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REVISED CONDITION RATING SURVEY MODELS TO REFLECT ALL DISTRESSES: VOLUME 1

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A report of the findings of
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16. Abstract

Pavement condition assessment plays a key role in infrastructure programming and planning processes. Similar to other state agencies, the Illinois Department of Transportation (IDOT) has been using a system to evaluate the condition of pavements since 1974. Since 1994–1995, IDOT has been using a system to project future pavement performance as well. The condition rating survey (CRS) value is the index between 1 (failed) and 9 (new), representing the overall condition of pavement. The purpose of this study was to update and revise the existing CRS calculation and prediction models using new data. To accomplish the goals of the study, the CRS data was received for the years 2000–2014. The data was initially processed and cleaned in preparation for modeling. CRS prediction models were prepared for Interstate and Non-Interstate pavement types. The two-slope model was used for all asphalt-surfaced pavements, whereas a new model was proposed for concrete-surfaced pavements. The proposed model for concrete-surfaced pavements is a nonlinear survival type designed to capture the distinct deterioration patterns of concrete pavements with little to no reduction in CRS—followed by a rapid and linear deterioration and a flatter region at the end, once the pavement is saturated with damage. The CRS calculation models were updated to incorporate new distresses. Based on the literature review and the analysis of distress composition, it was found that IDOT's distress ratings are generally in agreement with the ASTM standard—with the exception of alligator cracking. A database containing recorded distresses, used by experts, was referenced to add missing distresses, such as alligator cracking, for each Interstate model.

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EXECUTIVE SUMMARY

Pavement condition assessment, with current and historical condition calculation and future prediction, provides the two critical components of pavement management systems: 1) It plays a key role in infrastructure programming and planning processes; and 2) It provides the basic data to determine the amount of funding needed to maintain the state highway system to an acceptable level of condition. Similar to other state agencies, the Illinois Department of Transportation (IDOT), has been using a system to evaluate the condition of pavements since 1974. Since 1994–1995, IDOT has been using a system to project future pavement performance as well. The condition rating survey (CRS) value is the index between 1 (failed) and 9 (new), representing the overall condition of pavement.

According to the current procedures, two types of CRS models are used. The first type is the CRS calculation (or measurement) model resulting in the CRS value deduced from the identified and measured distress information, using a weighting factor for each distress type. There are several groups of pavement surface types, and each group has a separate CRS calculation model. Since the early 1990s, CRS calculation models have been derived from automated distress measurements and distress identification from images. The second type is the CRS prediction model used to estimate the CRS value when distress information is not available. Prediction of CRS for future performance of pavements is done using statistical models, considering the type/location of the pavement, the initial value of CRS, and a yearly deduct value which is based on a combination of factors. Deterministic models were developed in the work done by ERES Consultants in the early 1990s (Lee and Darter, 1994; ERES Consultants, 1995; Hall et al., 1994) and later improved by the work of Darter and his colleagues (Gharaibeh et al., 1999), Heckel and Ouyang (2007a, b, c), and Wolters et al. (2008).

The purpose of this study was to update and revise the existing CRS calculation and prediction models using new data. Two datasets were utilized in developing the prediction models. The majority of the surface types were modeled using the data for the years 2000-2014 obtained from the Illinois Roadway Information System (IRIS). The second dataset was obtained from the reports that IDOT authored related to conducting pavement performance monitoring surveys on mechanistically-designed pavements.

The data was initially processed in preparation for modeling. Initial data processing included data reduction and repopulation to monitor the progression of CRS over the years for each section marked with a beginning and ending station. The second stage of data preparation included cleaning the database of abnormalities and inconsistencies. An algorithm was developed to catch specific data trends and identify them with appropriate flags. These flags included negative slopes and various types of positive slopes (e.g. flats and risers). Positive slopes indicate potential rehabilitation (resurfacings), preservation, upstream, and downstream identifiers. An important assumption was to retain all of the data between two resurfacing events or original construction and resurfacing events, to develop a more realistic estimation of future CRS values.

CRS prediction models were prepared for the Interstate and Non-Interstate pavement types when sufficient data were available. Incremental models traditionally have been used for CRS predictions in which age is not an independent variable due to construction record inconsistencies in the database.

According to the incremental type of models, the slope between two consecutive data points is calculated and used in model development. A similar two-slope model was used for all asphalt-surfaced pavements including asphalt concrete (AC) and full-depth pavements (coded as ACP), whereas a new model was proposed for concrete-surfaced pavements. The proposed model for concrete-surfaced pavements is a nonlinear survival type designed to capture the distinct deterioration patterns of concrete pavements with little to no reduction in CRS—followed by a rapid and linear deterioration and a flatter region at the end, once the pavement is saturated with damage. The proposed model captures the initial slow deterioration trends commonly observed in concrete pavements with high accuracy. In addition, the model is more consistent with the underlying physics of pavement damage progression. Therefore, more consistent trends were obtained in terms of terminal service life even when there is not enough data available. In addition, a new pavement surface type was proposed to consider overlays on the full-depth HMA sections based on the observed faster deterioration rate as compared to that of original full-depth HMA pavements prior to first overlay. The data used to make the separation between original full-depth HMA (ACP) and overlays on full-depth HMA (AC/ACP) were obtained from two databases included in this study.

Table ES.1. Modeling Approach Used for Various Pavement Families

Two-Slope Model	Incremental Survival Model
Asphalt concrete pavement (ACP) – Full-depth HMA	Continuously Reinforced Concrete Pavement (CRCP)
AC overlays on ACP	Jointed Reinforced Concrete Pavement (JRCP)[1]
AC overlays on Jointed Plain Concrete Pavement (AC/JPCP)	Jointed Plain Concrete Pavement (JPCP)
AC overlays on Jointed Reinforced Concrete Pavement (AC/JRCP)	Portland Cement Concrete with reinforcement unknown (PCCun)
AC overlays on Continuously Reinforced Concrete Pavement (AC/CRCP)	Jointed Concrete Pavement with Hinged Joints (HJCP)[1]
AC overlays on Portland Cement Concrete with reinforcement unknown (AC/PCCun)	
Overlays on D-cracked concrete jointed concrete and CRCP pavements	
SMART overlays within ACP, AC/CRCP, AC/JRCP, AC/JPCP, and AC/PCCun types	

[1] These pavement types are no longer used in Illinois but models were developed based on the existing sections constructed in the past.

According to the results of prediction models for the Interstate system, service life to reach a CRS of 5.5 for asphalt-surfaced pavements varies from approximately 10 years (AC/JRCP overlays) to 13-14 years (AC/CRCP overlays) and 16.7 years (ACP type) as shown in Table ES.2. The sections with D-cracked underlying concrete are predicted to result in service lives about 26-44% shorter than the standard types. The data did not reveal any consistent differences between the northern and southern districts within the Interstate system.

Table ES.2. Service Life Predictions for Asphalt-Surfaced Pavements in the Interstate System

Type	Surface Type	Districts	Years to CRS = 5.5	Years to CRS = 4.5
Standard	AC/CRCP	1-4	14.3	21.2
		5-9	13.2	19.2
	AC/JRCP	1-4	10.2	14.7
		5-9	10.5	15.3
	AC/JPCP	1-4	NA	NA
		5-9	NA	NA
	AC/ACP	1-9	15.4	21.9
	ACP	1-9	16.7	25.0
D-cracked	Overlay on Jointed Rigid	1-9	7.5	10.7
	Overlay on CRCP	1-9	9.0	11.9

[NA] Not enough data to develop separate model. Use service lives for AC/JRCP until enough data is available for a model.

Similar trends were observed for the asphalt-surfaced pavements within the Non-Interstate system as shown in Table ES.3. A reduction of service life by approximately 18 to 29% was observed for overlays on JPCP and JRCP types as compared to those with CRCP. The ACP models were developed using the mechanistic database resulting in a service life of 16.7 years and 25.0 years to reach the CRS of 5.5 and 4.5, respectively. The service life to reach critical CRS values in southern districts for standard and SMART surface types is 3-30% higher than those in northern districts, except for AC overlays of PCCun surfaces. SMART sections showed comparable service life with standard type of overlays on concrete pavement types (AC/JRCP, AC/JPCP, AC/PCCun), except those on CRCP structures. Overlays on the concrete pavements with a D-cracking flag showed a similar reduction in service life within the range of 19 to 33%. There are two inconsistent and unexpected trends observed in the models developed for the Non-Interstate system. These are for AC/PCCun and SMART AC/CRCP surface types. The amount of data for AC/PCCun surface type is the highest; however, it contained some inconsistencies with the largest percentage of downstream positive slopes. This may indicate that those pavements are saturated to damage and resulted in an apparent increase in service life until next overlay. As for the SMART overlays in CRCP sections, there is very little data available that might have caused a bias. Therefore, it is recommended to collect additional information from districts for these sections and then perform a review of the models. The AC/PCCun category is a combination of several cross-sections which can cause high variability in performance. Additional efforts should be made to identify the actual cross-sections used in these pavement sections and those data points added to the correct category to improve those models.

Survival-type models were developed when there was enough data available for concrete pavements in the Interstate and Non-Interstate systems as shown with the results in Tables ES.4 and ES.5. Survival-type models were developed by using a coefficient to define the shape and service life to when it requires an overlay. Due to the lack of data at the later stages of concrete pavements, service life CRS values of 4.5 and 5.5 were used as a constraint to gauge how well the model fits with existing data based on earlier modeling efforts in Illinois for concrete pavements. The proposed model resulted in longer service life estimates as compared to the estimates of previous models. This can be attributed to the use of service life as a constraint in the model, as well as the performance data coming from more recently constructed sections. As data becomes available to indicate performance at the later stages of mechanistically-designed concrete pavements, the models should be reviewed.

Table ES.3. Service Life Predictions for Asphalt-Surfaced Pavements in the Non-Interstate System

Type	Surface Type	Districts	Years to CRS = 5.5	Years to CRS = 4.5
Standard	AC/CRCP	1-4	12.1	17.7
		5-9	13.1	18.8
	AC/JRCP	1-4	9.8	14.6
		5-9	11.1	16.4
	AC/JPCP	1-4	9.6	14.6
		5-9	10.0	15.1
	AC/PCCun	1-4	13.2[1]	20.2[1]
		5-9	10.3	15.0
	AC/ACP	1-4	12.4	18.0
		5-9	15.4	21.9
	ACP	1-9	16.7	25.0
SMART[3]	AC/CRCP	1-9	10.3[2]	14.5[2]
	AC/JRCP	1-4	10.3	15.4
		5-9	10.8	16.3
	AC/JPCP	1-4	10.0	15.7
		5-9	10.9	16.7
	AC/PCCun	1-4	12.7[1]	18.7[1]
		5-9	11.1[1]	16.2[1]
	ACP	1-4	10.5	15.2
		5-9	13.7	19.2
D-cracked	Overlays on Jointed Rigid	1-9	8.2	12.2
	Overlays on CRCP	1-9	8.9	13.2

[1] Apparent increase in service life for the AC/PCCun surface type may be due to large percentage of positive downstream slopes contributing to the increase in service life until the next overlay.

[2] Limited number of data points may have caused the underestimation of service life for SMART overlays on CRCP system.

[3] SMART overlays are placed on pavements with a higher CRS value, which may explain the longer service life to the terminal CRS values compared to some standard overlays.

Table ES.4 Service Life Predictions for Concrete-Surfaced Pavements in the Interstate System.

Type	Surface Type	Districts	Years to CRS = 5.5	Years to CRS = 4.5
Standard	CRCP	1-9	40	45
	JPCP	1-9	36	40
D-cracked	CRCP	1-9	31	35
	JPCP	1-9	27	30

Table ES.5. Service Life Predictions for Concrete-Surfaced Pavements in the Non-Interstate System

Type	Surface Type	Districts	Years to CRS = 5.5	Years to CRS = 4.5
Standard	CRCP	1-9	36	40
	JPCP	1-9	36	40
	JRCP	1-9	36	40
	PCCun	1-9	31	35
	HJCP	1-9	31	35
D-cracked	CRCP	1-9	27	30
	JPCP	1-9	27	30
	JRCP	1-9	27	30
	PCCun	1-9	22	25
	HJCP	1-9	22	25

The CRS calculation models were also revised. Based on the literature review and analysis of distress composition, it was discovered that IDOT's distress ratings are generally in agreement with the ASTM standard—with the exception of alligator cracking. Alligator cracking is one of the structural distresses with relatively low weight assigned or missing in the CRS calculations, as compared to national standards. It was also found that the primary drivers of CRS reductions, especially in asphalt-surfaced pavements, are the functional types of distress (such as centerline joint deterioration, weathering, or center-of-lane cracking) because relatively higher weights are assigned to such distresses.

CRS calculation models were updated to better incorporate new distresses. A database containing recorded distresses, used by experts, was referenced to add missing distresses, such as alligator cracking, for each Interstate model. The weight of each distress in the calculation model should reflect the importance of that distress on the overall performance of the pavement. The CRS calculation model has been used by IDOT for many years and consistency had been established in relating a pavement's condition to the CRS value. Any additional revisions to the CRS calculation model must be made very cautiously. If too many revisions are made, inconsistencies between calculated CRS and what raters perceive as the condition of the pavement surface will increase, resulting in more frequent overriding occurrences. Two recommendations were made for potential revisions to address overemphasized or underemphasized distresses.

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Deterioration of a pavement begins as soon as it is put into service. The effective management of pavement assets requires a good understanding of the life expectancy of each pavement type. Life expectancy of a pavement can be considered as the point in time at which a pavement must be rehabilitated or reconstructed at the end of its service life. Life expectancy of a pavement depends on the type of pavement, its structural properties (thickness, material properties, and base support), traffic, environmental conditions, and maintenance/preservation/rehabilitation activities. The ultimate objective of pavement management systems is to maintain or extend the life of a network of pavements at low costs. An essential element of any pavement management system is the pavement performance prediction models. These models are designed to estimate the life expectancy of a pavement by monitoring its condition from the time it is put into service.

To understand the concept and importance of pavement condition calculation and prediction, one must first understand pavement management. *Pavement management* refers to cost effectively maintaining pavement infrastructure. The importance of the systematic management of pavements is growing due to the increasing rate of deterioration of pavements and the declining level of funding. A complete pavement management system (PMS) can help agencies systematically plan and manage their pavement network and make informed decisions regarding treatment selection. A complete PMS consists of three major modules: database, analysis methods, and feedback system (IRF, 1995).

Pavement condition assessment and future prediction models play a key role in infrastructure programming and planning processes. They provide the basic data to determine the amount of funding needed to maintain the state highway system to an acceptable level of condition. This report presents the updates for the calculation and prediction models used by the Illinois Department of Transportation (IDOT).

1.2 PAVEMENT CONDITION CALCULATION

Many transportation agencies monitor the condition of their pavement assets by collecting various levels of information at the network level. One method of collecting information is related to the overall condition of a pavement, specifically, its ride quality. The present serviceability rating (PSR) and present serviceability index (PSI) derived from the PSR, were developed based on the findings of the AASHO road test. Another method is to directly evaluate the overall pavement condition using the International Roughness Index (IRI), which is measured by profiling vans. The second type of condition information is the individual pavement distresses, collected at the network level. The distress information is then used to create various indices such as the pavement condition index (PCI). It is a numerical value from 0 (worst) to 100 (best) that indicates the general condition of a pavement and is standardized in ASTM D6433, Standard Practice for Roads and Parking Lots Pavement Condition Index Surveys. PCI was developed by the United States Army Corps of Engineers, based on a visual survey of the severity and types of distresses in a pavement. Rutting, transverse cracking, fatigue cracking, longitudinal cracking, and block cracking are by far the most commonly collected types of distress data used in condition index calculations. The basic principle of PCI is based on the points deducted from the starting value of 100, with respect to type and severity of distresses.

In addition to standardized condition indices, a number of state highway and local transportation agencies have developed their own unique overall condition index—often referred to as pavement quality index (PQI) or condition rating survey (CRS) (Pierce et al. 2013). Ohio, Minnesota, South Carolina, Oklahoma, Nebraska, and Illinois are some of the states using customized pavement condition indices other than PCI or PSI.

Since 1974, IDOT has been using the condition rating survey (CRS) value to evaluate the condition of pavements. Since 1994–1995, IDOT has been using this system to project future pavement performance as well. CRS is a numerical index from 1 (failed) to 9 (new), representing the condition of pavement. IDOT has continued its efforts to build new models or revise the existing ones to enable prediction of future CRS values with enhanced accuracy (Gharaibeh et al., 1999; Heckel and Ouyang 2007a,b,c). The models to calculate CRS values are primarily a function of roughness, rutting, faulting, and other recorded distresses and their severity. According to the current procedures, two types of CRS models are used. The first is the CRS calculation (or measurement) model resulting from the CRS value deduced from the rated distress information, using a weighting factor for each distress type. There are several groups of pavement surface types, and each group has a separate CRS calculation model. The second type is the CRS prediction model used to estimate the CRS value when current distress information is not available. Prediction of CRS for the future performance of pavements is done using statistical models considering the type/location of pavement, initial value of CRS, and a yearly deduct value.

1.3 PAVEMENT CONDITION PREDICTION

Condition prediction is used at both the network and project levels to determine maintenance and rehabilitation (M&R) requirements. The most cost-effective way of conducting M&R activities is to do them at the right time. Using accurate pavement condition predictions is the key for timely M&R implementation. At the network level, prediction models can be used for condition forecasting, budget planning, inspection scheduling, and work planning. At the project level, prediction models are used to select specific rehabilitation alternatives to meet expected traffic and climate conditions. The prediction results can be used to perform a life-cycle cost analysis (LCCA) to compare the economics of various M&R alternatives. When planning M&R at the network level, one usually has concern regarding the level of M&R needed, which is normally used for planning purpose. However, at the project level, the concern is focused on specific M&R alternatives, including the preliminary design of each alternative. Therefore, accuracy of prediction is more important for a project-level analysis than for a network-level analysis (Shahin, 2005).

In a study by Wolters and Zimmerman in 2010, forms of pavement performance prediction models were categorized as (1) deterministic models, including simple linear regression, S-shaped deterioration curve, power function, and multiple-regression models; (2) probabilistic models, including survivor curves, Markov, and semi-Markov transition processes; (3) expert/knowledge-based models; and, (4) biologically inspired models, including genetic algorithms (GA) and artificial neural network (ANN)-based models. Deterministic models are usually developed for project-level evaluation and network-level management. Deterministic models were developed in the work done by ERES Consultants in the early 1990s (Lee and Darter, 1994; ERES Consultants, 1995; Hall et al., 1994) and later improved by the work of Darter and his colleagues (Gharaibeh et al., 1999) and Heckel and Ouyang (2007a). The performance of overlays in specific was also evaluated previously using different modeling approaches including two-slope models and survival models (Wolters et al., 2008). These models are in need of an update by the addition of new data to the database.

1.4 RESEARCH OBJECTIVES

The research work is aimed at addressing inconsistencies in the calculation of the CRS and improving accuracy of the prediction models of the CRS. The major goals of this research are the following:

- To develop new CRS prediction models for preventive maintenance/preservation treatments used by IDOT
- To develop new CRS prediction models or revise the existing ones to have a complete matrix
- To revise the existing calculation models to capture the impact of distresses that are currently thought to be overemphasized (e.g., weathering, raveling, segregation) or underemphasized (e.g., alligator cracking, edge cracking)

1.5 REPORT ORGANIZATION

The report is compiled in two volumes. The first volume deals with the pavement condition calculation models and prediction models. The organization of the report is as follows. A summary of the literature for calculation models is provided in this chapter, followed by the research objectives and methodology. Chapter 2 presents data and data preparation procedures followed in the study. Chapter 3 introduces the modeling methods. Chapter 4 presents pavement condition prediction modeling results. Chapter 5 presents the updates for the calculation models. The second volume introduces the models developed for pavement preservation treatments commonly used by IDOT.

CHAPTER 2: DATA PREPARATION AND CLEANING

This section introduces the processes followed in preparing the raw databases for the development of calculation and prediction models. The raw database contains Interstate and Non-Interstate pavement and condition inventories from 2000 to 2014 and was processed using the steps that will be discussed in detail in this chapter.

2.1 DATA COLLECTION

Two datasets were utilized in the project. Initially, Interstate and Non-Interstate pavement condition data was collected from IDOT for the years 2000 to 2014 from IRIS. The second dataset is the data used in the performance monitoring of mechanistically-designed pavements and documented as part of Physical Research Report 165 (IDOT, 2016). A summary of the data obtained from IRIS is shown in Table 2.1 and Table 2.2.

Table 2.1. Data Collected from IRIS and Surface Types in the Interstate System

Surface Type	Codes	Prediction Model Developed
AC/CRCP	640	Yes
AC/JPCP	600–615	Not sufficient data
AC/JRCP	620–630	Yes
ACP	550, 560	Yes
CRCP	740, 790, 792	Yes
JPCP	710, 765, 767	Yes
JRCP	720, 730,760–772, 780, 782	Not sufficient data

Table 2.2. Data Collected from IRIS and Surface Types in the Non-Interstate System

Surface Type	Codes	Prediction Model Developed
ACSTLT	300	Not sufficient data.
ACPLT	400,410	Not sufficient data.
ACSTHT	500	Not sufficient data.
ACRubb	501–540	Not sufficient data.
ACP	550, 560	Yes
AC/PCCun	600	Yes
AC/JPCP	610, 615	Yes
AC/JRCP	620–635	Yes
AC/CRCP	640	Yes
AC/BBO	650	Not sufficient data.
PCCun	700, 760, 762	Yes
JPCP	710, 765, 767	Yes
JRCP	720, 730, 770, 772, 780, 782	Yes
CRCP	740, 790, 792	Yes
HJCP	725, 775, 777	Yes

The second dataset will be referred to as the mechanistic database throughout the report. It included JPCP, CRCP and ACP sections derived from 105 contracts.

2.2 DATA GROUPING AND CONSOLIDATION

The overall goal of the data preparation was to make it consistent and manageable within the modeling period. The first step was grouping the data according to the following descriptors. Then, the sections with same identification information were grouped together. The identification items chosen were as follows:

- Inventory number
- Surface type
- CRS
- Pavement distresses
- Original construction year

- Surface construction year
- D-flag

The rows with the same identification numbers were grouped into one section, and the remaining data were recalculated by averaging all data within these years, such as taking the average of traffic information. An example of data consolidation is shown in Table 2.3.

Table 2.3. Data Consolidation Example

Before consolidation				After consolidation			
Beginning station	**Ending station**	**CRS**	**CRS year**	**Beginning station**	**Ending station**	**CRS**	**CRS year**
0	0.43	9	2000	0	8.59	9	2000
0.43	0.81	9	2000	8.59	8.98	8.5	2000
0.81	1.19	9	2000				
1.19	1.21	9	2000				
1.21	8.55	9	2000				
8.55	8.59	9	2000				
8.59	8.98	8.5	2000				

2.3 DATA REPOPULATION

It was very common in the database that the sections did not have consistent beginning and ending stations repeating at every CRS year. The sections were often divided into smaller sections, changing the beginning and ending stations. As a result, it was not possible to monitor CRS progression of a section over the years. Therefore, sections were evaluated one by one at each CRS year to find the year with the highest resolution. The beginning and ending stations with the highest resolution were used as a template to repeat in all the years. CRS values, distresses, and the rest of the data was assigned to the template distribution, resulting in the repopulation of the sections with consistent beginning and ending stations for all CRS years.

An example of data repopulation is shown in Table 2.4. The section with a beginning station of 0.00 and an ending station of 3.73 was split into new sections in 2002 and 2014. Using the smallest section within the period, a template was developed and repeated from 2000 to 2014. The CRS and other records were assigned to the template beginning and ending stations at each year. The records for each smaller section were inherited from the parent section at each year. For example, the sections from 0.00 to 0.50 at year 2000 were assigned the records of the section from 0.00 to 1.44, whereas the same record was used in 2002, 2004, and 2014.

Table 2.4. Example of Data Repopulation (Inventory Number 001 10172 000000)

2000	2002	2004	2014	Template used for 2000–2014
0.00	0.00	0.00	0.00	0.00
1.44	0.50	0.50	0.50	0.50
3.71	1.25	3.71	0.54	0.54
3.73	2.00	3.73	3.71	1.25
	3.71		3.73	1.44
	3.73		3.9	2.00
				3.71
				3.73
				3.90

2.4 DATA CLEANING AND CORRECTIONS

Once the database was consolidated, repopulated, and reduced, the next step before modeling was to find abnormalities and clean the database. The revisions included surface type correction, general cleaning, D-cracking flag correction, slope filtering, and artificial data cleaning. With these correction and cleaning procedures, abnormal or inconsistent records were removed.

