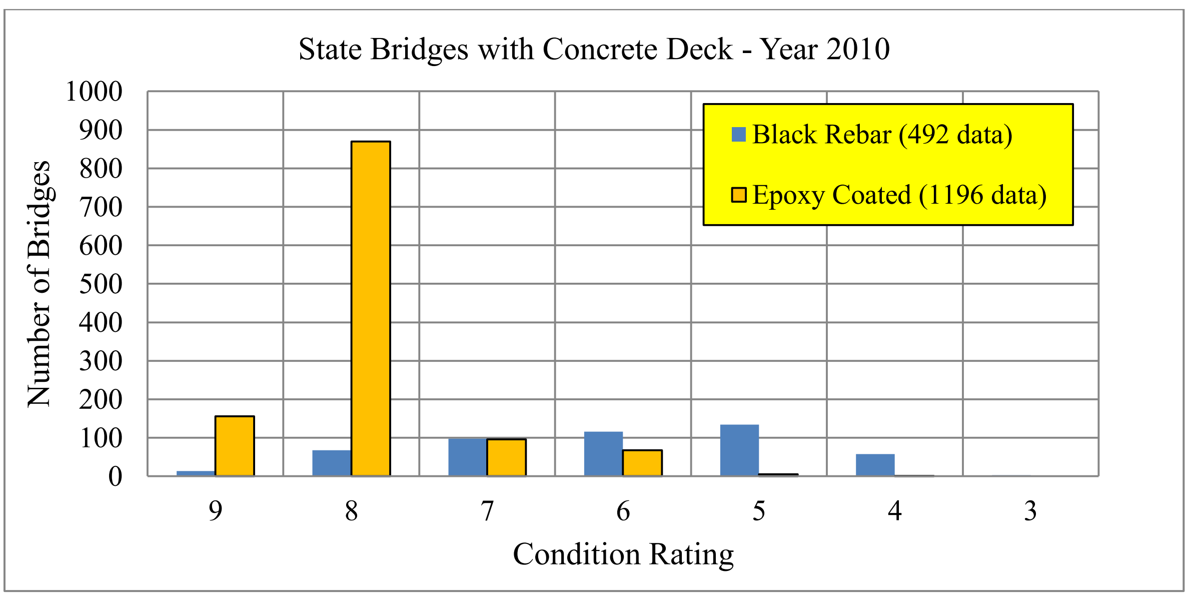


Figure 5-9: Number of bridge decks in each condition rating – year 2010

Table 5-7: Transition probability matrix for decks with ECR (NBI)

Condition	9	8	7	6	5	4	3	2	1
9	0.73	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.93	0.07	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.76	0.24	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.87	0.13	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.87	0.13	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.91	0.09	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.89	0.11	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.94	0.06
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

Table 5-8: Transition probability matrix for decks with BR (NBI)

Condition	9	8	7	6	5	4	3	2	1
9	0.67	0.23	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0.00	0.89	0.11	0.00	0.00	0.00	0.00	0.00	0.00
7	0.00	0.00	0.91	0.09	0.00	0.00	0.00	0.00	0.00
6	0.00	0.00	0.00	0.89	0.11	0.00	0.00	0.00	0.00
5	0.00	0.00	0.00	0.00	0.93	0.07	0.00	0.00	0.00
4	0.00	0.00	0.00	0.00	0.00	0.70	0.30	0.00	0.00
3	0.00	0.00	0.00	0.00	0.00	0.00	0.90	0.10	0.00
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.99	0.01
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

There isn't enough data for ECR decks in condition 5 and lower condition. Comparison between transition probability matrix of decks with ECR and decks with different environment show that decks with ECR are same as decks with moderate environment. Therefore, results of transition probability matrices for moderate environment in condition 5 and lower condition are used in developing transition probability matrix for decks with ECR. Transition probability matrices shown in tables 5-7 and 5-8 are used to develop the deterioration curves shown in Fig. 5-10.

