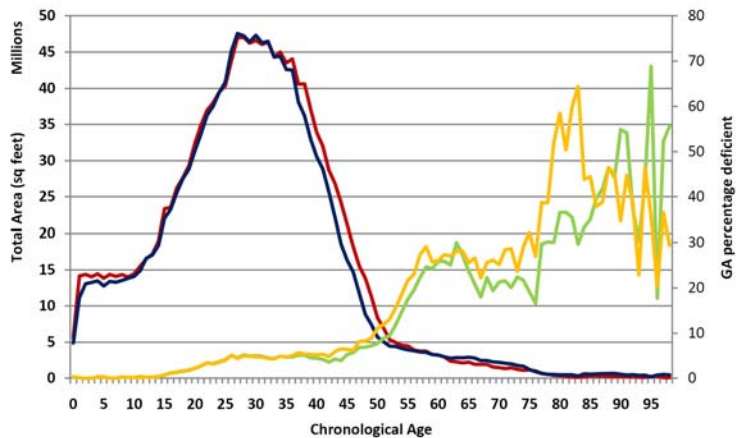


FINAL REPORT

Development of Degradation Rates for Various Bridge Types in the State of Ohio



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Swanson

for the
Ohio Department of Transportation
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16. Abstract - The Ohio Department of Transportation (ODOT) maintains a Bridge Management System (BMS) which is responsible for collecting and maintaining historical and longitudinal data by year for all the bridges in Ohio. The BMS aids ODOT in tracking, design, planning maintenance requests on bridges and funds allocation for maintenance. This project applied statistical analysis and modeling of the BMS data to provide insights to the rate of degradation and maintenance requirement of bridges under different environmental, location and other factors. Age resetting algorithms and Markov models were utilized in order to develop Operational Performance Indices (OPIs) forecasting for General Appraisal (GA), Wearing Surface (WS), Floor Condition (FC), and Protective Coating Systems (PCS). The results were validated against the actual values and the results were very positive. An understanding of the behavior of the existing bridges under the effect of different conditions and their future performance is essential for the BMS. Reliable bridge prediction and performance models facilitate inspection scheduling, cost analysis and budget optimization.					
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by

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To Sponsors

U.S. Department of Transportation
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and
Ohio Department of Transportation

March 2011

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1. INTRODUCTION

The goal of this research project is to assist Ohio Department of Transportation (ODOT) in decision making, fund allocation and maintenance and inspection scheduling by analyzing and modeling the historical inspection and inventory data available in ODOT's Bridge Management System (BMS). [3] and [4] details on data preprocessing, data warehouse creation, Data Modeling and OPI forecasting using First Order Markov Chains and result interpretations for different OPI's at the network level as well as for the subsets like districts and material types. The different phases of this project are as given below.

1.1 Phase I (September 2005 – June 2008)

Figure 1.10 gives a schematic representation of the different aspects of the project in Phase I. The input Dataset (Dataset I) for this phase consisted of 10 excel spreadsheets with inventory/inspection data covering years 1995 to 2004. This being the exploratory phase, feasibility of applying Markov models to BMS data was analyzed. Dataset I was preprocessed and data warehouse was constructed for further analyses. Markov models were developed and analysis and OPI forecasting was done in the year domain. Details of the Phase I of the project and Dataset I is given in [4].

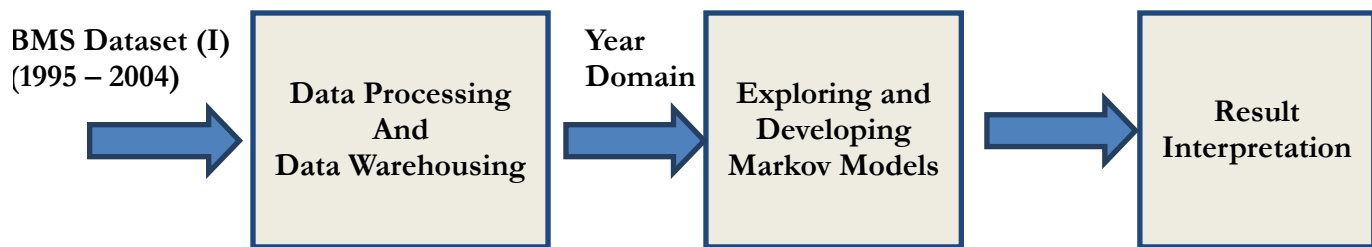


Figure 1.10: Phase I

1.2 Phase II (June 2008 – May 2009)

Figure 1.11 gives a schematic representation of the different aspects of the project in Phase II. The input Dataset for this phase (Dataset II) consisted of 24 excel spreadsheet with inventory/inspection data covering years 1985 to 2008. One important addition during this phase of the project was the Age Reset Algorithm [3]. With the age reset algorithm, the domain for our analysis was shifted from year domain to a Bridge Age domain. Automation of Markov calculations were completed in this phase. Additional excel spreadsheet called Bridge Work type spreadsheet (extracted from Item #153[1] in ODOT BMS) was available during this phase. This spreadsheet contains information on maintenance activities like major reconstruction, deck floor replacement date, wearing surface date and paint date and was used in the Age Rest calculations. Details of this phase are available in [3].

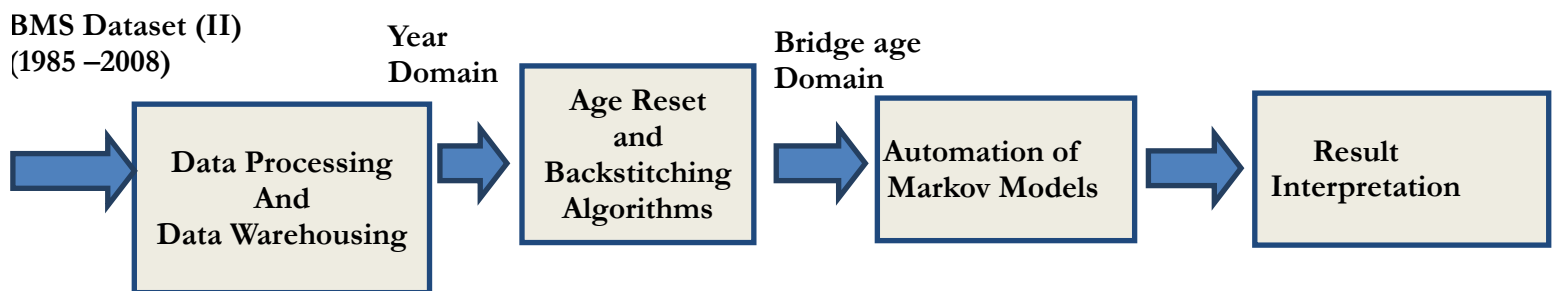


Figure 1.11: Phase II

1.3 Phase III (May 2009 - Present)

During a comparison of the datasets I and II several inconsistencies in the bridge inventory data like maintenance responsibility code, Longitudinal Member Type, Framing Type Code, Scour Critical Code, Railing Type, Wearing Surface Type [1] were discovered. The details and results of the comparison are given in [3]. Inconsistencies between the datasets affected the Markov Analysis and hence a new dataset (Dataset III) after resolving the inconsistencies was made available. Dataset III contained inventory/inspection data covering years 1985 to 2009. Figure 1.12 shows a schematic representation of this phase. The scope of this work lies on analyzing dataset III. All the Markov calculations and result interpretation done in Phases I and II were repeated in this phase. This phase focuses on ODOT Forecasting Spreadsheet, the details of which will be covered in Chapter 3.

Another important change in Phase III with respect to Phase II was the domain in which the analysis and result representation was done. While analysis and result interpretation in Phase II was done in Bridge Age Domain, the analysis in Phase III was done in the bridge age domain and the results were interpreted in the year domain. This is primarily because, ODOT Forecasting spreadsheet was based on a year wise calculations.

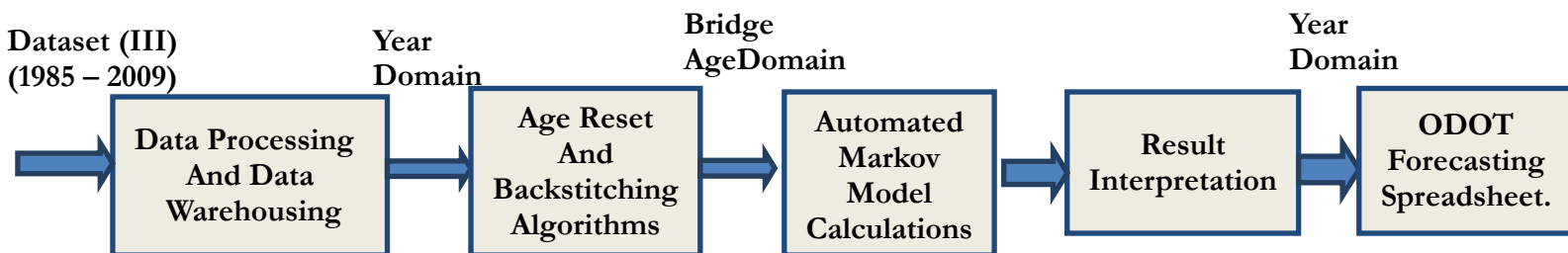


Figure 1.12: Phase III

1.4 Organization of the Report.

When Dataset III was made available, all the Markov calculations had to be redone for the newest dataset. Section 2 describes the results of applying Markov Modeling and result interpretation on Dataset III. Section 3 introduces the ODOT spreadsheet, establishes the definitions for various terms in the spreadsheet and the results of degradation modeling.

2. RESULTS FOR DATASET III

2.1 All State Owned And State Maintained Bridges.

This section describes the results obtained for Markov Chain Modeling of all State Owned and Maintained Bridges (SOSM) with age reset and backstitching. All 4 OPI's namely General Appraisal (GA), Deck Wearing Surface (WS), Deck Floor Condition (FC) and Protective coating surface are analyzed.

2.1.1 General Appraisal

Figure 2.1 shows a comparison of the total deck area distribution for different bridge ages and percentage of GA deficient area for different bridge ages for Dataset II and Dataset III without Age Reset. It can be observed that the total deck area and percentage deficient areas for Dataset II and Dataset III remain fairly close to each other. Dataset III shows more area between bridge age 33 to 54 and between bridge age 3 and 9. This is primarily because Dataset III has an additional data for inspections in 2008 -2009 inspection years. It is also observed that the Percent GA Deficient Area is

very high after Age 75. This can be explained by two factors. Firstly the statistical population of bridges with a bridge Age 75 is relatively small as can be observed from Figure 2.1. Secondly the bridges with a bridge age greater than 75 are relatively very old bridges and hence their GA ratings are to the lower bounds.

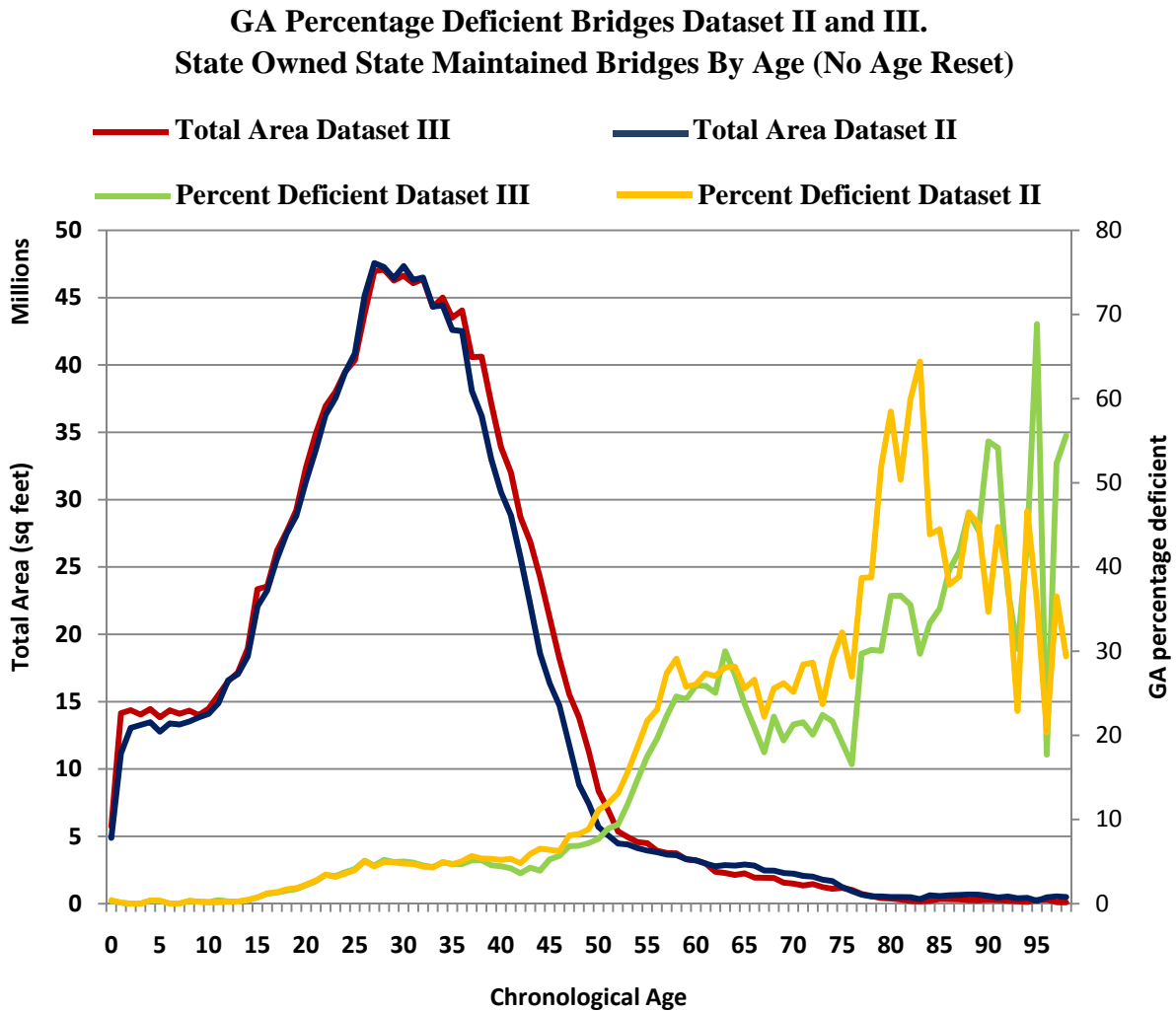


Figure 2.1: Total Deck Area and GA Percent Deficient Area.

The Mean Age until Reset for General Appraisal is defined as the average number of years since the bridge has been built for the occurrence of a Major Reconstruction. Figure 2.2 shows the Mean age

until reset for GA as a probability distribution. The Mean age until rest for General Appraisal is 34.2 years. This indicates that on an average a bridge gets Major Reconstruction 34 years after it has been built.

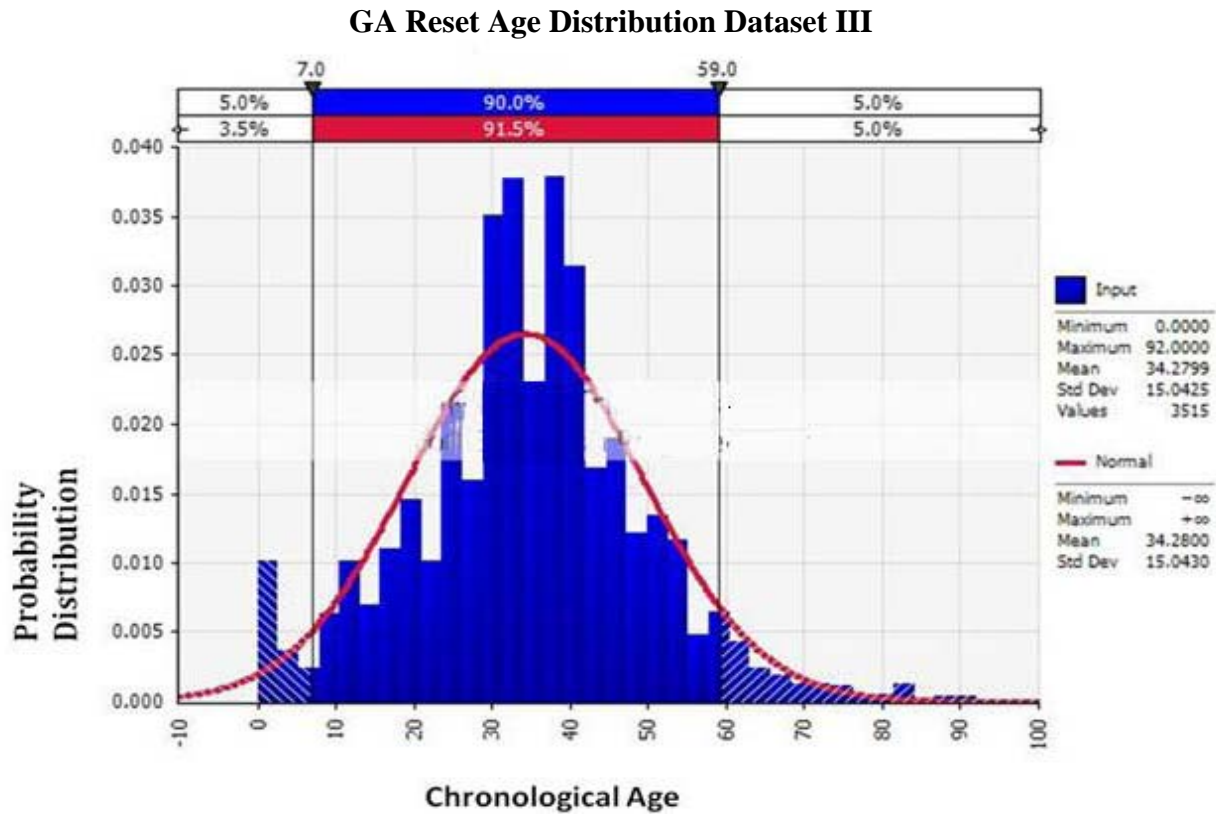


Figure 2.2: Mean Age until Reset GA.

The distribution of General Appraisal ratings at age 0, age 35 (the Mean Age until Reset) and Age 90 is compared in Figure 2.3. It can be observed that at Age0 GA rating is skewed to the GA=9 side and at Age 90 GA rating is skewed to GA=4 side. However at age=35 we find a reasonably uniform distribution of GA ratings. Figure 2.3 also indicates the Mean GA rating for each Bridge age as well as the standard deviation from the mean age for each bridge age.

GA Degradation Plot with Reset and Backstitching Dataset III State Owned State Maintained Bridges

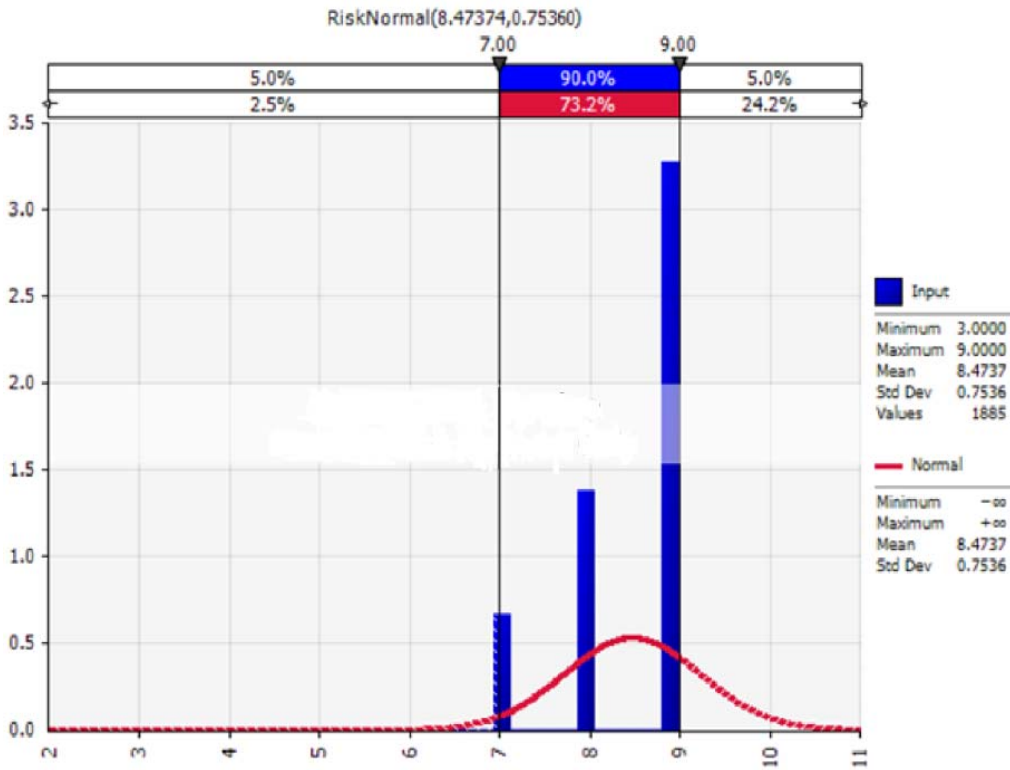
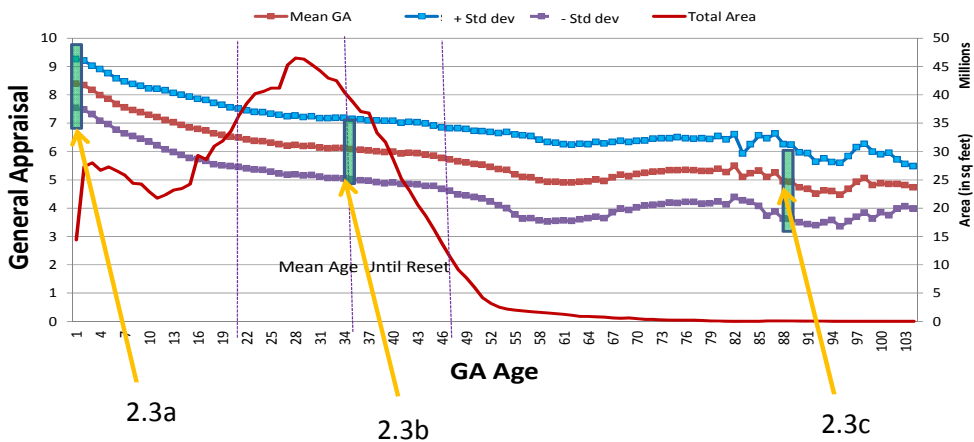


Figure 2.3a

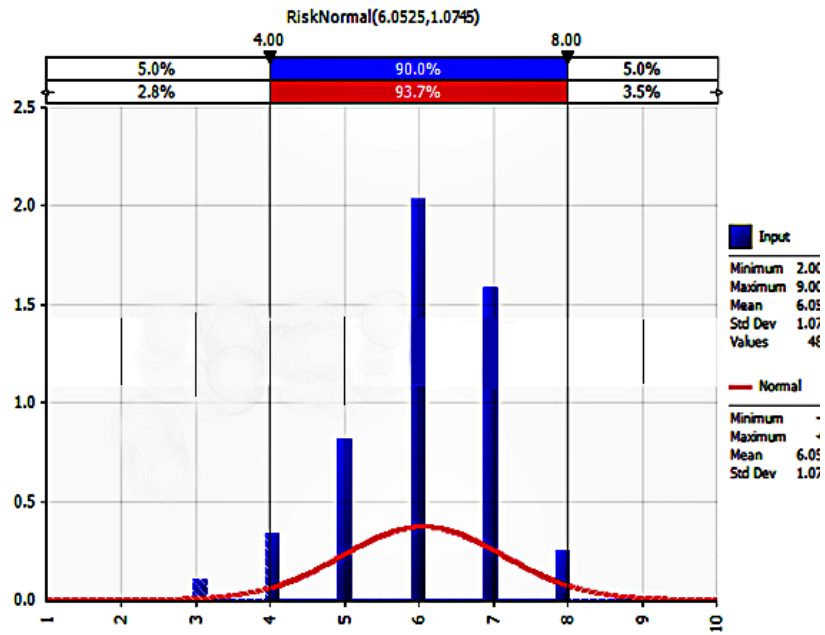


Figure 2.3b

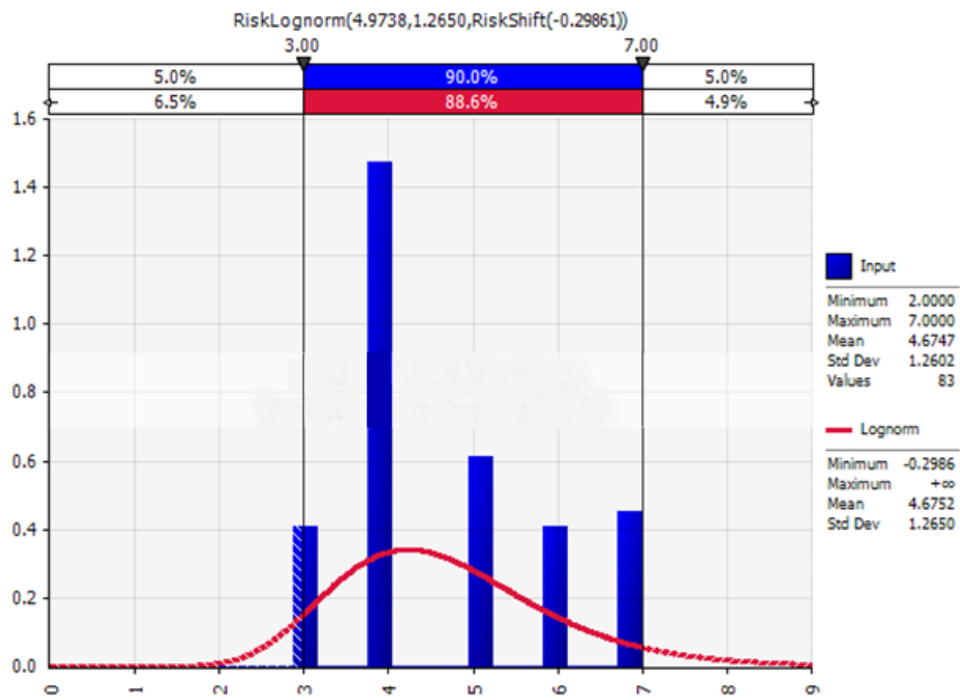


Figure 2.3c

Figure 2.3: Mean GA rating and Standard Deviation from Mean GA.