2.4.1 Removal of Inconsistencies

The following inconsistencies were identified and removed from the database:

- Surface type mismatch: The CRS records with distresses inconsistent with the declared surface type were deleted. For example, the asphalt-surfaced sections containing the concrete pavement distresses or vice versa were deleted. Because of the uncertainty of what was wrong, this kind of record was deleted to keep the data set as reliable as possible.
- Missing records: The sections without CRS records were deleted.
- Original and resurfacing construction date inconsistencies: There were many sections with an inconsistent original construction date and/or surface construction date. Normally, these records should be corrected or deleted. Such corrections require information from different databases and archives and were outside the scope of this study. Due to the large number of such records, it was also not possible to delete these records, as they contained some significant information and added to the data statistics. Therefore, the

modeling procedure was selected in such a way that prevented pavement age from becoming a modeling variable, as explained in Chapter 3.

2.4.2 D-Flag Correction

The asphalt- and concrete-surfaced sections contained a flag indicating the potential for D-cracking related distress development. It was noted by the Technical Review Panel (TRP) that D-flags were assigned to the sections after testing aggregates for susceptibility to D-cracking, not necessarily based on actual distresses. The research team evaluated these sections with and without the D-flag and revised the D-flag according to the occurrence of actual D-cracking. The overall rule for a concrete section to have a D-flag was consistent with progressing D-cracking distress. The following assumptions were made:

- Sections with only A1 distress without any progression should be removed from D-flagged sections.
- Sections should have at least records of “A” distress, with increasing severity levels indicating consistent progression.

An example of a section with an original D-flag was removed from the D-flagged database as shown in Tables 2.5 and 2.6, along with another section with an accepted D-flag showing the consistency and progression of D-cracking distress.

Table 2.5. Section with a Rejected D-Flag

Inventory number	Beginning station	Ending station	CRS year	CRS	Pavement distress	Real D-flag
058 20322 000000	7.74	8.08	2000	7.8	J1E1	0
058 20322 000000	7.74	8.08	2002	7.2	**A1**B1D1I1J1	0
058 20322 000000	7.74	8.08	2004	7.2	**A1**B1D1I1J1	0
058 20322 000000	7.74	8.08	2005	7	B2D1E1I1J1	0
058 20322 000000	7.74	8.08	2007	6.6	B1C1D1F3J3	0
058 20322 000000	7.74	8.08	2009	6.5	B1D2E3J3K1	0
058 20322 000000	7.74	8.08	2011	6.3	B2D2E3I2J3	0
058 20322 000000	7.74	8.08	2013	6.4	B3D1E3J3	0

Table 2.6. Section with an Accepted D-flag

Inventory number	Beginning station	Ending station	CRS year	CRS	Pavement distress	Real D-flag
048 20313 000000	2.15	2.53	2000	7.4	D1I1	1
048 20313 000000	2.15	2.53	2002	6.7	B2C1H1I2J1	1
048 20313 000000	2.15	2.53	2004	6.9	**A3**B4E3F3I2	1
048 20313 000000	2.15	2.53	2006	4.9	**A4**B5D1F3J3	1
048 20313 000000	2.15	2.53	2008	4.9	**A4**B5J3	1
048 20313 000000	2.15	2.53	2010	5.5	**A3**B3K3	1
048 20313 000000	2.15	2.53	2012	5.3	**A3**B4D1H1J2	1
048 20313 000000	2.15	2.53	2014	5.3	**A4**C3F3J3K3	1

On the other hand, for asphalt overlays, the existing sections with D-flags were kept by adding the sections that contains X distress for one or more years during the analysis period. This resulted in some increase in the number of D-cracked sections for overlays.

2.4.3 Slope Filtering

The slope is calculated based on the CRS difference divided by the CRS year difference. The CRS value of 9.0 is excluded in the slope calculation because a CRS value of 9.0 is often entered by the user and does not represent the actual condition of the pavement.

$$Slope = \ (CRS_{i+1} - \ CRS_i)/(CRS.Year_{i+1} - \ CRS.Year_i)$$

where

CRS_i is the CRS value in year i

Slope represents the deterioration of the pavement condition. The database was reviewed for slopes that may have had inconsistent trends for modeling purposes. The following categories of slopes were determined, as shown in Table 2.7. An algorithm was developed to identify the slopes and flag them with appropriate conditions. The details of the algorithm are provided in Appendix A. This allowed us to develop models with or without considering some of these slopes that should be considered as part of their natural degradation. In the earlier reports, these positive slopes were identified as *flats and risers* and removed from analysis (Heckel and Ouyang, 2007a). However, it is important to capture the contribution of some of these positive slopes in between two consecutive resurfacing activities (flagged as REHAB). The activities taking place during the two resurfacing activities may even include some minor maintenance and preservation works slowing down the deterioration of the pavement. In some other cases, pavement deterioration can be too slow (either at the beginning after resurfacing or at the end when pavement is saturated with damage) so the two consecutive readings can fluctuate and turn out to be positive. All of these cases can be considered as part of an expected deterioration trend of a pavement and can be included if the objective is to estimate a realistic future CRS and the number of years to the point where resurfacing will be needed.

Table 2.7. Slope Trigger Flags and Corresponding Action Taken in the Database

Flags	Description	Interstates	Non-Interstates
NOFLAG	Negative slopes indicating reduction in CRS	Only removed if slope is smaller than -1.0	Only removed if slope is smaller than -1.25
REHAB	A positive slope indicating a resurfacing event (decided by skipped years of CRS record OR jump in CRS OR large IRI correction, etc.)	Removed	Removed
PRESERVE	Positive slopes when current CRS_i is smaller than 7.5 that may indicate some maintenance or preservation work (decided by magnitude of positive slope OR IRI correction OR number of distresses changed, etc.)	Maintained[1]	Maintained[1]
DOWNSTREAM	Positive slope at CRS_i is less than a 6.5 CRS and the 5 distresses are recorded indicating that the pavement is saturated with damage toward the end of its service life	Maintained[2]	Maintained[2]
UPSTREAM	Positive slope when CRS_i and CRS_{i+1} are greater than 7.5 indicating slow deterioration at the early years	Maintained[3]	Maintained[3]
UNKNOWN	Any other condition that cannot be captured by the above flags	Removed	Removed

[1,2,3] Analyses were conducted with and without these positive slopes.

Typical examples of CRS progression with various positive slopes are shown in the following figures for Interstate (Figure 2.1) and Non-Interstate (Figure 2.2) systems. It is important to note that it is not possible to define the exact cause of a positive slope, whether it is related to some sort of maintenance work (patching, sealing, or micro-surfacing, etc.), or inconsistent ratings due to very slow deterioration either at the end or at the beginning. However, the algorithm used to pick these positive slopes helped in understanding more realistic deterioration patterns in between resurfacings. It is clear from some of these figures that the existence of such positive slopes delayed the need for resurfacing. Examining some of the preserve flags also helped in understanding the root cause of the positive slope by looking at the distresses. When the original idea behind the two-slope models were considered, including some of these positive slopes made sense because they are the ones that caused slow deterioration after the breakpoint. If positive slopes are excluded, the representative slope after the breakpoint can be as steep as the slope prior to the breakpoint and cause unrealistically short service life to reach backlog or critical backlog conditions. Historically, IDOT has used backlog-related terminology to describe its highway system and it is reflected in the data used for this study. Moving forward, however, IDOT will use the term “State of Acceptable Condition” when describing its highway system. A similar approach was also taken by one of the previous modeling efforts for the overlays by Wolters et al. (2008). The database was only cleaned from resurfacing events and major maintenance activities that were identified using another database for construction events and a similar CRS-based algorithm.

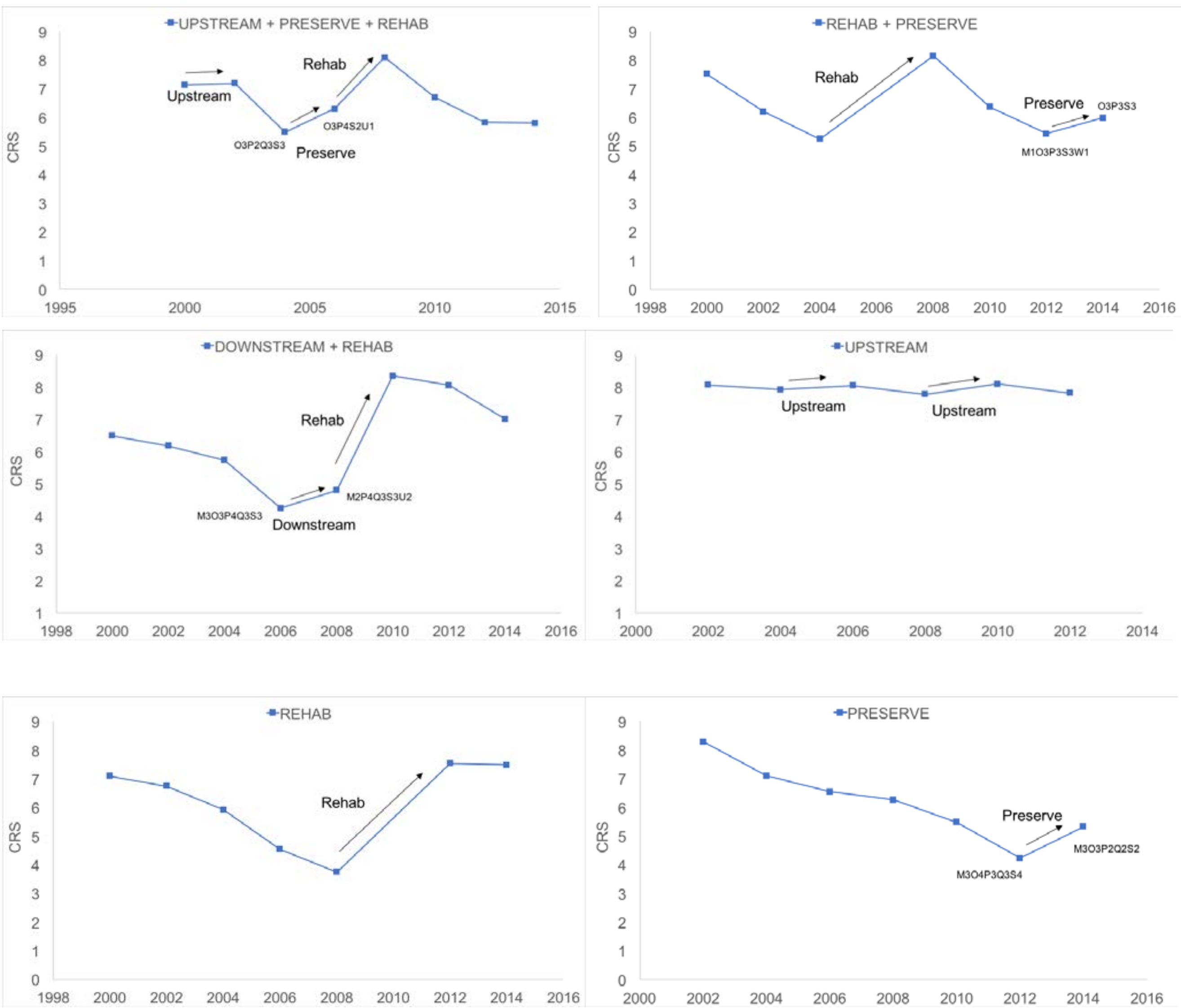


Figure 2.1. Examples of CRS progression with various positive slope flags from Interstate sections.

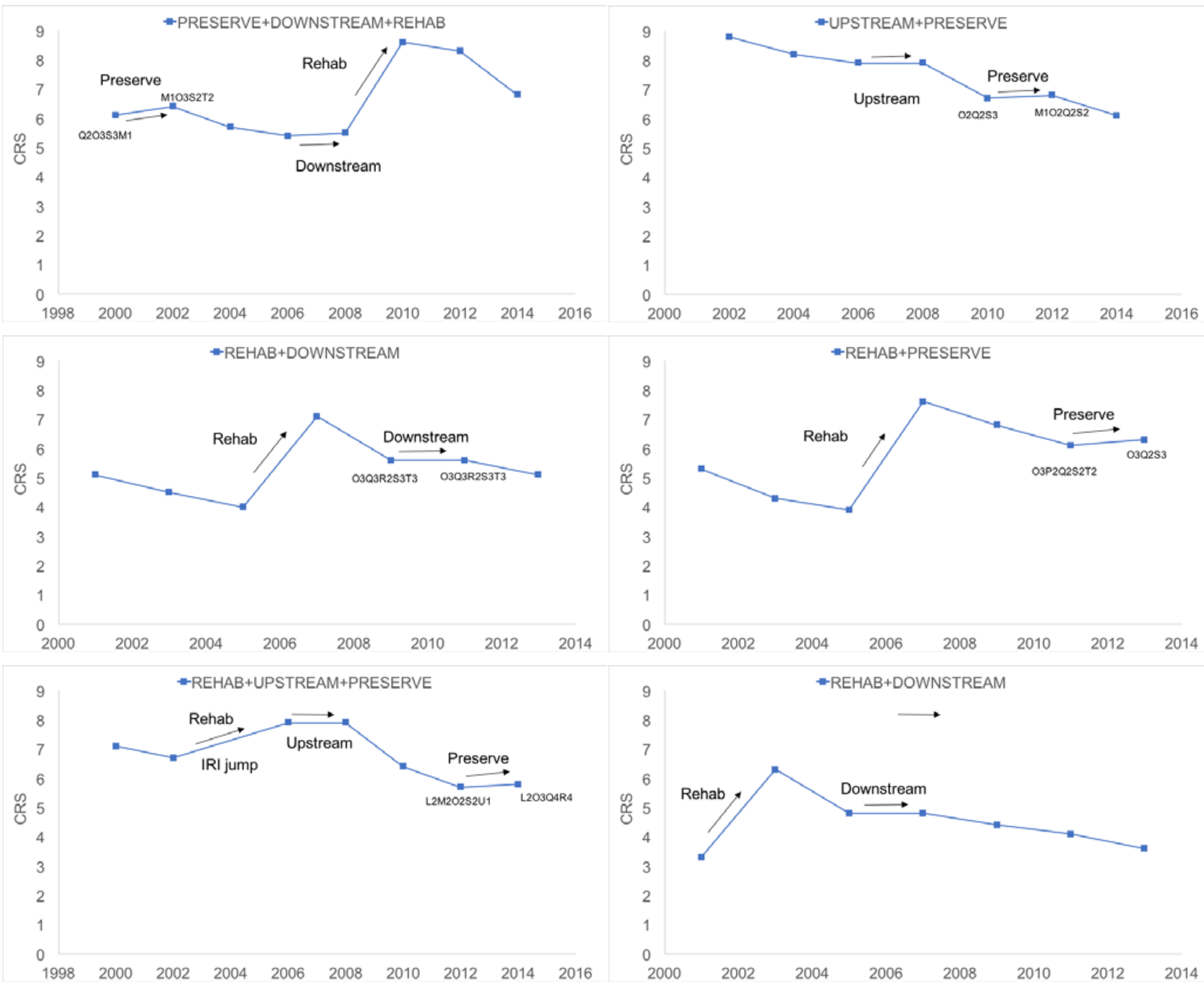


Figure 2.2. Examples of CRS progression with various positive slope flags from Non-Interstate sections.

2.5 DATA STATISTICS

2.5.1 Asphalt-Surfaced Pavements

The final database needed for the development of prediction models was obtained using the aforementioned data preparation and processing steps in this chapter. The original data and post-cleaning data are summarized for Interstates and Non-interstates in Table 2.8 and Table 2.9. The percentage of positive slope occurrences is also reported. The percentage of positive slopes including rehab, preserve, upstream, and downstream flags is consistently converging to 20–25% in the Interstate system. For the Non-interstate system, when there is enough data, the flags converge to 25–30%. When some of the surface types lack data such as D-cracked sections, the proportion of positive slopes may not represent a realistic population. Approximately 10–15% of total slopes are triggered with a rehab flag indicating resurfacing events. Preservation flags constitute approximately

5–10% of total slopes followed by upstream and downstream flags in general, with less than 5% of total slopes.

Table 2.8. Final Populated and Cleaned Database Statistics for Interstates

Surface type	Total Slopes	Positive Slope %	Downstream Flag %	Upstream Flag %	Preserve Flag %	Rehab Flag %
AC/CRCP						
Standard 1-4	1150	22	1	1	11	8
Standard 5-9	1732	21	1	3	9	8
D-cracked 1-4	168	25	1	0	7	16
D-cracked 5-9	705	28	0	7	2	16
AC/JRCP						
Standard 1-4	1052	24	2	1	6	14
Standard 5-9	2584	23	1	1	4	17
D-cracked 1-4	241	46	3	3	13	26
D-cracked 5-9	70	31	0	3	10	19

Table 2.9. Final Populated and Cleaned Database Statistics for Non-Interstates

Surface type	Total Slopes	Positive Slope %	Downstream Flag %	Upstream Flag %	Preserve Flag %	Rehab Flag %
AC/CRCP						
Standard 1-4	676	31	5	2	9	14
Standard 5-9	582	27	4	7	12	4
SMART 1-4	40	15	0	0	8	5
SMART 5-9	0	NA				
D-cracked 1-4	89	22	0	0	16	7
D-cracked 5-9	16	50	25	6	19	0
AC/JRCP						
Standard 1-4	16789	28	6	2	6	12
Standard 5-9	11278	24	6	2	7	9
SMART 1-4	4428	29	4	2	7	14

Surface type	Total Slopes	Positive Slope %	Downstream Flag %	Upstream Flag %	Preserve Flag %	Rehab Flag %
SMART 5-9	1584	24	5	2	8	9
D-cracked 1-4	179	30	7	5	3	15
D-cracked 5-9	229	32	5	0	21	6
AC/JPCP						
Standard 1-4	16159	27	6	1	6	13
Standard 5-9	18615	26	7	1	6	11
SMART 1-4	6303	27	5	0	6	14
SMART 5-9	3692	24	6	1	4	12
D-cracked 1-4	72	32	1	4	11	13
D-cracked 5-9	35	20	Not calculated			
AC/PCCun						
Standard 1-4	25901	33	8	3	7	14
Standard 5-9	22166	24	5	3	6	14
SMART 1-4	3629	27	4	3	8	11
SMART 5-9	6921	25	4	1	6	14
D-cracked 1-4	42	21	0	0	0	0
D-cracked 5-9	290	27	0	0	0	0
ACP						
Standard 1-4	4440	27	7	1	8	10
Standard 5-9	5752	29	5	4	8	11
SMART 1-4	846	22	4	1	5	11
SMART 5-9	799	26	5	2	7	11

2.5.2 Concrete-Surfaced Pavements

Following the data cleaning and preparation procedure, a final database for each concrete-surfaced pavement section was generated. Data available for concrete-surfaced pavement sections include CRCP type (standard and D-cracked) for Interstate and all other concrete types for Non-Interstate system. Figure 2.3 shows the distribution of data and number of data points for each pavement type.

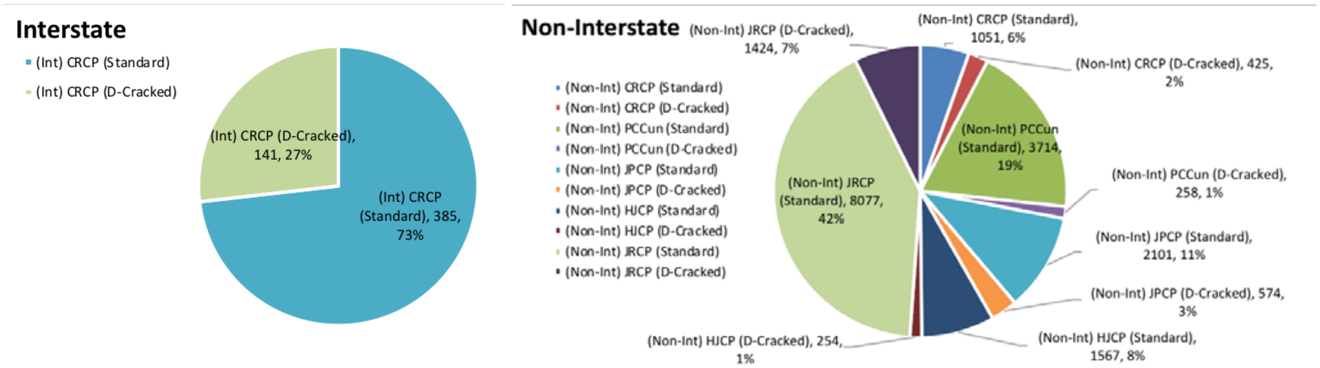


Figure 2.3. Data distribution of concrete-surfaced pavement sections.

2.5.3 Mechanistic Database for Rigid and Asphalt-Surfaced Pavements

The second dataset was obtained from the reports that IDOT authored related to conducting pavement performance monitoring surveys on mechanistically-designed pavements. The report contained the data for the performance of mechanistically-designed pavements. The database included CRCP, JPCP, and ACP sections from Interstate and Non-Interstate systems. Data distribution is shown as follows in Figure 2.4.

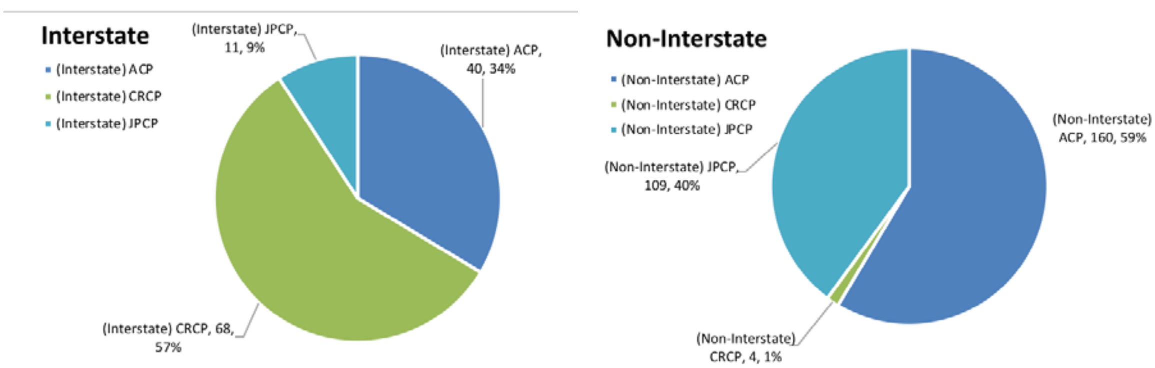


Figure 2.4. Mechanistic report data distribution and statistics.

CHAPTER 3: MODELING AND CALCULATION METHODS

This chapter introduces the modeling approach chosen for asphalt- and concrete-surfaced pavements. Model forms chosen for each pavement type and details of calculation procedures are described, along with an overview of pavement deterioration and relevant data statistics.

3.1 OVERVIEW OF METHODS

Two modeling approaches were used historically to model the future CRS value. One is the continuous modeling method, and the other is the incremental modeling method. The continuous modeling method uses individual data points to fit to a selected model with some independent variables. This data modeling technique is commonly used for pavement condition prediction, with age or time considered as an independent variable, along with some other parameters such as traffic, thickness, or climate. An earlier version of the CRS prediction model was based on a nonlinear model dependent on the age, traffic, and thickness of the sections (Gharaibeh et al., 1999). This modeling technique has some advantages, as it can be adjusted for local project conditions. However, it requires more comprehensive and reliable historical pavement information, such as age, pavement cross-section, and traffic. In the case of the CRS data used in this study, this modeling technique, with age as an independent variable, could not be utilized due to inconsistent records of construction history. These inconsistencies did not allow the use of time or age as an independent variable. Figure 3.1 shows an example of the data commonly observed in the data set. There are points with either missing updates of the reconstruction date or the original construction date. If accurate information can be found for each construction record to utilize complete CRS records, this modeling technique can be used.

The alternative modeling approach is the incremental modeling method based on the incremental CRS values and the slope. Instead of selecting age as the independent variable to model the predicted CRS value, the incremental modeling method focuses on the years of prediction, which is the age difference between two CRS data records. Years of prediction is defined as the difference between two CRS records that may or may not be from consecutive measurement years. This modeling method allows us to include all data available after cleaning to achieve a better modeling result. For the same reasons, the incremental slope-based modeling approach was traditionally used in earlier model development efforts (Gharaibeh et al., 1999; Heckel and Ouyang 2007a).