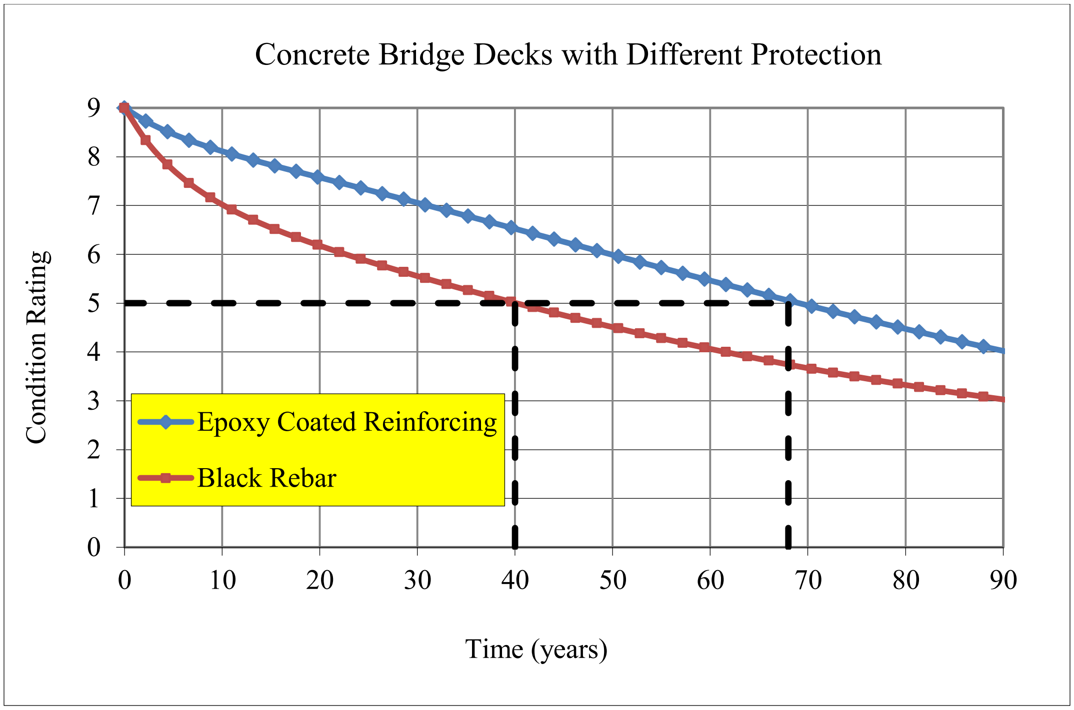


Figure 5-10: Deterioration curves of concrete bridge decks with EDR and BR

ECR bridges providing better performance than black rebar bridge decks. Comparison them at a deck surface rating before 5 show that expected service life of ECR bridge decks is about 2.5 to 3 times longer than BR bridge decks. If the condition 5 (fair condition) is adopted as the minimum acceptable deck condition, the predicted average service lives of bridge decks with ECR and BR are about 68 and 40 years. This numbers are in close agreement with work conducted by Michigan Department of Transportation (Boatman, 2010). Figure 4-14b was shown an average age of 35 to 40 years before re-decked, meaning that the deck likely had reached fair condition during this time, which correlates very well with the time to fair calculated for BR decks by using the transition probability matrix.

5.5. BRIDGE SUPERSTRUCTURE

Bridge superstructure is typically constructed with either steel or prestressed concrete girders. This section presents the Markov transition probabilities developed for bridge superstructure made of steel and prestressed concrete. Transition probabilities were calculated using NBMS superstructure condition ratings from 1998 to 2010 and the percentage prediction method presented earlier. Tables 5-9 and 5-10 show the transition probability matrices for state bridges containing steel and prestressed concrete superstructure respectively.