[3] Describes the different Markov Models that are used for modeling BMS data, namely the Actual Model, Predicted Model, Predicted with Advance Model and also Auto-Regressive Models. Figure 2.4 shows the OPI forecasting using Markov Models for General Appraisal. The comparison between Dataset II and III shows that the forecasted OPI remains similar although there is a difference in the GA OPI between GA Age 0 and GA Age 4. It can be observed from Figure 2.4 that the GA OPI rating for Dataset III is lower than the GA OPI rating for Dataset II between GA Age 0 and GA Age 4.

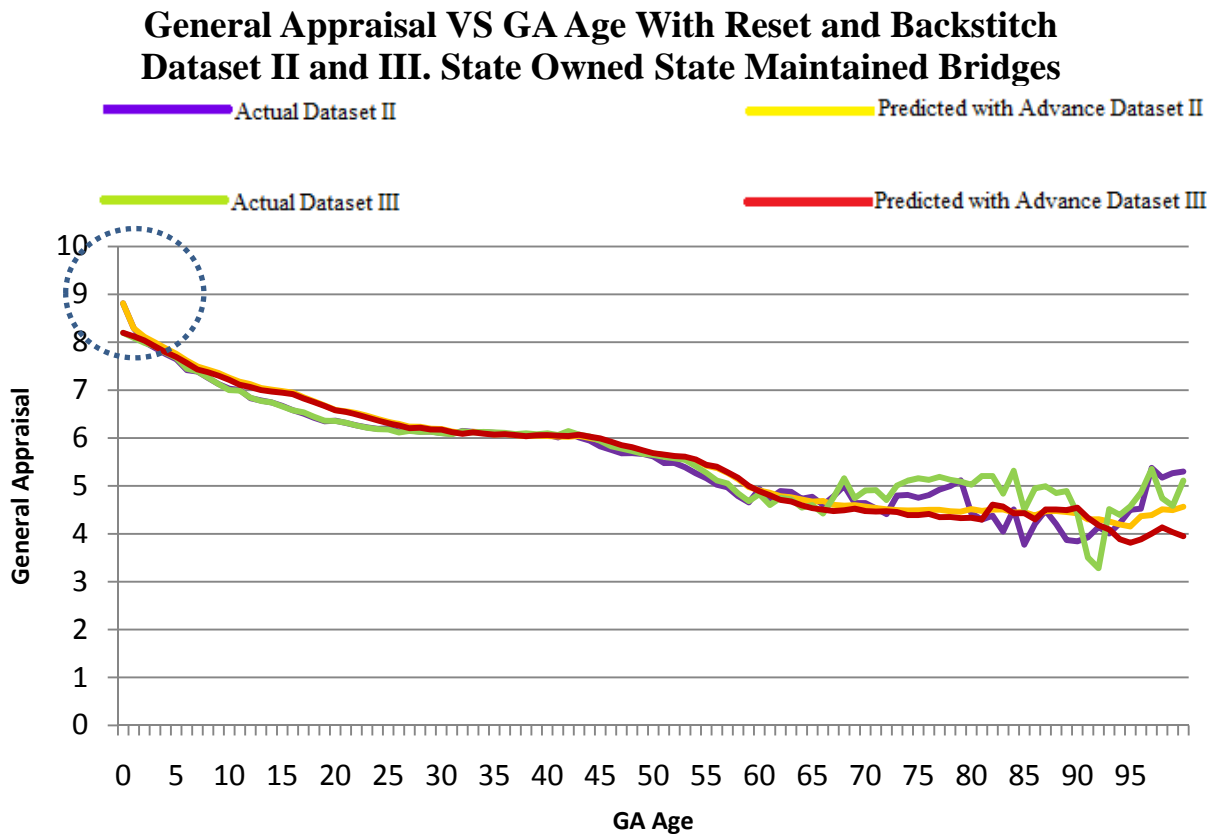


Figure 2.4: General Appraisal OPI Forecasting.

2.1.2 Deck Floor Condition (FC)

Deck Floor condition rating (FC) is an indicator of the condition of the major horizontal structural element that carries the riding surface [1]. Figure 2.5 shows the Total Deck Area distribution for bridge age and the FC Percent deficient area for the bridge Age without Age Reset and Backstitching. The Mean Age until reset for Deck Floor Conditioning is 28 years with a standard deviation of 17.7 years. Figure 2.6 shows the Mean Age until reset calculations. This indicates that on an average it takes 28 years for a deck replacement. Deck replacement is generally associated with Major reconstruction and hence the mean age until reset for Deck Floor Condition is close to mean age until reset for General Appraisal.

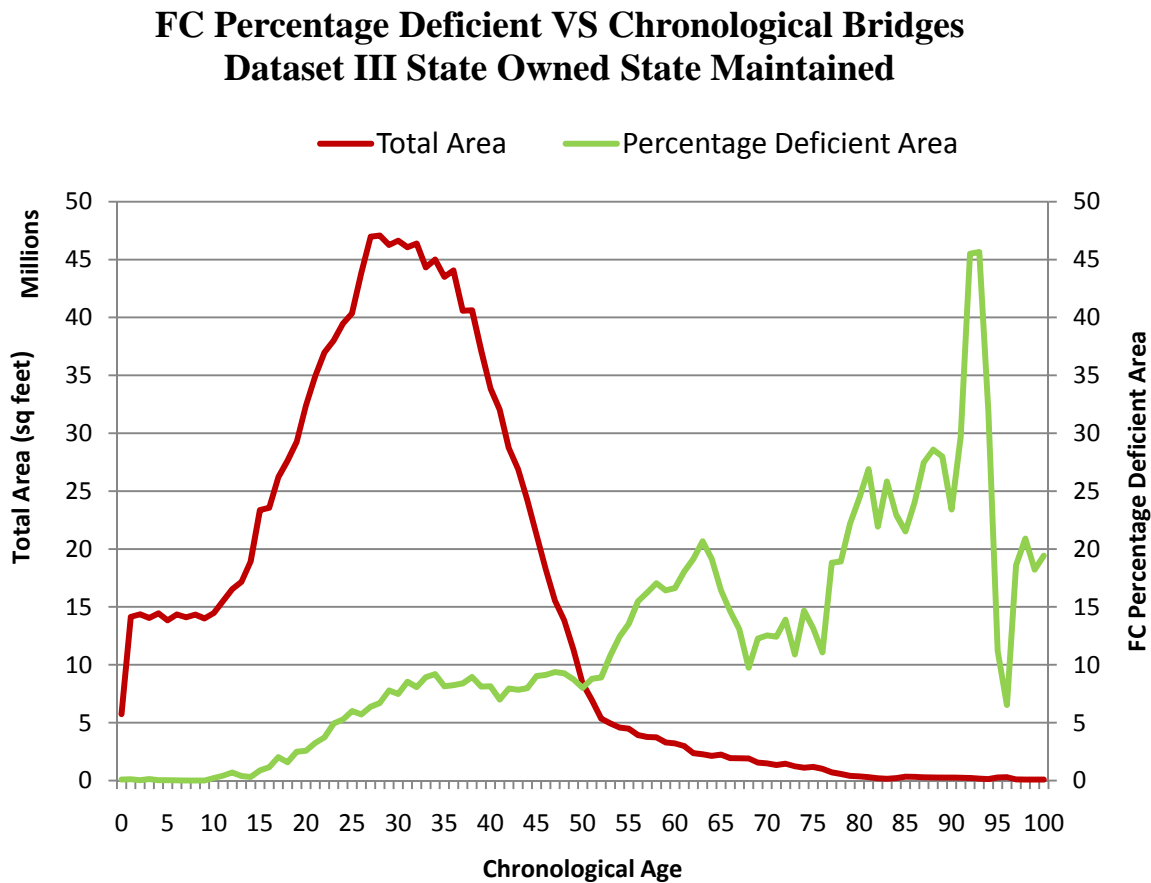


Figure 2.5: Total Deck Area and FC Deficient Area (No Reset)

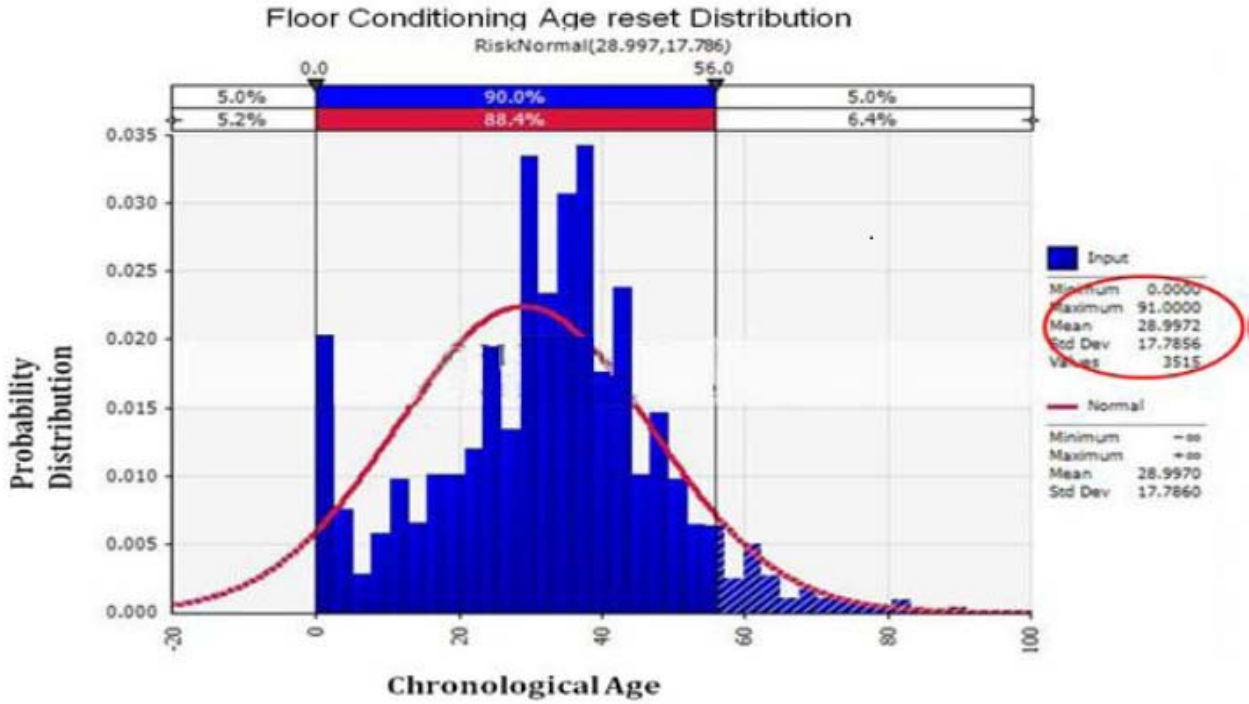


Figure 2.6: Mean Age until Reset FC.

The FC OPI forecasting and trending using Markov Models are shown in Figure 2.7. The figure also compares the FC Forecasting for Dataset II and Dataset III. Dataset II and III vary in their FC ratings between FC Age 9 and FC Age 32. A snapshot of the TPM Area for Age 17 shows that Dataset III has more area in FC rating =1 when compared to Dataset II and hence a higher rating for FC at FC Age 17.

Deck Floor VS FC Age with Reset and Backstitch Dataset II and Dataset III State Owned State Maintained Bridges

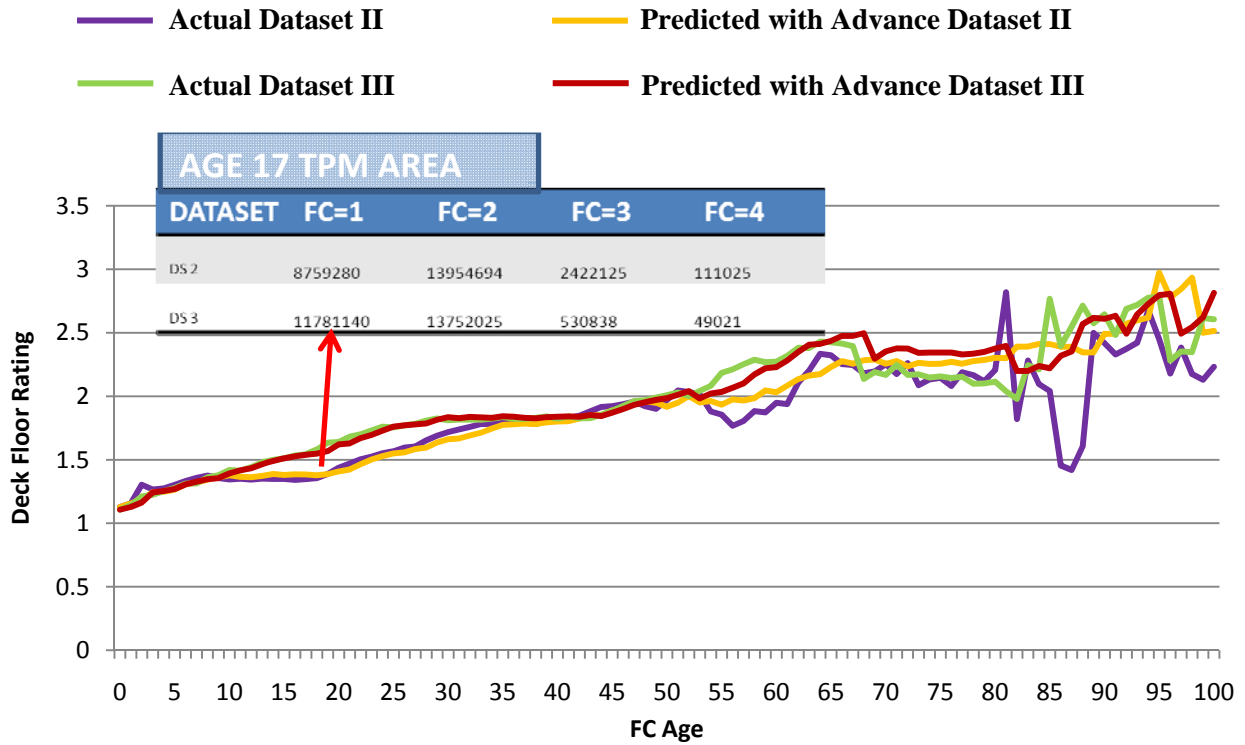


Figure 2.7: Deck Floor Condition OPI Forecasting

2.1.3 Deck Wearing Surface (WS).

Deck Wearing Surface OPI is an indicator of the condition of the bridge’s pavement surface exposed to vehicular surface. Figure 2.8 shows the Total deck area distribution with bridge Age and WS percent deficient area without applying Age Reset. Total Deck Area is 1 million square feet after Bridge Age 80 which indicates that the statistical population of bridges after Age 80 is very small. Because of the small statistical population and ageing bridges, WS percentage deficient shoots up after Age 80. Figure 2.9 shows the Mean Age until Reset for Deck Wearing Surface. Deck Wearing Surface is replaced more frequently as compare to Deck Floor; hence the Mean Age until reset is 18 years. This indicates than on an average the Deck Wearing Surface is replaced every 18 years.

WS Percentage Deficient Area VS Chronological Age Dataset III State Owned State Maintained Bridges

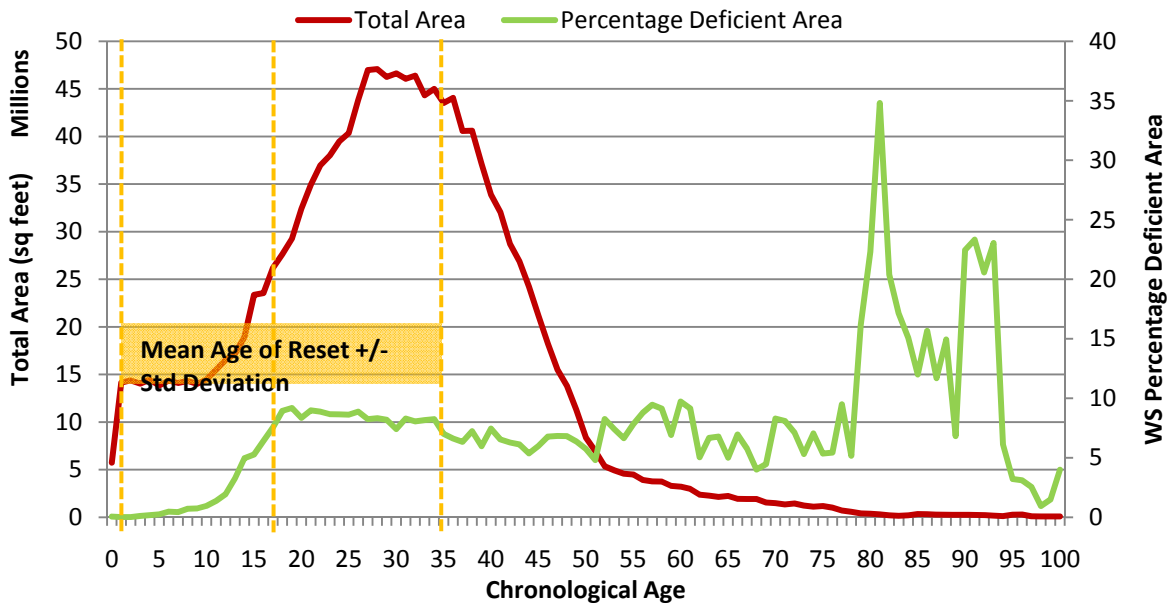


Figure 2.8: Total Deck Area and WS Deficient Area (No Reset).

Wearing Surface Age reset Distribution

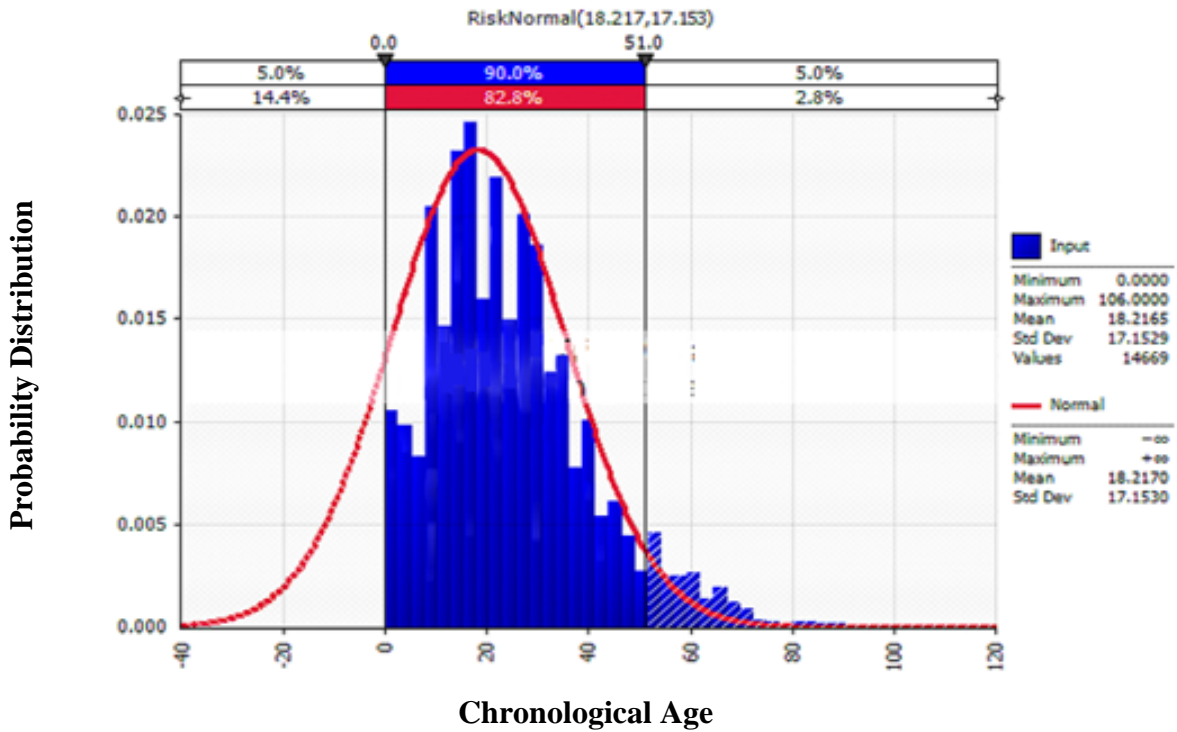


Figure 2.9: Mean Age until reset WS

Deck Wearing Surface OPI trending and forecasting using Markov Models are shown in Figure 2.10. It can be observed that the OPI plots for Deck Wearing Surface for Dataset II and Dataset III is quite similar.

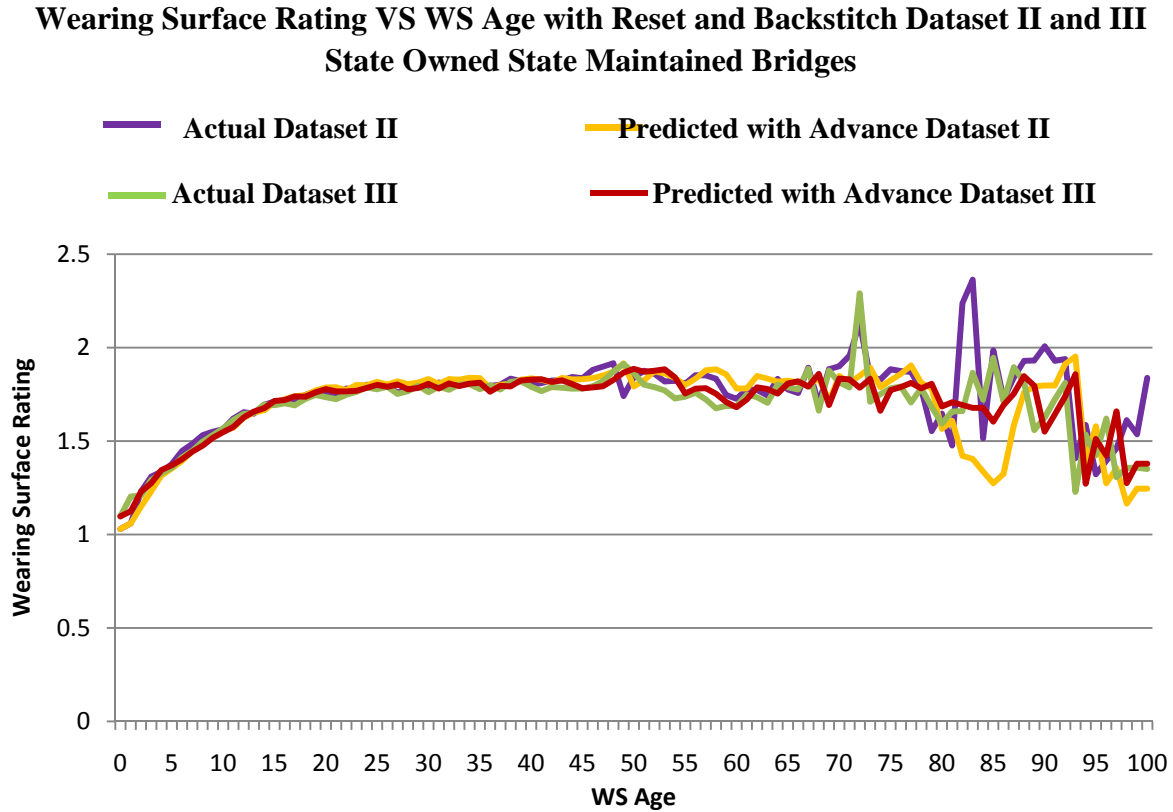


Figure 2.10: Deck Wearing Surface OPI forecasting.

2.1.4 Summary of Mean Age Until Reset Statistics.

A summary of the Mean Age until Reset statistics for General Appraisal, Deck Floor and Deck Wearing Surface is shown in Figure 2.11

<u>OPI</u>	<u>Reset Factors</u>	Dataset 2		Dataset 3	
		<u>Mean Years to Reset</u>	<u>Standard Deviation</u>	<u>Mean Years to Reset</u>	<u>Standard Deviation</u>
GA	Major Rehab	32	17	35.2	13.8
FC	Major Rehab Deck Replacement	33.5	15.5	32.8	15.5
WS	Major Rehab WS Replacement	25	15	28	15.4

Figure 2.11: Summary of Reset Statistics.

2.2 Subset Studies

Subsets of the State Owned and State Maintained bridges were created on the basis of geographical location and material types. On the basis of geographical locations, bridges in Ohio belong to one of the twelve districts. On the basis of material types, bridges can be made of Reinforced Concrete, Prestressed Concrete and Steel.

2.2.1 Districts in Ohio

Figure 2.12 shows the districts in Ohio and an area wise breakdown of the districts. The bigger districts in terms of area are District 4, District 6, District 8 and District 12.