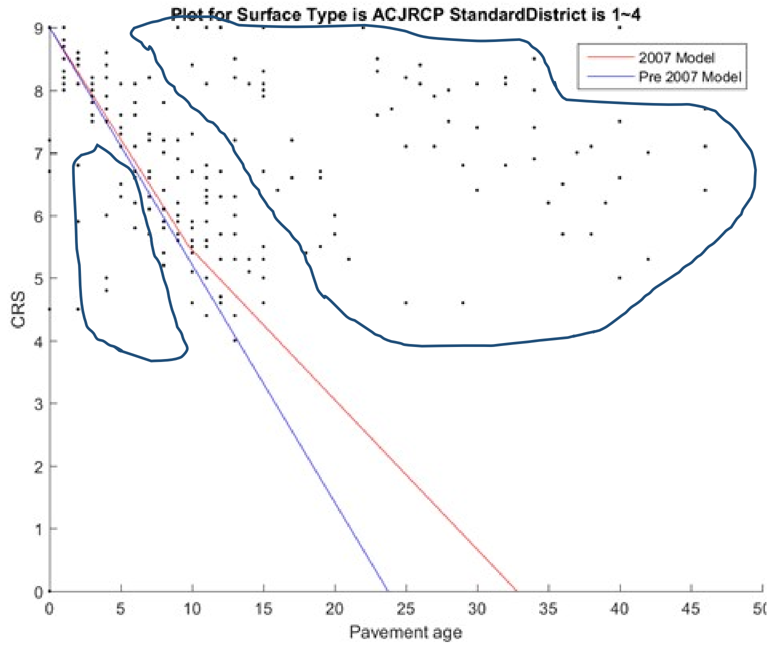


Figure 3.1. CRS data points illustrating pavement age inconsistencies due to either missing updates of reconstruction date or original construction date.

3.1.1 Incremental CRS Prediction Using the Two-Slope Model

The first type of model used in prediction of CRS is the conventional two-slope model. This model is traditionally used by IDOT and was developed in the early 1990s by Darter and colleagues. The format of the model was changed from one-slope to two-slope to better capture the deterioration pattern. Simplicity is the main advantage of the model and service life predictions are consistent with IDOT experiences (Gharaibeh et al., 1999).

The form of the model is shown below. Future CRS values can be calculated using the following equation:

$$CRS_{predicted} = CRS_{current} - m \times years\ of\ prediction \qquad 3.1$$

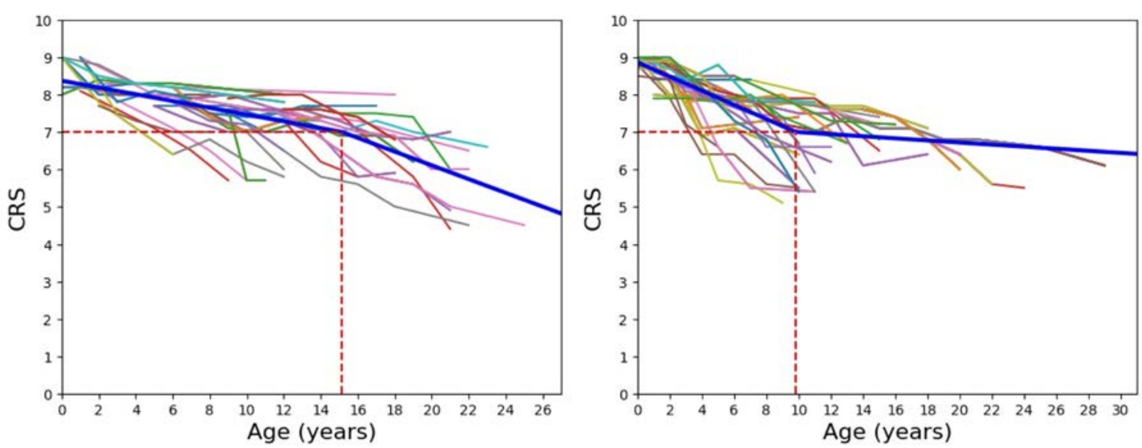
where *m* is the representative slope before and after the breakpoint calculated using the processed and cleaned database. Individual slopes are calculated using the two consecutive data points from CRS measurement years. Then the representative slope (*m*) is calculated using the following definition, which is a weighted average of individual slopes, assigning more weight to the longer sections.

$$m = \frac{\sum_{i=1}^{n} m_i \ * Length_i}{\sum_{i=1}^{n} Length_i} \qquad 3.2$$

where *m* is calculated as the weighted average of sections, considering the length of each section in the database. When the two-slope model is used, m_1 is the slope before the breakpoint and m_2 after the breakpoint. Both m_1 and m_2 are calculated using the above equation and lengths associated with the data before and after the breakpoint.

3.1.2 Incremental Nonlinear Survival-Type Deterioration Model

According to the initial modeling attempts, the incremental two-slope model development procedure was used for rigid pavement types; and representative slope models were developed. However, it was shown that such two-slope models may not accurately capture concrete pavement deterioration, as shown in Figure 3.2. CRS progression data was obtained from the mechanistic database for CRCP and JPCP types. The data clearly shows very slow deterioration within the first 10-15 years of pavement service life. Based on the potential service life for these concrete pavements and their age, there is very little data to capture downstream trends accurately (after breakpoint if using two-slope models). Therefore, the slope after the breakpoint for the JPCP type became flatter, whereas the same slope became steeper for the CRCP type. What is really driving the model here is not the actual pavement deterioration, but the model form and lack of data. This may be one of the reasons why such inconsistent service life estimates were reported for concrete pavements in the previous models.



(a) (b)

Figure 3.2. CRS progression in pavements in the mechanistic database and fitted two-slope model for (a) CRCP and (b) JPCP.

The earlier modeling efforts using two-slope models also showed some inconsistent trends in estimating service life for concrete pavements. According to the 1999 models, rigid pavements service lives to reach a CRS of 4.5 varied from 13.3 years (for JRCP in the Interstate system) and 14.4 years (for PCCun type in the Non-Interstate system) to 44.3 years (for JPCP type in the Non-Interstate system). Similarly, the 2007 models predicted service lives for concrete pavements as low as 20 to 25 years for the Non-Interstate JRCP and the Interstate JPCP pavements and as high as 51.4 years for the Interstate JRCP type. This is primarily due to low counts of data as well as rigidity of the two-slope model to capture deterioration trends in concrete pavements which can be drastically different than the flexible pavements.

In general, pavement performance curves for concrete sections show a very slow deterioration at the beginning and a relatively rapid drop in midlife, then the curves finally flatten out in the final years before reconstruction or resurfacing (as shown in Figure 3.3). This type of deterioration trend can be best captured using sigmoidal or survival-type models, also known as *S*-shaped damage curves, representing damage initiation and accumulation in materials (Gharaibeh and Darter, 2003; Gharaibeh et al., 1999; Wang and Allen, 2008).

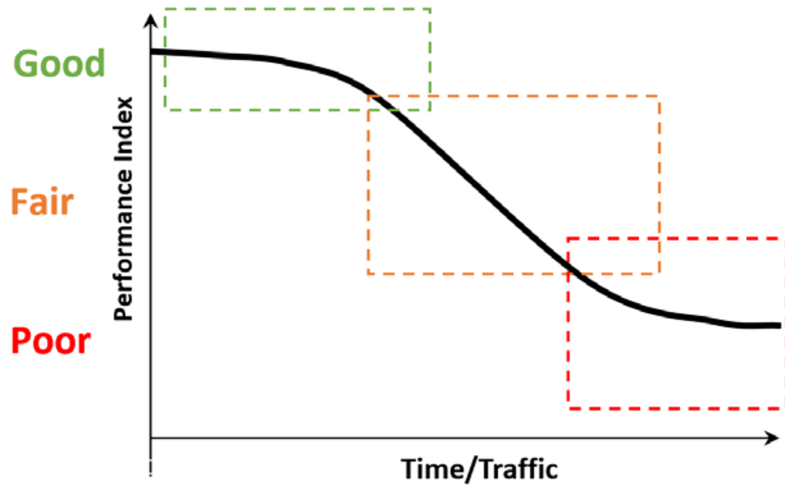


Figure 3.3. An example of the survival-type nonlinear damage curve.

However, it was still impossible to use the database as is to develop such a model in which age is an independent variable. Therefore, the model sought needed to be incremental, to predict future CRS values from the previous CRS values, because time could not be used directly to make future predictions. After a trial-and-error process, the following equation was proposed for rigid pavement structures:

$$CRS_t = \frac{9.0}{1 + \left(\frac{9.1}{CRS_{t-1}} - 1\right) e^{\alpha}} \qquad 3.7$$

where

CRS_t = CRS at year *t*
CRS_{t-1} = CRS at year *t-1*
α = Model parameter (shape factor)

In developing the models, two constraints were set to fit the data: 1) minimum CRS cutoff value (threshold) and 2) the time to reach that cutoff value (time to failure). In selecting the time to failure values, the decision was made to use a compromise between the literature values, as well as the model-fitting performance. Literature values were used as the lower bound of service life values. The upper bound was selected as the service life that best fits the data. The report prepared by IDOT for evaluation of mechanistic designs (IDOT, 2016) provides some useful service life information for some of the sections (JPCP and CRCP). Other service life ranges were obtained from the literature and an Illinois Tollway report (Premkumar, 2014). Table 3.1 summarizes the assumptions for various surfaces. The service life values presented in the table below were used as an initial estimate, which can change depending on the modeling results.

Table 3.1. Modeling Assumptions for CRS Threshold Values and Service Life Estimates for Concrete-Surfaced Pavements

Type	System	Time to CRS = 4.5 (1999 model)	Time to CRS = 4.5 (2007 model)	Others (CRS = 6.5)	Range for this study (CRS = 4.5)
CRCP (standard)	Interstate	33.7	29.0	27-34[1]	35-45
CRCP (D-cracking)	Interstate	19.2	22.2		25-35
JRCP (standard)	Interstate	13.3	20.4	27-35[2]	30-40
JRCP (D-cracking)	Interstate	19.2	20.0		25-30
HJCP (standard)	Interstate	26.8	32.1		30-40
HJCP (D-cracking)	Interstate	19.2	20.0		25-30
CRCP (standard)	Non-Interstate	33.7	39.2		35-40
CRCP (D-cracking)	Non-Interstate	19.2	23.0		25-30
PCCun (standard)	Non-Interstate	14.4	33.6		30-40
PCCun (D-cracking)	Non-Interstate	19.2	23.4		25-30
JPCP (standard)	Non-Interstate	44.3	24.0-31.6		35-40
JPCP (D-cracking)	Non-Interstate	19.2	23.4		25-30
HJCP (standard)	Non-Interstate	26.8	32.1		30-40
HJCP (D-cracking)	Non-Interstate	19.2	19.4-22.7		25-30
JRCP (standard)	Non-Interstate	18.2	30-51.4		30-40
JRCP (D-cracking)	Non-Interstate	19.2	19.4-22.7		25-30

[1] Service life calculated to reach CRS of 6.5 for varying thickness ranging from 12 to 13.5 inches (Premkumar et al., 2014).

[2] Service life calculated to reach CRS of 6.5 for varying thickness ranging from 11.5 to 13.5 inches (Premkumar et al., 2014).

Given the limited number of available data points for each section, models were developed using data from all districts. Further separating models into District groups 1–4 and 5–9 can be done once more data is available for concrete surfaces. The following nonlinear optimization problem was defined to fit the models:

$$\underset{\alpha}{argmin} \left\| CRS_t - \frac{9.0}{1 + \left(\frac{9.1}{CRS_{t-1}} - 1\right) e^{\alpha}} \right\|^2 \qquad 3.8$$

$$s.t. \quad \frac{9.0}{1 + \left(\frac{9.1}{9.0} - 1\right) e^{\alpha t_{FAIL}}} \leq CRS_{Threshold}$$

where $CRS_{Threshold}$ and t_{FAIL} are threshold CRS value and time to failure, respectively (Table 3.1).

In order to perform service life calculations in Chapter 4, the same survival-type model will be used with the initial CRS (CRS_o) assigned to 9.0. In this case, time (t) is taken as the number of years after the initial CRS rating is conducted. Implementation examples of the new concrete models are provided in Appendix D. Examples include calculations for service life predictions for new pavements and backlog calculations for existing pavements. The predicted CRS is calculated using the following equation:

$$CRS_t = CRS_0 - \frac{0.1e^{\alpha t}}{1 + \left(\frac{9.1}{9.0} - 1\right)e^{\alpha t}} \qquad 3.9$$

where t is time in years.

3.2 SELECTION OF BREAKPOINT

Breakpoints can also affect the accuracy of model predictions. A breakpoint was introduced with the two-slope model by Gharaibeh et al. (1999). The team observed that the CRS in many sections exhibits two distinct slopes: one generally steeper, between CRS values of 9.0 and 6.5; and a flatter slope, between 6.5 and 1.0. It was speculated that the slow deterioration during the later stages of a pavement's service life could be due to heavy maintenance activities, such as patching slowing down the reduction of CRS (used as 6.5 in the earlier studies (Gharaibeh et al. 1999). Previously, the breakpoint for concrete- and asphalt-surfaced pavements was used as 7.0 and 5.5, respectively (Heckel and Ouyang, 2007a). Some of these breakpoints were reviewed to improve precision. The following procedure was used in the selection of breakpoints, as shown in Figure 3.4.

The breakpoint-selection procedure was based on the representative method. For every value in the range between the CRS values of 4.5 and 7.5, a trial breakpoint was selected. A new data set was prepared according to the trial breakpoint to calculate the representative slope before and after the trial breakpoint, and unrealistic slopes were removed according to the same criteria introduced in Chapter 2. The new model with the trial breakpoint was used to predict CRS, and the overall root mean square error (RMSE) was calculated for each trial breakpoint. Therefore, for every single breakpoint value between the range [4.5, 7.5], there is a RMSE value for that specific model. The progression of the RMSE values for each breakpoint trial is shown in Figure 3.5.

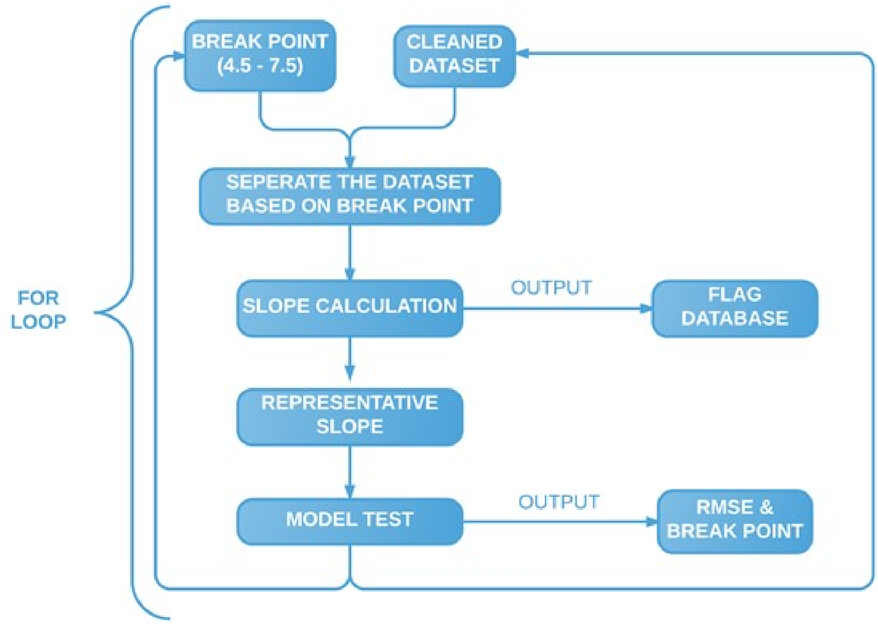


Figure 3.4. Flowchart illustrating the procedure applied to revise the breakpoints of the two-slope models.

Figure 3.5 indicates that a better CRS prediction may be obtained when using a CRS breakpoint between 6 and 7 for most pavement types. There is also an advantage to using a CRS breakpoint of 6.5, as it allows using more data points after the breakpoint, which can also improve overall accuracy of the model prediction. The breakpoint was chosen as 6.5 for all two-slope models. Concrete models used for Interstates and Non-Interstates are nonlinear and do not need a breakpoint.

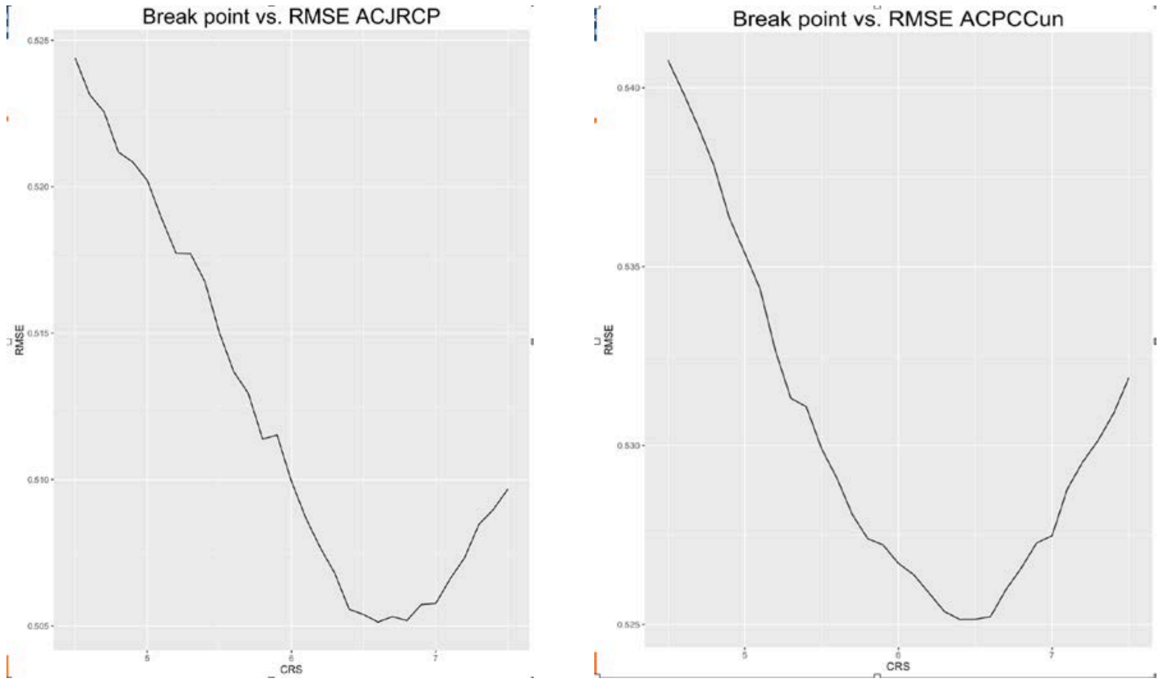


Figure 3.5. Progression of RMSE with the trial breakpoint.

3.3 SELECTION OF INITIAL CRS

In the current database, initial CRS values were artificially set to 9.0 right after reconstruction or resurfacing. An analysis was performed to find a more realistic initial CRS. An accurate initial start point can be important in predicting the service life of pavements. The following procedure was applied for some of the surface types to find the initial representative CRS.

A data set of sections from the newly constructed sections was collected using the following criteria:

- Find the sections with CRS values higher than 8.0.
- Find the section with age 0, 1, or 2.

The data were collected and plotted as a function of age, as shown in Figure 3.6. The data was extrapolated to the age of zero using linear regression to find the intercept. According to the linear regression, the initial point was found to be between 8.3 and 8.5, as shown in Figure 3.6 below with the intercepts. The initial CRS point for AC overlays was set at 8.4 for calculating the service life in Chapter 4. The initial CRS point for full-depth asphalt and concrete pavements remained 9.0.

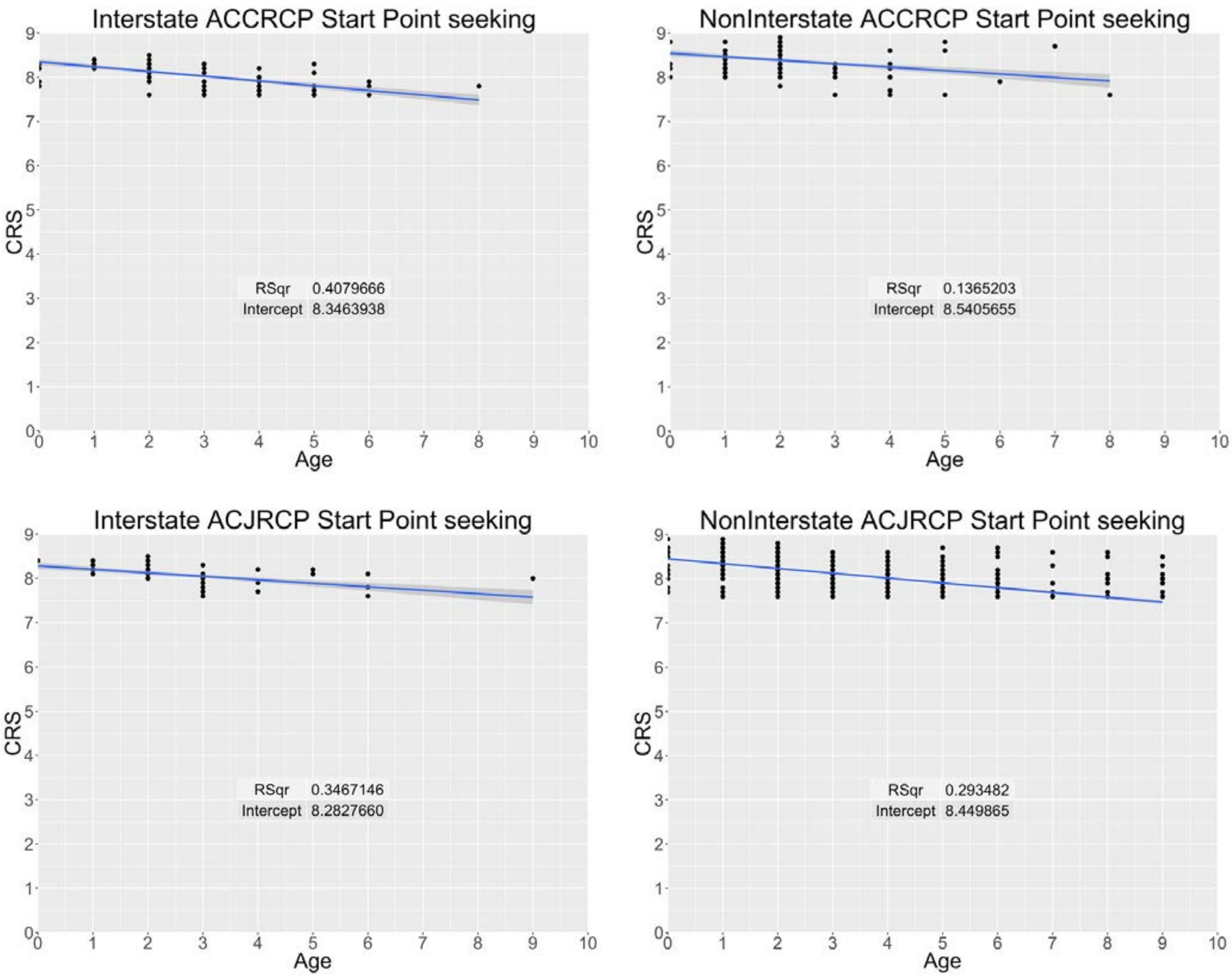


Figure 3.6. Early stages of progression of CRS after a new construction, for Interstate and Non-Interstate overlays.

CHAPTER 4: CRS PREDICTION MODELING RESULTS

This chapter introduces the results of the prediction models. Each section in the Interstate and Non-Interstate system will be discussed separately.

4.1 INTERSTATE PAVEMENT SECTIONS

Different modeling techniques were utilized for concrete and asphalt surfaces, as explained in Chapter 3. Asphalt surfaces were modeled using the representative slope method using the two-slope model, whereas concrete sections were modeled using the proposed survival-type nonlinear models. Each surface type will be introduced one by one with the modeling results as follows:

- A table showing the number of useable slope counts and calculated representative slope
- A comparison of predicted slope progression with the actual measured data progression (also compared to the 1999 and 2007 models)
- A table showing the service life comparison to reach CRS values of 5.5 and 4.5 between the proposed models and previously reported modeling results

4.1.1 CRCP Sections

Concrete surface types were modeled using the survival-type models. Model development is presented in Chapter 3. Figure 4.1 presents the progression of CRS curves, along with the actual data in different ranges of CRS. The model type is incremental and starts with a current CRS to predict a future CRS. In the figure below, CRS starting points were selected in the range of 4.5 to 9.0 with one-unit increments. The model can capture the progression of CRS for this surface type successfully.