Table 5-9: Transition probability matrix for steel superstructure (NBI)

Condition	9	8	7	6	5	4	3	2	1
9	0.92	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0	0.95	0.04	0.00	0.00	0.00	0.00	0.00	0.00
7	0	0	0.92	0.06	0.02	0.00	0.00	0.00	0.00
6	0	0	0	0.86	0.11	0.02	0.01	0.00	0.00
5	0	0	0	0	0.87	0.10	0.03	0.00	0.00
4	0	0	0	0	0	0.98	0.02	0.00	0.00
3	0	0	0	0	0	0	1.00	0.00	0.00
2	0	0	0	0	0	0	0	1.00	0.00
1	0	0	0	0	0	0	0	0	1.00

Table 5-10: Transition probability matrix for prestressed concrete superstructure (NBI)

Condition	9	8	7	6	5	4	3	2	1
9	0.89	0.10	0.01	0.00	0.00	0.00	0.00	0.00	0.00
8	0	0.93	0.05	0.01	0.01	0.00	0.00	0.00	0.00
7	0	0	0.88	0.09	0.02	0.00	0.00	0.00	0.00
6	0	0	0	0.93	0.07	0.00	0.00	0.00	0.00
5	0	0	0	0	0.92	0.08	0.00	0.00	0.00
4	0	0	0	0	0	1.00	0.00	0.00	0.00
3	0	0	0	0	0	0	1.00	0.00	0.00
2	0	0	0	0	0	0	0	1.00	0.00
1	0	0	0	0	0	0	0	0	1.00

To demonstrate the differences between steel and prestressed concrete superstructure with respect to the predicted performance and service life of bridge, the transition probability matrices shown in tables 5-9 and 5-10 are used to develop the deterioration curves in Fig. 5-11. This figure shows that the deterioration of steel and prestressed concrete superstructure has the same rate from condition 9 to condition 8, while prestressed concrete has slightly deterioration rate than steel superstructure in lower condition states.

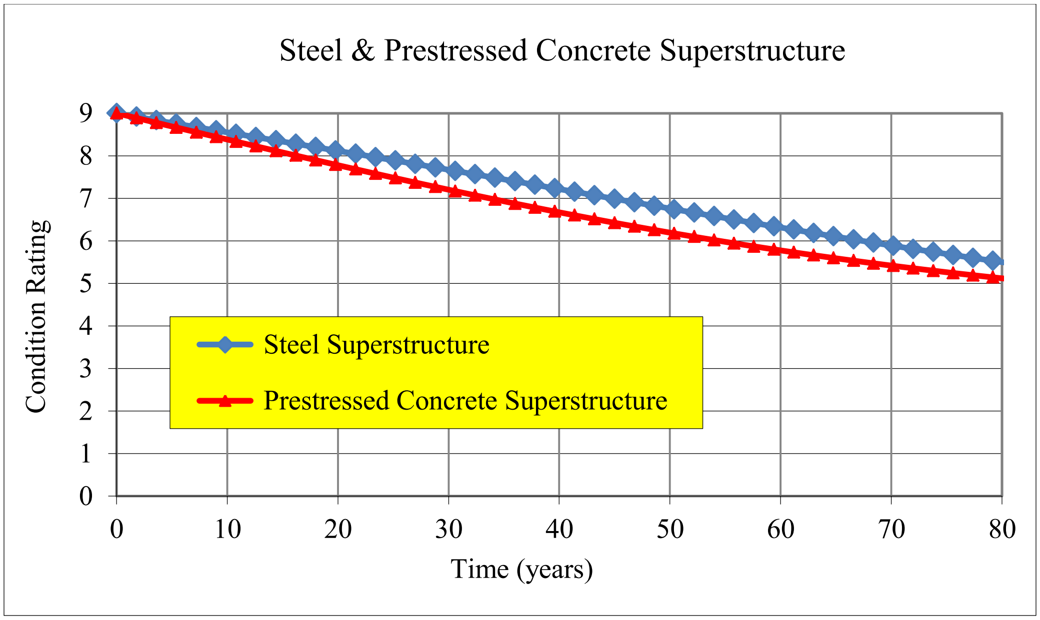


Figure 5-11: Deterioration curves of steel and prestressed concrete superstructure

5.6. BRIDGE SUBSTRUCTURE

This section presents Markov transition probabilities developed for substructure in state bridges. Transition probabilities were calculated using NBMS database from 1998 to 2010. Table 5-11 shows the transition probability matrix for bridge substructure.