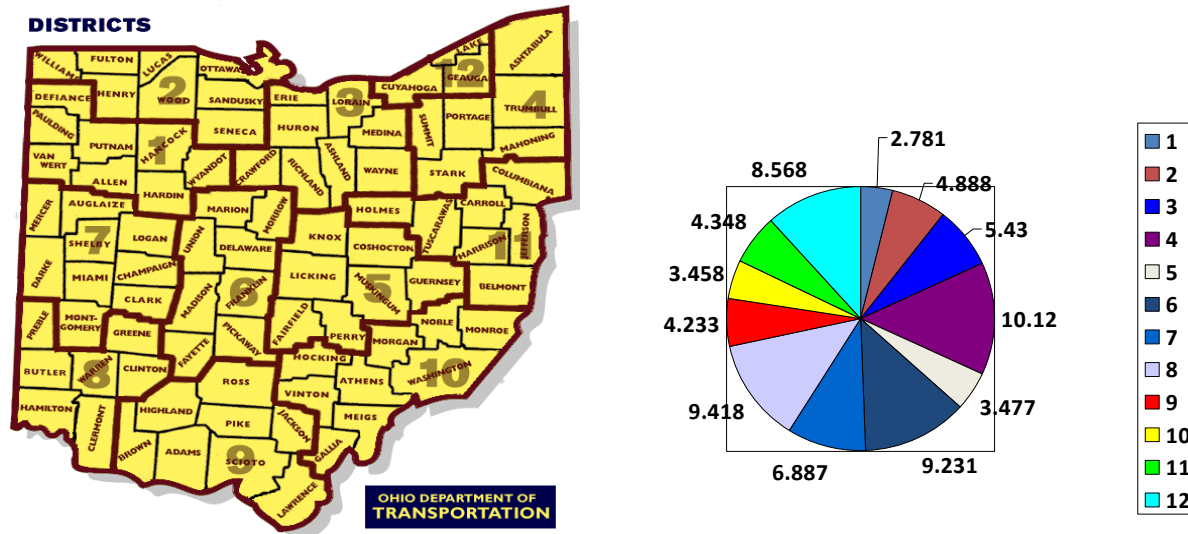


Figure 2.12: Percentage Area Breakdown of Districts in Ohio

2.2.1.1 General Appraisal

Figure 2.13 shows the General Appraisal OPI forecasting for districts in Ohio. The Markov model shown in the figure is Predicted with Advance Model. The Markov models shown in Fig 2.13 can be fitted with Auto Regressive (AR) models. Figure 2.14 shows the AR model fit for General Appraisal OPI. It can be observed that after age reset, District 2 has the lowest General Appraisal rating at Age 0. Bridges in District 12 has the lowest AR coefficient for initial Ages and hence they degrade faster compared to bridges in other district.

Districts in Ohio: General Appraisal Vs GA Age With Reset and Backstitch Dataset III. State Owned State Maintained Bridges

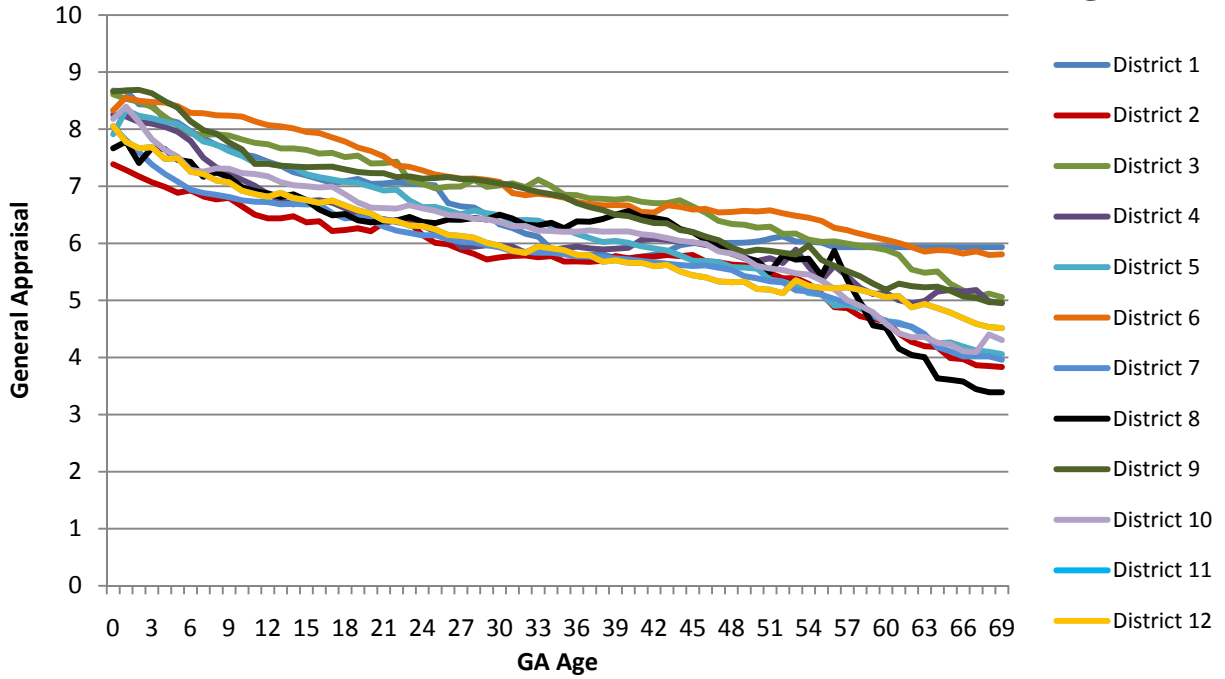


Figure 2.13: Predicted with Advance Model for Districts in Ohio

Districts in Ohio: General Appraisal VS GA Age Reset and Backstitch. State Owned State Maintained Bridges

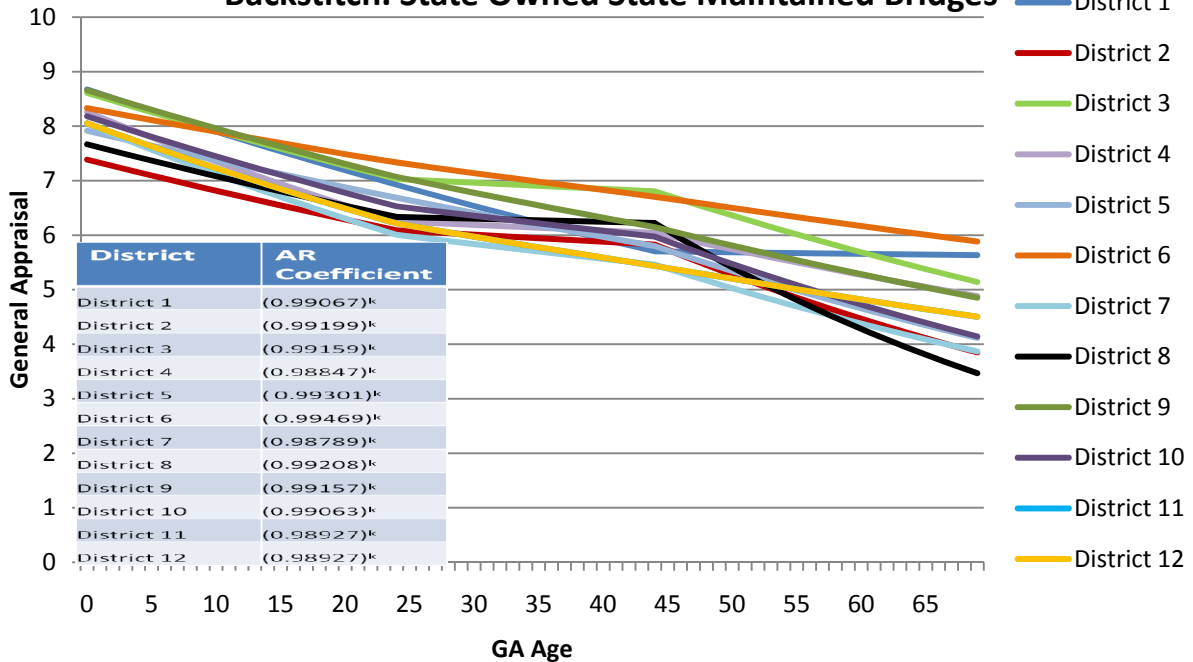


Figure 2.14: Auto Regressive Fit for General Appraisal.

2.2.1.2 Deck Wearing Surface.

Figure 2.15 shows the Auto Regressive Fit for Deck Wearing Surface OPI for districts in Ohio. It can be observed that District 6 has the lowest Deck Wearing Surface rating at Age 0 and District 7 has the highest degradation in the initial years.

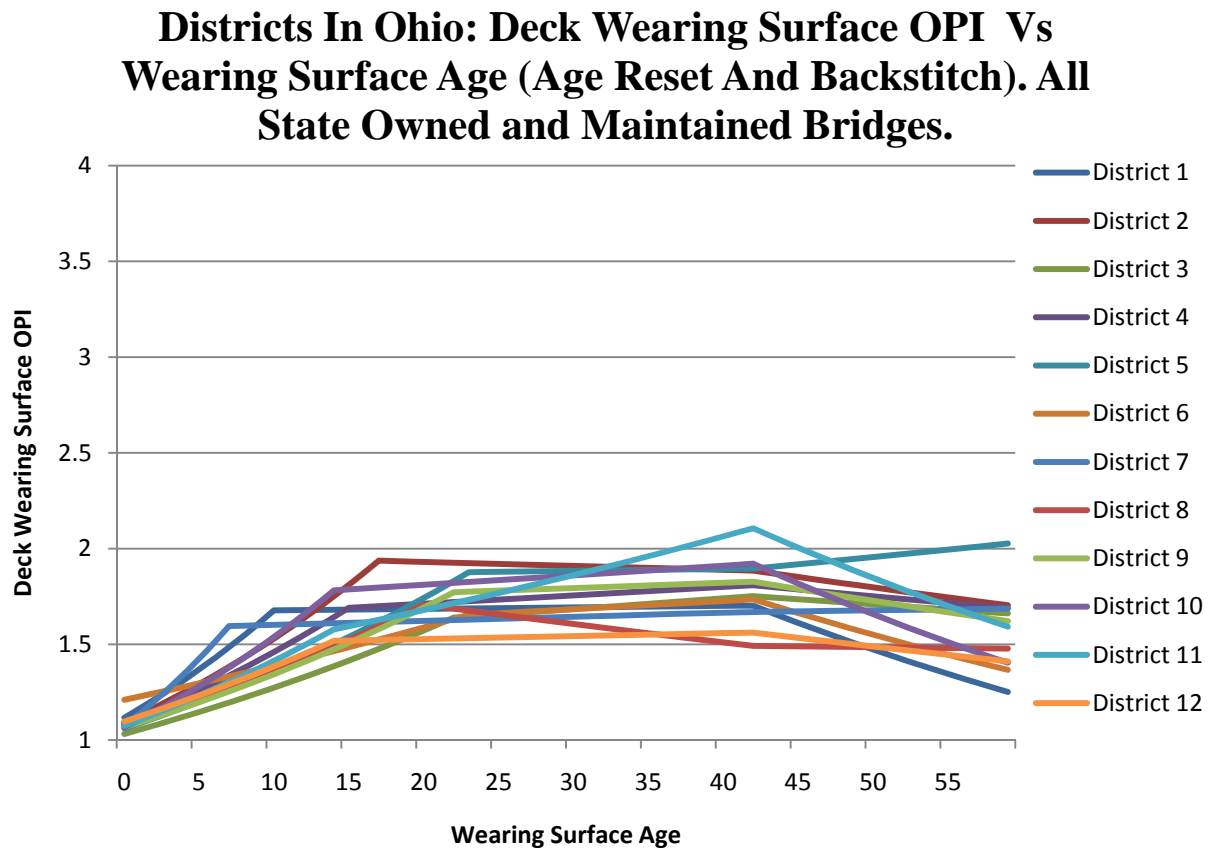


Figure 2.15: Auto Regressive Fit for Deck Wearing Surface OPI.

2.2.1.3 Deck Floor Condition

Figure 2.16 shows the Auto Regressive curve fit for Deck Floor Condition OPI plots obtained from Markov calculations. It can be observed that District 12 has the lowest FC at Age 0 and District 7 shows highest degradation in the initial Ages.

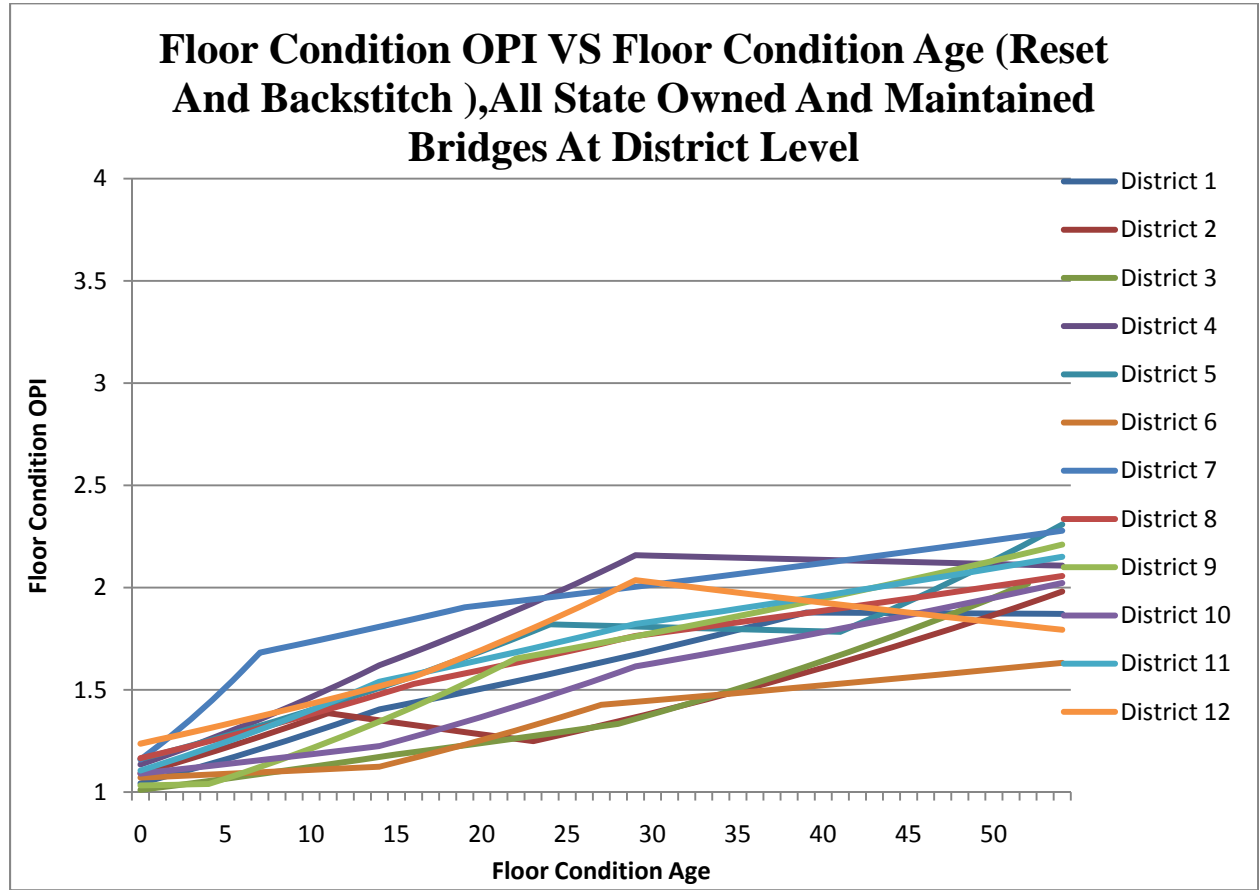


Figure 2.16: Auto Regressive Fit for Deck Floor Condition OPI.

2.2.2 Material Types.

Subsets of all the State Owned and Maintained Bridges in Ohio are created based on their structural material types (Steel, Reinforced Concrete, and Pre-stressed Concrete). Fig 2.17 shows an area wise breakdown of the material type subset. It can be observed that the majority of the State Owned and

Maintained Bridges (77.5%) in Ohio have a material type of steel. Reinforced concrete bridges form the smallest subset in terms of area (7.6%).

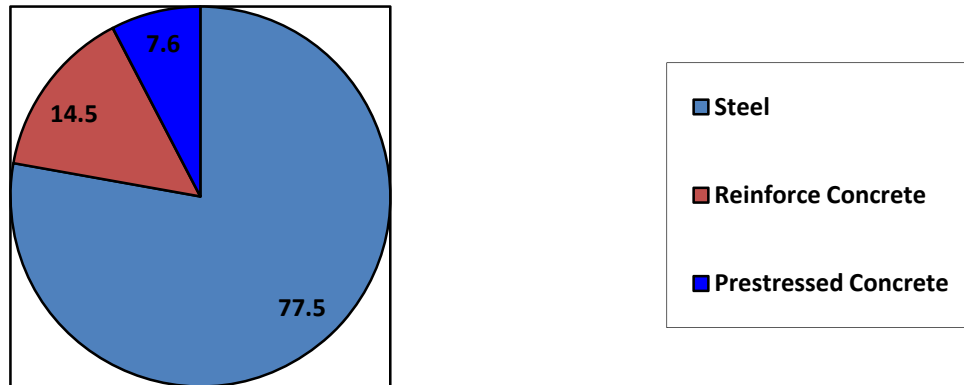


Figure 2.17: Area wise breakdown of bridges based on Material Type

Figure 2.18, Figure 2.19 and Figure 2.20 shows the Total deck area and Percentage General Appraisal Deficient Area distribution for Steel Bridges, Reinforced Concrete bridges, Pre-stressed Concrete bridges. As described above, it can be observed from Figure 2.18 that the majority of the bridges are steel bridges. From Figure 2.19 it can be observed that there are a considerable Reinforced Concrete bridges that are relatively new as well as between GA Ages 18 and GA Age 50. From figure 2.20 it can be observed that most of the Pre-stressed Concrete bridges are relatively new.

2.2.2.1 General Appraisal

GA Percentage Deficient Bridges Dataset III State Owned State Maintained Steel Bridges

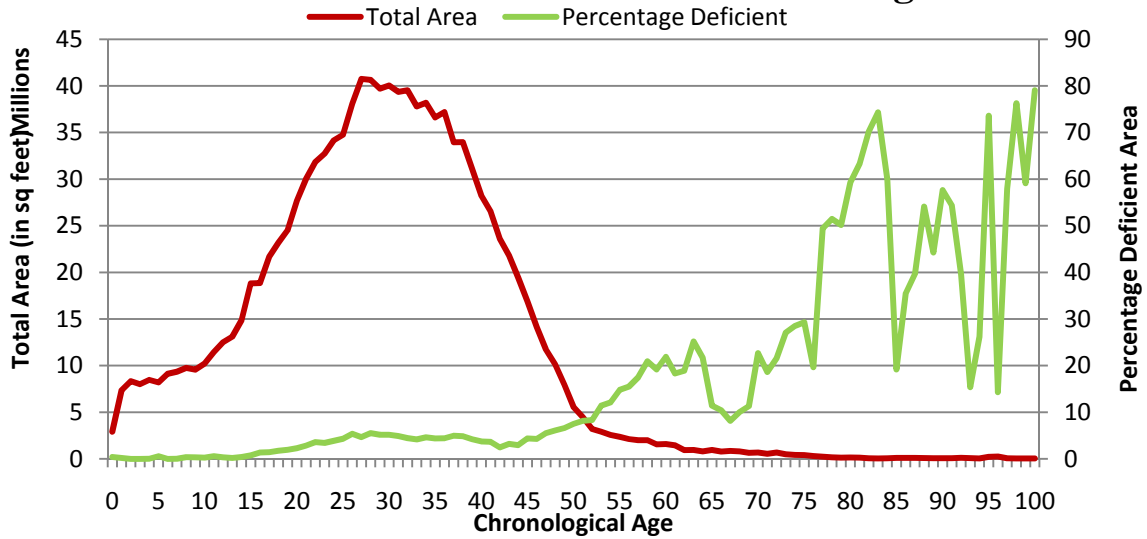


Figure 2.18: Total Deck Area and GA Percent Deficient Steel Bridges.

GA Percent Deficient Bridges No Reset Applied Dataset III State Owned State Maintained Reinforced Concrete Bridges

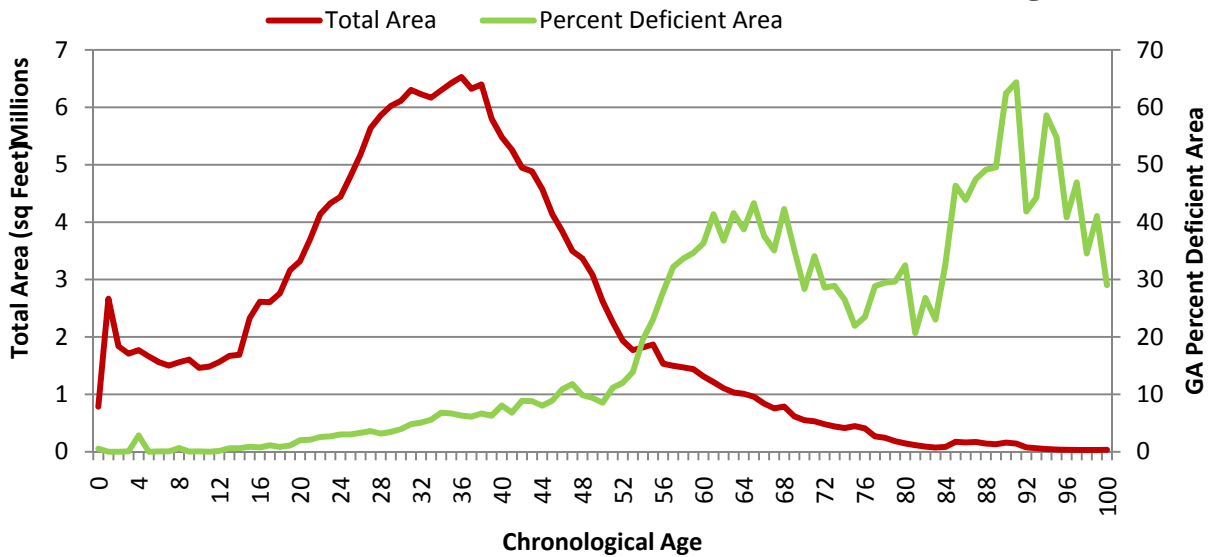


Figure 2.19: Total Deck Area and GA Percent Deficient Reinforced Concrete Bridges.

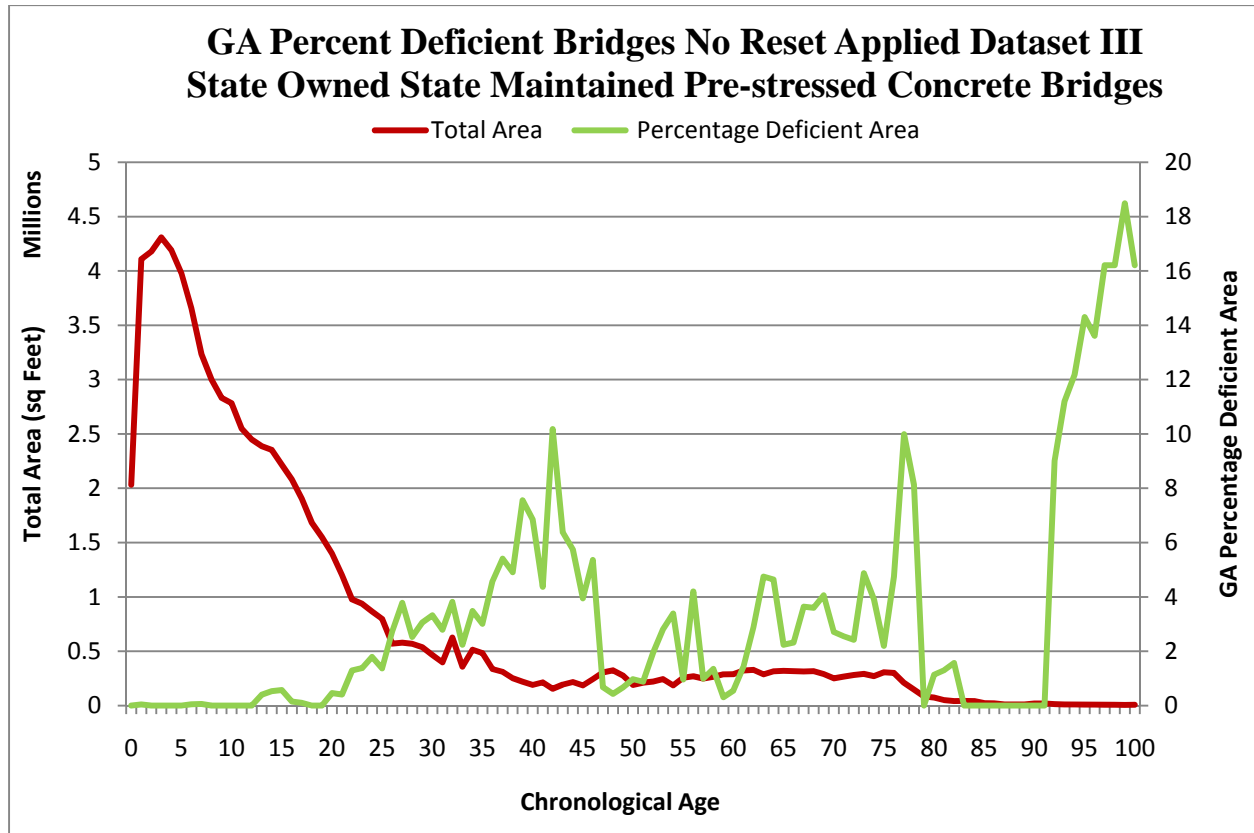


Figure 2.20: Total Deck Area and GA Percent Deficient Area Pre-stressed Concrete Bridges.

Figure 2.21 shows the General Appraisal OPI forecasting for Steel bridges, Reinforced Concrete bridges and Pre-stressed Concrete Bridges after Age Reset and Backstitching. It can be observed that Steel Bridges have relatively lower GA values in the initial ages followed by Reinforced Concrete bridges. Figure 2.22 shows the AR curve fit for the GA OPI for the material types. It can be observed that the degradation of Concrete bridges are relatively fasted compared to Steel bridges with Reinforced Concrete Bridges having the highest degradation rate.