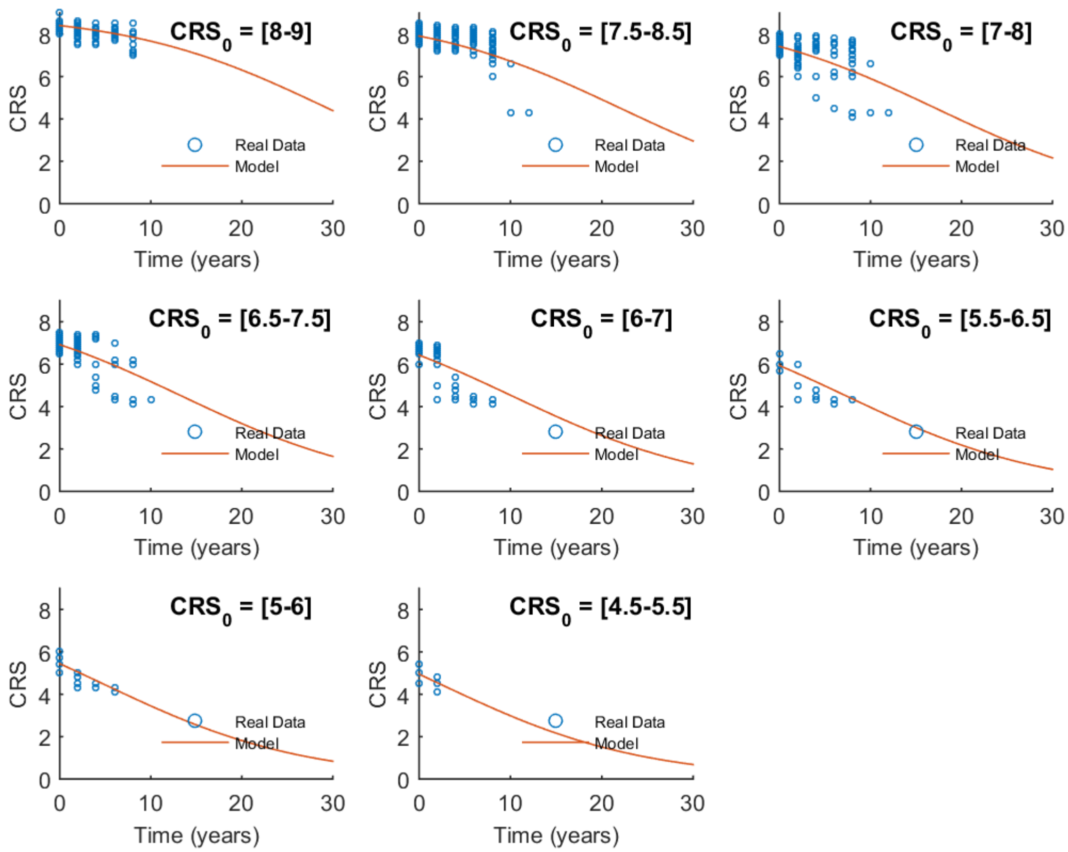
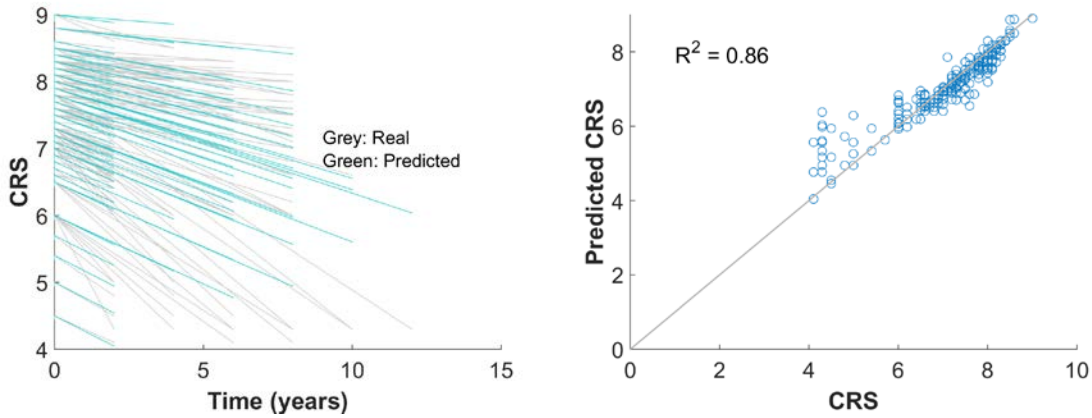
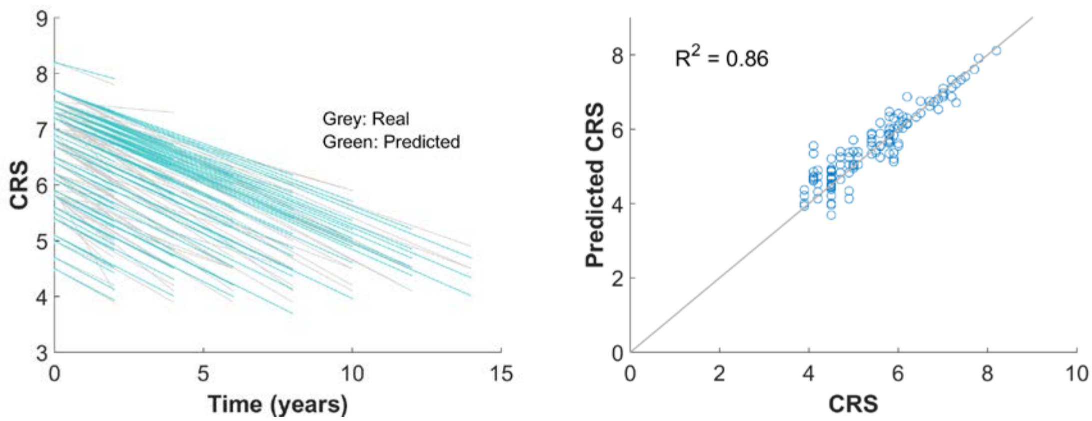


Figure 4.1. Interstate CRCP standard progression curve versus real data at different initial CRS (CRS_0) ranges.

The accuracy of the model was tested, as shown with the figures below. Predicted CRS is compared to the actual CRS using the individual data points (figures on the right), as well as the predicted and actual slopes (figures on the left). The model has very good accuracy, especially when CRS values are higher than 6.0. Figure 4.2 also shows that very little data is available when the CRS is less than 6.0. Most of these sections are relatively new and have not yet reached low CRS ranges. Therefore, the model accuracy is relatively low for long-term predictions. The model form can also be improved to capture long-term CRS predictions.



(a) Standard



(b) D-Cracked

Figure 4.2. Interstate CRCP time series (left) and scatter plots (right) for (a) standard and (b) D-cracked sections.

Model parameters and the R^2 values are shown in Table 4.1. Service life estimates for the CRCP type was 33.7 and 29.0 years to reach CRS of 4.5 according to the 1999 and 2007 models, respectively.

Table 4.1. Interstate CRCP Survival-Type Model Parameter Estimates

Type	System	Failure CRS	Years to reach CRS = 5.5	α	R^2
CRCP (standard)	Interstate	5.5	45	0.090	0.86
CRCP (D-cracked)	Interstate	5.5	35	0.116	0.86

The survival-type model developed for the CRCP surface type was checked against the performance data available in the mechanistic reports. The comparison also allowed us to check whether survival-type models could provide a meaningful correlation with the data available in the mechanistic database. Figure 4.3 shows the progression of CRS and fitted models to the existing data. The shape of the survival curve captures the initial slow deterioration that is typically observed in CRCP pavements. The existing data is mostly in this initial range. It can be concluded that this model type could be successfully used to capture realistic deterioration patterns at the beginning stages that may include rapid deterioration and later stages of concrete pavement service life when pavement is saturated with damage. There is not sufficient data for recently designed and constructed CRCP surface type in the later stages of service life. Many of these CRCP sections in the mechanistic database are as old as 30 years and have not received their first overlay. Therefore, according to the trends in the mechanistic data, the proposed CRCP model appears to be a good fit. It is also a very simple model to calibrate as it only relies on a single parameter that controls shape and terminal service life.

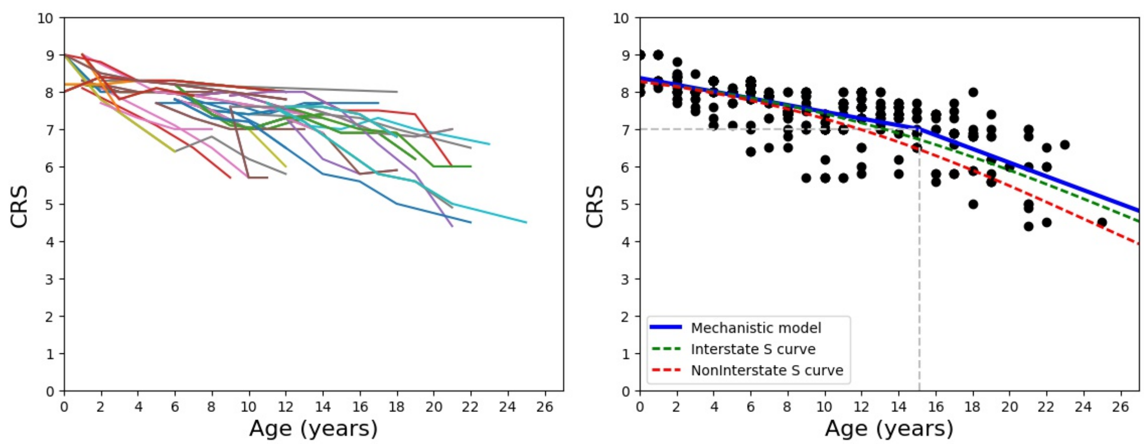


Figure 4.3. Progression of CRS in the mechanistic database for CRCP surface type and models illustrating correlation with the data.

4.1.2 JPCP Sections

Due to insufficient data, modeling of the JPCP section specific to the Interstate system was not done. However, the JPCP models were developed for the Non-Interstate system and correlated with data obtained from the mechanistic performance monitoring database.

4.1.3 JRCP Sections

Due to insufficient data, modeling of the JRCP section specific to the Interstate system was not done. This cross-section is no longer being constructed, so no models need to be developed at this time.

4.1.4 AC/CRCP Overlays

A two-slope model was used for the AC/CRCP surface type. The representative slopes before and after the breakpoint are shown in Table 4.2. Figure 4.4 shows the progression of CRS plotted with the measured data points. A comparison of the service life to reach a CRS of 5.5 and 4.5 is also shown in Table 4.3 with and without the inclusion of selected positive slopes. The service life to reach a CRS of 5.5 using the proposed model is around 13-14 years with the selected positive slopes. When only negative slopes are used, service life to reach CRS values of 5.5 and 4.5 reduces by 4-6 years. D-cracked sections reach a critical CRS of 5.5 in less than 10 years and there is a clear reduction in the number of years to reach CRS values of 5.5 and 4.5 as compared to standard sections. The starting point for CRS was selected as 8.4 to calculate service lives.

Table 4.2 CRS Prediction Model Coefficients for Interstate AC/CRCP Overlays

Districts and CRS Ranges	With Selected Positive Slopes		Without Positive Slopes	
	Standard	D-cracked[1,2]	Standard	D-cracked[1,2]
1-4, CRS ≥ 6.5	-0.2551	NA	-0.2890	-0.3136
1-4, CRS < 6.5	-0.1450	NA	-0.2673	-0.3447
5-9, CRS ≥ 6.5	-0.2690	NA	-0.3027	-0.3136
5-9, CRS < 6.5	-0.1640	NA	-0.2907	-0.3447

[1] Representative slopes for D-cracked sections were calculated without positive slopes due to limited data rule.
[2] Data from Districts 1-4 and 5-9 were combined to calculate representative slope.

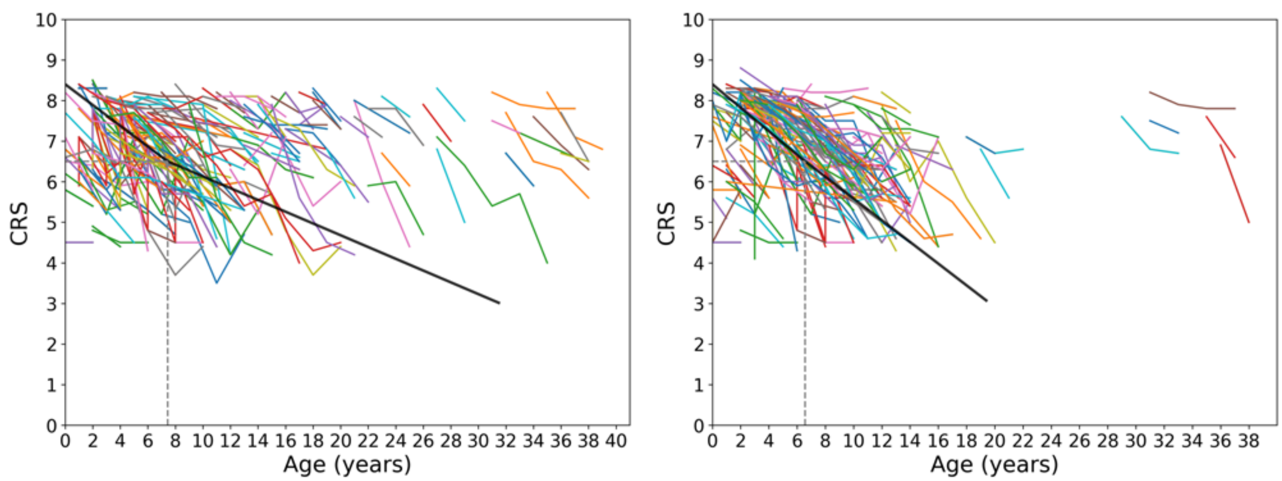


Figure 4.4. Progression of measured slopes and predicted CRS for Interstate AC/CRCP standard sections, Districts 1–4 (left) and 5–9 (right).

Table 4.3. Service Life Check and Comparison with the Previous Models for Interstate AC/CRCP Sections

Interstate AC/CRCP		Years to reach CRS = 5.5	Years to reach CRS = 4.5		
Pavement Type and Districts		Proposed Model	1999 Model	2007 Model	Proposed Model
Standard	1–4	10.3-14.3	19.8	12.6	14.1-21.2
	5–9	9.7-13.2		16.7	13.2-19.3
D-cracked	1–4[1]	9.0	15.6	12.6	11.2
	5–9[1]	9.0	9.9	11.4	11.2

[1] D-cracked sections were calculated using one representative slope only without positive slopes.

4.1.5 AC/JPCP Overlays

There is not sufficient data available for this surface type in the Interstate system. Therefore, the models developed for AC/JRCP can be used to represent this surface type until sufficient data is accumulated.

4.1.6 AC/JRCP Overlays

A two-slope model was used for the AC/JRCP surface type. The representative slope before and after the breakpoint is shown in Table 4.4. Figure 4.5 shows the progression of CRS plotted with the measured data points. A comparison of the service life to reach CRS values of 4.5 and 5.5 is also shown in Table 4.5. The service life to reach a CRS of 5.5 using the proposed model is around 8-10 years with and without selected positive slopes. Similar to the CRCP sections, there is a gain in service life of 3.5 years when selected positive slopes are added to the model. D-cracked sections reach a critical CRS of 5.5 in 7.5 years and there is a clear reduction in the number of years to reach CRS values of 5.5 and 4.5 as compared to standard sections. The starting point for CRS was selected as 8.4 to calculate service lives.

Table 4.4 CRS Prediction Model Coefficients for Interstate AC/JRCP Overlays

Districts and CRS Ranges	With Selected Positive Slopes		Without Positive Slopes	
	Standard	D-cracked[1,2]	Standard	D-cracked[1,2]
1-4, CRS $\geq$ 6.5	-0.3306	NA	-0.3658	-0.4490
1-4, CRS $<$ 6.5	-0.2232	NA	-0.2915	-0.3084
5-9, CRS $\geq$ 6.5	-0.3310	NA	-0.3511	-0.4490
5-9, CRS $<$ 6.5	-0.2082	NA	-0.2636	-0.3084

[1] Representative slopes for D-cracked sections were calculated without positive slopes due to limited data rule.
[2] Data from Districts 1-4 and 5-9 were combined to calculate representative slope.

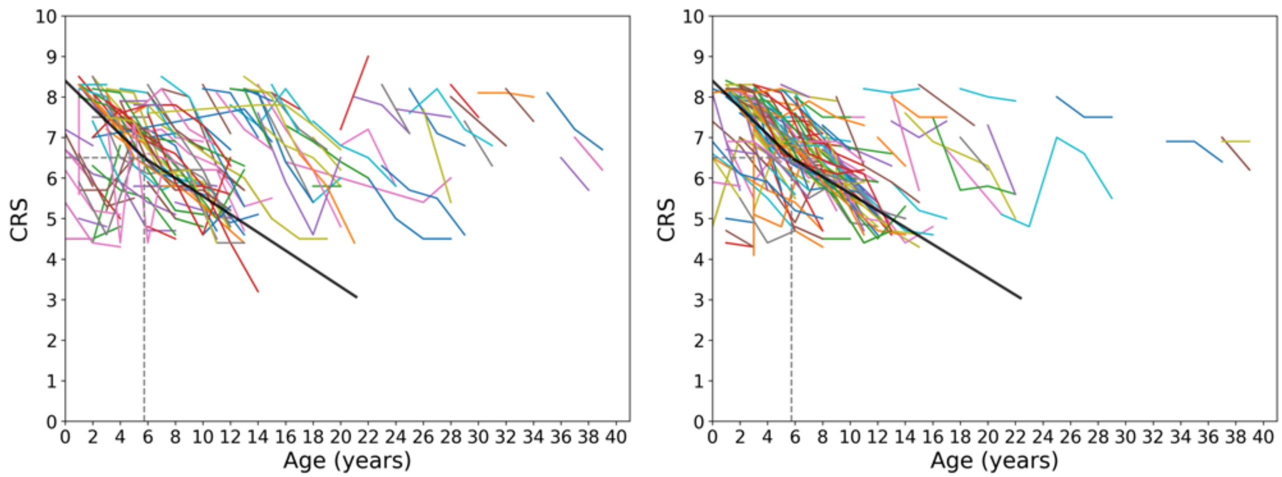


Figure 4.5. Progression of measured slopes and predicted CRS for Interstate AC/JRCP standard sections, Districts 1–4 (left) and 5–9 (right).

Table 4.5. Service Life Check and Comparison with the Previous Models for Interstate AC/JRCP Sections

Interstate AC/JCRCP		Years to reach CRS = 5.5	Years to reach CRS = 4.5		
Pavement Type and Districts		**Proposed Model**	**1999 Model**	**2007 Model**	**Proposed Model**
Standard	1–4	8.6-10.2	18.6	14	12.1-14.7
	5–9	9.2-10.5		15.4	13.0-15.3
D-cracked	1–4[1]	7.5	15.6	14	10.7
	5–9[1]	7.5	9.9	9.3	10.7

[1] D-cracked sections were calculated using one representative slope only without positive slopes.

4.1.7 Full-Depth HMA Sections

Modeling for full-depth HMA sections were completed using multiple databases. There was very little amount of data available for full-depth HMA sections in the Interstate system. The models were developed for the Non-Interstate system using a representative two-slope model. This will be introduced in the section for Non-Interstate models. In addition, the data from the mechanistic reports were also used to develop two-slope models for full-depth HMA sections. Since the age information is believed to be more reliable in the mechanistic database, linear regression was used to fit the two-slope models to the existing data. The mechanistic report contains CRS data after original construction until the first overlay and subsequent overlays. The data were trimmed to develop models only from original construction until the first overlay. The data were obtained primarily from the Non-Interstate system since there were few sections in the Interstate system. The models were developed separately for the Interstate and Non-Interstate systems initially. However, there is a chance of bias when limited data is used in modeling. Therefore, a combined dataset was used in developing models for the full-depth HMA sections. Figure 4.6 shows the data points and the two-slope model developed to fit those data points belonging to the Interstate system. As shown in the figure, there is insufficient data and the model outcome is skewed, resulting in a very small slope after the breakpoint.

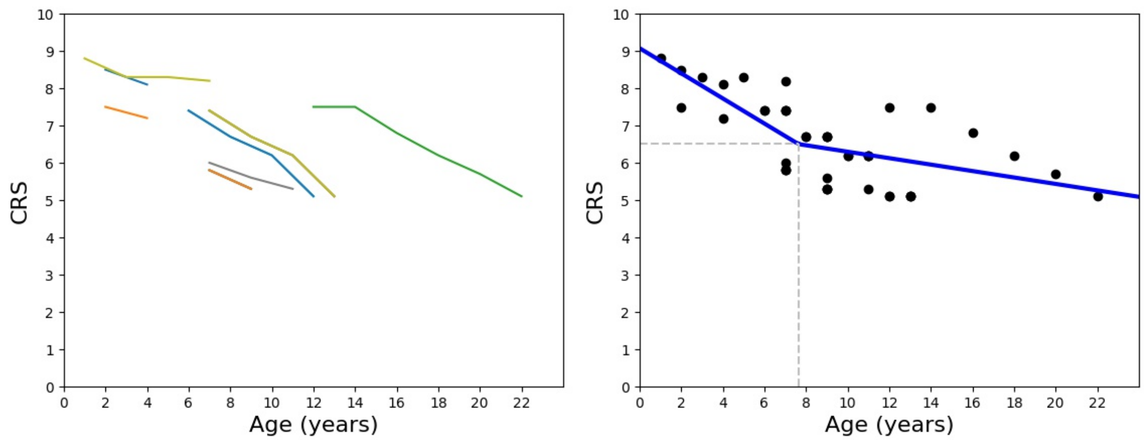


Figure 4.6. Progression of measured slopes and predicted CRS for Interstate ACP standard sections.

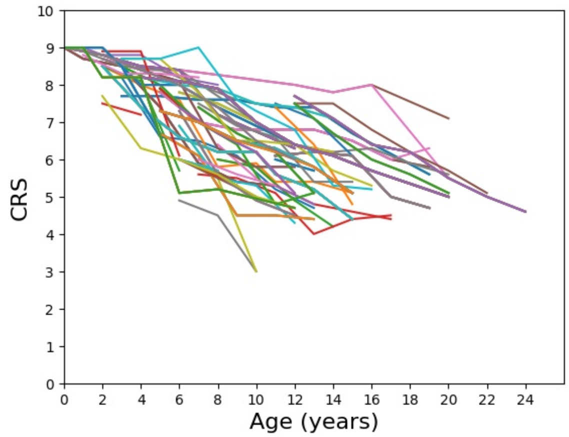
Therefore, the combined dataset in the mechanistic reports was used for sections belonging to the Interstate and Non-Interstate systems. Figure 4.7 shows the progression of slopes for the combined dataset. The model coefficient that fits to the existing data is shown below. The same model applies to Districts 1–4 and 5–9. When fitting was used, the data showed that the initial CRS can be higher than 9.0. However, it is proposed to use an initial CRS of 9.0 for the full-depth HMA sections. The predicted CRS values before and after the breakpoint can be calculated using the following equations:

$$CRS \geq 6.5 \qquad CRS_t = 9.0 - 0.30 * t \qquad (4.1)$$

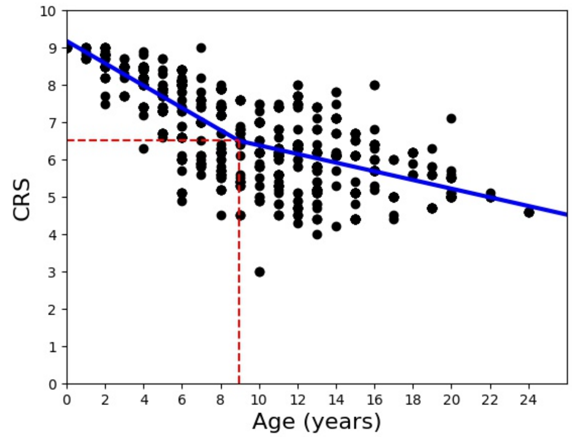
$$CRS < 6.5 \qquad CRS_t = 6.5 - 0.12 * t \qquad (4.2)$$

where *t* is years of prediction after an initial CRS. Slopes were the same for Districts 1-4 and 5-9 since the combined dataset was used in modeling.