Table 5-11: Transition probability matrix for substructure (NBI)

Condition	9	8	7	6	5	4	3	2	1
9	0.85	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00
8	0	0.95	0.05	0.00	0.00	0.00	0.00	0.00	0.00
7	0	0	0.95	0.04	0.01	0.00	0.00	0.00	0.00
6	0	0	0	0.93	0.05	0.01	0.00	0.00	0.00
5	0	0	0	0	0.95	0.04	0.01	0.00	0.00
4	0	0	0	0	0	0.95	0.05	0.00	0.00
3	0	0	0	0	0	0	0.93	0.07	0.00
2	0	0	0	0	0	0	0	1.00	0.00
1	0	0	0	0	0	0	0	0	1.00

In order to compare the results for superstructure and substructure, the transition probability matrices shown in tables 5-9, 5-10 and 5-11 are used to develop the deterioration curves in Fig. 5-12. This figure indicates the similarity in the deterioration rates of bridge superstructure and substructure components.

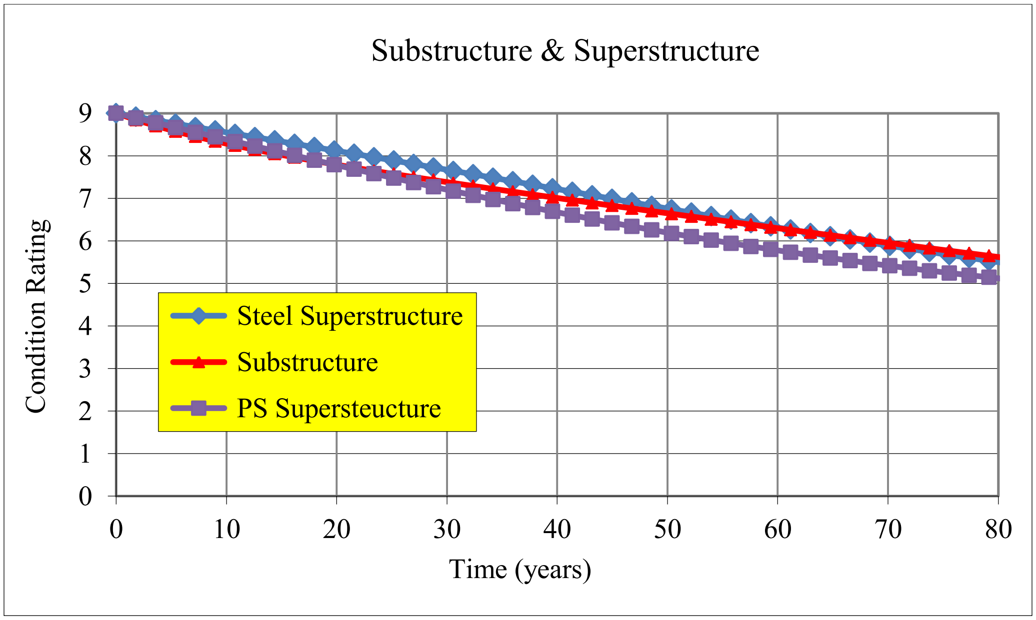


Figure 5-12: Deterioration curves of bridge superstructure and substructure

6 MODEL UPDATING

6.1 INTRODUCTION

In this chapter, the procedures followed in developing the models presented in chapters 4 and 5 are simplified and automated to a great extent in order to facilitate updating the developed models when new data becomes available. This is accomplished using the visual basic programming capabilities of Microsoft Excel. The database file can be updated on the basis of the procedure presented below.