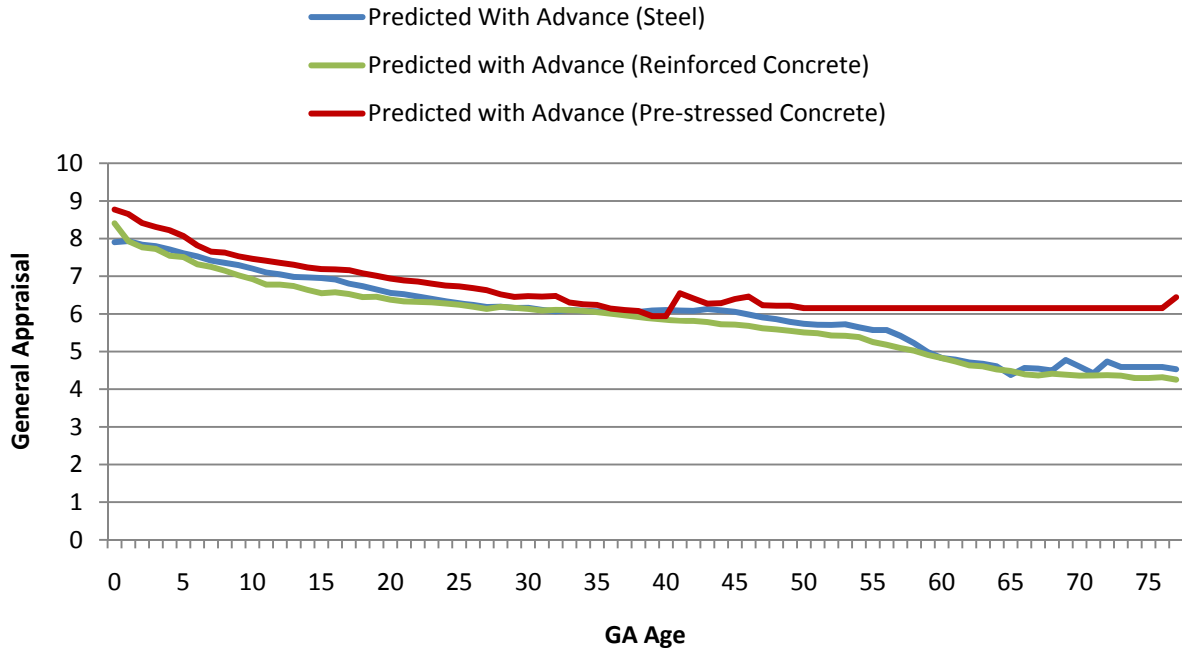


Figure 2.21: General Appraisal Plot for Steel Reinforced Concrete and Pre-stressed Bridges.

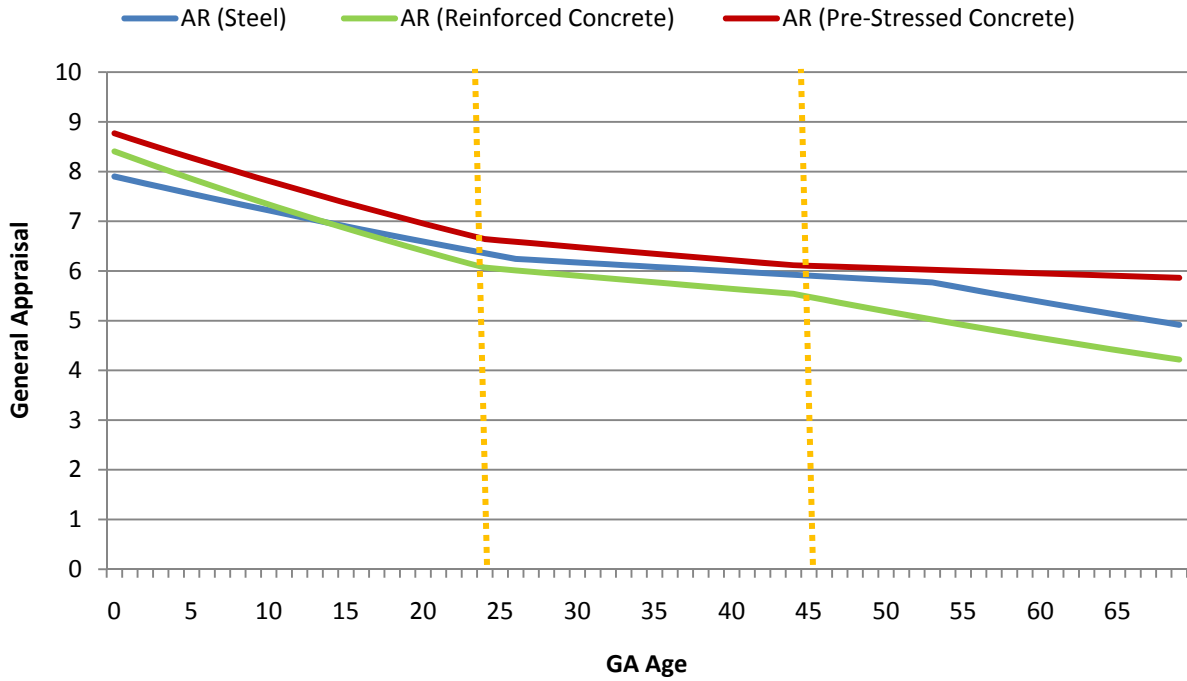


Figure 2.22: AR curve Fit for General Appraisal OPI

Summary of the Mean Age until Reset statistics is given in Figure 2.23. It can be seen that both Steel as well as Reinforced Concrete bridges have a similar Mean Age until Reset statistics. Pre-stressed Concrete bridges are relatively new bridges and hence Mean Age until Reset was not calculated.

Dataset 3		
<u>Type</u>	<u>Mean Years to Reset</u>	<u>Standard Deviation</u>
Steel	34.7	12
Reinforced Concrete	34.1	15.5
Pre-stressed Concrete	New Bridges	New Bridges

Figure 2.23 Mean Age until Reset Statistics for Material Types.

2.2.2.2 Deck Wearing Surface

Figure 2.24 shows the Deck Wearing Surface OPI forecasting after Age Reset and Backstitching using the Predicted with Advance model. It can be observed that Steel bridges start with the lowest Deck Wearing Surface rating at Age 0. Figure 2.25 shows the AR curve fit and Figure 2.26 shows the AR coefficient for the material types. It can be see that between Age 0 and Age 12 both the concrete

bridges degrade faster than Steel bridges. Between Age 12 and Age 42 Pre-stressed concrete bridges have the highest degradation rate.

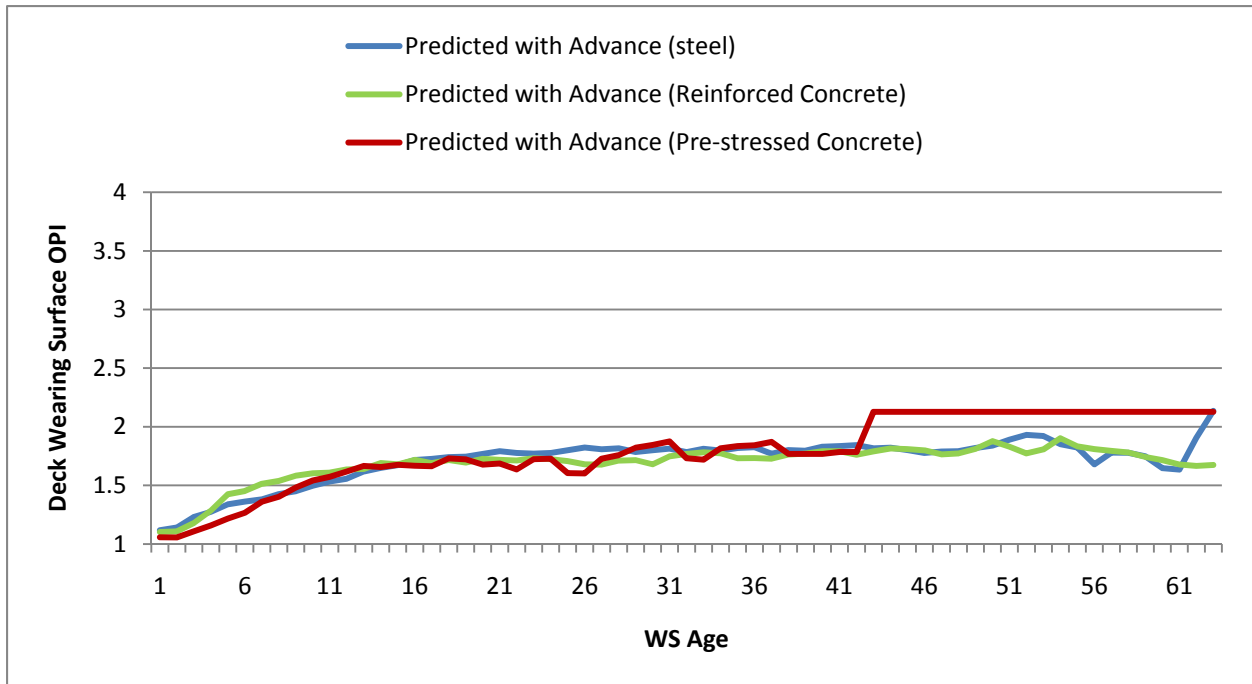


Figure 2.24 Deck Wearing Surface OPI Plots for Material Types.

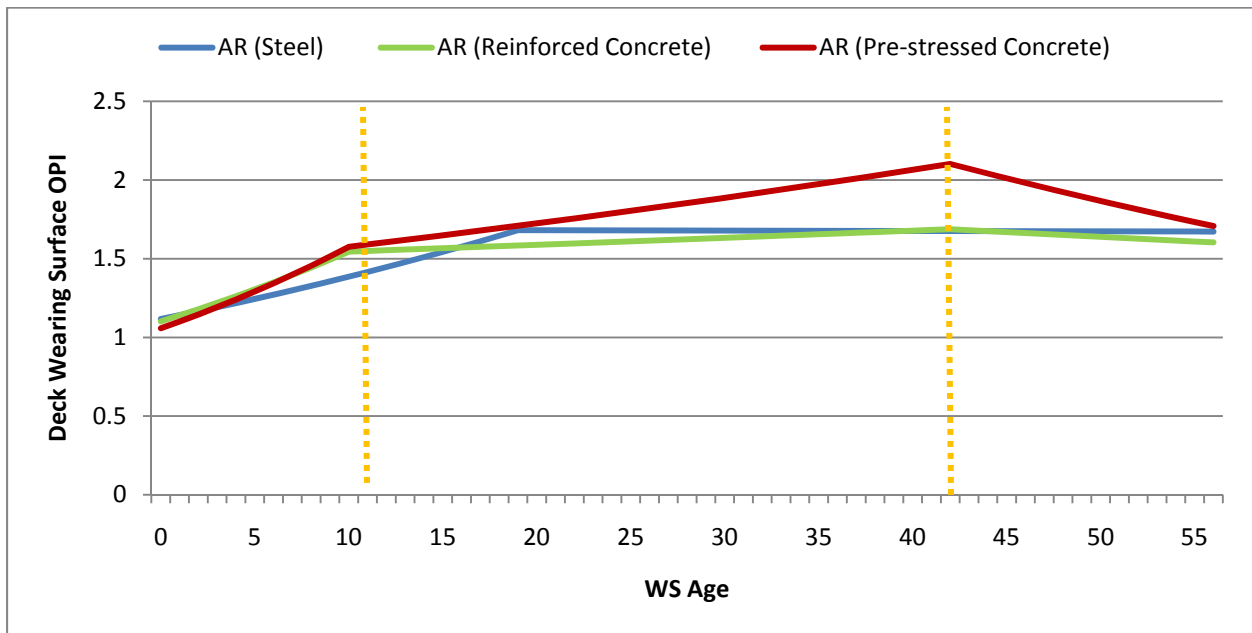


Figure 2.25: AR Curve Fit for Deck Wearing Surface OPI.

Dataset 3

<u>Material</u>	<u>AR Coefficient</u> (Age 0 –Age 11)	<u>AR Coefficient</u> (Age 12 –Age 42)
Steel	1.02	0.99
Reinforced Concrete	1.03	1.00
Pre-stressed Concrete	1.04	1.01

Figure 2.26: AR Coefficients Deck Wearing Surface OPI for Material Types.

2.2.2.3 Deck Floor Condition.

Figure 2.27 shows the Deck Floor Condition OPI forecasting using Markov Models. It can be seen that the Steel bridges have the lowest Deck Floor Condition rating after Age Reset and Backstitching at Age0 as compared to General Appraisal and Deck Wearing Surface OPI.

Figure 2.28 shows the AR curve fits for the plots in Figure 2.27 and the corresponding AR coefficients can be seen in Figure 2.29.

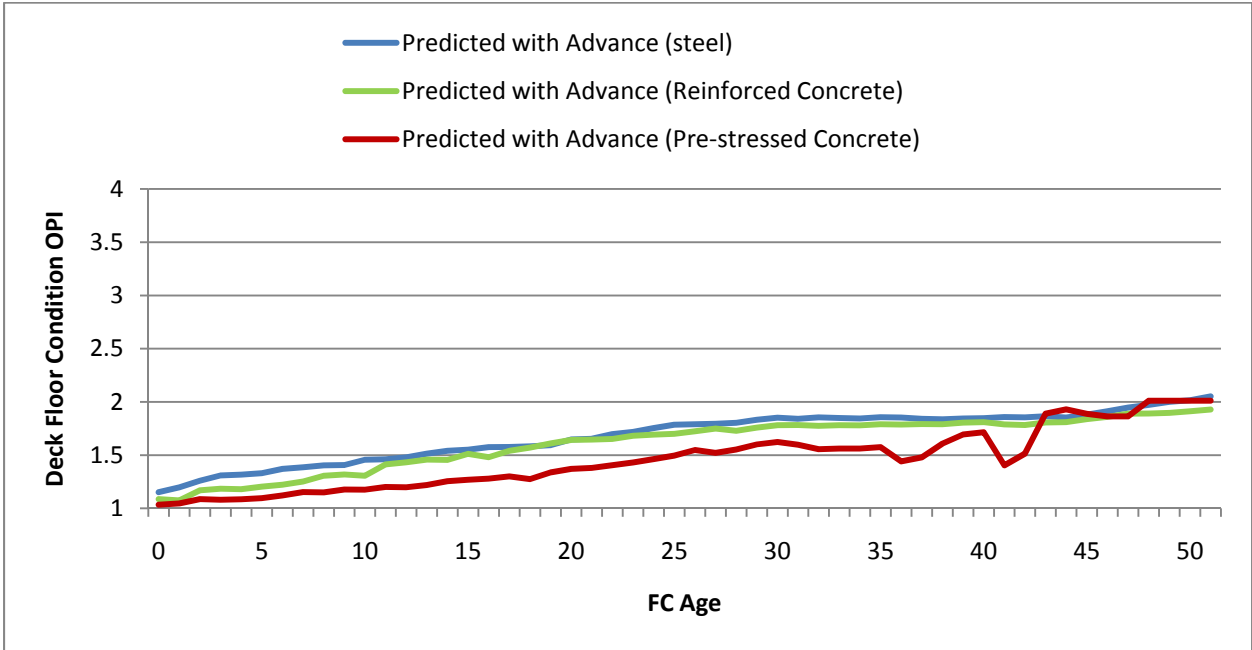


Figure 2.27: Deck Floor Condition OPI Plot for Material Types.

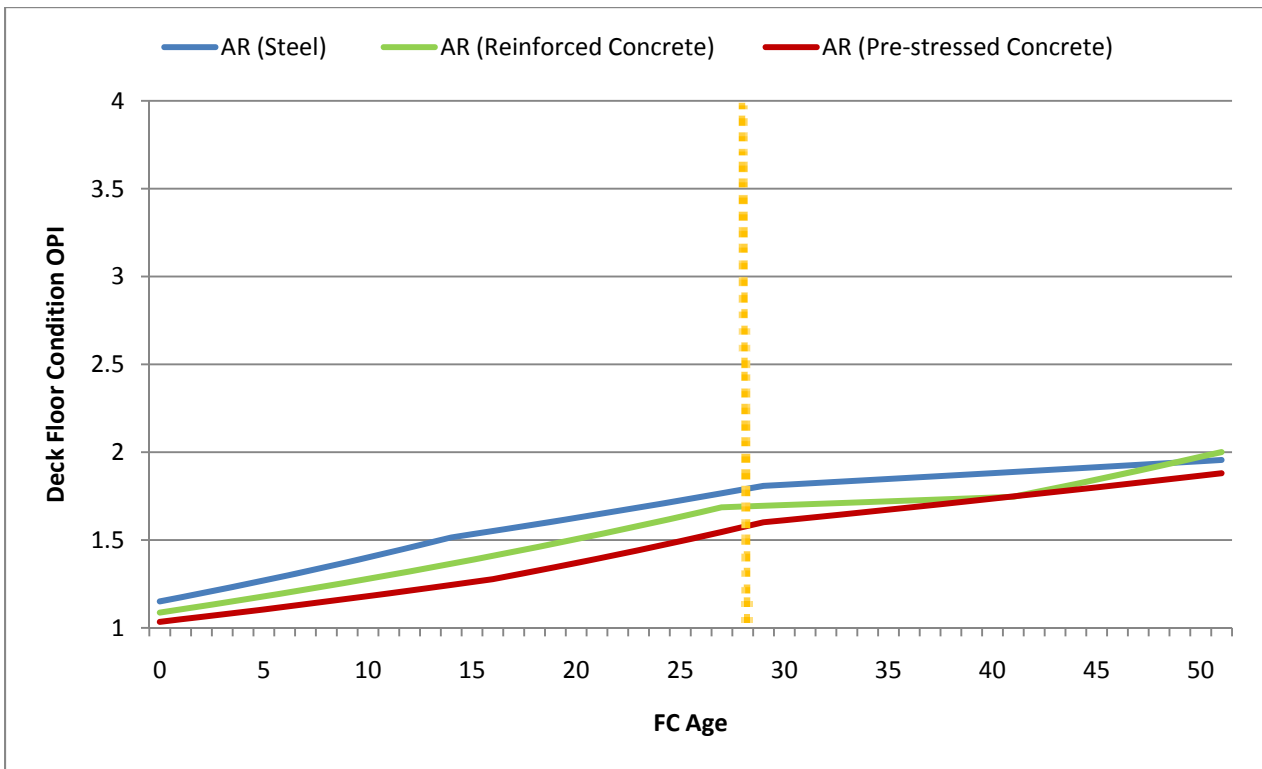


Figure 2.28: AR Curve fit for Deck Floor Condition OPI for Material Types.

Dataset 3

<u>Material</u>	<u>AR Coefficient</u> (Age 0 –Age 28)	<u>AR Coifficient</u> (Age 28 –Age 52)
Steel	1.019	1.003
Reinforced Concrete	1.016	1.002
Pre-stressed Concrete	1.013	1.007

Figure 2.29: Coefficients Deck Floor Condition OPI for Material Types.

3. ODOT Forecasting Spreadsheet.

3.1 Introduction.

ODOT records its projected maintenance and degradations using an Excel Spread Sheet which we call the ODOT Forecasting Spreadsheet. This Spread Sheet assists ODOT in their planning, decision making and maintenance requests. ODOT Forecasting Spreadsheet contains the following data for all four OPI's namely General Appraisal, Deck Floor Condition, Deck Wearing Surface and Protective Coating Surface

- 1) Cumulative Maintenance in square foot on bridges at district level and state level for a period from 2/05/2008 to 6/18/2012.
- 2) Cumulative Degradation in square foot on bridges at district level and state level for a period from 2/05/2008 to 6/18/2012.
- 3) OPI goal, which is the acceptable percentage of deficient bridges at each year with respect to a particular OPI.
- 4) Predicted OPI goal which is the projected percentage of deficient bridges at each year with respect to a particular OPI.

Details of all the terms in the Spreadsheet and their definition will be given in the coming sections.

The projected Maintenance and Degradations are calculated by using a constant Degradation rate for each OPI. A general definition for degradation rate is the percentage of bridges that goes unhealthy with respect to particular OPI at each year. Figure 3.2 shows the Degradation rate for each OPI as per the ODOT Forecasting Spreadsheet. Specific definitions for Degradation rates with respect to the different OPI's and ODOT Spreadsheet will be detailed in Sections 3.3 to Section 3.6.

District	1	2	3	4	5	6
Total Sq. Ft. of Deck - No major bridges included	3,328,548	5,586,582	7,126,003	11,651,174	4,667,579	12,080,679
General Appraisal						
Deficient = (%LL>0<100 & GA>=5) or GA<5						
2008 - GA						
Current Percent Deficient 2/05/2008	1.57%	1.40%	3.07%	3.34%	3.65%	1.94%
Sq. Ft. Current Deficiencies	52,151	78,136	218,583	388,849	170,276	234,722
Sq. Ft. Programmed through 6/18/2008	24,638	7,084	65,909	20,171	22,971	34,414
Current Sq. Ft. Deficient w/o Project	27,513	71,052	152,674	368,678	147,305	200,308
Sq. Ft. Almost Deficient	158,319	618,890	663,114	1,033,754	251,709	397,590
Sq. Ft. Programmed through 6/18/2008	5,726	56,177	54,755	118,242	23,767	25,790
Sq. Ft. Almost Deficient Less Programmed Projects	152,593	562,713	608,359	915,512	227,942	371,800
Almost Def. Projected To Go Def thru 6/18/2008	2,543	9,379	10,139	15,259	3,799	6,197
Predicted GA at 2008	0.90%	1.44%	2.28%	3.30%	3.24%	1.71%
2008 OPI Goal	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%
Sq. Ft. +/- Goal	103,086	143,033	122,227	82,110	35,599	276,722
2009 - GA						
Current Sq. Ft. Deficient 2/05/2008	52,151	78,136	218,583	388,849	170,276	234,722
Sq. Ft. Programmed through 6/18/2009	24,638	7,504	81,515	54,519	37,008	55,092
Current Sq. Ft. Deficient w/o Project	27,513	70,632	137,068	334,330	133,268	179,630
Sq. Ft. Almost Deficient	158,319	618,890	663,114	1,033,754	251,709	397,590
Sq. Ft. Programmed through 6/18/2009	35,467	56,597	69,911	211,201	25,629	54,842
Sq. Ft. Almost Deficient Less Programmed Projects	122,852	562,293	593,203	822,553	226,080	342,748
Almost Def. Projected To Go Def thru 6/18/2009	6,962	31,863	33,615	46,611	12,811	19,422
Predicted GA at 2009	1.04%	1.83%	2.40%	3.27%	3.13%	1.65%
2010 OPI Goal	4.00%	4.00%	4.00%	4.00%	4.00%	4.00%
Sq. Ft. +/- Goal	98,667	120,968	114,357	85,106	40,624	284,175

Figure 3.1: Snapshot of ODOT Forecasting Spreadsheet.

OPI	Degradation Rate
General Appraisal	4.0 %
Deck Floor Condition	1.5 %
Deck Wearing Surface	2.0 %
Protective Coating Surface	5.0 %

Figure 3.2: Degradation Rate for each OPI.

3.2 Goal of ODOT Forecasting Spreadsheet Modeling.

Figure 3.3 shows the Deficient Area in square foot and Maintenance and Policy change trends from 2001 to 2008 for GA OPI. A bridge is considered deficient with respect to General Appraisal if it has a GA <5. Maintenance on the GA deficient bridge is the square foot of area making a GA transition GA<5 to GA >=5. From the figure it can be observed that the Total GA deficient area and Maintenance on GA deficient area keeps varying across years. Also there have been two major policy changes in 2002 and 2006 respectively resulting in some uncertainty in the estimation of total deficient area. In 2002 approximately 0.27 Million square foot of area was removed from further inspection and in 2006 approximately 0.56 Million square foot of area which was not earlier maintained and owned by the state were changed to State Owned and Maintained bridge area. Having a constant degradation rate across all years will not be able to capture the changes in maintenance and policy changes as shown in Figure 3.3.

From a broader perspective the goal of this project is to assist ODOT in decision making by analyzing data collected in BMS and arriving at conclusions on the degradation rates of bridges. As the percentage area that goes deficient keeps varying as per the changes in maintenance and policies, the

more specific goal of this project is to find a Degradation rate that which gives the most accurate predictions. The Degradation rate thus obtained can be plugged in to the ODOT spreadsheet for better projection of maintenance needs and fund allocations. This research work is thus an attempt to model the ODOT spreadsheet and a Forecasting mechanism with more accuracy. In this attempt we have also tried to develop maintenance models for each district and at the state level for all four OPI's. A good knowledge of the degradation rate and the maintenance rate for bridges will certainly enable better forecasting and hence optimized usage of the funds available for ODOT.

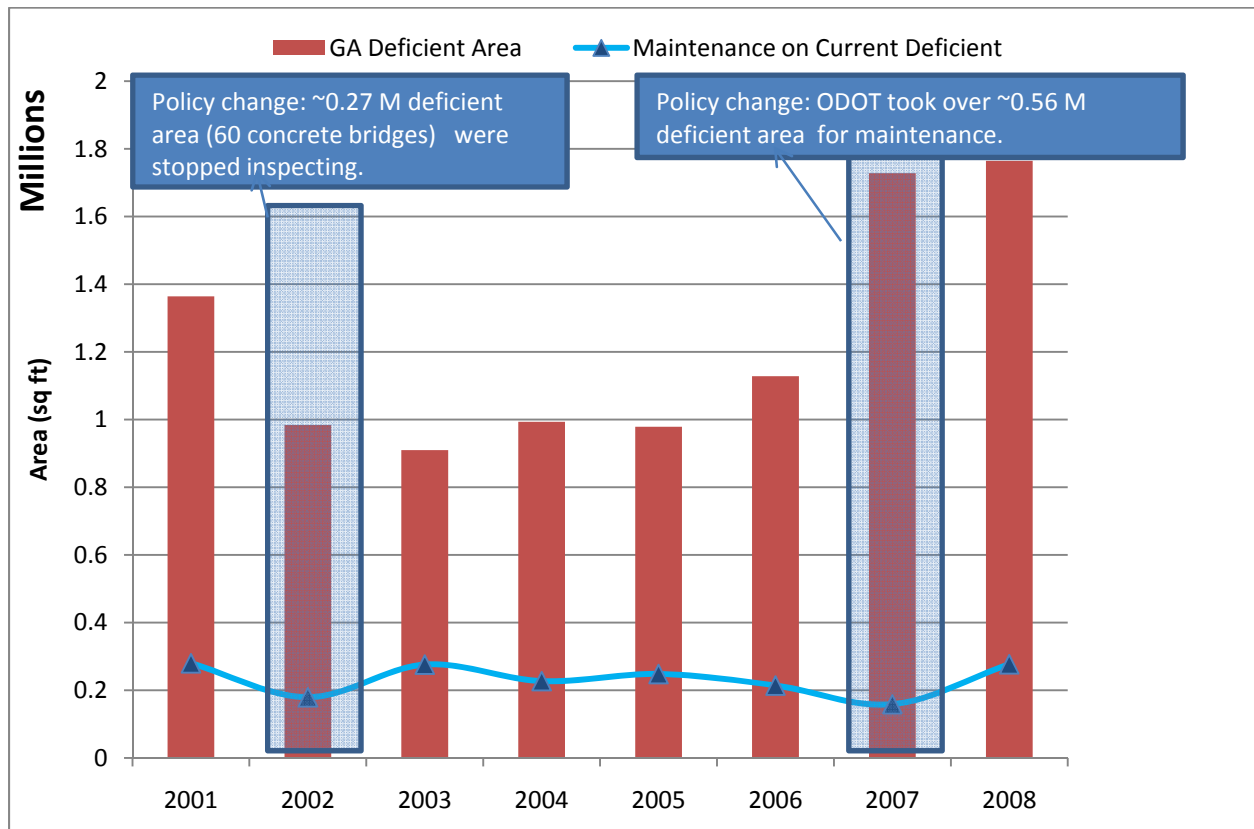


Figure 3.3: GA Maintenance and Policy Changes.