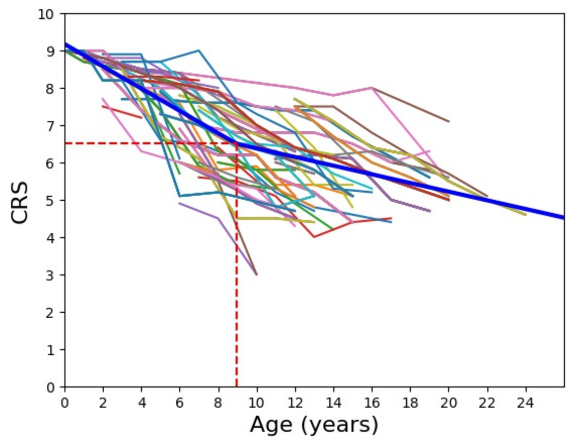
The model fitted to the existing data points is shown in Figure 4.7 (b) and the same model fitted with data curves is shown in Figure 4.7(c). Regression coefficient and root mean square error in the two-slope model were found to be 0.42 and 0.59, respectively. The model appears to be following the actual data trends.



(a) Cleaned data containing only before-treatment



(b) Fitted model with data points



(c) Fitted model with data curves

Figure 4.7. Progression of measured slopes and predicted CRS for Interstate ACP standard sections.

The number of years to reach CRS values of 4.5 and 5.5 are shown below in Table 4.6 as compared to the previous modeling efforts. The proposed model predictions appear to be consistent with the 1999 model, whereas the 2007 model predicts much shorter service life for ACP sections.

Table 4.6. Service Life Check and Comparison with the Previous Models for Interstate ACP Sections

Interstate ACP		Years to Reach CRS = 5.5	Years to Reach CRS = 4.5		
Pavement Type and Districts		Proposed Model	1999 Model	2007 Model	Proposed Model
Standard	1–4	16.7	22	10	25
	5–9	16.7		16.5	25

4.1.8 Summary of Interstate Concrete-Surfaced Sections

A summary of survival model parameters used for Interstate concrete-surfaced pavements is shown in Table 4.7 and Figure 4.8. The time to failure for D-cracked sections was initially determined to be approximately 20% less than that for the standard sections, similar to the earlier modeling practices (Gharaibeh et al., 1999; Heckel and Ouyang, 2007a). Models for CRCP sections were developed. The entire data without separating into different district zones were used due to data limitations. There was not enough data to develop models for other concrete sections in the Interstate system. The models developed for the Non-Interstate JPCP are recommended to be used until more data become available.

Survival-type models were defined by the α coefficient defining the shape and terminal service life to reach when it requires an overlay. It captures the initial slow deterioration trends commonly observed in concrete pavements followed by faster damage accumulation at an almost constant rate and saturation of damage at later stages. The models were developed using the data available primarily belonging to the initial stages of pavements where the CRS was greater than 6.0. The models were compared to the trends in the mechanistic database that includes verified and clean detailed historical performance data. The proposed survival curve is capable of capturing the existing trend in the mechanistic database. Additionally, many of these sections in the mechanistic database (as old as 30 years) have not received their first overlay. Therefore, the team concluded that the survival-type damage curve is considered to be a good candidate to estimate performance of concrete pavements in the Interstate as well as the Non-Interstate system.

As compared to the previous models developed in 1999 and 2007, the proposed models resulted in relatively longer service life estimates. The terminal service life was selected to determine how well the model fits with existing data based on earlier modeling efforts in Illinois for concrete pavements (1999 and 2007 IDOT models, and 2014 Tollway model presented by Premkumar et al. 2014). This can be attributed to the components of the model as well as the performance data coming from more recently constructed sections. However, it is strongly recommended to verify these models when there is enough data available to indicate performance of recently constructed concrete pavements at the later stages of pavement life. This is the case for both the Interstate and Non-Interstate systems.

Table 4.7. Summary of Survival-Type Model Parameters for Interstate Concrete-Surfaced Sections

Type	Surface Type	Districts	α	Initial CRS	Years to CRS = 5.5	Years to CRS = 4.5
Standard	CRCP	1-9	0.100	9.0	40.0	45.0
	JPCP	1-9	0.112	9.0	36.0	40.0
D-cracked	CRCP	1-9	0.129	9.0	31.0	35.0
	JPCP	1-9	0.150	9.0	27.0	30.0

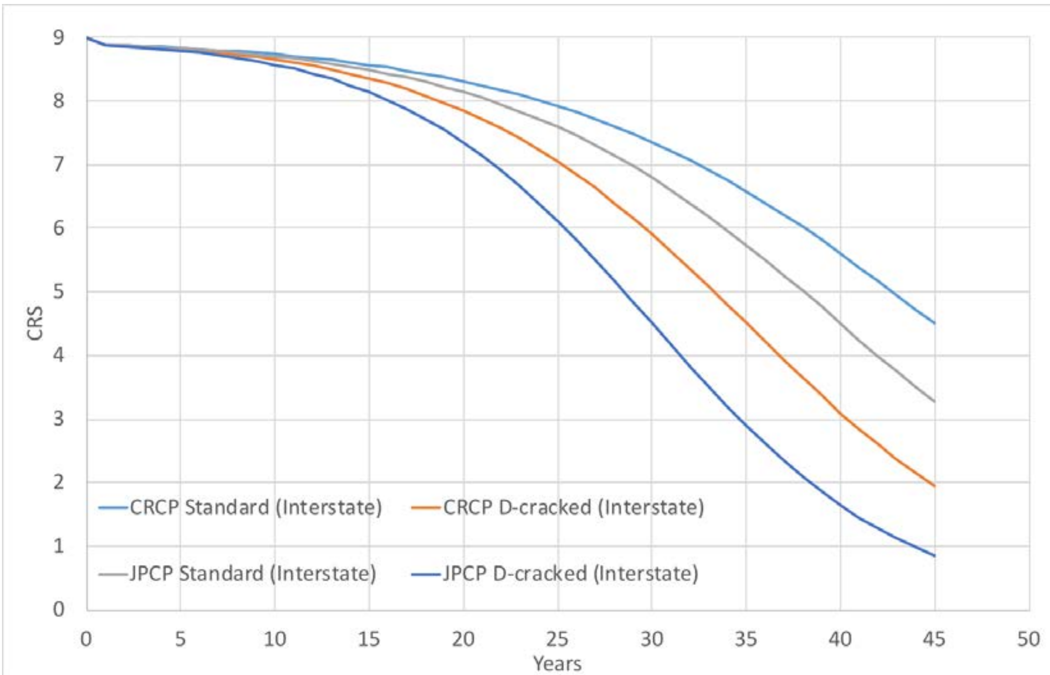


Figure 4.8. Progression curve plots for Interstate rigid pavement sections.

4.1.9 Summary of Interstate Asphalt-Surfaced Sections

A summary of asphalt-surfaced sections is provided below. Table 4.8 summarizes expected service life to reach CRS values of both 5.5 and 4.5 for standard and D-cracked surface types. Slopes and service life predictions were completed using the two-slope models based on the dataset that included all CRS values within the rehabilitation events. The flags were assigned to each section using the algorithm developed to include data points that should be considered as part of a pavement's natural deterioration or maintenance/preservation activities. The analysis was done with and without adding positive slopes (defined as flats and risers in the previous study). The total percentage of positive slopes were around 20-30%. The flags indicating the resurfacing events represented most of the positive slopes. Significant service life gains were observed for asphalt overlays of concrete pavements, especially for AC/CRCP sections with the addition of positive slopes, except for the ones indicating a resurfacing or major reconstruction event.

In general, the service life to reach a CRS of 5.5 varies from 10 to 14 years for overlays on rigid surfaces, whereas service life predictions for the original full-depth HMA and an overlay of a full-depth HMA pavement is within 15-17 years. The surface types AC/CRCP and overlays of full-depth HMA pavement have comparable service life predictions to reach CRS values of 5.5 and 4.5. Considerable reduction in service life of asphalt overlays on D-cracked pavement surfaces was observed.

The following observations can be made with regards to the data and results:

- The performance of AC/CRCP surface type is clearly doing better than the AC/JRCP type by about 25-40%.
- No significant difference was observed between northern and southern districts in the Interstate system. This is consistent with the findings of the previous study for the Interstate pavement family by Wolters et al. (2008).
- There is a significant reduction in the service life of D-cracked pavements as compared to standard surface types. Reduction is within the range of 26 and 44%. It is important to note that D-cracked sections include the ones with D-cracking flags in the database and sections with at least one X type of distress.
- There is not sufficient data available for AC/JPCP surface types. Until enough historical data are collected, the slope coefficients of AC/JRCP were assigned to AC/JPCP.
- Due to the lack of full-depth HMA pavements in the database, the models developed using the mechanistic database were assigned to the standard Interstate ACP surface types. The standard ACP surface-type model was derived from the mechanistic database including the historical data after original construction until the first overlay.
- Considering the changes in performance expectancy after each overlay for full-depth HMA pavements, the standard overlay type for full-depth HMA (AC/ACP) is recommended. The two-slope model coefficients obtained for the Non-Interstate database for Districts 5-9 was assigned to the model for this surface type. Even though the previous study by Wolters et al. (2008) found an unexpected trend of performance increase with the increasing number of overlays, the effect of the number of overlays needs to be investigated by more precise models. This should include existing thickness, milling depth, and type of HMA in each overlay. There have been recent anecdotal notes regarding the superior performance of SMA type mixes when they are used as overlays.

Table 4.8. Summary of Model Parameters for Interstate Asphalt-Surfaced Sections

Type	Surface Type	Districts	Slope when CRS ≥ 6.5	Slope when CRS < 6.5	Initial CRS	Years to CRS = 5.5	Years to CRS = 4.5
Standard	AC/CRCP	1-4	-0.2551	-0.1450	8.4	14.3	21.2
		5-9	-0.2690	-0.1640	8.4	13.2	19.2
	AC/JRCP	1-4	-0.3306	-0.2232	8.4	10.2	14.7
		5-9	-0.3310	-0.2082	8.4	10.5	15.3
	AC/JPCP	1-4	-0.3306	-0.2232	8.4	10.2	14.7
		5-9	-0.3310	-0.2082	8.4	10.5	15.3
	AC/ACP	1-9	-0.2828	-0.1535	9.0	15.4	21.9
	ACP	1-9	-0.3000	-0.1200	9.0	16.7	25.0
D-cracked	Jointed Rigid	1-9	-0.4490	-0.3084	8.4	7.5	10.7
	CRCP	1-9	-0.3136	-0.3447	8.4	9.0	11.9

4.2 NON-INTERSTATE PAVEMENT SECTIONS

4.2.1 CRCP

Non-Interstate concrete-surfaced pavements were also modeled using the survival-type model. The initial estimates of service life were taken to be 45 and 35 years for standard and D-cracked sections, respectively. Unlike the approach with Interstate sections, time to failure is calculated to find the time to reach a CRS of 4.5. Similar to findings for the Interstate concrete sections, Figure 4.9 presents the progression of CRS curves, along with the actual data in different ranges of CRS. The model type is incremental, starting with a current CRS to predict a future CRS. The model can capture progression of CRS for this surface type successfully.

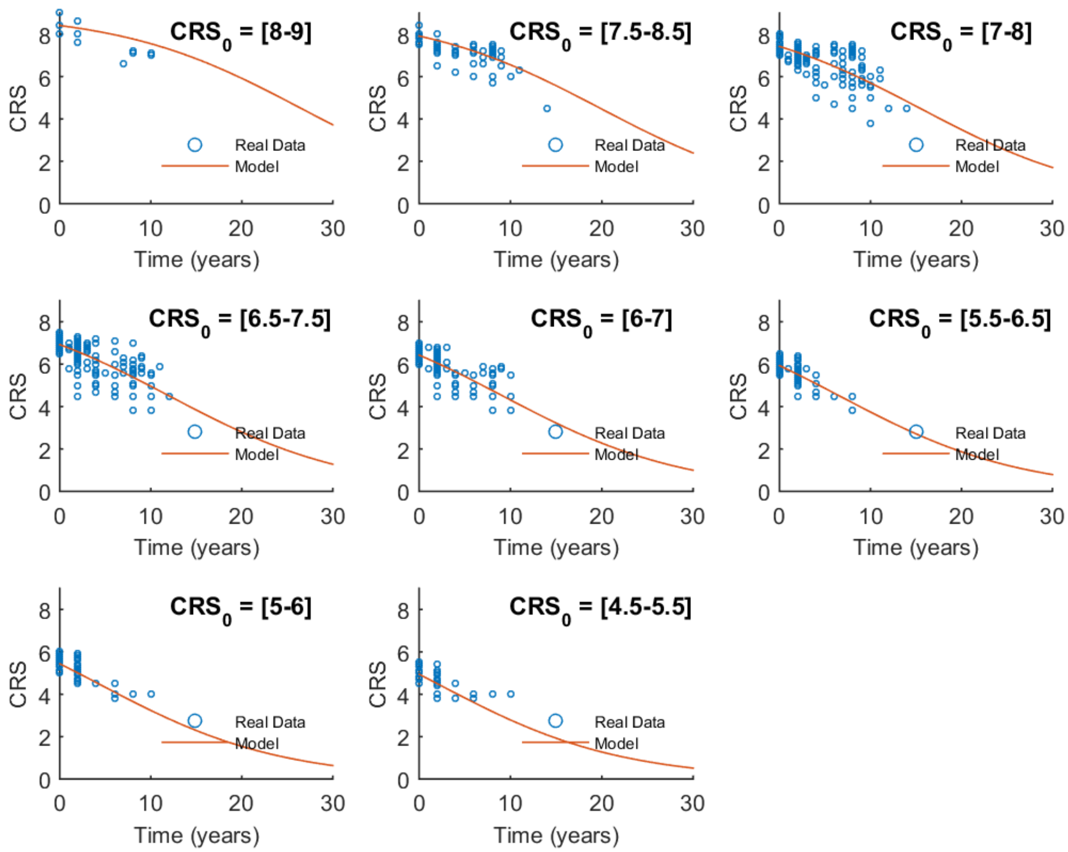
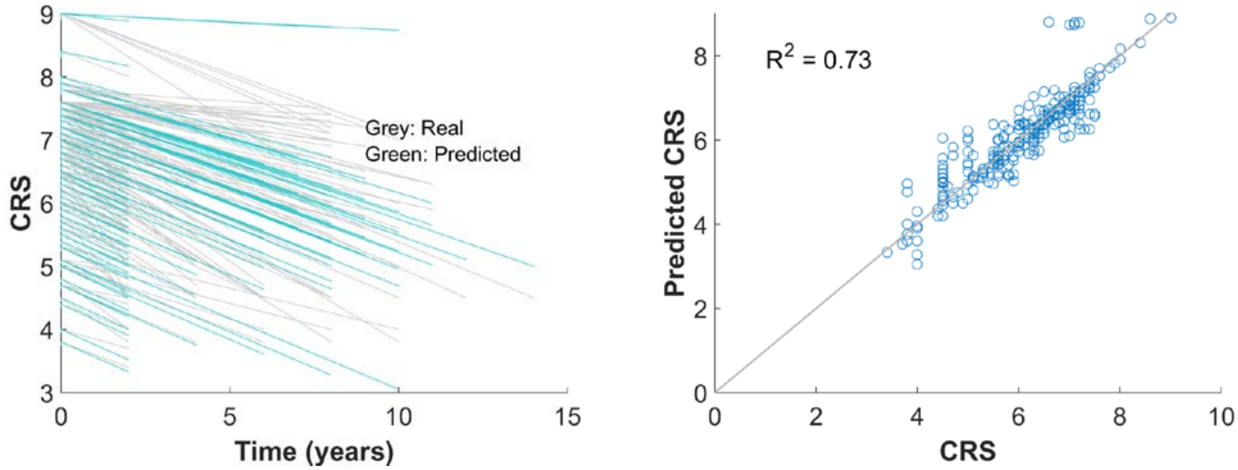
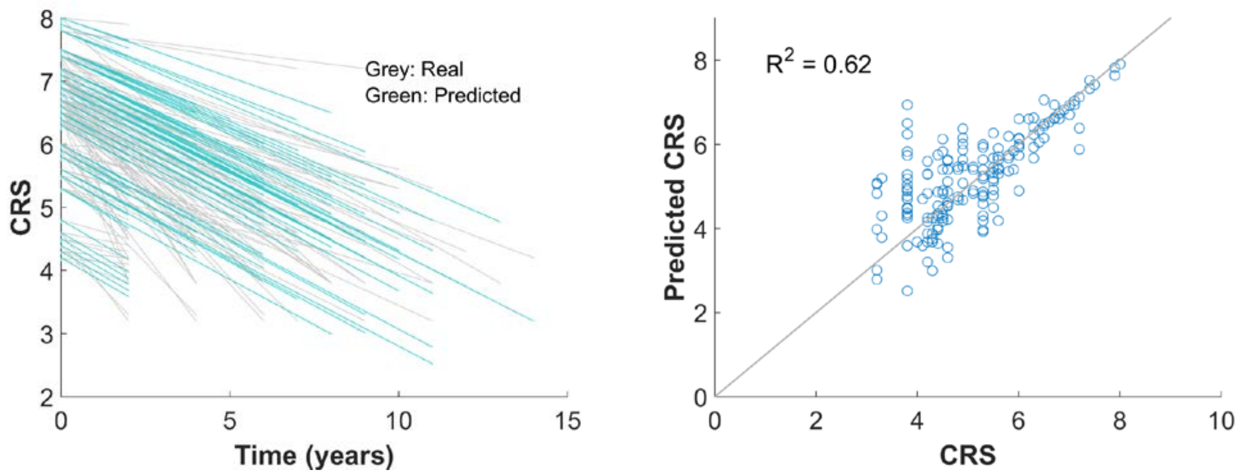


Figure 4.9. Non-Interstate CRCP standard progression curve versus real data at different initial CRS (CRS_0) ranges.

The accuracy of the model was tested, as shown in Figure 4.10. The predicted CRS is compared to the actual CRS using the data points individually (figures on the right), as well as the slopes predicted and actual (figures on the left). The standard model has very good accuracy, especially when CRS values are higher than 6.0. Accuracy of the D-cracked model is relatively low, but still can be considered acceptable. Similar to the situation with Interstate CRCP sections, very little data is available when CRS is less than 6.0. Therefore, in general, the model accuracy is relatively low for long-term predictions.



(a) Standard



(b) D-Cracked

Figure 4.10. Non-Interstate CRCP time series (left) and scatter plots (right) for (a) standard and (b) D-cracked sections.

Model parameters and the R^2 values are shown in Table 4.9. The estimated service life to reach a CRS of 4.5 for this surface type was 33.7 years and 39.2 years according to the 1999 and 2007 models.

Table 4.9. Non-Interstate CRCP Survival-Type Model Parameter Estimates

Type	System	Failure CRS	Time to Failure	α	R^2
CRCP (standard)	Interstate	4.5	40	0.112	0.70
CRCP (D-cracked)	Interstate	4.5	30	0.150	0.60

4.2.2 JPCP

A similar approach was followed for the JPCP sections. Figure 4.11 presents the progression of CRS curves, along with the actual data in different ranges of CRS for standard sections.

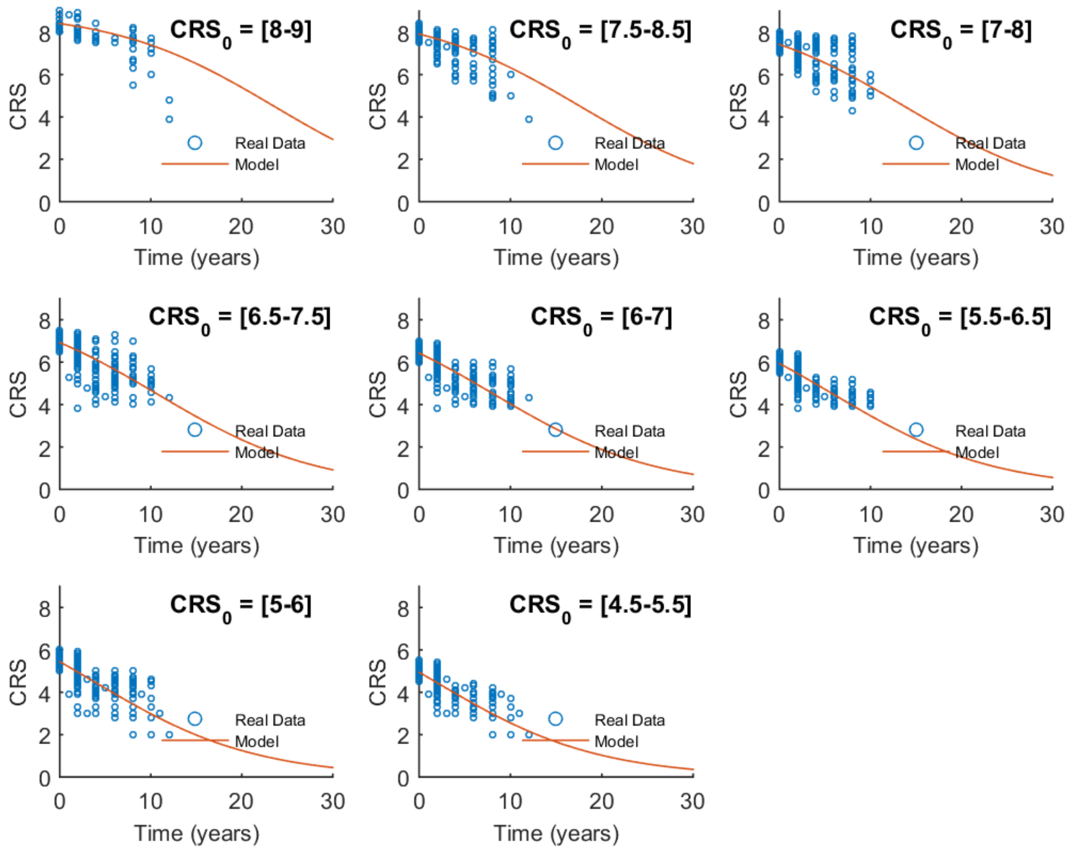
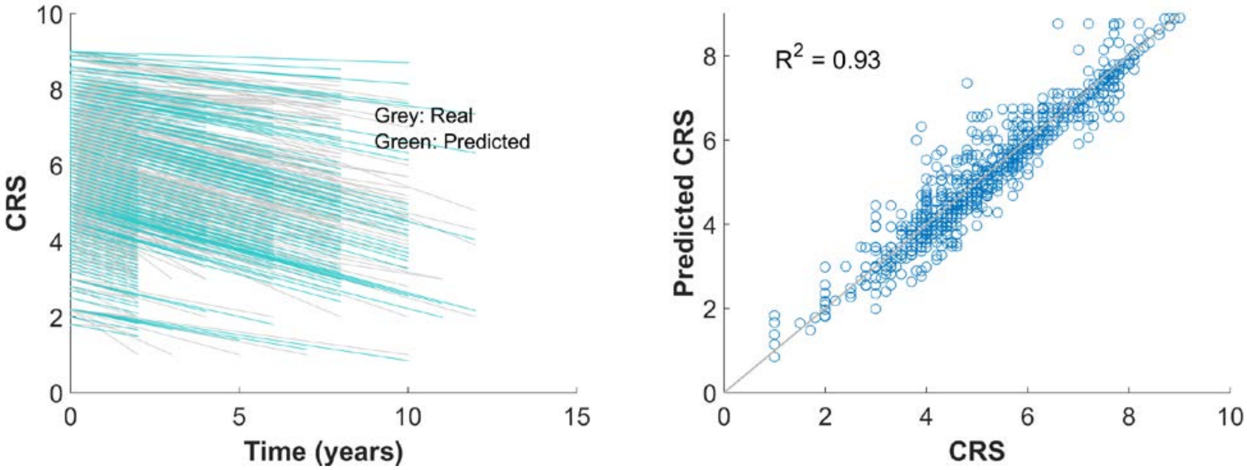
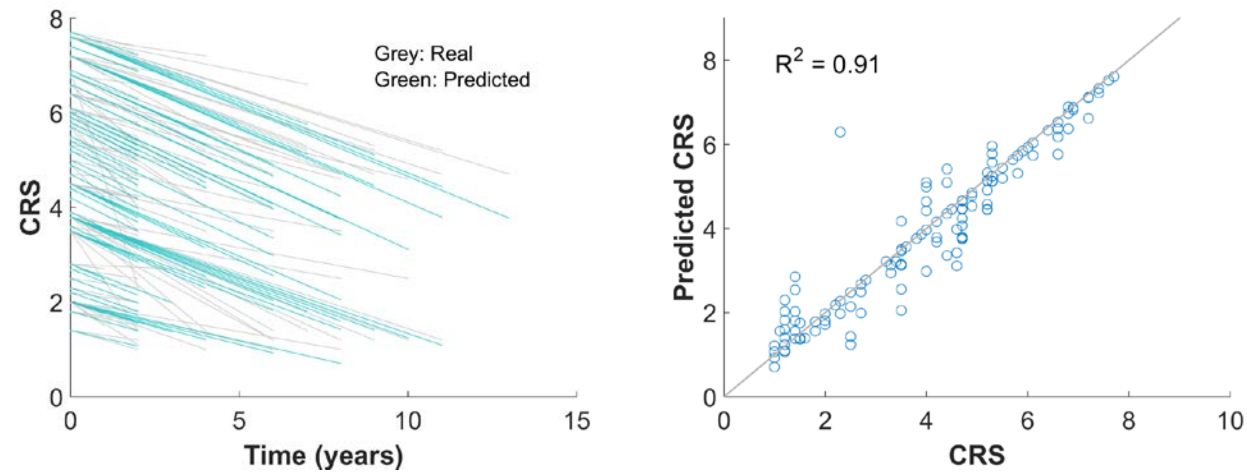


Figure 4.11. Non-Interstate JPCP standard progression curve versus real data at different initial CRS (CRS$_0$) ranges.