6.2. MODEL UPDATING

To update the bridge data from NDOR database, the procedures listed below will need to follow:

1. Import the items INV 002B (District), INV 005B (Route signing prefix), INV 008 (Bridge number), INV 26 (Functional classification), INV 27 (Year built), INV 29 (Average daily traffic), INV 42 A (Type of service), 43A (Material Type), 43B (Structure type), INV 106 (Year reconstruct), INV 107 (Deck structure type), INV 108A (Type of wearing surface), INV 108C (Deck Protection), INV 109 (Average daily truck traffic), RAT 58 (Deck), RAT 59 (Superstructure), RAT 60 (Substructure) and RAT 90 (Inspection date) from Microsoft Access to Microsoft Excel. Example is shown in Fig. 6-1.
2. Remove duplicate data from item INV 008 and RAT90. Example is shown in Fig. 6-2.
3. Put the number of data and click on button “Start” for running the program. This will perform all data filtering operations as well as age-built and age-reconstruct calculations.
4. Click on buttons “ADTT”, “ADT”, “Re-deck”, “Original Deck”, “Overlay”, “Silica Fume”, “Latex Concrete”, “Low Slump Concrete”, “Districts 1 to 8”, “District 1,3 and 4”, “District 5 to 8”, “Superstructure” and “Substructure” to develop deterministic deterioration models with frequency diagram. Example is shown in Fig. 6-3.
5. For stochastic deterioration models, similar buttons are available in different excel sheets. Please refer to the attached files.