3.3 GA Degradation Rate

Figure 3.4 shows the General Appraisal Degradation calculations from ODOT spreadsheet. General Appraisal Degradation rate calculations depends on

- 1) General Appraisal OPI rating for bridges
- 2) Percentage Legal Load rating for the bridge.

District	1
Total Sq. Ft. of Deck - No major bridges included	3,328,548
General Appraisal	
Deficient = (%LL>0<100 & GA>=5) or GA<5	
2008 - GA	
Current Percent Deficient 2/05/2008	1.57%
Sq. Ft. Current Deficiencies	52,151
Sq. Ft. Programmed through 6/18/2008	24,638
Current Sq. Ft. Deficient w/o Project	27,513
Sq. Ft. Almost Deficient	158,319
Sq. Ft. Programmed through 6/18/2008	5,726
Sq. Ft. Almost Deficient Less Programmed Projects	152,593
Almost Def. Projected To Go Def thru 6/18/2008	2,543
Predicted GA at 2008	0.90%
2008 OPI Goal	4.00%
Sq. Ft. +/- Goal	103,086

Figure 3.4: General Appraisal Degradation Calculation from Spreadsheet.

Figure 3.5 details a comparison of bridges which are deficient as per GA rating (GA rating <5) and deficient as per Percent Legal Load rating (GA >=5 and %LL>0 and <100). It can be observed that bridges deficient as per the Percent Legal Load rating is very small compared to bridges deficient as per GA rating and hence we ignore the Percent Legal Load Factor from GA Degradation rate calculation.

The definitions for different terms (after ignoring Percent Legal Load) and the abbreviations we are following are tabulated in Figure 3.6.

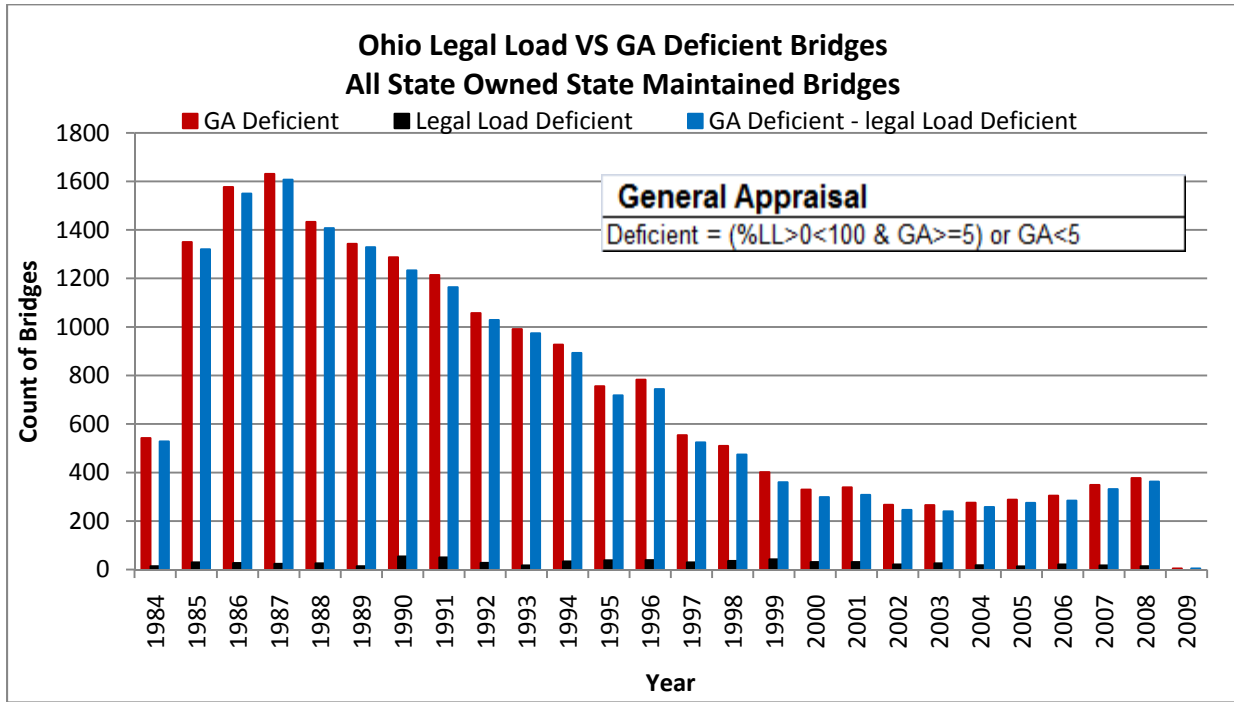


Figure 3.5: Ohio Legal Load and GA Deficient Bridges.

Term In Spreadsheet	UCII Abbreviation	Definition
Total Sq Ft of Deck	A_T	Net Deck Area Of Bridges at any year.
Sq Ft Current Deficiencies	A_{CD}	Sq Ft of Area with $GA < 5$
Sq Ft Programmed through on(A_{CD})	M_{CD}	Maintenance on A_{CD} : Sq Ft of Area making transition ($GA < 5$) to ($GA \geq 5$) between two consecutive years.
Current Sq Ft Deficient without project	A_{CNM}	$A_{CD} - M_{CD}$
Sq Ft Almost Deficiencies	A_{ND}	Sq Ft of Area with $GA = 5$
Sq Ft Programmed through on(A_{ND})	M_{ND}	Maintenance on A_{CD} : Sq Ft of Area making transition ($GA = 5$) to ($GA > 5$) between two consecutive years.
Current Sq Ft Deficient without project	A_{NNM}	$A_{ND} - M_{ND}$
Almost Def to go Deficient	A_{deg}	Sq Ft of Area making a transition $GA = 5$ to $GA < 5$ between two consecutive years.
Predicted GA		$(A_{CNM} + A_{deg}) * 100 / A_T$

Figure 3.6: Definitions For GA Calculations.

3.3.1 SQL Queries for GA Calculation in Spreadsheet.

The following SQL queries were used to fetch data from UCII database. Calculations shown below uses year 2001 as an example.

1) A_T :

```
mysql> select sum(deck_area) from yearsosm2001;
+-----+
| sum(deck_area) |
+-----+
|          65808211 |
+-----+
1 row in set (0.22 sec)
```

2) A_{CD}

```
mysql> select sum(deck_area) from yearsosm2001 where general_appraisal<5;
+-----+
| sum(deck_area) |
+-----+
|          1363849 |
+-----+
1 row in set (0.08 sec)
```

3) M_{CD}

```
mysql> select sum(y1.deck_area) from yearsosm2001 as y1 inner join yearsosm2002 as y2 on y1.sfn=y2.sfn and y1.general_appraisal<5 and y2.general_appraisal>5;
+-----+
| sum(y1.deck_area) |
+-----+
|          179317 |
+-----+
1 row in set (0.40 sec)
```

4) A_{ND}

```
mysql> select sum(deck_area) from yearsosm2001 where general_appraisal=5;
+-----+
| sum(deck_area) |
+-----+
|          6739039 |
+-----+
1 row in set (0.08 sec)
```

5) M_{ND}

```
mysql> select sum(y1.deck_area) from yearsosm2001 as y1 inner join yearsosm2002 as y2 on y1.sfn=y2.sfn and y1.general_appraisal=5 and y2.general_appraisal>5;
+-----+
| sum(y1.deck_area) |
+-----+
|          887221 |
+-----+
1 row in set (0.29 sec)
```

3.3.2 General Appraisal Degradation Rate(GA Drate) and Deficient Area.

General Appraisal Degradation rate is defined by the equation below.

$$\text{GA Drate} = (A_{deg}) * 100 / (A_{ND} - M_{ND})$$

A_{deg} denotes a subset of bridges which were almost deficient without maintenance (A_{NNM}) at one year and becomes deficient in the next year. Hence A_{deg} is defined as a factor of A_{NNM} . As shown in Figure

3.2 ODOT uses a constant 4% degradation rate for General Appraisal and as per the ODOT spreadsheet A_{deg} is calculated as follows.

$$A_{deg} = 4\% \text{ of } A_{NNM}$$

UCII uses Markov Models and STM calculations to find A_{deg} which is more dynamic and keeps changing every year depending on the maintenance and policy change trends. A_{ND} and M_{ND} are obtained from UCII database using the SQL queries in Section 3.3.1.

GA Deficient Areas or each inspection year is predicted using the equation below.

$$\text{GA Deficient Area (year k)} = (A_{CNM} + A_{deg}), \text{ where } A_{deg} \text{ is GA Drate} * (A_{ND} - M_{ND})$$

ODOT uses a constant GA Drate of 4% and UCII predicts GA Drate from Markov Calculations.

Figure 3.7 summarizes the GA Drate and GA deficient Area calculations using ODOT spreadsheet calculation, Markov Models and Actual Data from Database.

	A_{CNM}	A_{deg}	Drate	Deficient Area
ODOT Spreadsheet calculations	Obtained using SQL queries(section 3.3.1)	4 % of ($A_{ND} - M_{ND}$)	Constant 4%	$(A_{CNM} + A_{deg})$
UCII Calculations	Obtained using SQL queries(section 3.3.1)	Obtained by Markov calculations	Obtained by Markov calculations	$(A_{CNM} + A_{deg})$
Actual Data From Database				A_{CD} : Obtained using SQL queries (Section 3.3.1)

Figure 3.7

3.3.3 Multi-Year Degradation Rate Calculation using Markov Models.

Markov Chain is a random process which follows the Markov Property: The future state depends solely on the current state and not on past states. [3] and [4] has described Markov Calculations in detail for BMS data. This work builds on the Markov Models developed in [3] and [4] to make multi-year forecasting. In order to predict the future area distribution, Markov Calculations use the current area distribution and the state transition matrix [3]. A set of years have to be chosen for building the State Transition Matrix as well as for validating the results for prediction.

Training Years: Training years refers to a set of inspection years; the area distribution of which were used to develop State Transition Matrix.

Validation Years: Validation years refer to a set of inspection years used to validate the predicted degradation rates.

The rationales behind the choice of training and validation years are as follows

- 1) [3] and [4] describes major change in maintenance policy after 1994. Considering years before 1994 would not have yielded State Transition Probabilities which are consistent with ODOT's current decision making trends.
- 2) Since the goal of the project was to develop long term prediction, we chose inspection years 2003 – 2008 as validation years which would help us validate 6 years of prediction.
- 3) The training years were chosen to be close to 2002 so that the predicted degradation rates compares well with the actual degradation rate.
- 4) In order to have a good statistical population without compromising accuracy we observed that 5 to 6 years of inspection years need to be used for developing State Transition Matrix.

3.3.3.1 Fixed STM Approach

The first approach to model degradation rate is termed Fixed STM Approach. As the name suggests, this method locks the STMs for multi-year predictions. The training years used for this approach was inspection years 1997 – 2002 and the validation years used were years 2003 -2008. The following steps described how Degradation Rates were predicted in this approach.

Step 1: In this step Area distributions of inspection year 1997 -2002 were converted to Bridge Age Areas and age reset was applied to them. After Applying age reset State Transition Matrix was calculated.

Step 2: In this step Area Distribution of Year 2002 was converted to Bridge Age Area and age reset applied.

Step 3: In this step Product of Area Distribution in step 2 and State Transition Matrix of step 1 gives predicted Area Distribution of Year 2003. Bridge Area making a GA=5 to GA<5 between 2002 and 2003 is recorded and stored.

Step 4: Product of Predicted Area 2003 and State Transition Matrix of step 1 gives Predicted Area 2004. Bridge Area making transition GA=5 to GA<5 between 2003 and 2004 were recorded and stored.

Total Area Making Transition from GA=5 to GA<5 is sum of transition GA=5 to GA <5 in years 2002 – 2003 and 2003 -2004 and is denoted by $A_{deg(2002)}$. Figure 3.8 gives a schematic description of the same.

Calculations For Multi-Year Predictions.

Example: Predicting 2004 using area distribution year 2002

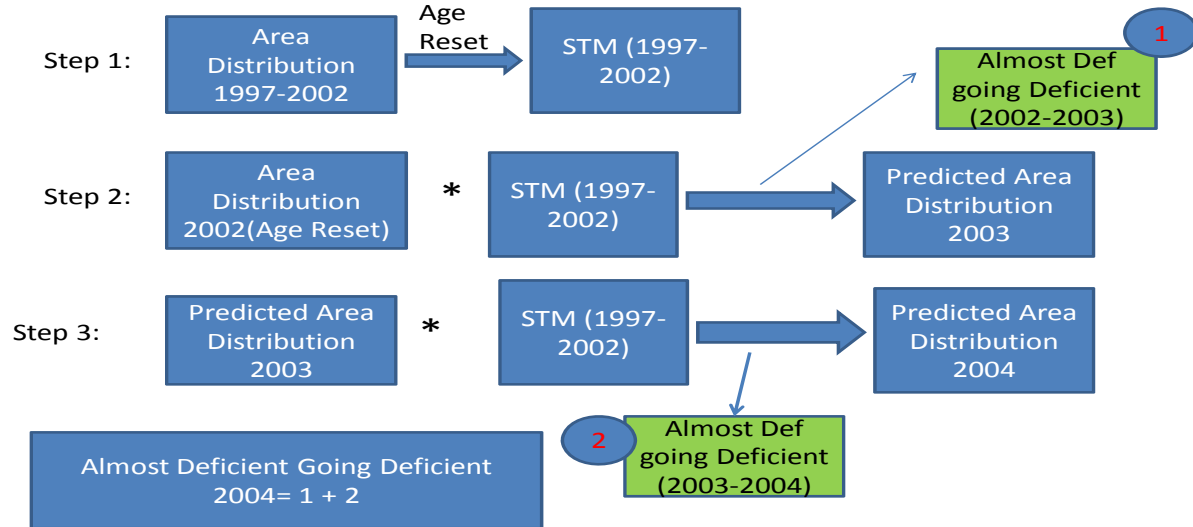


Figure 3.8: Multi-year Prediction using Fixed STM's

For example, consider the calculation of GA Deficient Area (year 2003) using STM (1997 – 2002) and area distribution of year 2002.

$A_{\text{CNM}} = 708,313$ Sq Ft of Area. $A_{\text{ND}}(\text{year 2002}) = 5,674,429$ Sq Ft of Area.

$M_{\text{ND}}(\text{year 2002 to year 2003}) = 708,781$ Sq Ft of Area.

- 1) GA Deficient Area 2003 as per ODOT calculations:

Deficient Area (2003) = $708,313 + 4\%$ of $(5,674,429 - 708,781) = 906,939$ Sq Ft of Area.

- 2) GA Deficient Area 2003 using Fixed STM approach:

Deficient Area (2003) = $708,313 + A_{\text{deg}}$ from Markov Calculations = **867,353** Sq Ft of Area.

- 3) Actual GA Deficient Area 2003 from UCII Database:

Obtained from SQL queries in section 3.3.1 = 909,755 Sq Ft of Area.

Figure 3.9 shows the GA Deficient Area calculations using ODOT's constant 4% Drate, UCII Markov Calculations and Actual GA Deficient Areas in the UCII database obtained by SQL queries .It can be observed that both Fixed STM approach as well as ODOT constant 4% Drate fails to capture the policy changes in year 2007 and hence the predictions do not give accurate results. A more sophisticated approach called the Moving STM Window approach is detailed in the next section.

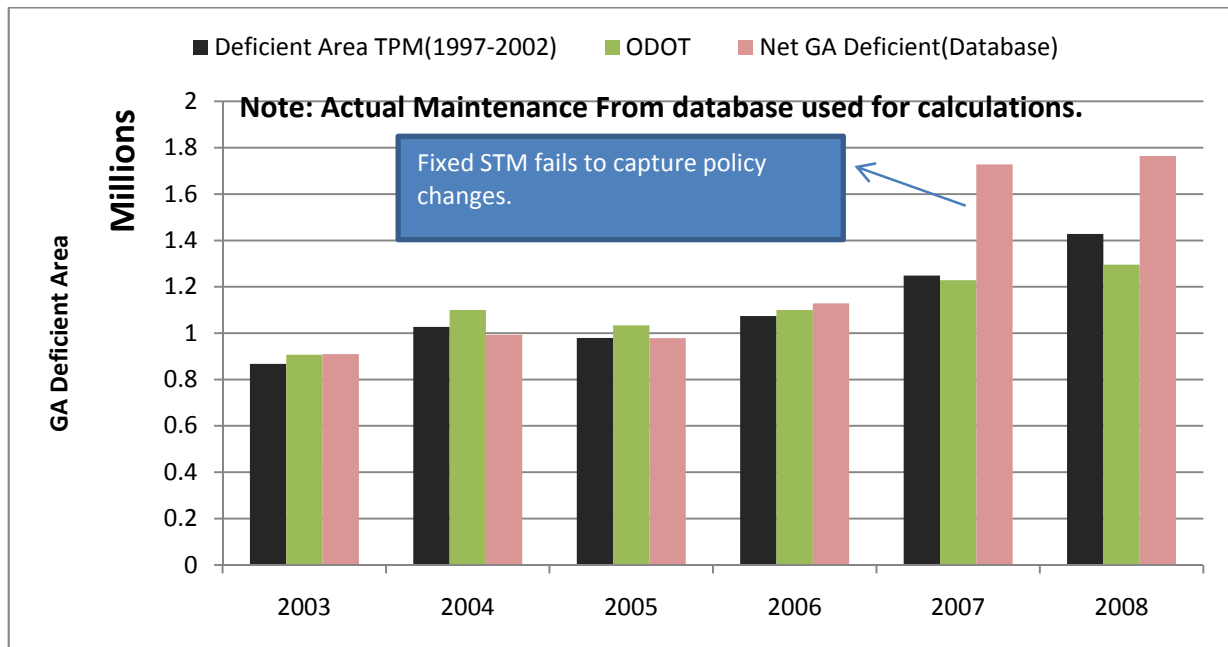


Figure 3.9: GA Deficient Area with Fixed STM Approach.

3.3.3.2 Moving Window of STM's

Maintenance activities on the bridge and ODOT's planning and decision making policies changes every year. Using a fixed set of inspection years to develop State Transition Matrix (STM's) will lock the degradation rate and would fail to capture the changes in maintenance and policies. In this approach an attempt has been made to make the STM more dynamic by including the latest available

area distribution and excluding the oldest available area distribution from STM calculations. Thus the area distribution used for STM calculations can be considered as a window which keeps advancing with time. By including the latest available area distribution an attempt is made to make predictions more consistent and dynamic with the current available maintenance and policy trends. In this work we use two type of Moving Window of STM approach namely a 5 year Moving Window of STM and a 2 year Moving Window of STM.

1) 5 year Moving Window of STM

- a. 5 consecutive inspection years are used to calculate the STM.
- b. Changes in maintenance and policies are reflected gradually as 5 years of area distribution is used at a time to calculate STM.
- c. Window advances by including the latest available area distribution and excluding the oldest available area distribution.

2) 2 year Moving Window of STM

- a. 2 consecutive inspection years are used to calculate the STM.
- b. Changes in maintenance and policies are reflected immediately although delayed by a year as the two latest available years are used for STM calculations.
- c. Window advances by including the latest available area distribution and excluding the oldest available area distribution.

Figure 3.10 gives a schematic description of the 5 year Moving Window of STM calculations and Figure 3.11 gives a schematic description of the 2 year Moving Window of STM calculations. The validation years used for both the models are years 2001 -2008 and the training years used for 5 year Moving window starts with year 1996 -2000 and for 2 year Moving window starts with year 1999 -

2000. It can be observed that the STM's gets updated every year by including the latest available area distribution and excluding the oldest available area distribution.

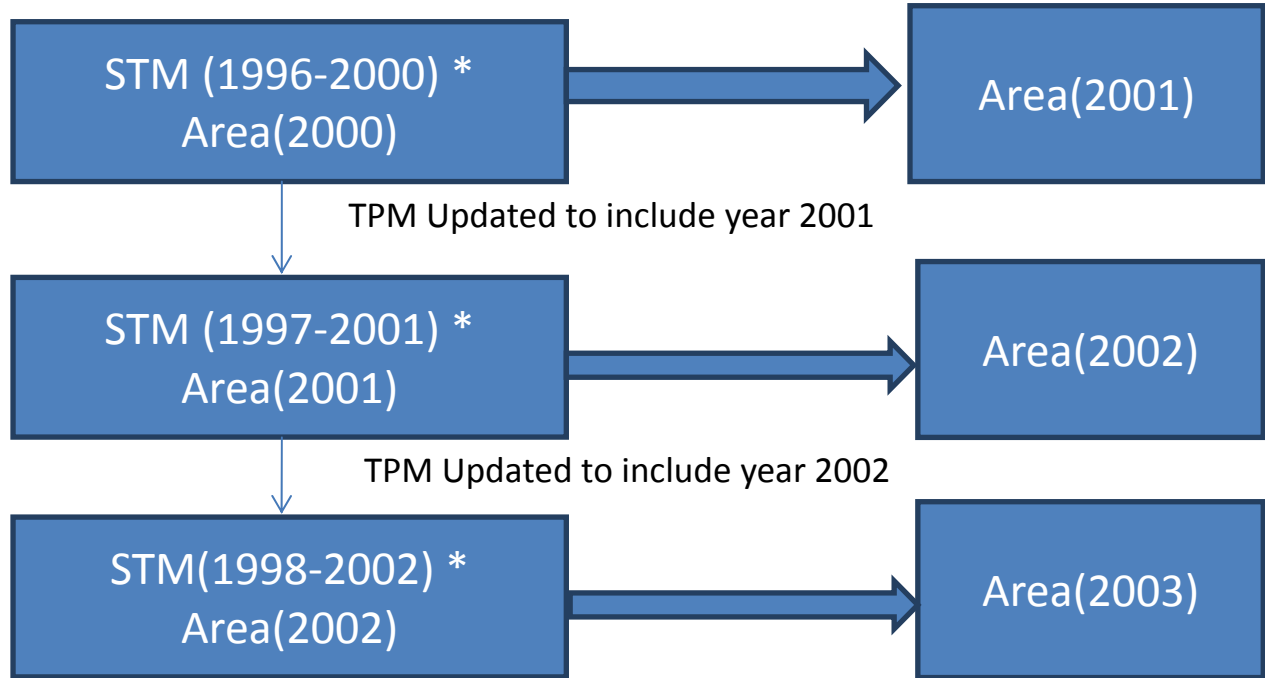


Figure 3.10: 5 Year Moving Window

Calculations

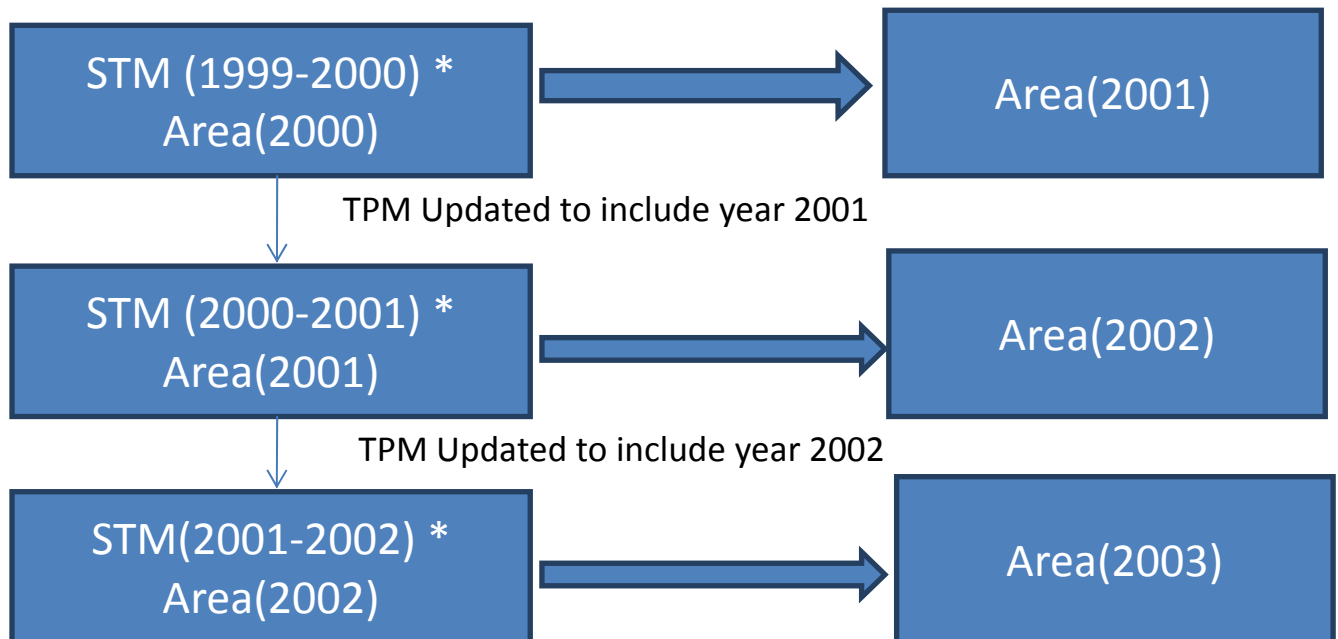


Figure 3.11: 2 Year Moving Window Calculations.