Figure 4.12 shows the accuracy of the model to be similar to that of the previous concrete surfaces. The standard model has very good accuracy across a wide range of data. Contrary to the CRCP sections, as the number of data points increased at low CRS ranges, the accuracy of the model also increased.



(a) Standard



(b) D-Cracked

Figure 4.12. Non-Interstate JPCP time series (left) and scatter plots (right) for (a) standard and (b) D-cracked sections.

Model parameters and the R^2 values are shown in Table 4.10. The estimated service life to reach a CRS of 4.5 for this surface type was 44.3 years using the proposed model and 24.0 to 31.6 years according to the 1999 and 2007 models, respectively.

Table 4.10. Non-Interstate JPCP Survival-Type Model Parameter Estimates

Type	System	Failure CRS	Time to failure	α	R^2
JPCP (standard)	Non-Interstate	4.5	40	0.113	0.93
JPCP (D-cracked)	Non-Interstate	4.5	30	0.150	0.91

4.2.3 JRCP

Figure 4.13 presents the progression of CRS curves, along with the actual data in different ranges of CRS.

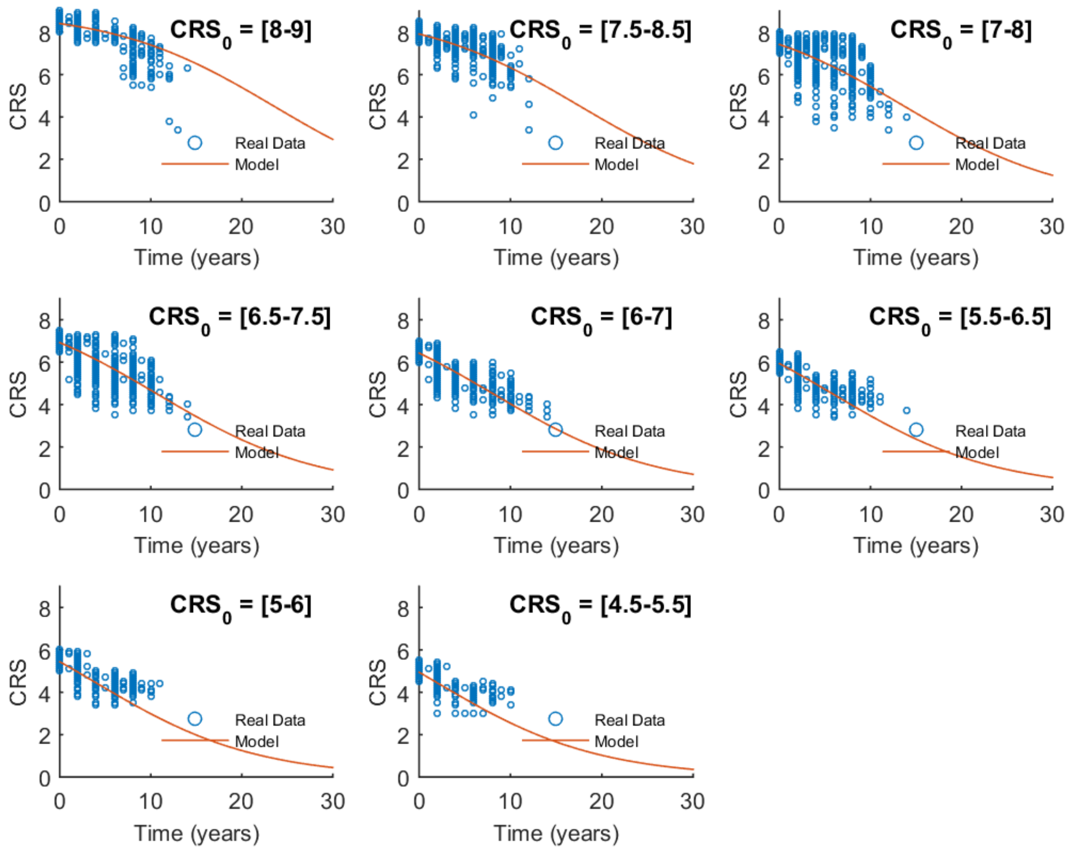
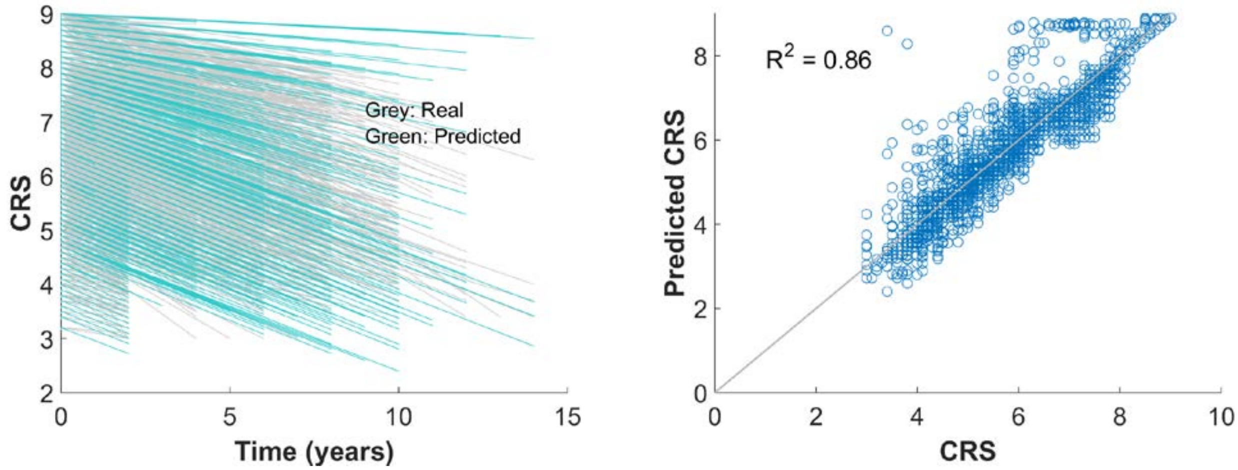
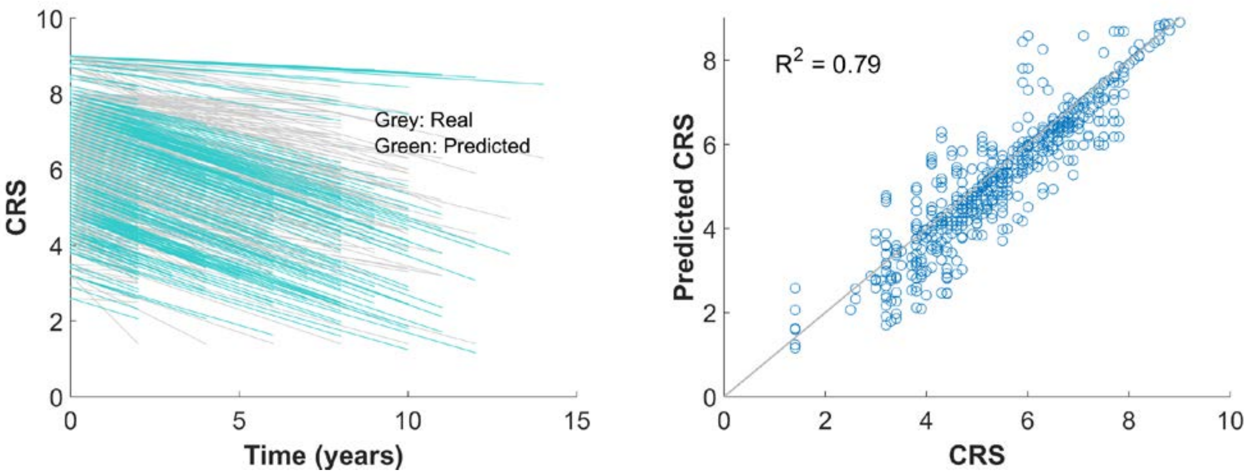


Figure 4.13. Non-Interstate JRCP standard progression curve versus real data at different initial CRS (CRS_0) ranges.

A similar accuracy was achieved with the JRCP section models, as shown in Figure 4.14. The model can be improved with additional data cleaning. As shown in the previous figure and the figure below with standard sections, there are some data points with low actual CRS values (ranging from 2 to 6 years) within the first 10 years after construction. These can be associated with incorrect construction dates or early deterioration due to design and construction quality.



(a) Standard



(b) D-Cracked

Figure 4.14. Non-Interstate JRCP time series (left) and scatter plots (right) for (a) standard and (b) D-cracked sections.

Model parameters and the R^2 values are shown in Table 4.11. The estimated service life to reach a CRS of 4.5 for this surface type was 18.2 years using the proposed model and 30.0 to 51.4 years according to the 1999 and 2007 models, respectively.

Table 4.11. Non-Interstate JRCP Survival-Type Model Parameter Estimates

Type	System	Failure CRS	Time to failure	α	R^2
JRCP (standard)	Non-Interstate	4.5	40	0.113	0.86
JRCP (D-cracked)	Non-Interstate	4.5	30	0.150	0.79

4.2.4 PCCun

The model progression and accuracy for PCCun are shown in Figures 4.15 and 4.16. There is a sufficient number of data points across a wide range of CRS values for this type. Therefore, the model accuracy is high for both standard and D-cracked sections.

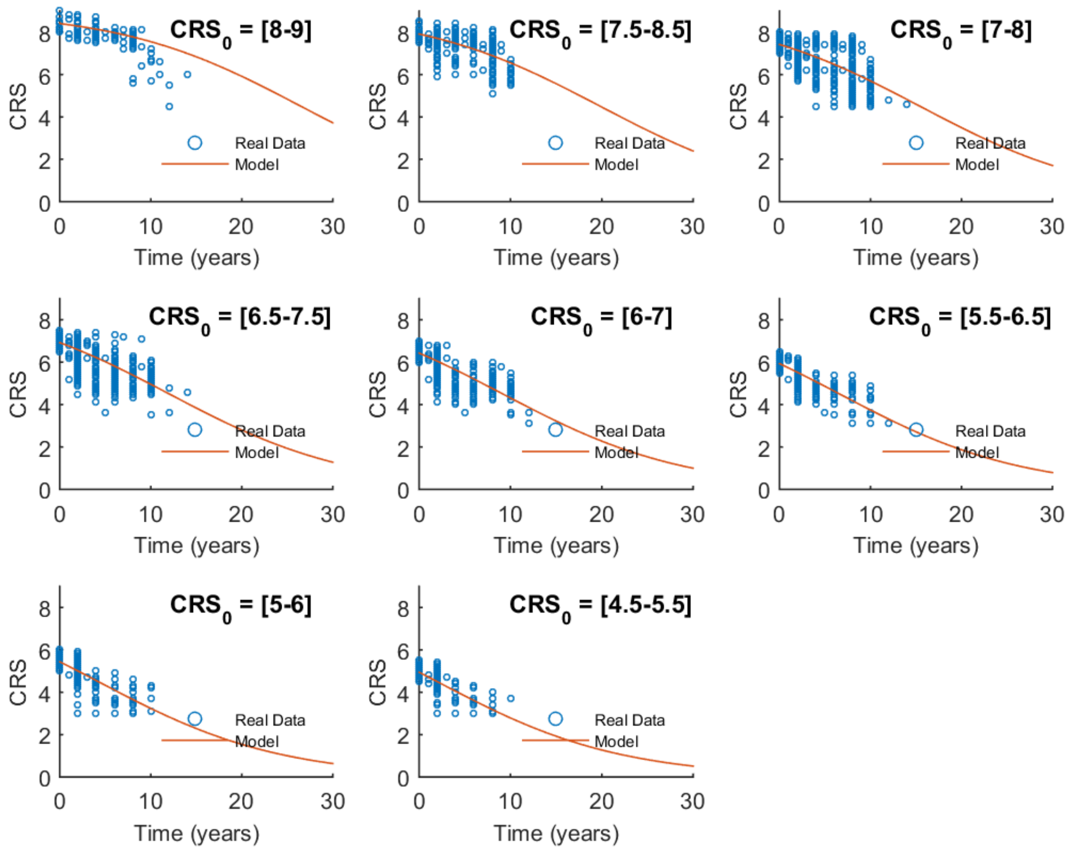
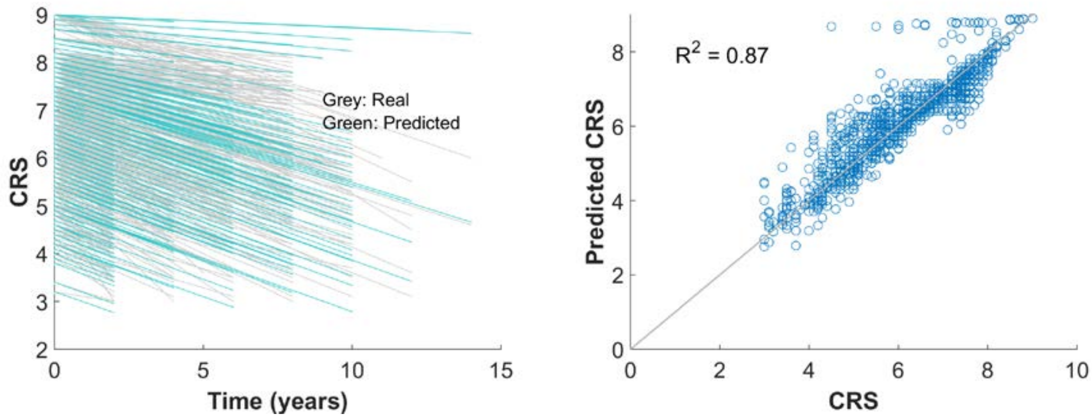
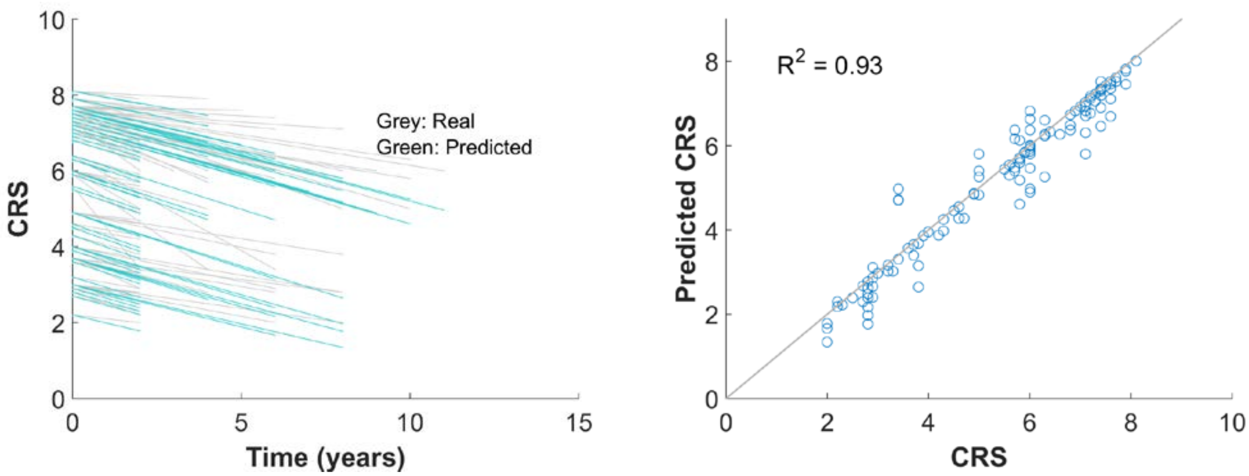


Figure 4.15. Non-Interstate PCCun standard progression curve versus real data at different initial CRS (CRS_0) ranges.



(a) Standard



(b) D-Cracked

Figure 4.16. Non-Interstate PCCun time series (left) and scatter plots (right) for (a) standard and (b) D-cracked sections.

Model parameters and the R^2 values are shown in Table 4.12. The estimated service life to reach a CRS of 4.5 for this surface type was 14.4 years using the proposed model and 33.6 years according to both the 1999 and 2007 models.

Table 4.12. Non-Interstate PCCun Survival-Type Model Parameter Estimates

Type	System	Failure CRS	Time to failure	α	R^2
PCCun (standard)	Non-Interstate	4.5	35	0.128	0.82
PCCun (D-cracked)	Non-Interstate	4.5	25	0.180	0.82

4.2.5 HJCP

The model progression and accuracy for HJCP are shown in Figures 4.17 and 4.18.

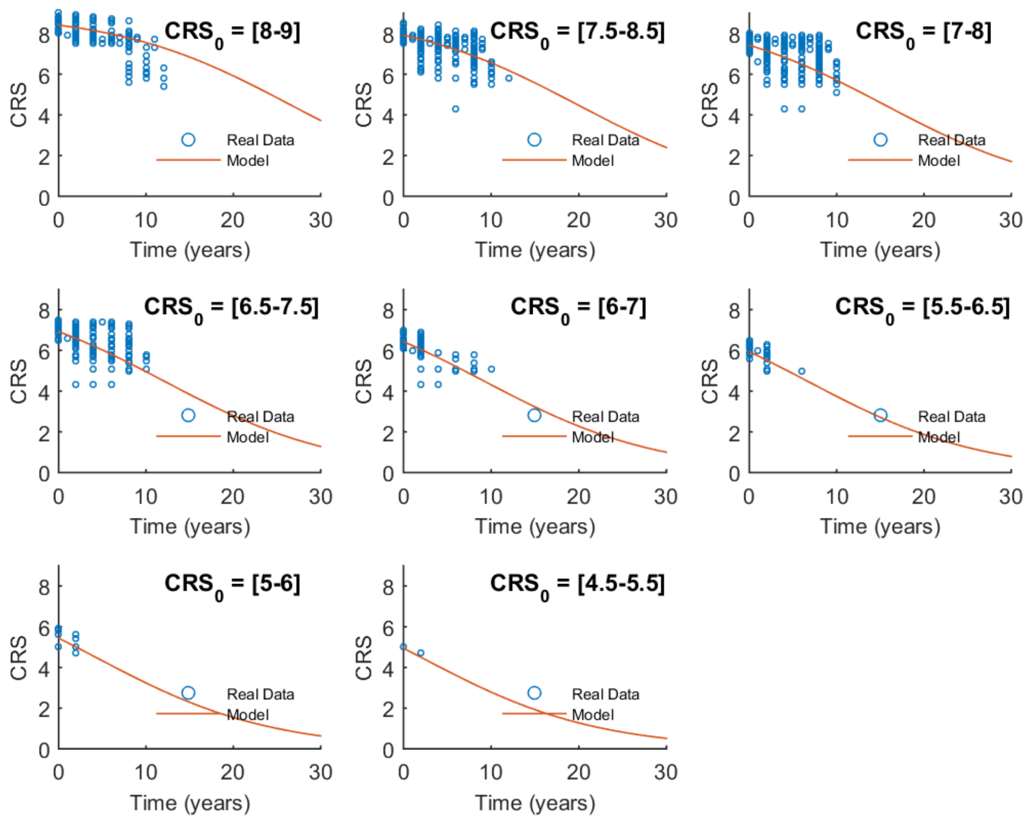
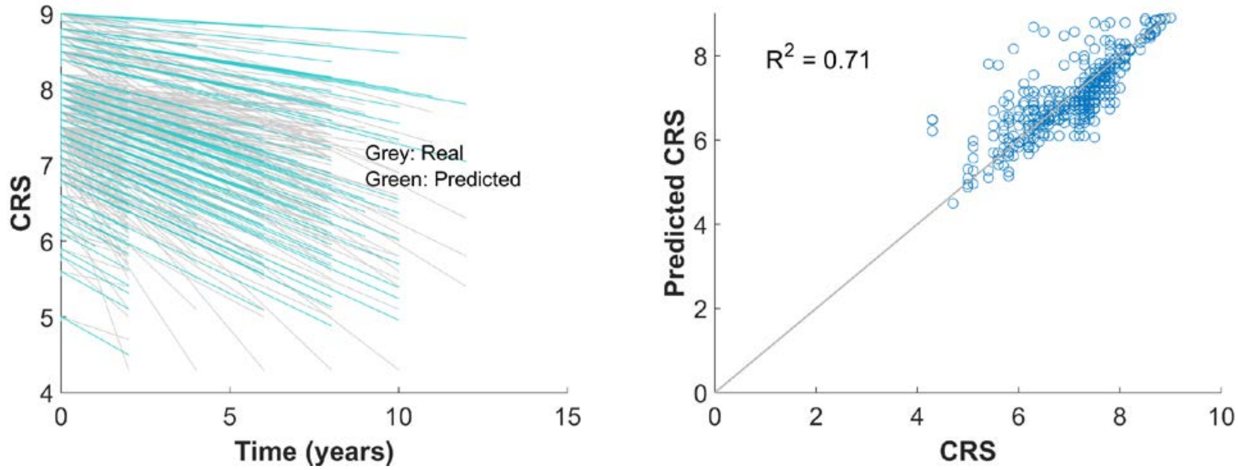
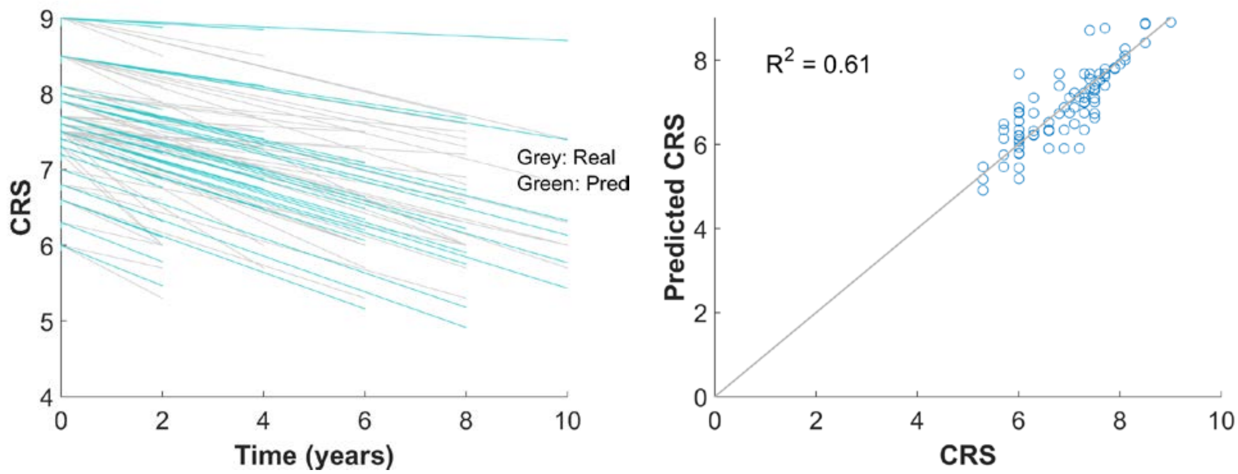


Figure 4.17. Non-Interstate HJCP standard progression curve versus real data at different initial CRS (CRS_0) ranges.



(a) Standard



(b) D-Cracked

Figure 4.18. Non-Interstate HJCP time series (left) and scatter plots (right) for (a) standard and (b) D-cracked sections.

The model parameters and the R^2 values are shown in Table 4.13. This pavement type is no longer used by IDOT, but the model was developed for previously constructed pavements.