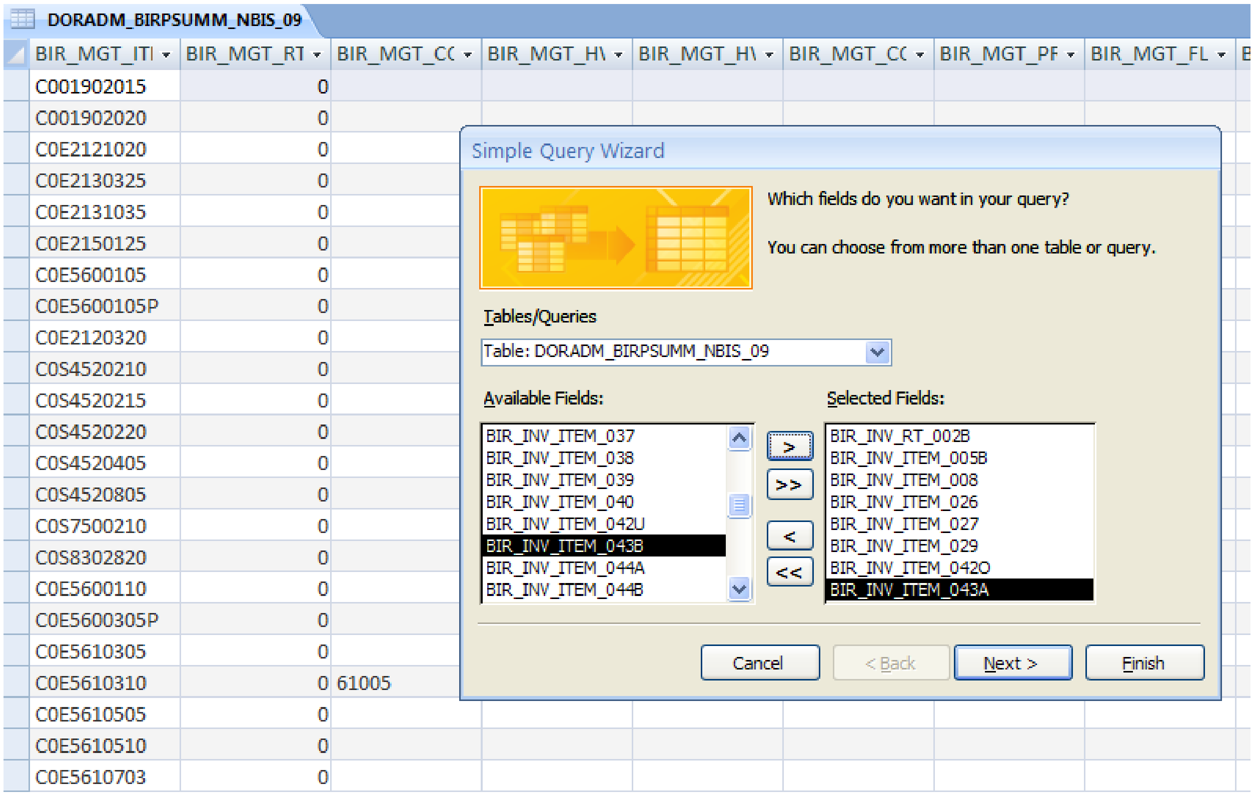


Figure 6-1: Selecting necessary items from Microsoft access database