Figure 3.12 shows the degradation rates calculated using the 5 year Moving Window, 2 year Moving Window, and 4% constant degradation rate as per the spreadsheet and the actual degradation rate from the database. The equations for calculating the degradation rates are detailed in section 3.3.2. It can be observed that the actual degradation rate is not constant and keeps varying across years. The 2 year Moving window follows the actual degradation rate delayed by a year whereas the 5 year Moving window follows the actual degradation rate gradually. Between year 2001 and 2004, degradation rates calculated by 5 year moving Window, 2 Year Moving window and actual degradation rate from database is lower than the constant 4% degradation rate of ODOT spreadsheet. Between 2005 and 2008 we find an increase in degradation rate calculated by 5 year Moving window, 2 year Moving Window and the actual degradation rate. At 2008 the actual degradation rate from database shows a degradation rate close to ODOT's constant degradation rate of 4%.

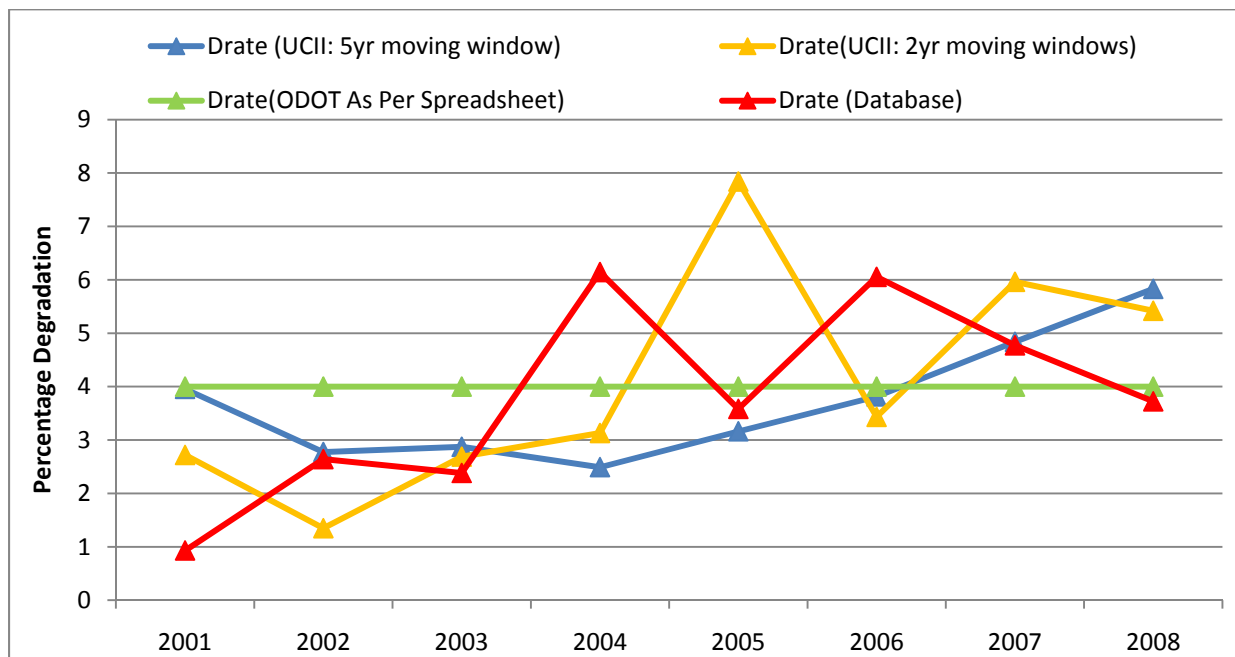


Figure 3.12: Degradation Rates for Moving Window of STM approach.

Figure 3.13 shows the GA deficient area calculated using equations in Section 3.3.2 for 5 year Moving Window, 2 year Moving Window, ODOT's constant 4% degradation rate, degradation rate from database and Actual Deficient Area at each year. It can be observed that although delayed, both the Moving Window of STM's capture the change in policy trends at year 2006. Deficient area obtained by using Drate from database is different from deficient area from database. This is because of the following reasons.

- 1) Deficient Area from database(A_{CD}) is calculated using SQL queries as described in Section 3.3.1 whereas Deficient area using Drate from database utilizes the Drate obtained from database (Figure 3.11) to calculate Deficient Area equation in 3.3.2
- 2) Deficient area using Drate from database only considers bridges common between two consecutive years whereas Deficient Area from database is the actual deficient area in database at any given inspection year.

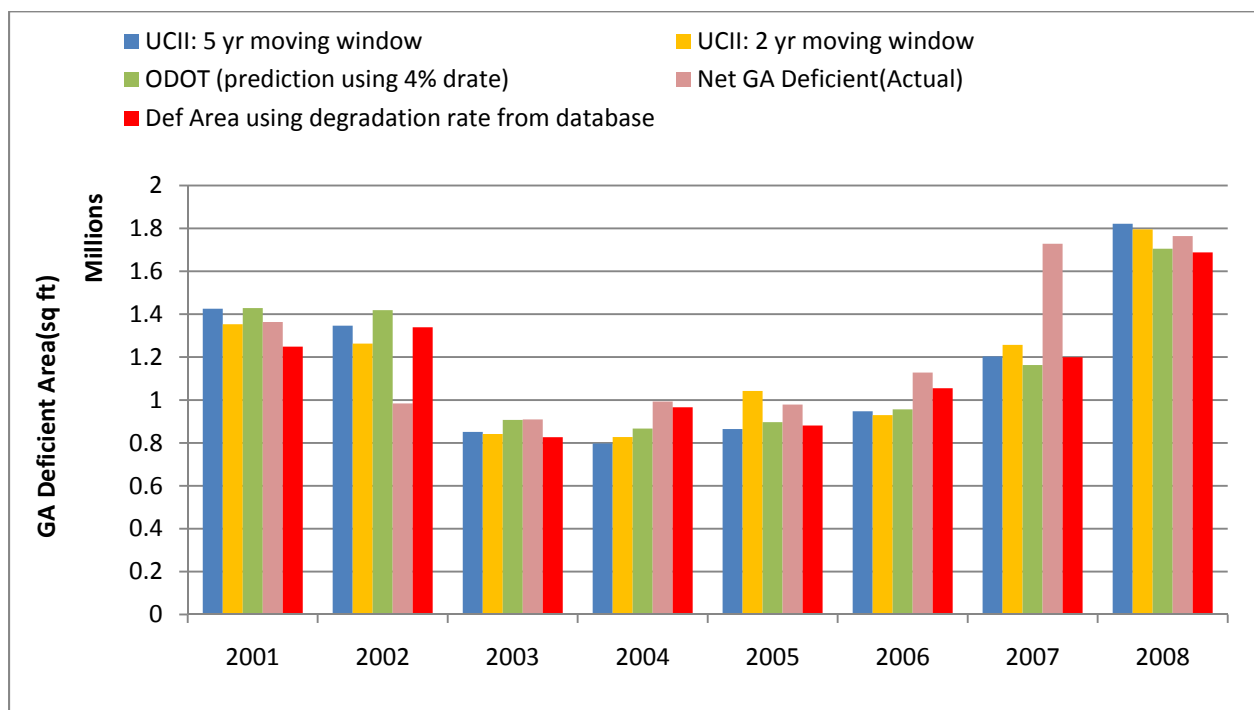


Figure 3.13: GA Deficient Area using Moving Window Approach.

Figure 3.14 compares the Sq Ft of area of Almost deficient bridges which are maintained (M_{ND}) to the Area of Degradation(A_{deg}) obtained from 5 year Moving Window of STM, 2 year Moving Window of STM and 4% constant Degradation of ODOT Spreadsheet. It can be observed that the Sq Ft of area maintained is comparatively closer to Sq Ft of Degradation Area and hence the system is at steady state.

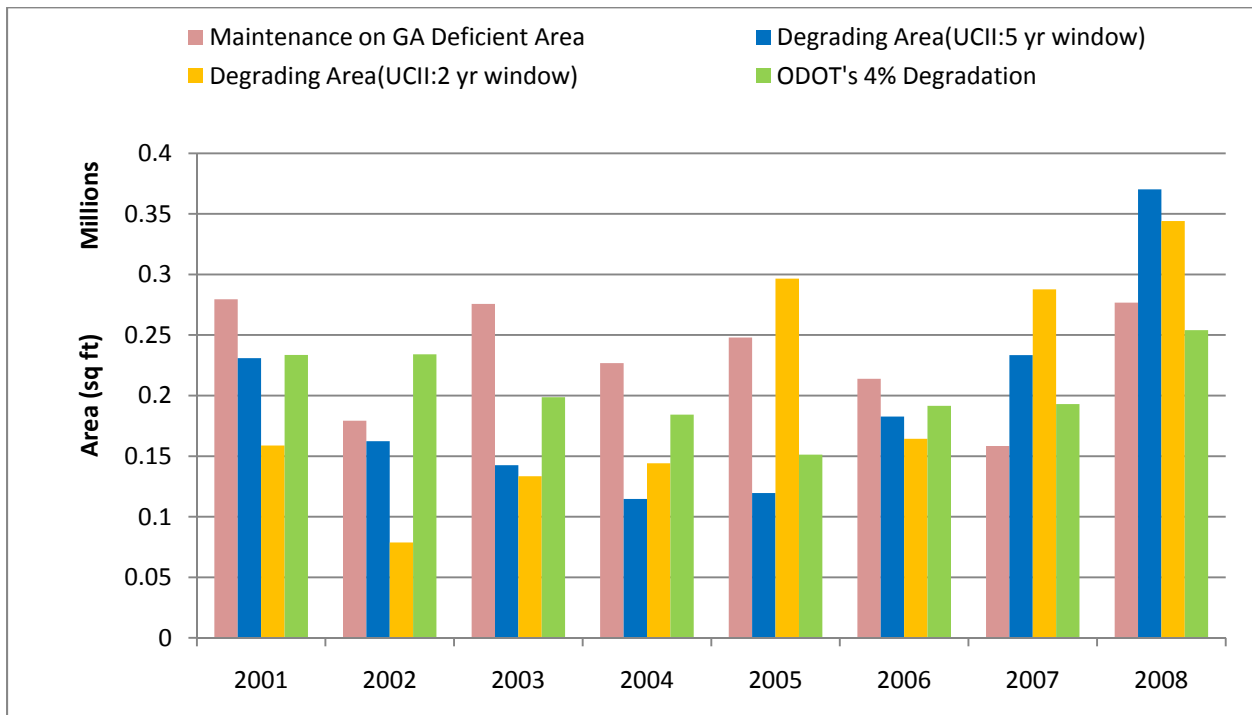


Figure 3.14: Comparison of Maintenance and Degradation.

3.3.4 GA Degradation Rate for Districts.

The degradation rate for districts in Ohio obtained from the UCII database is tabulated in Figure 3.15.

These degradation rates are obtained by using the equation

$$\text{GA Drate} = (A_{\text{deg}}) * 100 / (A_{\text{ND}} - M_{\text{ND}})$$

Where A_{deg} , A_{ND} , M_{ND} are all obtained from UCII database using SQL queries described in Section 3.3.1. It can be observed that the degradation rates from districts vary with each inspection year. Every District except District 3, District 5, District 9, District 10 and District 11 has at least one year between 2001 and 2008 where the degradation rate is 0. District 1 has 5 years between 2001 and 2008 where the degradation rate is 0. The highest degradation rate is shown by District 4 in year 2004. From the average Drate's, it can be observed that District 3, District 4, District 5 and District 6 have higher degradation rate as compared to other districts.

Year	Dist 1	Dist 2	Dist 3	Dist 4	Dist 5	Dist 6	Dist 7	Dist 8	Dist 9	Dist 10	Dist 11	Dist 12
2001	0.00	0.92	0.48	0.11	2.45	0.91	0.00	2.08	2.87	5.92	0.48	1.15
2002	3.48	1.73	0.31	0.00	9.48	0.00	0.16	1.19	3.75	5.01	4.05	7.86
2003	7.64	2.49	7.90	0.00	4.40	0.22	2.27	5.88	2.58	2.24	5.42	0.00
2004	0.00	0.00	5.64	25.94	1.58	2.08	1.38	0.00	0.42	7.26	6.81	0.25
2005	9.79	1.68	7.85	2.85	4.00	0.00	4.76	0.39	0.56	11.94	4.38	2.15
2006	0.00	0.00	6.95	13.31	9.04	17.01	6.21	3.36	8.15	0.95	5.87	0.00
2007	0.00	0.69	11.02	6.63	6.50	20.72	2.38	1.28	1.55	1.23	6.07	2.23
2008	0.00	3.86	2.91	0.63	10.73	9.44	1.41	13.61	1.25	1.92	2.60	3.90
Avg(Drate)	2.61	1.42	5.38	6.18	6.02	6.30	2.32	3.47	2.64	4.56	4.46	2.19

Figure 3.15: GA Degradation Rate For Districts.

3.4 Deck Floor Condition Degradation Rate

Figure 3.16 shows the ODOT Spreadsheet calculations for Deck Floor Condition OPI. Deck Floor Condition Degradation rate depends on two factors.

- 1) Deck Floor Condition OPI rating for the bridge.
- 2) General Appraisal rating of the bridge.

Figure 3.17 details a comparison of bridges which are deficient for Deck Floor Condition OPI (FC>2) and bridges which are deficient with respect FC but are healthy with respect to GA OPI (GA>=5 and FC>2). Bridges which is FC deficient forms the superset of bridges which are FC deficient but health GA. From the comparison it can be observed that bridges which are FC deficient but healthy GA forms 60 – 70% of bridges which are FC deficient and hence for the Degradation Rate analysis both FC and GA factors are considered.

Floor Condition	
Deficient = GA >= 5 and FC >2	
2008 - FC	
Current Percent Deficient 2/05/2008	0.21%
Sq. Ft. Current Deficiencies	7,040
Sq. Ft. Programmed through 6/18/2008	0
Current Sq. Ft. Deficient w/o Project	7,040
Sq. Ft. Almost Deficient	1,112,525
Sq. Ft. Programmed through 6/18/2008	2,368
Sq. Ft. Almost Deficient Less Programmed Projects	1,110,157
Almost Def. Projected To Go Def thru 6/18/2008	2,405
Predicted FC at 2008	0.28%
2008 OPI Goal	3.00%
Sq. Ft. +/- Goal	90,411

Figure 3.16: FC Degradation Calculation in ODOT Spreadsheet.

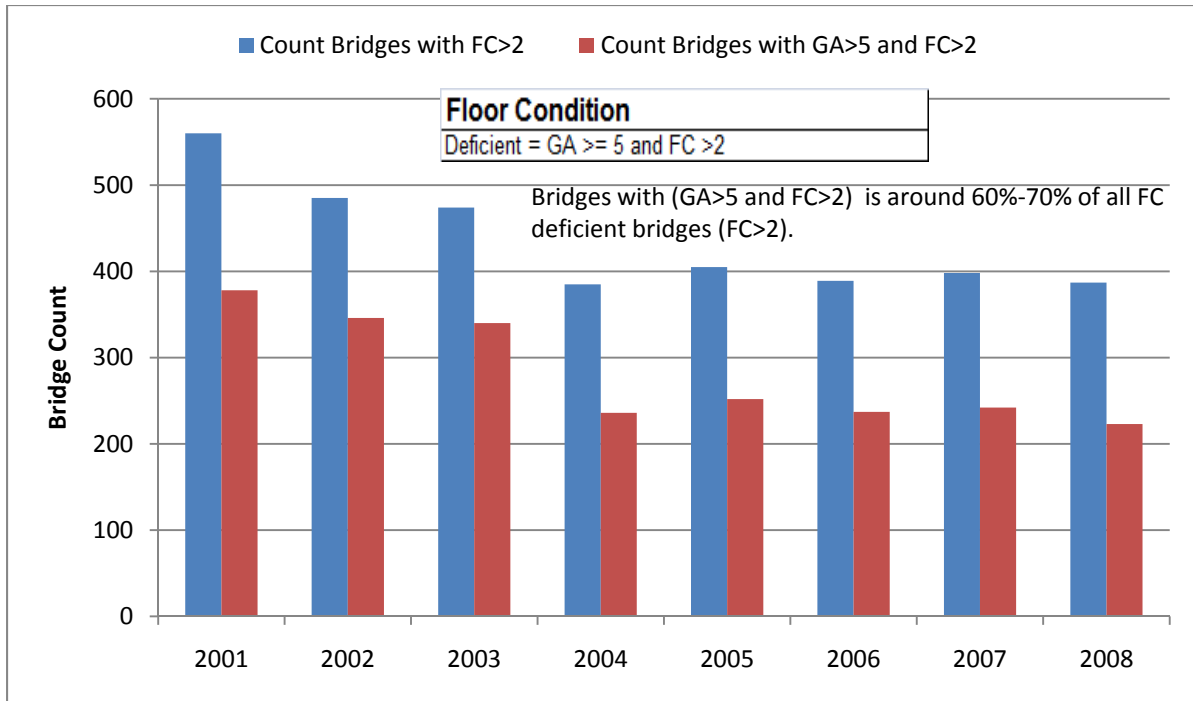


Figure 3.17: Factors Affecting Deck Floor Condition Degradation Rate.

The definitions for different terms in FC degradation rate calculations are tabulated in Figure 3.18. As described above a bridge is considered deficient with respect to FC OPI only if its FC OPI rating > 2 and GA OPI rating ≥ 5 .

Term In Spreadsheet	UCII Abbreviation	Definition
Total Sq Ft of Deck	A_T	Net Deck Area Of Bridges at any year.
Sq Ft Current Deficiencies	A_{CD}	Sq Ft of Area with $FC > 2$ and $GA \geq 5$
Sq Ft Programmed through on(A_{CD})	M_{CD}	Maintenance on A_{CD} : Sq Ft of Area making transition ($FC > 2$ and $GA \geq 5$) to ($FC \leq 2$ and $GA \geq 5$) between two consecutive years.
Current Sq Ft Deficient without project	A_{CNM}	$A_{CD} - M_{CD}$
Sq Ft Almost Deficiencies	A_{ND}	Sq Ft of Area with $FC = 2$ and $GA \geq 5$
Sq Ft Programmed through	M_{ND}	Maintenance on A_{CD} : Sq Ft of Area making

on(A_{ND})		transition ($FC=2$ and $GA \geq 5$) to ($FC < 2$ and $GA \geq 5$) between two consecutive years.
Current Sq Ft Deficient without project	A_{NNM}	$A_{ND} - M_{ND}$
Almost Def to go Deficient	A_{deg}	Sq Ft of Area making a transition ($FC=2$ and $GA \geq 5$) to ($FC > 2$ and $GA \geq 5$) between two consecutive years.
Predicted GA		$(A_{CNM} + A_{deg}) * 100 / A_T$

Figure 3.18: Definitions for FC Calculations.

Degradation rate is calculated by using the equation below.

$$D_{rate} = A_{Deg} / (A_{ND} - M_{ND}).$$

ODOT spreadsheet uses a constant Drate of 1.50 % for Deck Floor Condition OPI. UCII calculates the A_{Deg} using the 5 year Moving Window of STM's and 2 year Moving Window of STM's. A_{ND} and M_{ND} are the actual data obtained from database obtained using SQL queries.

3.4.1 SQL Queries for FC Degradation Calculations.

The following SQL queries were used to fetch data from UCII database for FC degradation rate calculations. The definition for each term is given in the section above.

- 1) A_T :

```
mysql> select sum(deck_area) from yearsosm2001;
+-----+
| sum(deck_area) |
+-----+
|          65808211 |
+-----+
1 row in set (0.22 sec)
```

- 2) A_{CD}

```
mysql>
mysql> Select sum(deck_area) from yearsosm2001 where deck_floor>2 and general_appraisal>=5;
+-----+
| sum(deck_area) |
+-----+
|          3695574 |
+-----+
1 row in set (0.20 sec)
```

3) M_{CD}

```
mysql> select sum(y1.deck_area) from yearsosm2001 as y1 inner join yearsosm2002 as y2 on y1.sfn=y2.sfn and y1.deck_floor>2 and y1.gen
eral_appraisal>=5 and y2.deck_floor<=2 and y2.general_appraisal>=5;
+-----+
| sum(y1.deck_area) |
+-----+
|          442603 |
+-----+
1 row in set (0.39 sec)
```

4) A_{ND}

```
mysql> Select sum(deck_area) from yearsosm2001 where deck_floor=2 and general_appraisal>=5;
+-----+
| sum(deck_area) |
+-----+
|          33382398 |
+-----+
1 row in set (0.09 sec)
```

5) M_{ND}

```
mysql> select sum(y1.deck_area) from yearsosm2001 as y1 inner join yearsosm2002 as y2 on y1.sfn=y2.sfn and y1.deck_floor=2 and y1.gen
eral_appraisal>=5 and y2.deck_floor<2 and y2.general_appraisal>=5;
+-----+
| sum(y1.deck_area) |
+-----+
|          1147629 |
+-----+
1 row in set (0.21 sec)
```

3.4.2 Moving Window of STM's For FC Degradation Rate Calculation.

Figure 3.19 shows the Maintenance on FC Deficient bridges (M_{CD}) and the current FC deficient bridges (A_{CD}). It can be observed that the maintenance on FC deficient bridges and FC current

deficient bridges changes across years and as described in Section 3.3.3.1 keeping a constant Degradation rate will not be able to capture this changes.

Details on the algorithm used for Moving TPM approach for the 5 year Window of STM's and 2 year Window of STM is given in Section 3.3.3.2. Figure 3.20 shows the results of Degradation Rate calculations for FC OPI. It can be observed that the FC degradation rate varies across years 2001 to 2008. For the period 2001 to 2008, the predicted degradation rate using 5 year Moving Window, 2 year Moving Window as well as the actual degradation rate obtained from the database, is lower than the constant degradation rate of 1.5% used by ODOT Spreadsheet.

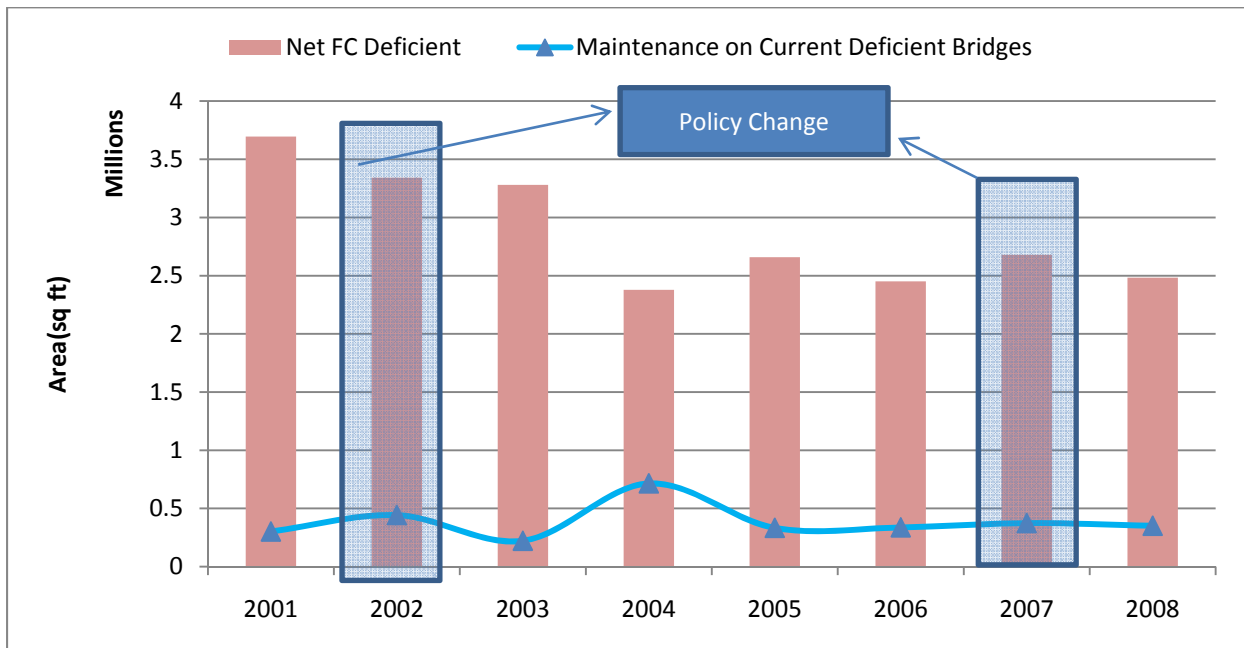


Figure 3.19: FC Maintenance and Policy Changes.

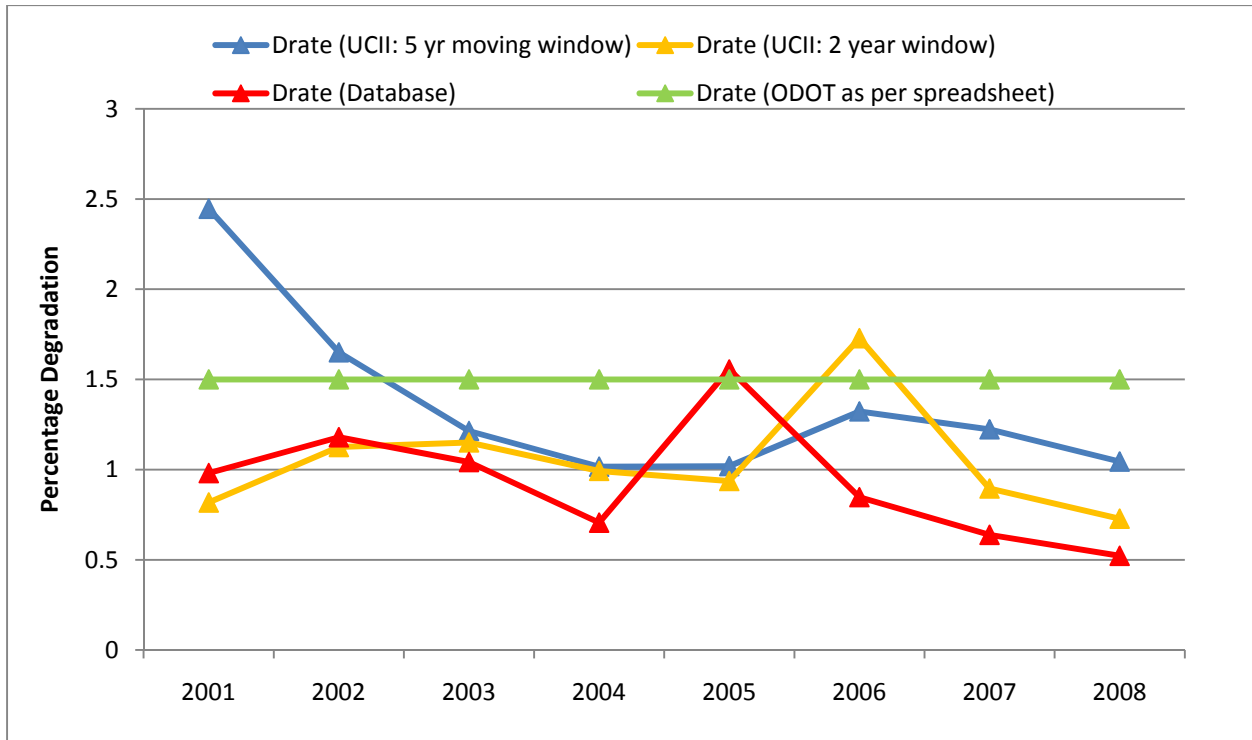


Figure 3.20: FC Degradation Rate.