Table 4.13. Non-Interstate HJCP Survival-Type Model Parameter Estimates

Type	System	Failure CRS	Time to failure	α	R^2
HJCP (standard)	Non-Interstate	4.5	35	0.128	0.54
HJCP (D-cracked)	Non-Interstate	4.5	25	0.180	0.81

4.2.6 AC/CRCP Overlays

A two-slope model was used for the AC/CRCP surface type. The slope values before and after the breakpoint are shown in Table 4.14. The slopes for standard sections clearly show a slow deterioration trend before and after breakpoint. During the data analysis, an observation was made that the slope for standard sections after the breakpoint can be extremely small, indicating very slow deterioration. The number of slopes for Districts 1–4 and 5–9 are 676 and 582, respectively. This includes a relatively high percentage of positive slopes as compared to other sections, which may add bias to the slopes after breakpoint, when the data count is relatively low. Therefore, downstream positive slopes were excluded for the representative slope calculations for the standard sections in order to obtain a realistic downstream slope. The deterioration patterns after breakpoint, especially for Districts 5–9, were too slow even after removing some of the positive slopes. The data was checked manually. There were no obvious inconsistencies in the data or flags. Such erroneous trends are often caused by limited data and the lack of a representative proportion of various positive flags in the whole dataset. The same issue applies to the D-cracked and SMART sections with very little data for each (less than 100). A more careful examination of SMART sections is necessary if more precise models are needed.

Table 4.14. CRS Prediction Model Coefficients for the Non-Interstate AC/CRCP Overlays

Districts and CRS Ranges	With Selected Positive Slopes			Without Positive Slopes		
	Standard[3]	D-cracked[1,2]	SMART[1,2]	Standard	D-cracked[1,2]	SMART[1,2]
1-4, CRS ≥ 6.5	-0.2836	NA	NA	-0.3793	-0.3325	-0.3128
1-4, CRS < 6.5	-0.1742	NA	NA	-0.3398	-0.2767	-0.2374
5-9, CRS ≥ 6.5	-0.2108	NA	NA	-0.3767	-0.3325	-0.3128
5-9, CRS < 6.5	NA [4]	NA	NA	-0.2054	-0.2767	-0.2374

[1] Representative slopes for D-cracked and SMART sections were calculated without positive slopes due to limited data rule.
[2] Data from Districts 1-4 and 5-9 were combined to calculate representative slope.
[3] Downstream positive slopes were excluded including the ones with downstream and preserve flags.
[4] The slope calculated according to Footnote 3 was -0.04 for this section after breakpoint. Such slow deterioration is not realistic and it is usually caused by insufficient representativeness of data. Therefore, the slope without positive slopes were used.

Figure 4.19 shows the progression of CRS plotted with the measured data slopes. A comparison of the service life to reach CRS values of 5.5 and 4.5 is also shown in Table 4.15. The service life to reach a CRS of 5.5 using the proposed model is in the range between 8–12 years and 9–13 years for Districts 1–4 and 5–9, respectively. The upper value of the range represents the prediction with the inclusion of positive slopes. The number of years to reach a CRS of 4.5 is 11–18 and 15–19 years for Districts 1–4 and 5–9, respectively. The analyses with and without positive slopes show an increase of about 2–3 years to reach a CRS of 5.5 and 4–6 years to reach a CRS of 4.5. When the positive slopes are added, the predictions are shown to be consistent with the earlier 1999 model predictions.

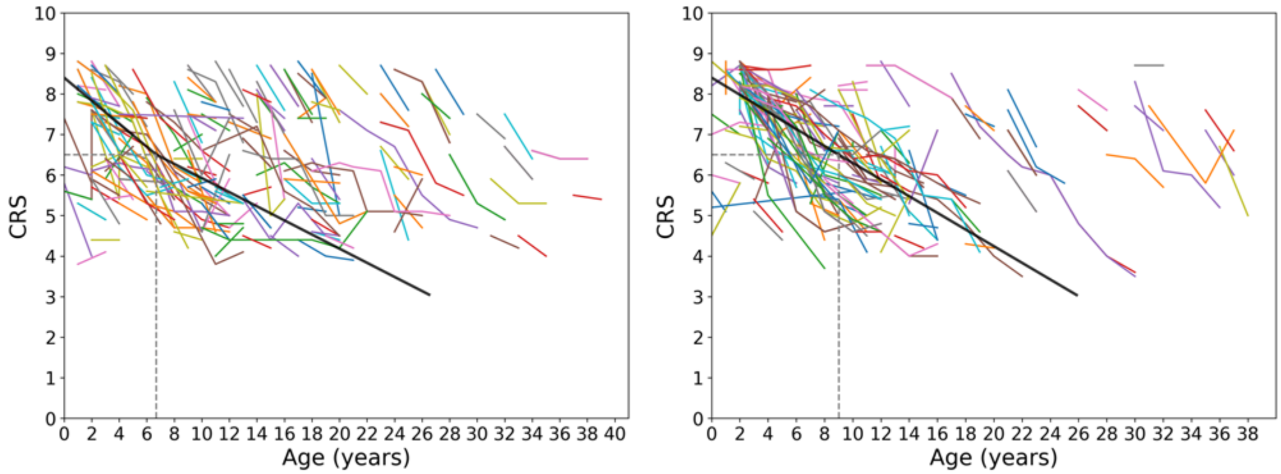


Figure 4.19. Progression of CRS prediction and actual CRS data for the Non-Interstate AC/CRCP standard sections, Districts 1–4 (left) and 5–9 (right).

Table 4.15. Service life Check and Comparison with the Previous Models for Non-Interstate AC/CRCP Sections

Non-Interstate AC/CRCP		Years to reach CRS = 5.5	Years to reach CRS = 4.5		
Pavement Type and Districts		Proposed Model	1999 Model	2007 Model	Proposed Model
Standard	1–4	8.0-12.1	19.1	14.5	10.9-17.7
	5–9	9.9-13.1		14.5	14.8-18.8
D-cracked	1–4	9.3	15.6	12.7	12.9
	5–9	9.3	9.9	12.7	12.9
SMART	1–4	10.3	19.1	15.5	14.5
	5–9	10.3		15.5	14.5

4.2.7 AC/JRCP Overlays

A two-slope model was used for the AC/JRCP surface type. The slope values before and after the breakpoint are shown in Table 4.16. This surface is among those with the highest number of data counts for standard and SMART sections as shown in Chapter 2. Due to low data counts for D-cracked sections, Districts 1–4 and 5–9 are combined.

Table 4.16. CRS Prediction Model Coefficients for Non-Interstate AC/JRCP Sections

Districts and CRS Ranges	With Selected Positive Slopes			Without Positive Slopes		
	Standard	D-cracked[1,2]	SMART	Standard	D-cracked[1,2]	SMART
1-4, CRS ≥ 6.5	-0.3790	NA	-0.3642	-0.3941	-0.4434	-0.3980
1-4, CRS < 6.5	-0.2088	NA	-0.1961	-0.2627	-0.2420	-0.2554
5-9, CRS ≥ 6.5	-0.3358	NA	-0.3623	-0.3714	-0.4434	-0.3847
5-9, CRS < 6.5	-0.1854	NA	-0.1801	-0.2728	-0.2420	-0.2470

[1] Representative slopes for D-cracked sections were calculated without positive slopes due to limited data rule.

[2] Data from Districts 1-4 and 5-9 were combined to calculate representative slope.

Figures 4.20 and 4.21 show the progression of the CRS model plotted with the measured data slopes for standard and SMART sections. In general, it can be observed that the CRS model captures the progression of CRS deterioration; and no significant differences were observed between standard and SMART sections. Actual data also demonstrate a significant part of the data with incorrect original construction dates.

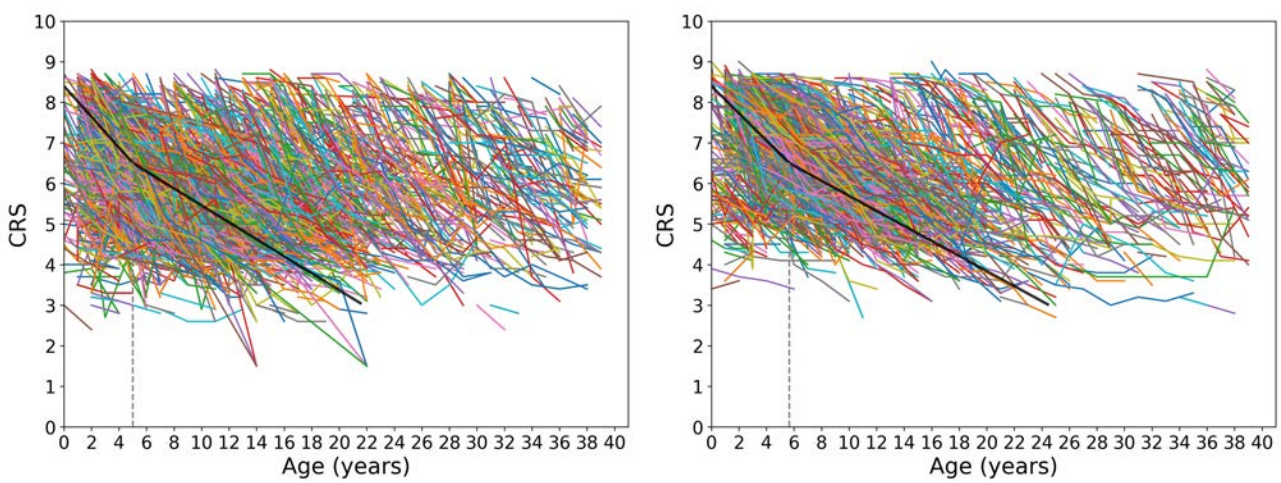


Figure 4.20. Progression of CRS prediction and actual CRS data for Non-Interstate AC/JRCP standard sections, Districts 1–4 (left) and 5–9 (right).

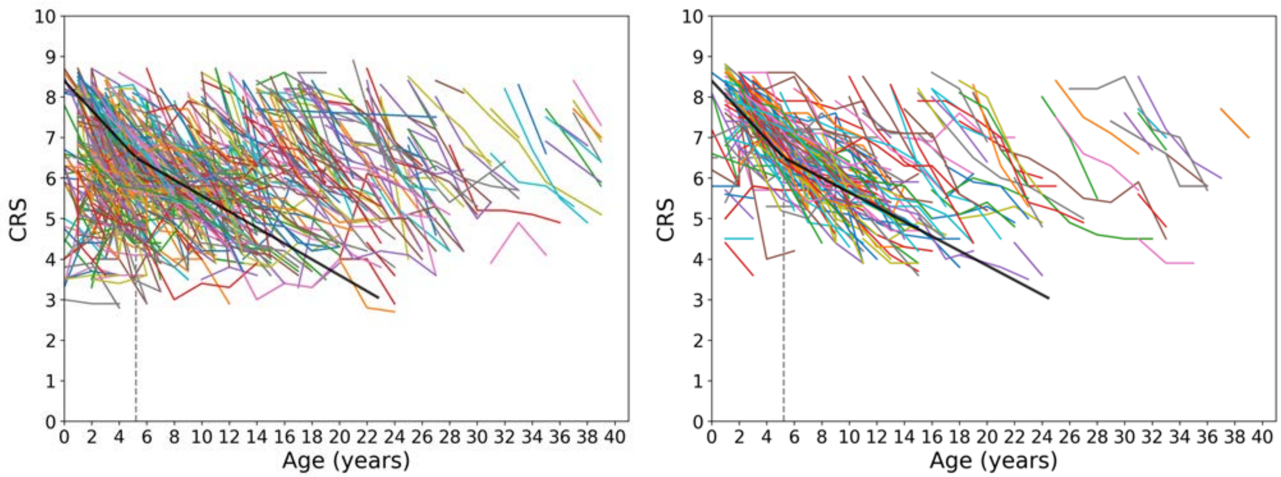


Figure 4.21 Progression of CRS prediction and actual CRS data for Non-Interstate AC/JRCP SMART sections, Districts 1–4 (left) and 5–9 (right).

A comparison of the service life to reach CRS values of 5.5 and 4.5 is also shown in Table 4.17. The service life to reach a CRS of 5.5 using the proposed model is in the range between 9–10 years and 9–11 years for Districts 1–4 and 5–9, respectively. The number of years to reach a CRS of 4.5 is 12–15 and 12–16 years for Districts 1–4 and 5–9, respectively. The analyses with and without positive slopes show an increase of about 1–2 years to reach a CRS of 5.5 and 2–4 years to reach a CRS of 4.5. This gain is smaller compared to the AC/CRCP sections. This may reinforce the fact that the deterioration is faster with or without positive slopes for AC/JRCP sections. Also, neglecting positive slopes may have a greater effect on AC/CRCP surfaces due to relatively slow deterioration causing inconsistent CRS ratings sometimes flagged as upstream, downstream, or preserve in the algorithm. The data shows some reduction in service life with D-cracked sections. SMART sections showed similar or slightly longer service life. This was also the case in the previous models. The data count was healthy enough to converge to a statistically meaningful solution. However, it is important to note that this does not guarantee performance of SMART sections as the structure and condition at the time of placement are not known. A more detailed analysis of SMART sections is needed to predict its performance more precisely.

Table 4.17. Service Life Check and Comparison with the Previous Models for Non-Interstate AC/JRCP Sections

Non-Interstate AC/JRCP		Years to reach CRS = 5.5	Years to reach CRS = 4.5		
Pavement Type and Districts		Proposed Model	1999 Model	2007 Model	Proposed Model
Standard	1–4	8.6-9.8	13.8	14	12.4-14.6
	5–9	8.8-11.1	22.1	18	12.4-16.4
D-cracked	1–4	8.4	15.6	12.7	12.6
	5–9	8.4	9.9	12.7	12.6
SMART	1–4	8.7-10.3	16.6	12.6	12.6-15.4
	5–9	9.0-10.8	23.7	14.6	13.0-16.3

4.2.8 AC/JPCP Overlays

A two-slope model was used for the AC/JPCP surface type. The slope values are shown in Table 4.18. Similar to the AC/JRCP type, this surface is among those with the highest number of data counts.

Table 4.18. CRS Prediction Model Coefficients for the Non-Interstate AC/JPCP Overlays

Districts and CRS Ranges	With Selected Positive Slopes			Without Positive Slopes		
	Standard	D-cracked[1,2]	SMART	Standard	D-cracked[1,2]	SMART
1-4, CRS $\geq$ 6.5	-0.4055	NA	-0.4371	-0.4308	-0.5587	-0.4704
1-4, CRS $<$ 6.5	-0.2027	NA	-0.1765	-0.2723	-0.3080	-0.2555
5-9, CRS $\geq$ 6.5	-0.3836	NA	-0.3785	-0.4098	-0.5587	-0.4000
5-9, CRS $<$ 6.5	-0.1976	NA	-0.1709	-0.2650	-0.3080	-0.2297

[1] Representative slopes for D-cracked were calculated without positive slopes due to limited data rule.
[2] Data from Districts 1-4 and 5-9 were combined to calculate representative slope.

Figures 4.22 and 4.23 show the progression of the CRS model plotted with the measured data slopes for standard and SMART sections. In general, it can be observed that the CRS model captures the progression of CRS deterioration; and no significant differences were observed between standard and SMART sections.

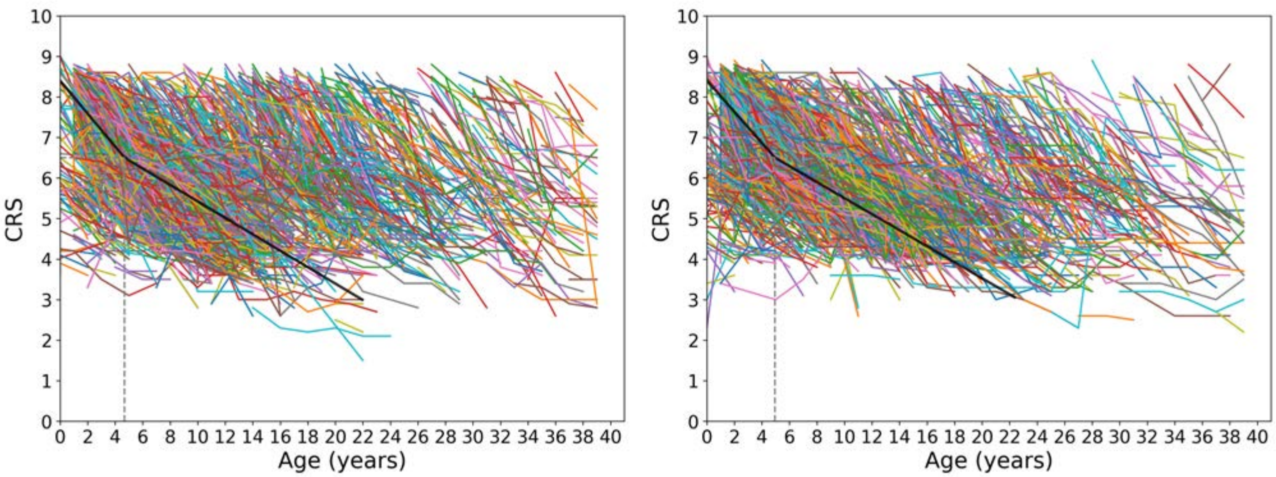


Figure 4.22. Progression of CRS prediction and actual CRS data for Non-Interstate AC/JPCP standard sections, Districts 1–4 (left) and 5–9 (right).

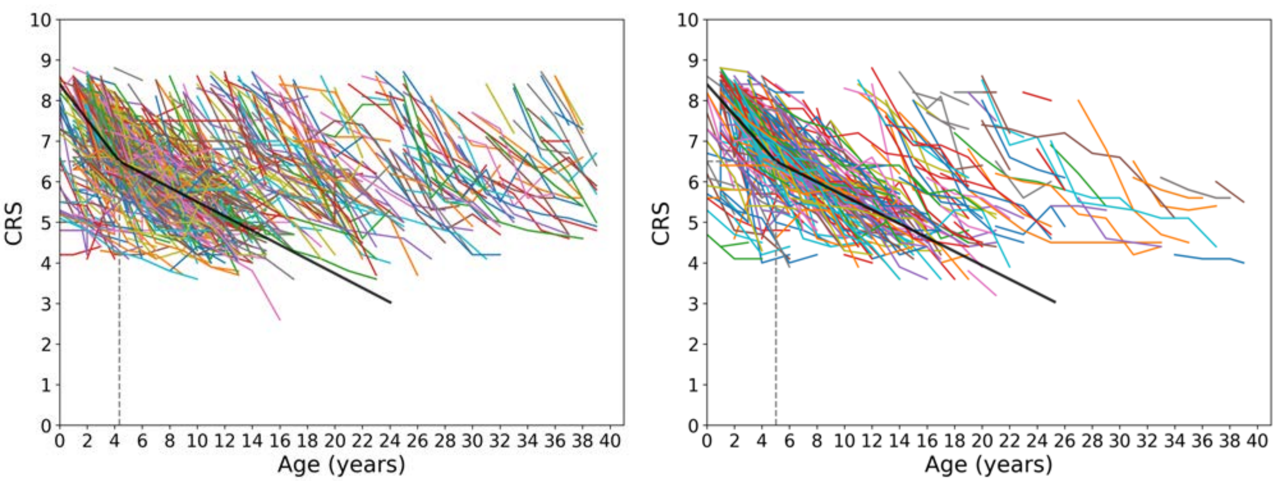


Figure 4.23. Progression of CRS prediction and actual CRS data for Non-Interstate AC/JPCP SMART sections, Districts 1–4 (left) and 5–9 (right).

A comparison of the service life to reach CRS values of 5.5 and 4.5 is also shown in Table 4.19. The ranges are consistent with the AC/JRCP section predictions. Standard sections reach a CRS of 5.5 in under 10 years. There is some gain with the addition of positive slopes before they reach a CRS of 5.5, which is consistent with the AC/JRCP overlays, but not as much as the AC/CRCP sections. The number of years to reach a CRS of 4.5 is in the range of approximately 12–15 years for both Districts 1–4 and 5–9. The sections in Districts 5–9 have a slightly better service life. The service life addition with positive slopes is approximately 2–3 years, similar to the AC/JRCP sections. D-cracked sections exhibit considerably lower service lives (7–10 years). Similar to the AC/JRCP sections, SMART sections showed slightly better service life as compared to standard sections. This was also observed in the results of the previous models.

Table 4.19. Service Life Check and Comparison with the Previous Models for Non-Interstate AC/JPCP Sections

Non-Interstate AC/JPCP		Years to Reach CRS = 5.5	Years to Reach CRS = 4.5		
Pavement Type and Districts		Proposed Model	1999 Model	2007 Model	Proposed Model
Standard	1–4	8.1-9.6	14.9	13.3	11.8-14.6
	5–9	8.4-10.0	21.2	16.4	12.2-15.1
D-cracked	1–4	6.6	15.6	12.7	9.9
	5–9	6.6	9.9	12.7	9.9
SMART	1–4	8.0-10.0	15.1	12.4	11.9-15.7
	5–9	9.1-10.9	23.7	16	13.5-16.7

4.2.9 AC/PCCun Overlays

A two-slope model was used for the AC/PCCun surface type. The slope values are shown in Table 4.20. This surface type had the highest number of data counts.

Table 4.20 CRS Prediction Model Coefficients for the Non-Interstate AC/PCCun Overlays

Districts and CRS Ranges	With Selected Positive Slopes			Without Positive Slopes		
	Standard	D-cracked[1,2]	SMART	Standard	D-cracked[1,2]	SMART
1-4, CRS ≥ 6.5	-0.3103	NA	-0.2840	-0.3575	-0.4218	-0.3285
1-4, CRS < 6.5	-0.1420	NA	-0.1670	-0.2435	-0.2260	-0.2541
5-9, CRS ≥ 6.5	-0.3380	NA	-0.3197	-0.3670	-0.4218	-0.3529
5-9, CRS < 6.5	-0.2139	NA	-0.1946	-0.2770	-0.2260	-0.2485

[1] Representative slopes for D-cracked sections were calculated without positive slopes due to limited data rule.
[2] Data from Districts 1-4 and 5-9 were combined to calculate representative slope.

Figures 4.24 and 4.25 show the progression of the CRS model plotted with the measured data slopes for standard and SMART sections. In general, it can be observed that the CRS model captures the progression of CRS deterioration; and no significant differences were observed between standard and SMART sections.

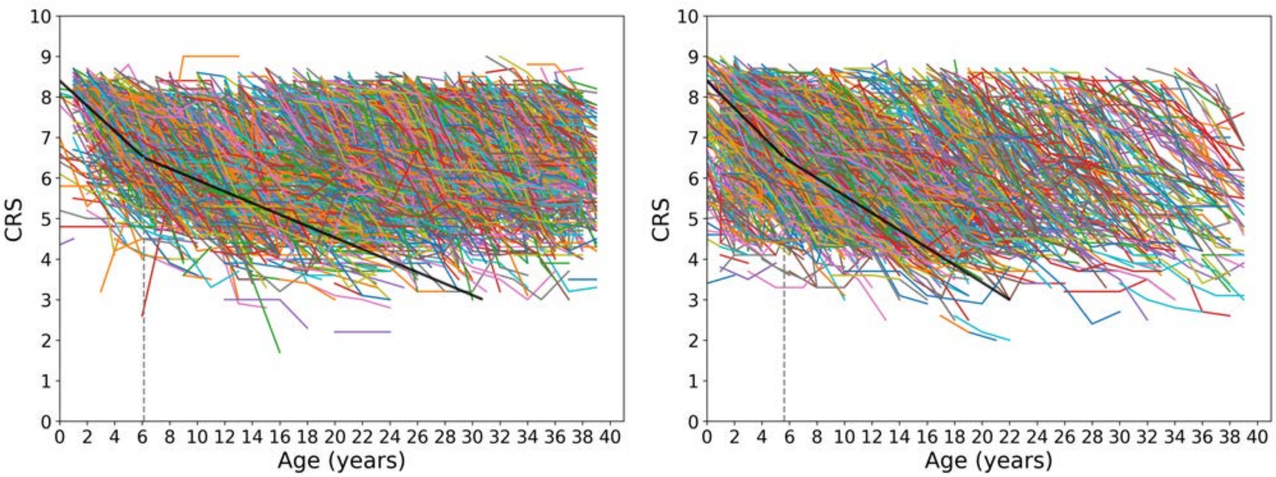


Figure 4.24. Progression of CRS prediction and actual CRS data for Non-Interstate AC/PCCun standard sections, Districts 1–4 (left) and 5–9 (right).