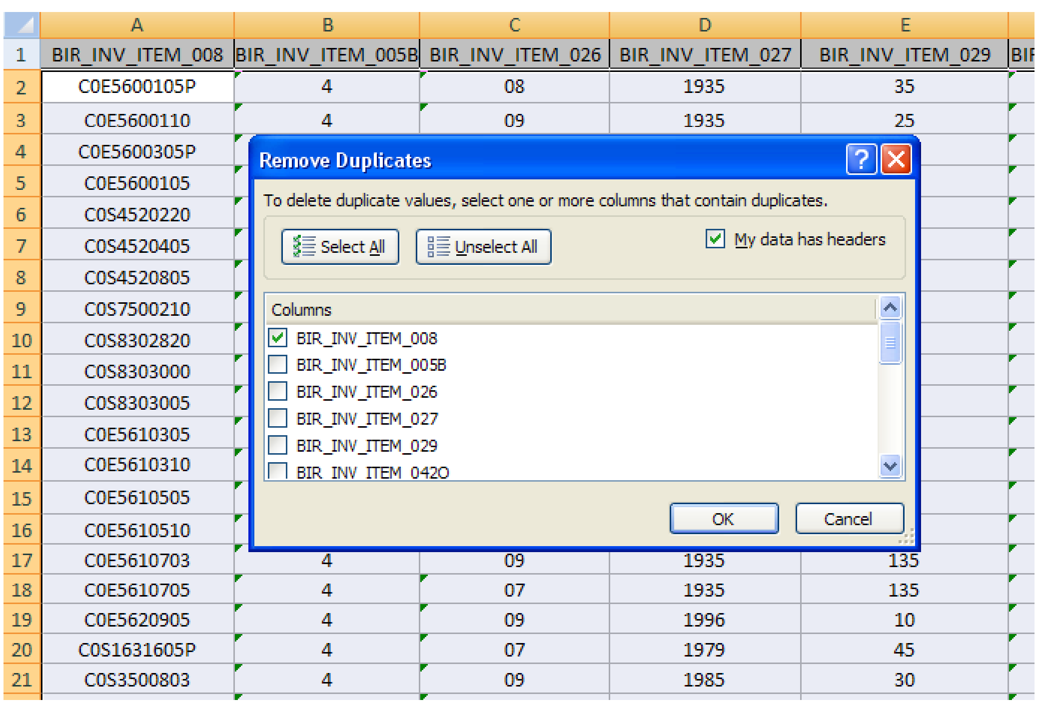
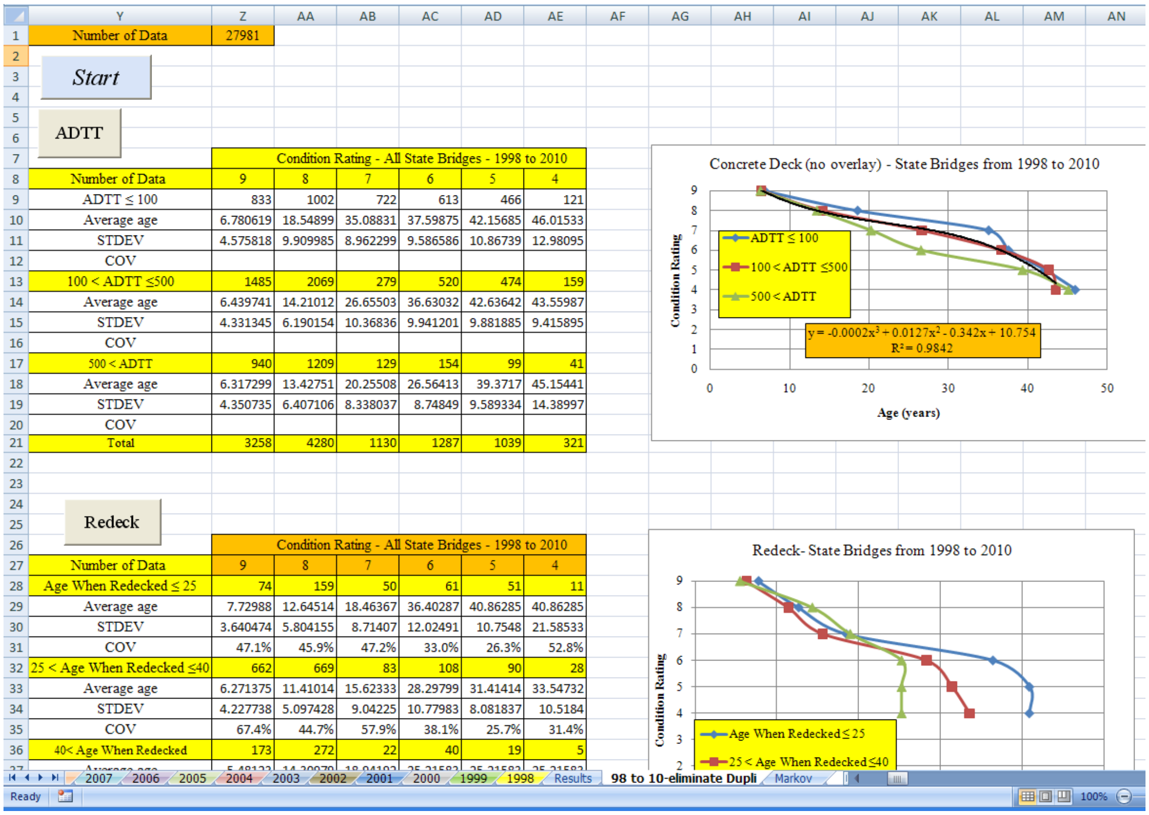