The predicted deficient area using 5 year and 2 year Moving Windows of STM, ODOT Spreadsheet constant degradation rate of 1.5%, actual deficient area from the database are shown in Figure 3.21.

The predicted deficient areas were calculated using equation described in Section 3.3.2. A comparison of the Maintenance on Almost Deficient FC bridges and Degradation on Almost Deficient bridges are shown in Figure 3.22. It can be seen that Sq Ft of area Maintained every year is close to the Sq Ft of area degrading every year. This result is similar to the result seen for GA maintenance and degradation.

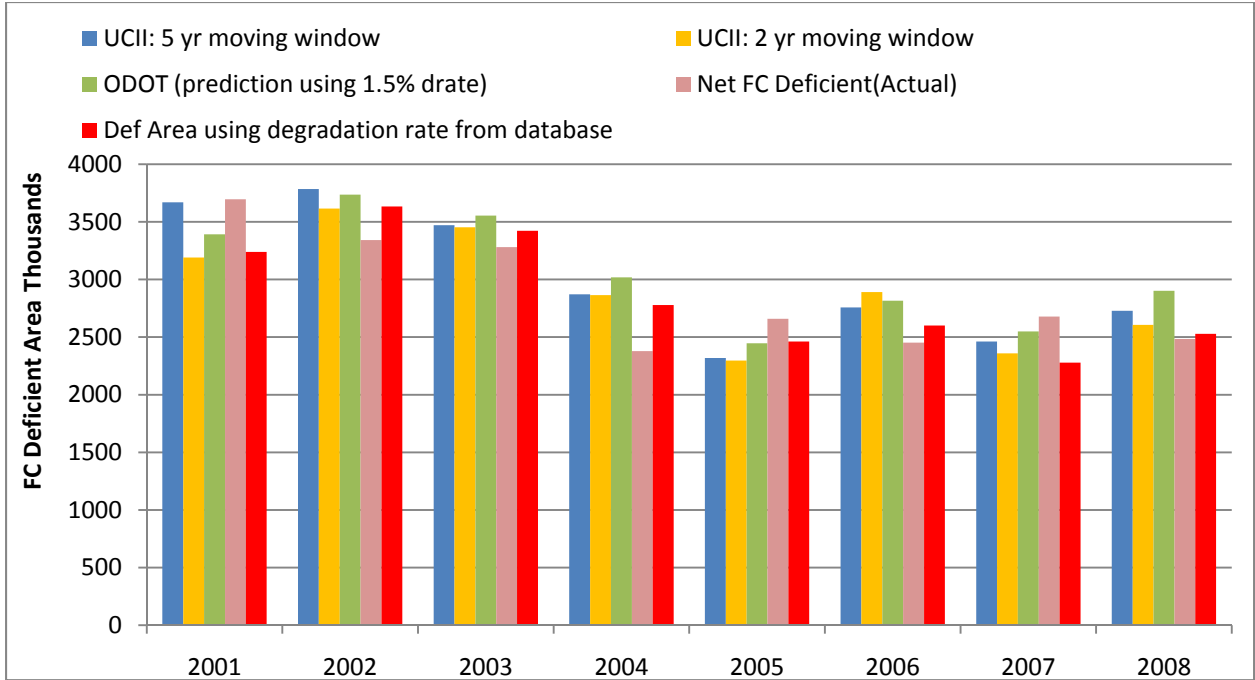


Figure 3.21: Predicted Deficient Area for FC OPI.

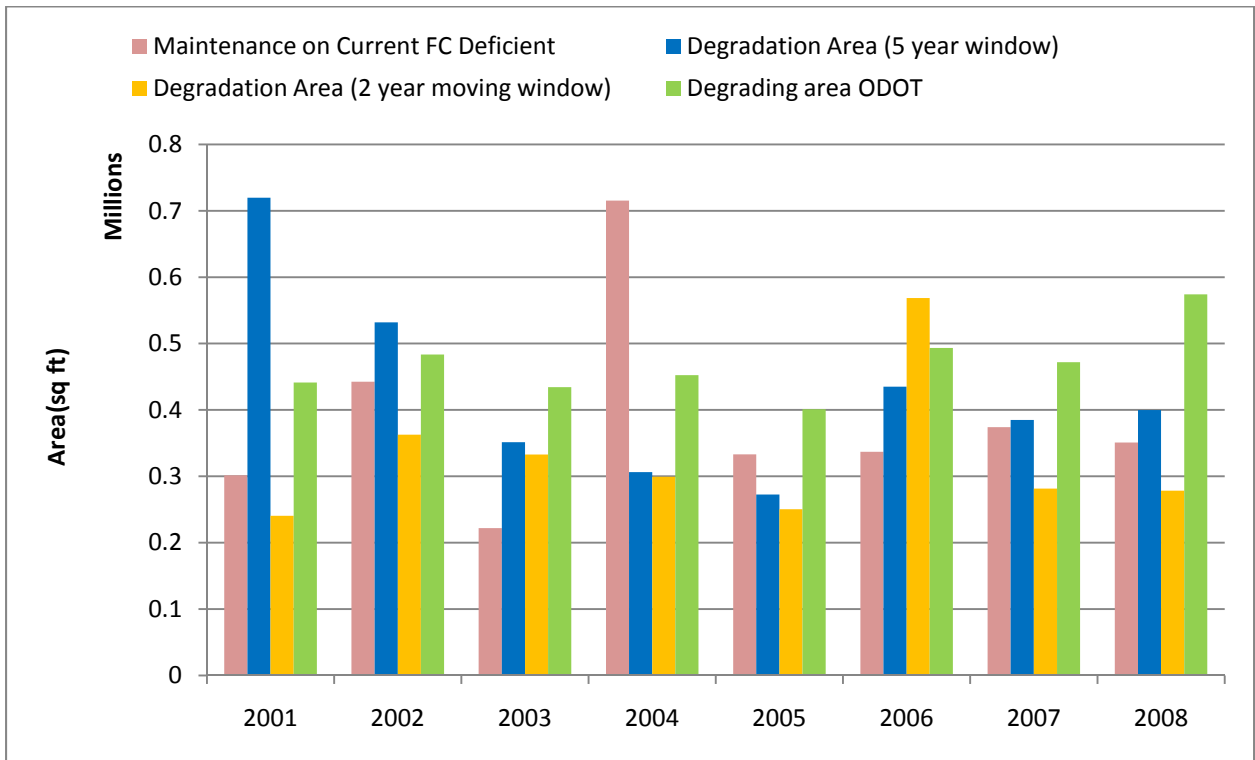


Figure 3.22: Comparison of Maintenance and Degradation for FC OPI.

3.4.3 FC Degradation Rate for Districts.

Figure 3.23 shows the degradation rate for FC OPI for districts in Ohio. The degradation rates are obtained from the database using SQL queries. From the average Degradation Rates it can be seen that District 4, District 5, District 8 and District 12 have relatively higher FC degradation rates and District 1 and District 7 have the lowest degradation rate. District 1 records a 0 degradation rate from 2002 to 2007.

Year	Dist 1	Dist 2	Dist 3	Dist 4	Dist 5	Dist 6	Dist 7	Dist 8	Dist 9	Dist 10	Dist 11	Dist 12
2001	0.73	1.57	0.72	1.76	0.25	0.80	0.18	0.34	0.26	1.79	0.47	2.50
2002	0.00	0.42	2.02	1.41	1.90	0.00	0.58	2.71	0.21	1.53	0.23	1.06
2003	0.00	1.83	0.00	2.28	0.00	0.51	0.14	1.10	0.68	0.78	1.95	0.56
2004	0.00	0.00	0.00	0.82	2.67	0.00	0.40	0.78	1.42	3.42	0.40	0.59
2005	0.00	1.22	0.87	3.10	0.98	0.00	0.00	1.75	1.76	0.00	0.73	2.22
2006	0.00	0.02	3.27	0.82	1.27	0.50	0.58	1.17	0.80	0.78	1.31	0.00
2007	0.00	1.41	0.00	1.46	0.38	0.65	0.33	0.37	0.00	0.00	1.36	0.46
2008	2.48	0.00	0.00	0.53	0.78	2.49	0.00	0.74	0.39	0.35	0.21	0.29
Avg(Drate)	0.40	0.81	0.86	1.52	1.03	0.62	0.28	1.12	0.69	1.08	0.83	0.96

Figure 3.23: FC Degradation Rate for Districts.

3.5 Deck Wearing Surface Degradation Rate

Figure 3.24 shows the Deck Wearing Surface OPI degradation calculation from ODOT Spreadsheet.

Deck Wearing Surface degradation depends on 3 factors.

- 1) Deck Wearing Surface OPI rating of the bridge.
- 2) General Appraisal OPI rating of the bridge
- 3) Deck Floor Condition OPI rating of the bridge

A comparison study of the bridges which are Deck Wearing Surface deficient (WS >2) and bridges which are Deck Wearing Surface deficient but healthy General Appraisal (GA >=5) and Deck Floor Condition (FC <=2) is shown in Figure 3.25. It can be seen that bridges which are Deck Wearing Surface deficient but healthy General Appraisal (GA >=5) and Deck Floor Condition (FC <=2) is a subset of all Deck Wearing Surface deficient bridges and about 60-70% of all Deck Wearing Surface deficient bridges. Because of the considerable reduction in bridge area we consider all three factors (WS, GA and FC rating) for WS degradation calculations.

Wearing Surface	
Deficient = GA >= 5 and FC <= 2 and WS >2	
2008 - WS	
Current Percent Deficient 2/05/2008	1.18%
Current Sq. Ft. Deficient 2/05/2008	39,407
Sq. Ft. Programmed through 6/18/2008	13,767
Current Sq. Ft. Deficient w/o Project	25,640
Sq. Ft. Almost Deficient	250,328
Sq. Ft. Programmed through 6/18/2008	0
Sq. Ft. Almost Deficient Less Programmed Projects	250,328
Almost Def. Projected To Go Def thru 6/18/2008	2,086
Predicted WS at 2008	0.83%
2008 OPI Goal	3.00%
Sq. Ft. +/- Goal	72,130

Figure 3.24: WS Degradation Calculations in ODOT Spreadsheet.

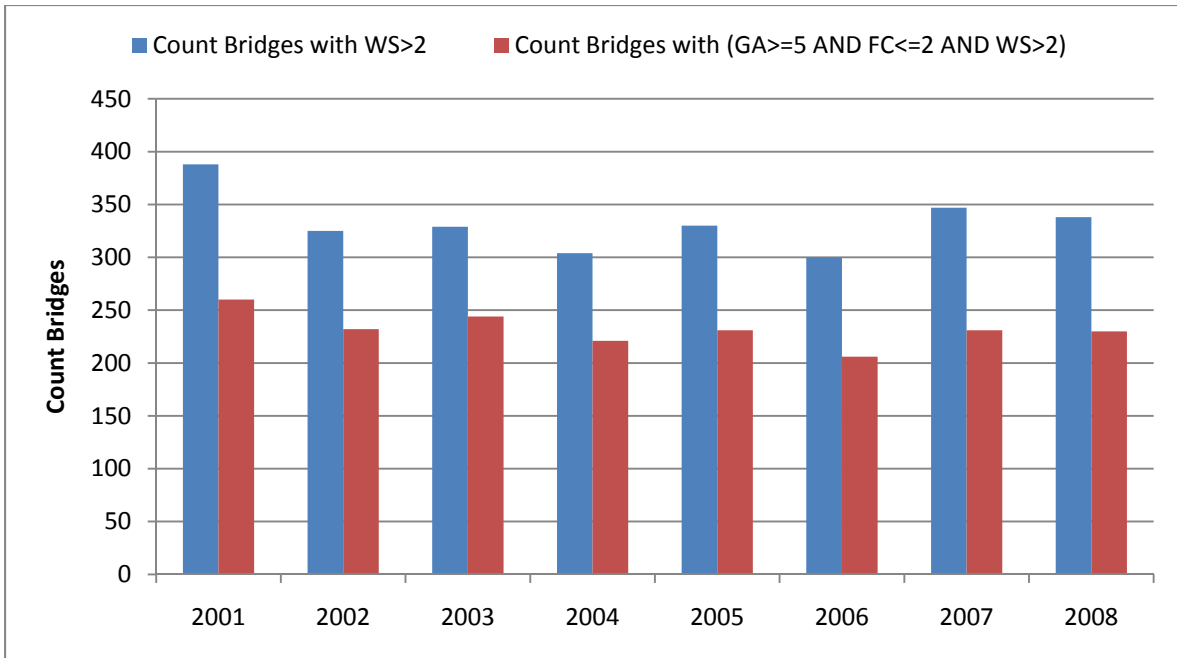


Figure 3.25: Factors Affecting WS Degradation Rate.

The definitions for different terms in WS degradation rate calculations are tabulated in Figure 3.26. As described above a bridge is considered deficient with respect to WS OPI only if it's WS OPI rating > 2, FC OPI rating <= 2 and GA OPI rating >= 5.

Term In Spreadsheet	UCII Abbreviation	Definition
Total Sq Ft of Deck	A_T	Net Deck Area Of Bridges at any year.
Sq Ft Current Deficiencies	A_{CD}	Sq Ft of Area with $WS > 2, FC \leq 2$ and $GA \geq 5$
Sq Ft Programmed through on(A_{CD})	M_{CD}	Maintenance on A_{CD} : Sq Ft of Area making transition ($WS > 2, FC \leq 2$ and $GA \geq 5$) to ($WS \leq 2, FC \leq 2$ and $GA \geq 5$) between two consecutive years.
Current Sq Ft Deficient without project	A_{CNM}	$A_{CD} - M_{CD}$

Sq Ft Almost Deficiencies	A_{ND}	Sq Ft of Area with $WS=2$, $FC \leq 2$ and $GA \geq 5$
Sq Ft Programmed through on(A_{ND})	M_{ND}	Maintenance on A_{CD} : Sq Ft of Area making transition ($WS=2$, $FC \leq 2$ and $GA \geq 5$) to ($WS < 2$, $FC \leq 2$ and $GA \geq 5$) between two consecutive years.
Current Sq Ft Deficient without project	A_{NNM}	$A_{ND} - M_{ND}$
Almost Def to go Deficient	A_{deg}	Sq Ft of Area making a transition ($WS=2$, $FC \leq 2$ and $GA \geq 5$) to ($WS > 2$, $FC \leq 2$ and $GA \geq 5$) between two consecutive years.
Predicted GA		$(A_{CNM} + A_{deg}) * 100 / A_T$

Figure 3.26: Definitions for WS Calculations.

Degradation rate is calculated by using the equation below

$$D_{rate} = A_{Deg} / (A_{ND} - M_{ND}).$$

ODOT spreadsheet uses a constant Drate of 2.0 % for Deck Floor Condition OPI. UCII calculates the A_{Deg} using the 5 year Moving Window of STM's and 2 year Moving Window of STM's. A_{ND} and M_{ND} are the actual data obtained from database obtained using SQL queries.

3.5.1 SQL Queries for WS Calculations

The following SQL queries were used to fetch data from UCII database for WS degradation rate calculations. The definition for each term is given in the section above.

1) A_T :

```
mysql> select sum(deck_area) from yearsosm2001;
+-----+
| sum(deck_area) |
+-----+
|          65808211 |
+-----+
1 row in set (0.22 sec)
```

2) A_{CD}

```
mysql> Select sum(deck_area) from yearsosm2001 where deck_wearing_surface>2 and deck_floor<=2 and general_appraisal=5;
+-----+
| sum(deck_area) |
+-----+
|          2292821 |
+-----+
1 row in set (0.09 sec)
```

3) M_{CD}

```
mysql> select sum(y1.deck_area) from yearsosm2001 as y1 inner join yearsosm2002 as y2 on y1.sfn=y2.sfn and y1.deck_wearing_surface>2
and y1.deck_floor<=2 and y1.general_appraisal=5 and y2.deck_wearing_surface<=2 and y2.deck_floor<=2 and y2.general_appraisal=5;
+-----+
| sum(y1.deck_area) |
+-----+
|          579160 |
+-----+
1 row in set (0.29 sec)
```

4) A_{ND}

```
mysql> Select sum(deck_area) from yearsosm2001 where deck_wearing_surface=2 and deck_floor<=2 and general_appraisal=5;
+-----+
| sum(deck_area) |
+-----+
|          27864601 |
+-----+
1 row in set (0.08 sec)
```

5) M_{ND}

```
mysql> select sum(y1.deck_area) from yearsosm2001 as y1 inner join yearsosm2002 as y2 on y1.sfn=y2.sfn and y1.deck_wearing_surface=2
and y1.deck_floor<=2 and y1.general_appraisal=5 and y2.deck_wearing_surface<2 and y2.deck_floor<=2 and y2.general_appraisal=5;
+-----+
| sum(y1.deck_area) |
+-----+
|          3188395 |
+-----+
1 row in set (0.20 sec)
```

3.5.2 Moving Window of STM's For WS Degradation Rate Calculation.

Figure 3.27 shows the Maintenance on WS Deficient bridges (M_{CD}) and the current WS deficient bridges (A_{CD}). It can be observed that the maintenance on WS deficient bridges and WS current deficient bridges changes across years. Keeping a constant Degradation rate will not be able to capture this changes as described in Section 3.3.3.1.

Details on the algorithm used for Moving TPM approach for the 5 year Window of STM's and 2 year Window of STM is given in Section 3.3.3.2. Figure 3.28 shows the results of Degradation Rate calculations for WS OPI. It can be observed that the WS degradation rate varies across years 2001 to 2008. The degradation rate calculated using the 5 year Moving Window and 2 year Moving Window is above the ODOT's constant degradation rate of 2% for most of the years between 2001 and 2008. The actual degradation rate from database is above ODOT's 2% rate from 2001 to 2005 and then drops below 2%. At 2008 5 years Moving Window and actual degradation rate from database records a degradation rate equal to 2%. The 2 year Moving Window follows the actual degradation rate plot but delayed by a year.

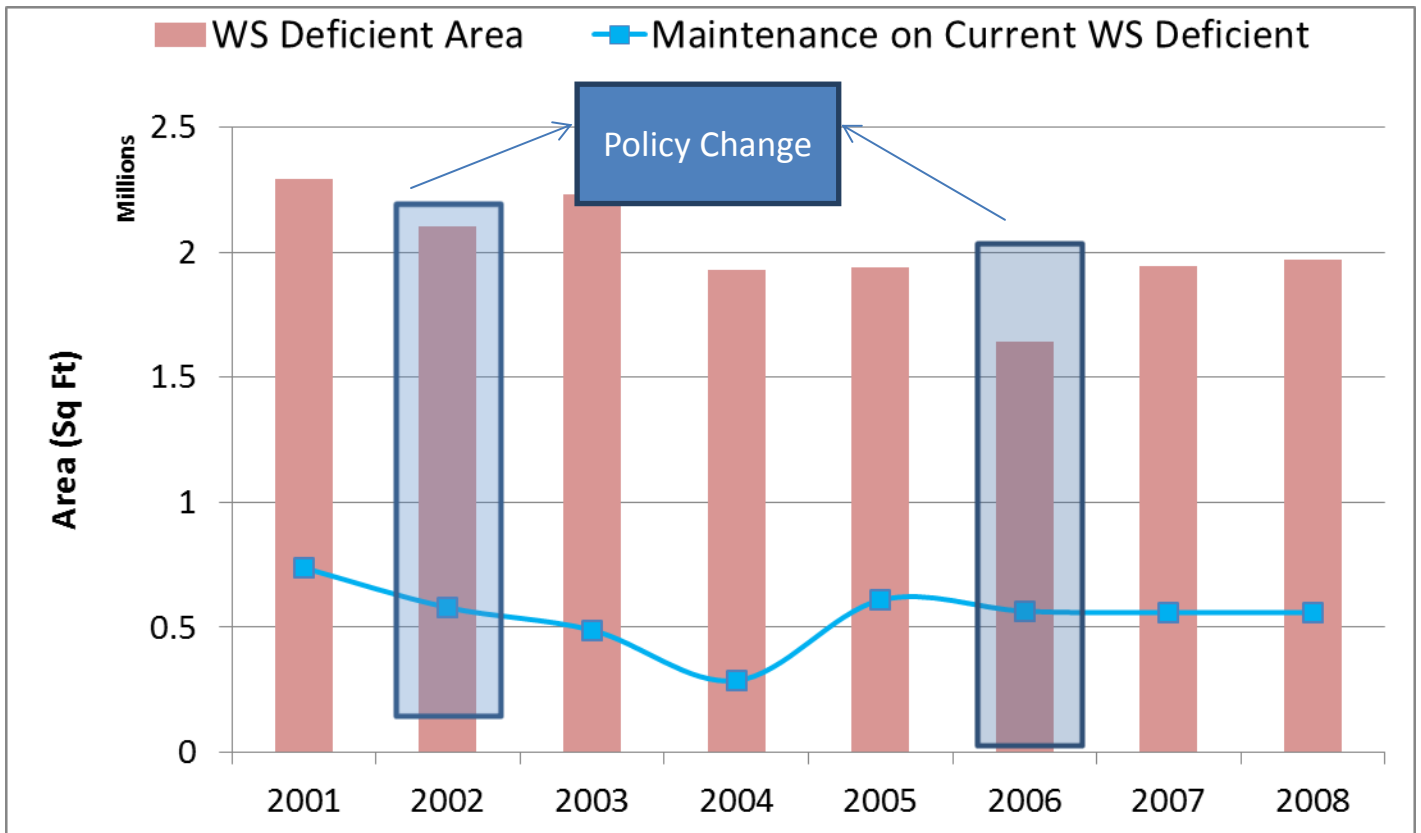


Figure 3.27: WS Maintenance and Policy Changes.

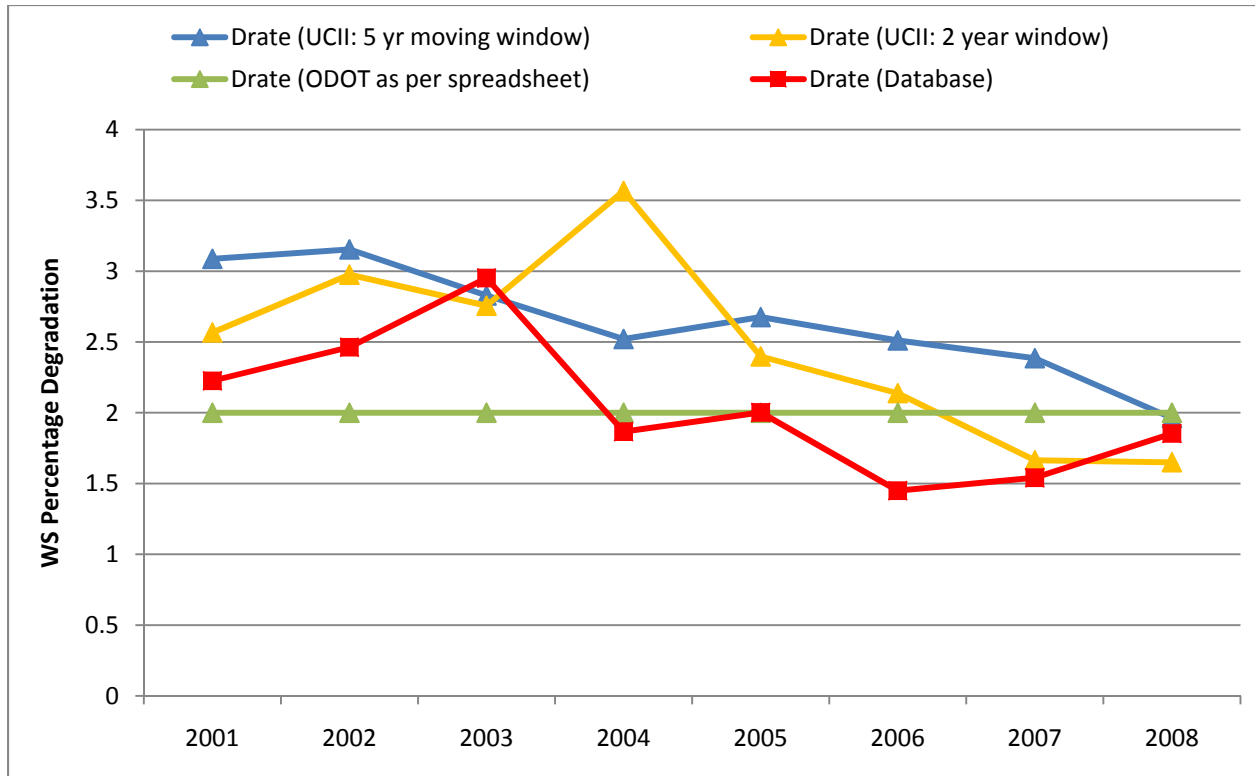


Figure 3.28: WS Degradation Rate.

The predicted deficient area using 5 year and 2 year Moving Windows of STM, ODOT Spreadsheet constant degradation rate of 2%, actual deficient area from the database are shown in Figure 3.29.

The predicted deficient areas were calculated using equation described in Section 3.3.2. A comparison of the Maintenance on Almost Deficient WS bridges and Degradation on Almost Deficient bridges are shown in Figure 3.30. It can be seen that Sq Ft of area Maintained every year is close to the Sq Ft of area degrading every year. This result is similar to the results seen for GA as well as WS maintenance and degradation.

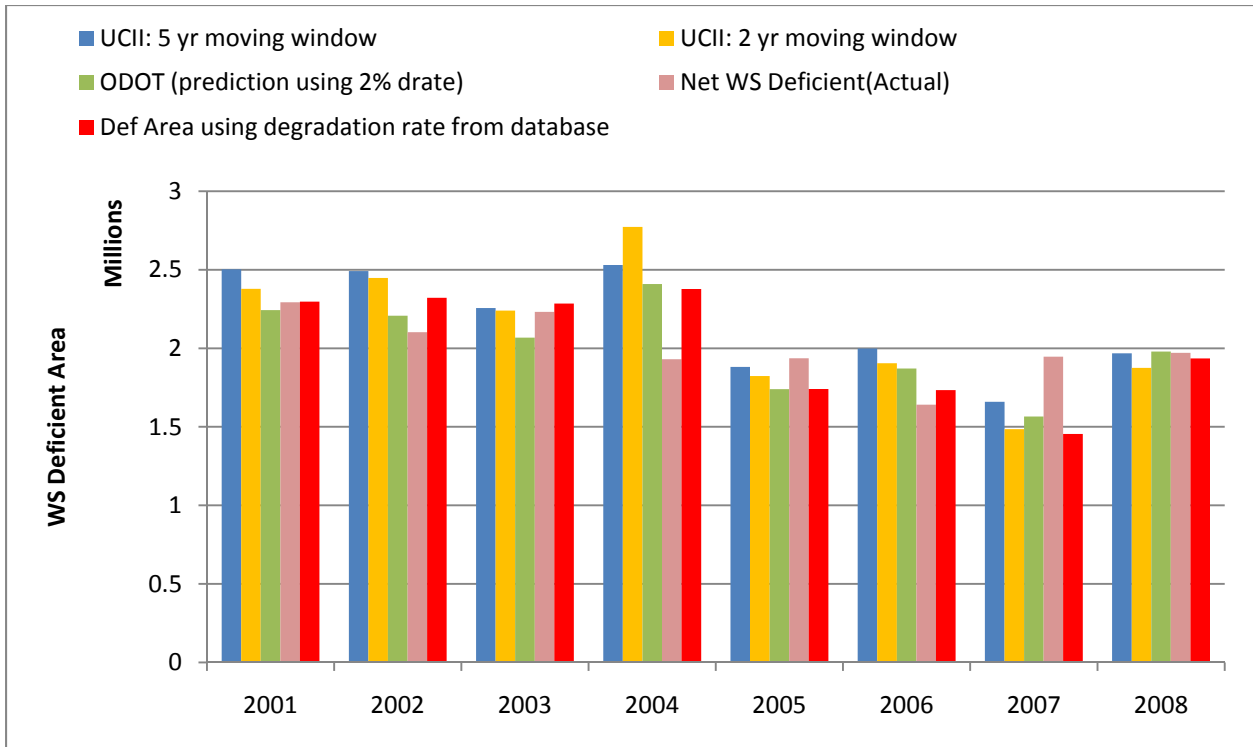


Figure 3.29: Predicted Wearing Surface Deficient Area.

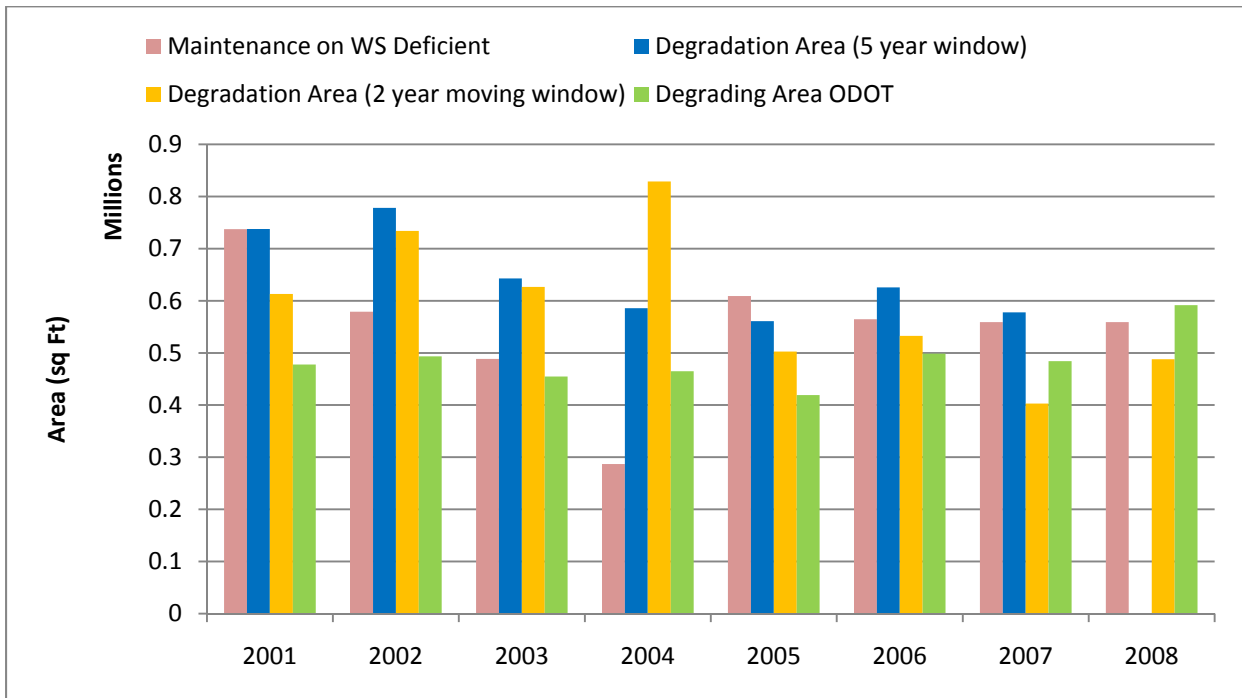


Figure 3.30: WS Maintenance and Degradation.

3.5.3 WS Degradation Rate for Districts.

Figure 3.31 tabulates the WS Degradation rates obtained from the UCII Database for districts in Ohio. It can be observed from the average degradation rates that District 7 records the lowest degradation rate. The highest degradation rates were recorded for District 6. District 1 recorded a degradation rate of 0 for 3 consecutive years from 2002 to 2004. The overall degradation rate for year 2003 is the highest with the bigger districts like District 6, District 8 and District 12 recording degradation rates of 14.75% , 5.73% and 4.75 respectively.

Year	Dist 1	Dist 2	Dist 3	Dist 4	Dist 5	Dist 6	Dist 7	Dist 8	Dist 9	Dist 10	Dist 11	Dist 12
2001	1.60	2.72	1.54	0.00	4.96	12.51	0.00	0.96	0.24	6.47	0.84	2.64
2002	0.00	1.33	2.33	0.00	0.00	11.74	0.97	1.39	0.00	8.58	1.23	5.58
2003	0.00	0.00	2.35	0.03	0.00	14.75	0.68	5.73	1.80	7.84	0.81	4.76
2004	0.00	2.04	5.35	1.46	10.45	10.63	0.00	0.54	0.87	0.26	1.27	0.52
2005	2.81	0.88	5.81	1.61	0.79	6.38	0.98	0.67	4.08	1.79	0.27	0.40
2006	1.95	0.57	3.50	1.43	4.07	3.44	1.01	0.81	0.94	2.66	1.15	0.00
2007	0.28	0.12	1.99	0.46	3.24	5.84	0.00	1.66	0.59	2.90	3.47	0.88
2008	2.13	0.31	6.11	0.68	1.61	6.59	0.06	0.67	5.17	3.69	0.72	0.30
Avg(Drate)	1.10	1.00	3.62	0.71	3.14	8.99	0.46	1.55	1.71	4.27	1.22	1.88

Figure 3.31: WS Degradation Rate for Districts.

3.6 Protective Coating System Degradation Rate.

Figure 3.32 shows the Protective Coating Surface OPI degradation calculation from ODOT Spreadsheet. Protective Coating Surface degradation depends on 2 factors.

- 1) Protective Coating Surface OPI rating of the bridge.
- 2) General Appraisal OPI rating of the bridge

A comparison study of the bridges which are Protective Coating Surface deficient (PCS<5) and bridges which are Protective Coating Surface deficient but healthy General Appraisal (PCS<5 and GA>=5) is shown in Figure 3.33. It can be seen that bridges which are Protective Coating Surface deficient but healthy General Appraisal(PCS<5 and GA>=5) is a subset of all Protective Coating Surface deficient bridges and constitutes about 70-80% of all Protective Coating Surface deficient bridges. Because of the considerable reduction in bridge area we consider all the factors (PCS, GA) for PCS degradation calculations.

Paint Condition	
Deficient = GA >= 5 and PC <5	
2008 - PC	
Current Percent Deficient 2/05/2008	1.12%
Sq. Ft. Current Deficiencies	37,438
Sq. Ft. Programmed through 6/18/2008	0
Current Sq. Ft. Deficient w/o Project	37,438
Sq. Ft. Almost Deficient	92,593
Sq. Ft. Programmed through 6/18/2008	0
Sq. Ft. Almost Deficient Less Programmed Projects	92,593
Almost Def. Projected To Go Def thru 6/18/2008	1,929
Predicted PC at 2008	1.18%
2008 OPI Goal	10.00%
Sq. Ft. +/- Goal	293,488

Figure 3.32 PCS Degradation Rate Calculation in ODOT Spreadsheet.

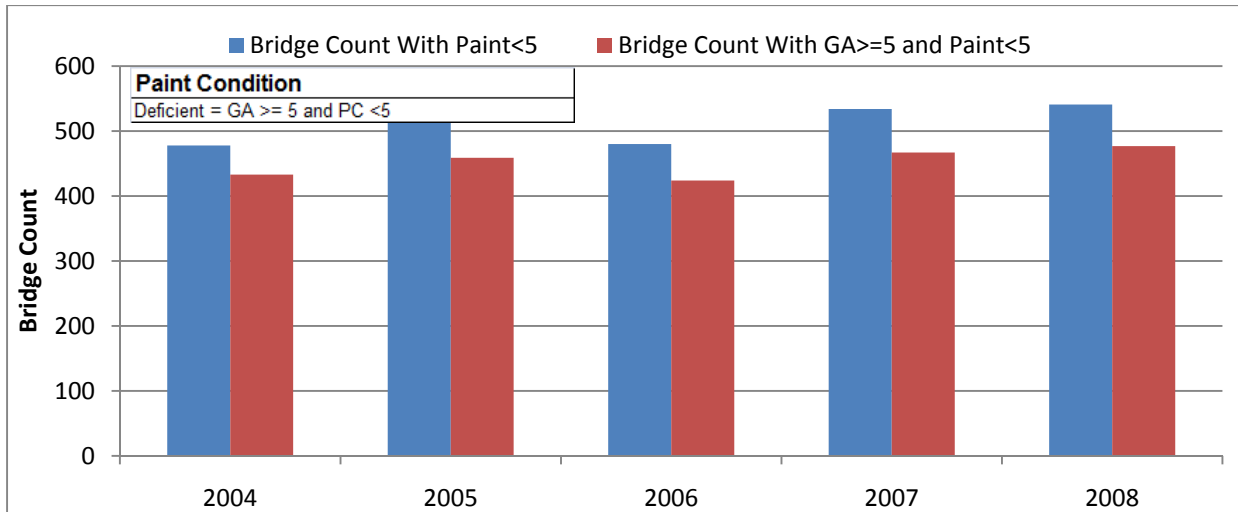


Figure 3.33 Factors Affecting PCS Degradation Rate.

The definitions for different terms in PCS degradation rate calculations are tabulated in Figure 3.34. As described above a bridge is considered deficient with respect to PCS OPI only if its PCS OPI rating < 5 and GA OPI rating ≥ 5.

Term In Spreadsheet	UCII Abbreviation	Definition
Total Sq Ft of Deck	A_T	Net Deck Area Of Bridges at any year.
Sq Ft Current Deficiencies	A_{CD}	Sq Ft of Area with PCS < 5 and GA ≥ 5
Sq Ft Programmed through on(A_{CD})	M_{CD}	Maintenance on A_{CD} : Sq Ft of Area making transition (PCS < 5 and GA ≥ 5) to (PCS ≥ 5 and GA ≥ 5) between two consecutive years.
Current Sq Ft Deficient without project	A_{CNM}	$A_{CD} - M_{CD}$
Sq Ft Almost Deficiencies	A_{ND}	Sq Ft of Area with PCS = 5 and GA ≥ 5
Sq Ft Programmed through on(A_{ND})	M_{ND}	Maintenance on A_{CD} : Sq Ft of Area making transition (PCS = 5 and GA ≥ 5) to (PCS > 5 and

		GA >=5) between two consecutive years.
Current Sq Ft Deficient without project	A_{NNM}	$A_{ND} - M_{ND}$
Almost Def to go Deficient	A_{deg}	Sq Ft of Area making a transition (PCS=5 and GA>=5) to (PCS<5 and GA>=5) between two consecutive years.
Predicted GA		$(A_{CNM} + A_{deg}) * 100 / A_T$

Figure 3.34: Definitions for WS Calculations.

Degradation rate is calculated by using the equation below

$$Drate = A_{Deg} / (A_{ND} - M_{ND}).$$

ODOT spreadsheet uses a constant Drate of 5.0 % for Protective Coating System OPI. UCII calculates the A_{Deg} using the 5 year Moving Window of STM's and 2 year Moving Window of STM's. A_{ND} and M_{ND} are the actual data obtained from database obtained using SQL queries.

3.6.1 Dataset Used for PCS Calculations.

Protective Coating System is an indicator of the condition of the corrosion protection applied to the bridge structural steel. Concrete bridges do not have Protective Coating System and hence only steel bridges are used for PCS analysis [1]. Some of the steel bridges, namely A588 Weathering bridges do not have a Protective Coating System and hence they are also removed from the analysis.

Protective Coating System OPI was converted from a 1-4 scale to a 0-9 scale in 2002 and 2003[1]. For the purpose of this analysis, bridges in the new scale were only considered. This means that the available area distribution for degradation modeling is from years 2004 – 2008. Using the two year

Moving window with year 2003 and year 2004 as the initial years for STM calculations, predictions from 2005 to 2008 were made. Actual degradation from database was also used to predict degradation from 2005 to 2008. 5 year Moving Window used 2003 -2007 as the years for computing STM and predicted degradation rate for 2008.

3.6.2 SQL Queries For PCS Calculations.

The following SQL queries were used to fetch data from UCII database for PCS degradation rate calculations. The definition for each term is given in the section above.

1) A_T :

```
mysql> select sum(deck_area) from yearsosm2005;
+-----+
| sum(deck_area) |
+-----+
|          50460598 |
+-----+
1 row in set (0.08 sec)
```

2) A_{CD}

```
mysql> select sum(deck_area) from yearsosm2005 where paint<5 and general_appraisal>=5;
+-----+
| sum(deck_area) |
+-----+
|          5302370 |
+-----+
1 row in set (0.21 sec)
```

3) M_{CD}

```
mysql> select sum(y1.deck_area) from yearsosm2005 as y1 inner join yearsosm2006 as y2 on y1.sfn=y2.sfn and y1.paint<5 and y1.genera
appraisal>=5 and y2.paint>=5 and y2.general_appraisal>=5;
+-----+
| sum(y1.deck_area) |
+-----+
|           444823 |
+-----+
1 row in set (0.32 sec)
```

4) A_{ND}

```
mysql> select sum(deck_area) from yearsosm2005 where paint=5 and general_appraisal>=5;
+-----+
| sum(deck_area) |
+-----+
|          6659360 |
+-----+
1 row in set (0.08 sec)
```

5) M_{ND}

```
mysql> select sum(y1.deck_area) from yearsosm2005 as y1 inner join yearsosm2006 as y2 on y1.sfn=y2.sfn and y1.paint=5 and y1.genera
appraisal>=5 and y2.paint>=5 and y2.general_appraisal=5;
+-----+
| sum(y1.deck_area) |
+-----+
|          816151 |
+-----+
1 row in set (0.09 sec)
```

3.6.3 Moving Window of STM's For PCS Degradation Rate Calculation.

Figure 3.35 shows the Maintenance on PCS Deficient bridges (M_{CD}) and the current PCS deficient bridges (A_{CD}). It can be observed that the maintenance on PCS deficient bridges and PCS current deficient bridges changes across years. Keeping a constant Degradation rate will not be able to capture this changes as described in Section 3.3.3.1.

Details on the algorithm used for Moving TPM approach for the 5 year Window of STM's and 2 year Window of STM is given in Section 3.3.3.2. Figure 3.36 shows the results of Degradation Rate calculations for PCS OPI. The actual degradation rate from database is more than constant 5% degradation in ODOT Spreadsheet for year 2005 and year 2006 and then starts to dip down. Both the Moving Windows and actual degradation from database are at 4.5% at year 2008.

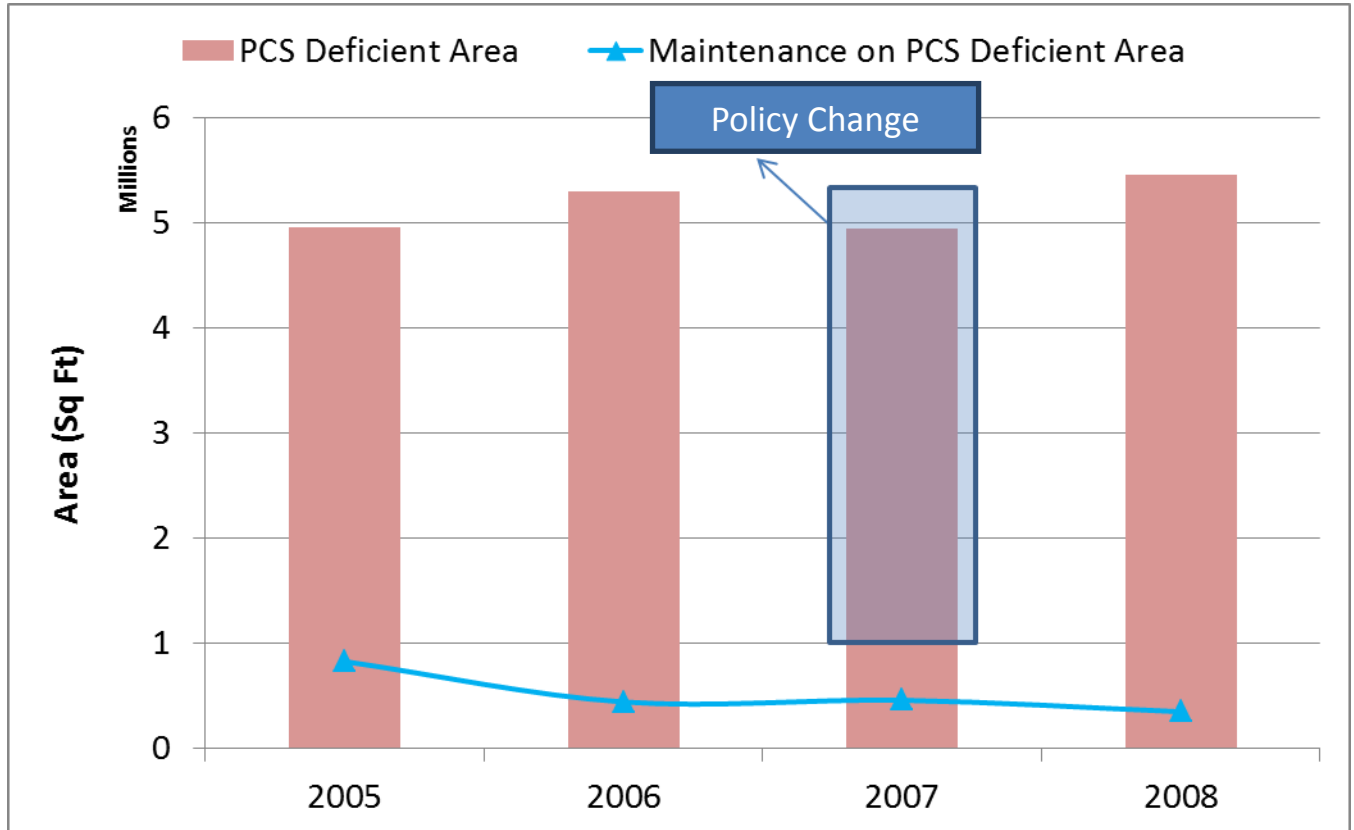


Figure 3.35: PCS Maintenance and Policy Changes.

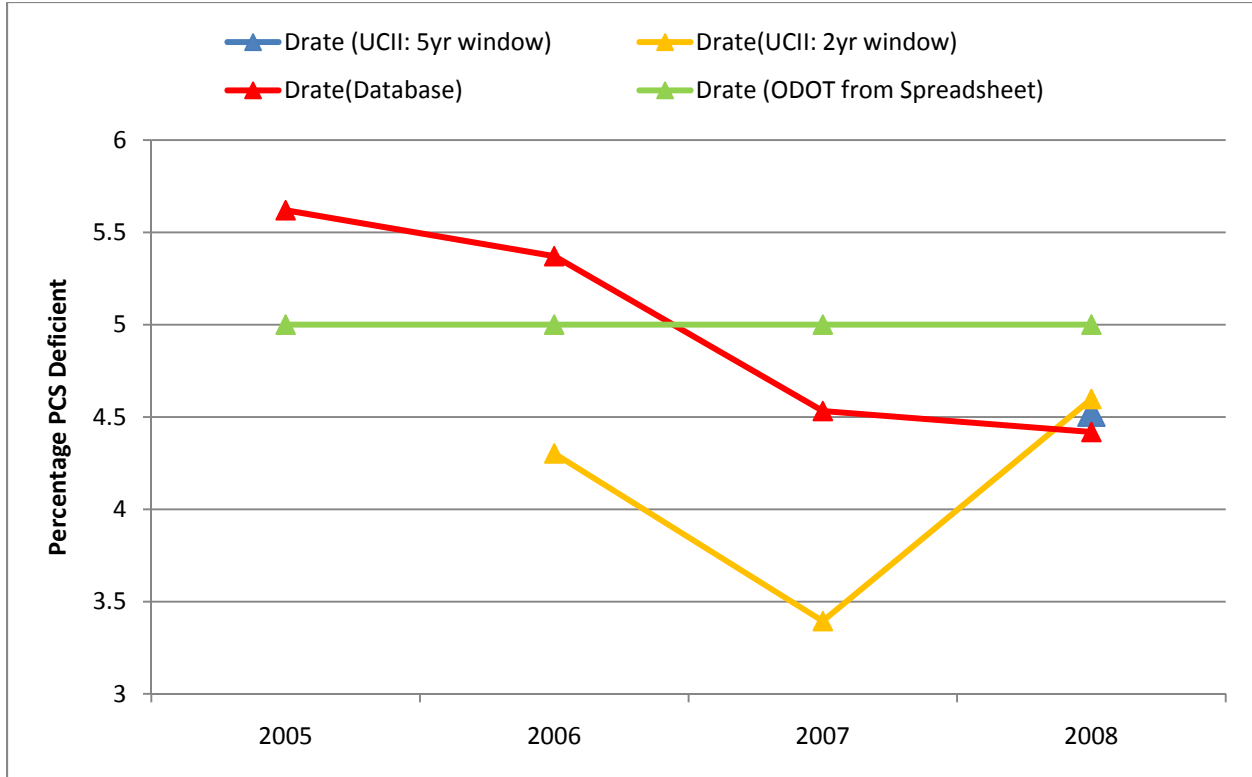


Figure 3.36: PCS Degradation Rates

3.6.4 PCS Degradation Rate for Districts.

PCS degradation rate for different districts in Ohio and the average PCS degradation rate for a period 2005 to 2008 are tabulated in Figure 3.37. It can be observed from the average degradation rates that District 5 has the highest degradation rate followed by District 1 and District 6. In general Districts in Central Ohio (District 5, District 6, District 7, and District 11) have higher PCS degradation rates as compared to other districts.

Year	Dist 1	Dist 2	Dist 3	Dist 4	Dist 5	Dist 6	Dist 7	Dist 8	Dist 9	Dist 10	Dist 11	Dist 12
2005	19.48	0.00	15.37	2.05	10.00	5.50	8.97	4.72	8.76	2.75	0.00	0.00
2006	15.25	3.05	8.25	3.20	15.10	7.93	8.25	4.43	4.68	1.13	0.00	1.34
2007	5.31	0.00	2.77	4.23	15.34	10.76	1.14	3.44	0.00	9.97	12.09	1.47
2008	0.00	1.75	1.38	1.93	25.96	14.34	5.29	2.90	0.00	2.34	9.43	1.45
Avg(Drate)	10.01	1.20	6.94	2.85	16.60	9.63	5.91	3.87	3.36	4.05	5.38	1.06

Figure 3.37: PCS Degradation Rate for Districts.

References

1. Office of Structural Engineering, Ohio Department of Transportation; "Bridge Inventory and Appraisal Coding Guide", December 1989, pp. 1-215
2. Kothottil. Dinek, "Markov-based Predictive Models For Estimation of Degradation Rates of Bridges in the State of Ohio", August 2010, MS Thesis, Division of Research and Advanced Studies University of Cincinnati
3. Ramani. S, "A Markov-based Analysis of the State of Ohio's Bridge Inventory and Novel Approaches to the Estimation of Bridge Degradation Rates", February 2010, MS Thesis, Division of Research and Advanced Studies, University of Cincinnati.
4. Zambre. N, "Degradation Rate Modeling of Ohio", January 2009, MS Thesis, Division of Research and Advanced Studies, University of Cincinnati.