Figure 6-2: Removing duplicate data from Microsoft excel database



Number of Data	27981

	Condition Rating - All State Bridges - 1998 to 2010					
Number of Data	9	8	7	6	5	4
ADTT ≤ 100	833	1002	722	613	466	121
Average age	6.780619	18.54899	35.08831	37.59875	42.15685	46.01533
STDEV	4.575818	9.909985	8.962299	9.586586	10.86739	12.98095
COV						
100 < ADTT ≤500	1485	2069	279	520	474	159
Average age	6.439741	14.21012	26.65503	36.63032	42.63642	43.55987
STDEV	4.331345	6.190154	10.36836	9.941201	9.881885	9.415895
COV						
500 < ADTT	940	1209	129	154	99	41
Average age	6.317299	13.42751	20.25508	26.56413	39.3717	45.15441
STDEV	4.350735	6.407106	8.338037	8.74849	9.589334	14.38997
COV						
Total	3258	4280	1130	1287	1039	321

	Condition Rating - All State Bridges - 1998 to 2010					
Number of Data	9	8	7	6	5	4
Age When Redecked ≤ 25	74	159	50	61	51	11
Average age	7.72988	12.64514	18.46367	36.40287	40.86285	40.86285
STDEV	3.640474	5.804155	8.71407	12.02491	10.7548	21.58533
COV	47.1%	45.9%	47.2%	33.0%	26.3%	52.8%
25 < Age When Redecked ≤40	662	669	83	108	90	28
Average age	6.271375	11.41014	15.62333	28.29799	31.41414	33.54732
STDEV	4.227738	5.097428	9.04225	10.77983	8.081837	10.5184
COV	67.4%	44.7%	57.9%	38.1%	25.7%	31.4%
40< Age When Redecked	173	272	22	40	19	5

Figure 6-3: General view of the sheet used for deterministic models

7 CONCLUSIONS

Deterministic and stochastic deterioration models were developed for the three main bridge components: deck, superstructure, and substructure using the visual inspection data collected from year 1998 to 2010. For bridge decks, the impact of the following deterioration parameters was considered: type of wearing surface, average daily traffic (ADT) volume, average daily truck traffic (ADTT), deck protection, and highway district. Deterioration curves were developed for bare concrete decks and decks with low-slump concrete overlay. Also, deterioration curves and transition probability matrices were developed for concrete decks in state bridges in three different environmental categories: low environment (ADT < 1000 and ADTT < 100), moderate environment (1000 < ADT < 5000 and 100 < ADTT < 500), and severe environment (ADT > 5000 and ADTT > 500).

For bridge superstructure, deterioration curves and transition probability matrices were also developed for the two most dominant types of bridge superstructure in state bridges: steel girders and prestressed concrete girders. One deterioration curve and transition probability matric was also developed for bridge substructure and compared versus those of superstructure. For all bridge components, average transition periods from one condition state to the lower condition state were also estimated and the procedure for updating the developed models when new condition data becomes available are presented. The main conclusions of this report can be summarized as follows:

1) Deterioration rate for original concrete decks is slightly lower than the national average.
2) Deterioration rate for low-slump concrete overlay is significantly higher than that of original concrete deck.
3) The higher the traffic volume, the higher the deterioration rate of concrete bridge decks.
4) Bridge decks in districts 2 have higher deterioration rate than those in districts 1,3, and 4, which already have higher deterioration rates than those in districts 5,6,7, and 8.
5) Service life of bridge decks with epoxy coated reinforcement and black rebar at fair condition (condition 5) are approximately 68 and 40 years, respectively.
6) Prestressed concrete superstructures have similar performance to steel superstructure up to condition 6. No adequate condition data for prestressed concrete below condition 6.
7) Bridge superstructure and substructure components are lower than national average.

IMPLEMENTATION

By Fouad Jaber

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At the meantime, the approach adopted by NDOR bridge division to predict the future condition of bridge components is based on national average deterioration rates, which are one drop in the deck condition rating every eight years and one drop in the superstructure and substructure condition rating every ten years. This approach does not account for the impact of traffic volume, weight, structure and material type, and environmental impacts specific to Nebraska bridges, which might result in unreliable prediction of bridge future condition. The deterioration models developed in this project were entirely based on the condition data collected in the period from 1998 to 2010 by visual inspections. These data were analyzed to account for the effect of material type, wearing surface type, deck protection, average daily traffic, average daily truck traffic, highway district, and highway authority. Two categories of models were developed: a) deterministic models (i.e. deterioration curves and equations) to be used within the existing Nebraska bridge management system for life-cycle cost assessment of maintenance, rehabilitation, and replacement decisions; b) stochastic models (i.e. transition probability matrices) to be used in PONTIS for modeling bridge deck deterioration using elemental inspection data. The implementation of the developed models will be investigated within the recently funded research project titled "Life-Cycle Cost Assessment of Nebraska Bridges" for 2011-2012 fiscal years. Because there is an urgent need for updating the existing bridge management system in Nebraska, the results of this project will have an immediate use. The results of the LCCA will be used to replace the existing decision-support flow charts and change the way improvement actions are selected. In addition, the outcome of this project will assist NDOR bridge division in utilizing the decision support capabilities of Pontis.

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