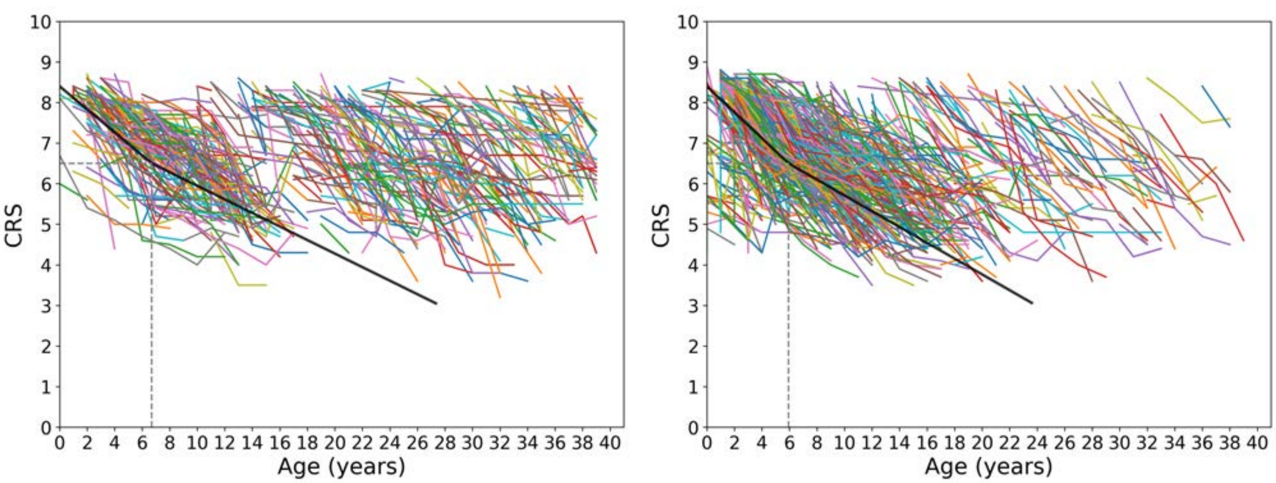


Figure 4.25. Progression of CRS prediction and actual CRS data for Non-Interstate AC/PCCun SMART sections, Districts 1–4 (left) and 5–9 (right).

A comparison of the service life to reach CRS values of 5.5 and 4.5 is also shown in Table 4.21. The results are more comparable to deterioration patterns with the AC/CRCP sections even though AC/PCCun showed slower deterioration patterns especially with the sections in Districts 1–4. However, it is important to note that the percentage of positive slopes in Districts 1–4 is 33% of total slopes, which is comparatively higher than the average (around 25%). There is a remarkable increase in the downstream flagged positive slopes that may have contributed to the observed better performance in Districts 1–4 sections. Such downstream positive slopes may indicate the condition of pavements saturated to damage and the apparent extension of service life until the next overlay. Therefore, the data belonging to these sections will have to examined further by collecting information from the districts. The performance of SMART sections is comparable to standard sections. The AC/PCCun category is a combination of several cross-sections which can cause high variability in performance. Additional efforts should be made to identify the actual cross-sections used in these pavement sections and those data points added to the correct category to improve those models.

Table 4.21. Service Life Check and Comparison with the Previous Models for Non-Interstate AC/PCCun Sections

Non-Interstate AC/PCCun		Years to Reach CRS = 5.5	Years to Reach CRS = 4.5		
Pavement Type and Districts		Proposed Model	1999 Model	2007 Model	Proposed Model
Standard	1–4	9.4-13.2	17.7	17.5	13.5-20.2
	5–9	8.8-10.3	17.2	17.5	12.4-15.0
D-cracked	1–4	8.9	15.6	12.7	13.4
	5–9	8.9	9.9	12.7	13.4
SMART	1–4	9.7-12.7	14.6	16.4	13.7-18.7
	5–9	9.4-11.1	17.5	16.4	13.4-16.2

4.2.10 Full-Depth HMA

Two different modeling approaches were used for the full-depth HMA sections. A two-slope model similar to the overlays using the representative slope approach, as well as the regression-based two-slope model, was developed using the mechanistic database. The linear regression-based two-slope model was introduced in section 4.1.7 with the slope coefficients and the service life predictions. Table 4.22 summarizes the representative slopes before and after breakpoint.

Table 4.22. CRS Prediction Model Coefficients for Non-Interstate ACP

Districts and CRS Ranges	With Selected Positive Slopes		Without Positive Slopes	
	Standard	SMART	Standard	SMART
1-4, CRS ≥ 6.5	-0.3694	-0.4372	-0.4180	-0.4615
1-4, CRS < 6.5	-0.1785	-0.2107	-0.2814	-0.2702
5-9, CRS ≥ 6.5	-0.2828	-0.3068	-0.3420	-0.3500
5-9, CRS < 6.5	-0.1535	-0.1813	-0.2862	-0.3574

Figures 4.26 and 4.27 show the progression of the CRS model plotted with the measured data slopes for standard and SMART sections.

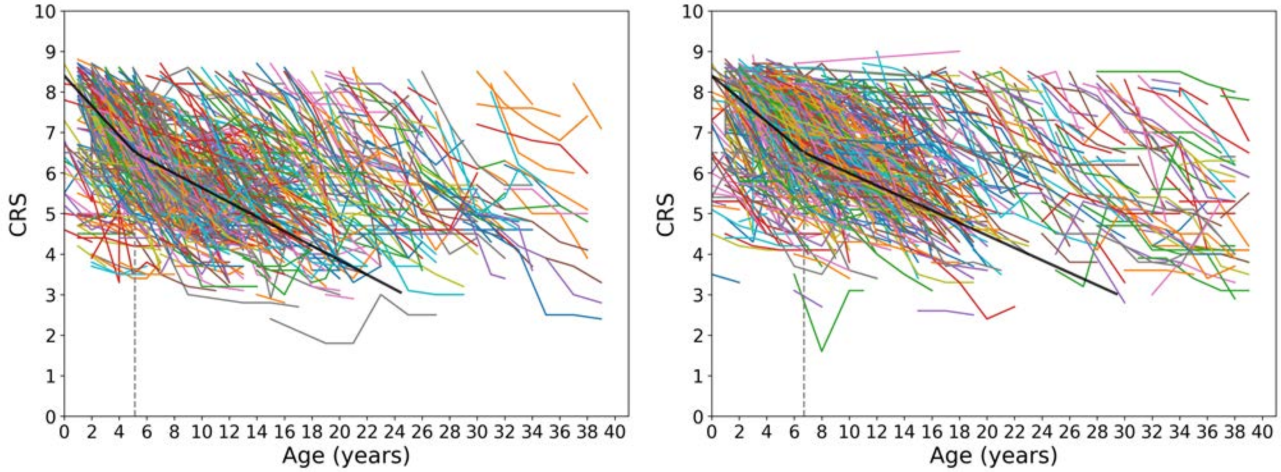


Figure 4.26. Progression of CRS prediction and actual CRS data for Non-Interstate ACP standard sections, Districts 1–4 (left) and 5–9 (right).

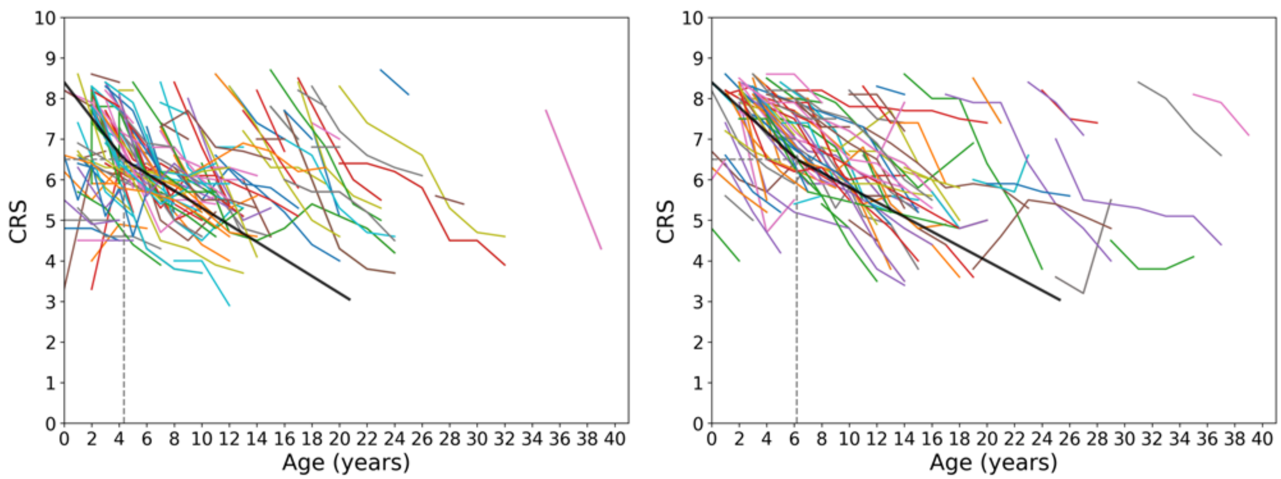


Figure 4.27. Progression of CRS prediction and actual CRS data for Non-Interstate ACP SMART sections, Districts 1–4 (left) and 5–9 (right).

A comparison of the service life to reach CRS values of 5.5 and 4.5 is shown in Table 4.23. Service life gains with the addition of positive slopes to reach CRS values of 5.5 and 4.5 are approximately 3–4 and 5–7 years, respectively. This is similar to the gains reported with the AC/CRCP sections. The gain to reach a CRS of 5.5 is especially noticeable, which may be due to actual slow deterioration of these sections captured by some of the positive slope flags. The full-depth HMA sections in Districts 5–9 performed much better than those in Districts 1–4. Overall service life predictions and trends between southern and northern districts are consistent with previous modeling results. SMART sections exhibited 2–3 years of reduction in service life consistently for each region.

Table 4.23. Service Life Check and Comparison with the Previous Models for Non-Interstate ACP Sections

Non-Interstate ACP		Years to Reach CRS = 5.5	Years to Reach CRS = 4.5		
Pavement Type and Districts		Proposed Model	1999 Model	2007 Model	Proposed Model
Standard	1–4	9.5-12.4	13.4	14	13.1-18.0
	5–9	10.8-15.4	18.6	16.2	14.3-21.9
SMART	1–4	9.1-10.5	NA[1]	13.1	12.8-15.2
	5–9	9.9-13.7	NA[1]	16.7	12.7-19.2

[1] Models were not developed for SMART overlays on ACP sections as part of 1999 models.

The linear regression-based two-slope model resulted in service lives of 16.7 and 25.0 years to reach CRS values of 5.5 and 4.5, respectively, as shown in Table 4.24. The model used in the regression-based two-slope model is based on the data in the mechanistic database. The data used in the model contained all the data from northern and southern districts prior to the first overlay, including potential positive slopes due to various reasons that could be flagged according to the algorithm. Since the data is only up to the first overlay and these sections were obtained from specific contracts, it can be expected to perform better than the sections in the entire dataset obtained from IRIS. This may include the original full-depth HMA sections as well as the overlaid full-depth HMA sections. Therefore, when there is reliable information, using the slope coefficients obtained from the mechanistic database for the original full-depth HMA sections is highly recommended. However, since it would be difficult to know which sections are original full-depth HMA prior to the first overlay in the IRIS database, one approach is to use Standard AC/ACP and SMART models for sections in the IRIS database, unless there is reliable information to identify the section as original full-depth HMA prior to the first overlay. The slopes for overlaid full depth HMA, including SMART, can be taken from the values presented in this section.

Table 4.24 Summary of Representative Slopes for Full-Depth HMA Sections

Districts and CRS Ranges	Full-Depth HMA Sections		
	Standard ACP[1]	Standard AC/ACP	SMART
1-4, CRS $\geq$ 6.5	-0.3000	-0.3694	-0.4372
1-4, CRS $<$ 6.5	-0.1200	-0.1785	-0.2107
5-9, CRS $\geq$ 6.5	-0.3000	-0.2828	-0.3068
5-9, CRS $<$ 6.5	-0.1200	-0.1535	-0.1813

[1] Standard ACP model is derived from the combined dataset in the mechanistically-designed pavement database for all districts.

4.2.11 Summary of Non-Interstate Concrete-Surfaced Sections

A summary of Non-Interstate concrete-surfaced pavements is presented in Table 4.25 and Figure 4.28. Similar to the Interstate concrete pavement model, time to failure was determined to gauge how well it fits with existing data addressing previous concrete pavement efforts in the Illinois roadway system. Most of the concrete pavements in the Non-Interstate system consisted of the standard JRCP and PCCun type (42% and 19%, respectively) followed by JPCP and HJCP types (11% and 8%, respectively). The standard CRCP sections were 6% of the total data points.

As more data is available, terminal service life estimates can be modified to fine-tune the results. The proposed model has two distinctive advantages over the previously used two-slope models. The survival-type curve is more consistent with the deterioration patterns commonly observed in concrete pavements. That is why the proposed model can provide much higher accuracy of CRS prediction within the first 10 to 20 years of service life in concrete pavements as shown in the data. The second advantage is that it provides consistent predictions and minimizes the chances of unrealistic predictions in the case of rigid two-slope models, especially when the data is skewed due to a limited quantity. Similar to the Interstate concrete pavement predictions, the proposed model resulted in longer service life estimates as compared to the estimates of previous models. However, it is important to note that there is very little data available to make terminal service life predictions for concrete pavements.

Table 4.25. Summary of Survival Model Parameters for Non-Interstate Concrete-Surfaced Pavements

Type	Surface Type	Districts	α	Initial CRS	Years to CRS = 5.5	Years to CRS = 4.5
Standard	CRCP	1-9	0.112	9.0	36	40
	JPCP	1-9	0.112	9.0	36	40
	JRCP	1-9	0.112	9.0	36	40
	PCCun	1-9	0.128	9.0	31	35
	HJCP	1-9	0.128	9.0	31	35
D-cracked	CRCP	1-9	0.129	9.0	27	30
	JPCP	1-9	0.150	9.0	27	30
	JRCP	1-9	0.150	9.0	27	30
	PCCun	1-9	0.180	9.0	22	25
	HJCP	1-9	0.180	9.0	22	25

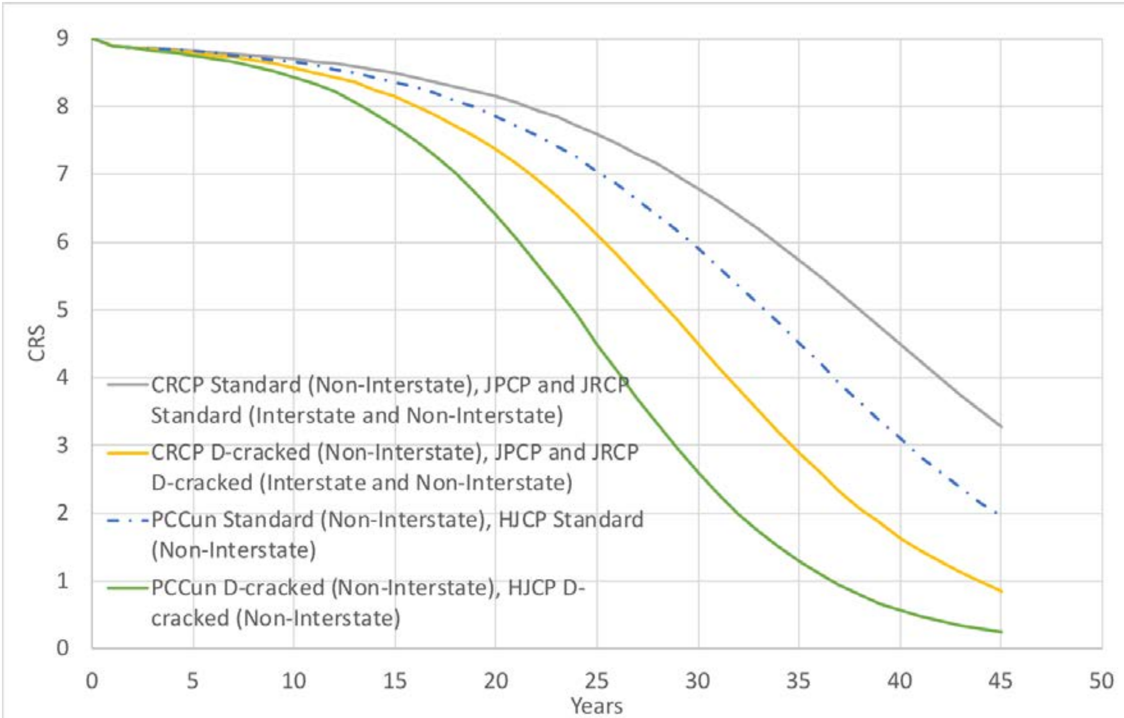


Figure 4.28. Progression curve plots for Non-Interstate rigid pavement sections.

4.2.12 Summary of Non-Interstate Asphalt-Surfaced Sections

A summary of Non-Interstate asphalt-surfaced pavements is presented in Table 4.26. According to the service life estimates for standard sections, the number of years to reach CRS values of 5.5 and 4.5 for standard overlays is between 9–15 years and 14–22 years, respectively. Within this range, AC overlays on jointed concrete pavements (AC/JRCP and AC/JPCP) has the shortest service life (9–11 years to reach a CRS of 5.5 and 14–16 years to reach CRS of 4.5). Overlays in full-depth HMA sections had the highest service life (18–22 years to reach a CRS of 4.5 and 12–15 years to reach a CRS of 5.5). AC overlays on CRCP sections had a service life approximately 2–3 years more than the overlays on jointed concrete sections. AC overlays on PCCun surfaces performed comparable with overlays on jointed concrete sections in Districts 5–9, whereas AC/PCCun sections had superior performance comparable with overlays in full-depth HMA sections in Districts 1–4. However, it is important to note that the AC/PCCun sections in Districts 1–4 had remarkably higher percentage of positive slopes which probably contributed to the increase in its service life. Slow deterioration in those pavement types in Districts 1–4 can be due to actual pavement performance or a high frequency of interventions. In general, with the exception of AC/PCCun, standard pavement types in Districts 5–9 performed better than those in Districts 1–4.

The performance of SMART sections is comparable to standard sections when they are used as part of overlays on jointed concrete structures. SMART sections on full-depth HMA structures resulted in 11–16% reduction in service life as compared to standard surface types. SMART sections within the AC/CRCP surface type resulted in approximately a 20% reduction in service life as compared to the standard AC/CRCP overlays. However, this is most likely due to very low data counts (only 40 slopes in Districts 1–4). This is consistent with the analysis performed by Wolters et al. (2008) to compare the standard and SMART overlay types on Non-Interstate rigid and flexible pavement systems. According to this study, SMART sections had an overall shorter service life as part of the Non-Interstate flexible system. However, they have comparable service life within the Non-Interstate rigid system. The data contain multiple groups of overlays on rigid pavements in standard and SMART surface types and thickness is not known. As a result, the historical performance of overlays does not allow us to distinguish SMART from standard types.

D-cracked sections had the lowest data counts. However, there was a clear trend of reduction in the number of years to reach critical CRS values. It appears that the service life to reach critical CRS values reduced by approximately 25–35% for overlays on D-cracked jointed pavements, and approximately 15–20% for overlays on CRCP or PCCun. Therefore, D-cracked model coefficients can further be simplified to overlays on D-cracked jointed concrete and CRCP and PCCun.

Based on the analysis of the data and comparison of the result, key findings are summarized as follows:

- The service life for AC overlays on jointed concrete pavements (AC/JPCP and AC/JRCP) is 18–29% less than those on CRCP surfaces.
- There is a consistent trend between the performance of sections in Districts 1–4 and 5–9. The service life to reach critical values of CRS in southern districts for standard and SMART surface types is 3–30% higher than those in northern districts (3–4% in the case of standard AC/JPCP and 20–30% standard and SMART full-depth HMA sections). This trend is not valid for AC overlays PCCun surfaces.
- SMART sections showed comparable service life with standard overlays on concrete pavement (AC/JRCP, AC/JPCP, AC/PCCun), except those on CRCP structures. The SMART sections on CRCP pavement had very small amounts of data, which may have skewed the outcome. This observation may indicate that the structure added by policy overlays or SMART overlays is not capable of preventing reflective cracks which often drive CRS deterioration in these types of pavements. On the other hand, SMART sections as part of the full-depth HMA system resulted in 11–16% reduction in service life as compared to standard overlays in the same system. In a dataset of mixed structures and unknown existing thickness prior to SMART application, it is not possible to distinguish the performance of SMART overlays from standard overlays.
- The data in the mechanistic database was analyzed to develop models for original full-depth HMA pavements. The data contained sections from primarily Non-Interstate sections. The data was cleaned to keep only the data after original construction and before the first overlay. Service life of an original full-depth HMA pavement in the Interstate or Non-Interstate system can have a potential to last 16.7 years and 25.0 years to reach CRS values of 5.5 and 4.5, respectively.
- Full-depth HMA sections available in the main dataset were also analyzed. The data may include performance history before and after the first overlay. Therefore, the models

developed using this database were assigned to a surface type called AC/ACP for overlays in full-depth HMA sections. There is a considerable difference in the performance of these sections in northern and southern districts favoring the sections in the southern districts. Service life predictions for Districts 5–9 (15.4 and 21.9 years to reach CRS values of 5.5 and 4.5, respectively) are more consistent with the mechanistic database. When the data in the mechanistic database was investigated, it can also be seen that a majority of the full-depth HMA sections were in Districts 5–9.

- The data and models from the mechanistic report are more consistent with the models developed for Districts 5–9. Therefore, using the model for standard and SMART overlays for the full-depth HMA surface type in the Non-Interstate and Interstate systems, as demonstrated in Districts 5–9, is recommended. The models developed for full-depth HMA can be improved to add thickness at the very least.
- Overlays on rigid pavements with D-cracking showed a consistent 19–33% reduction in service life as compared to standard types. This observation is consistent with the earlier models (Gharaibeh et al., 1999 and Wolters et al., 2008). However, there are several features that may complicate the comparison of this surface type even though the results made sense. First, there is very little data in this category even after sections with "X" distresses were added to the list of sections with original D-cracking flag. Secondly, some of these sections may have been overlaid several times on the D-cracked concrete, which may obscure the reflection of large joint or panel movements to the surface. Once again, existing overlay thickness (it may also be important to know whether it is in good condition or not) must be known in order to make a more accurate prediction about overlays on potentially D-cracked sections. At this point, the research team recommends to using the model coefficients that were developed. As the data counts are low, further simplifications were applied to combine the models to use as overlays on jointed and unjointed/unknown rigid pavements in this category, similar to the approach used in Gharaibeh et al. (1999).

Table 4.26. Summary of Model Parameters for Non-Interstate Asphalt-Surfaced Pavements

Type	Surface Type	Districts	Slope when CRS ≥ 6.5	Slope when CRS < 6.5	Initial CRS	Years to CRS = 5.5	Years to CRS = 4.5
Standard	AC/CRCP	1-4	-0.2836	-0.1742	8.4	12.1	17.7
		5-9	-0.2108	-0.2054	8.4	13.1	18.8
	AC/JRCP	1-4	-0.3790	-0.2088	8.4	9.8	14.6
		5-9	-0.3358	-0.1854	8.4	11.1	16.4
	AC/JPCP	1-4	-0.4055	-0.2027	8.4	9.6	14.6
		5-9	-0.3836	-0.1976	8.4	10.0	15.1
	AC/PCCun	1-4	-0.3103	-0.1420	8.4	13.2	20.2
		5-9	-0.3380	-0.2139	8.4	10.3	15.0
	AC/ACP	1-4	-0.3694	-0.1785	9.0	12.4	18.0
		5-9	-0.2828	-0.1535	9.0	15.4	21.9
	ACP	1-9	-0.3000	-0.1200	9.0	16.7	25.0
SMART	AC/CRCP	1-9	-0.3128	-0.2374	8.4	10.3	14.5
	AC/JRCP	1-4	-0.3642	-0.1961	8.4	10.3	15.4
		5-9	-0.3623	-0.1801	8.4	10.8	16.3
	AC/JPCP	1-4	-0.4371	-0.1765	8.4	10.0	15.7
		5-9	-0.3785	-0.1709	8.4	10.9	16.7
	AC/PCCun	1-4	-0.2840	-0.1670	8.4	12.7	18.7
		5-9	-0.3197	-0.1946	8.4	11.1	16.2
	ACP	1-4	-0.4372	-0.2107	9.0	10.5	15.2
		5-9	-0.3068	-0.1813	9.0	13.7	19.2
D-cracked	Overlays on Jointed Rigid[1]	1-9	-0.4509	-0.2510	8.4	8.2	12.2
	Overlays on CRCP[2]	1-9	-0.4037	-0.2367	8.4	8.9	13.2

[1] Based on the combined JRCP and JPCP D-cracked sections.

[2] Based on the combined CRCP and PCCun D-cracked sections.

CHAPTER 5: CRS CALCULATION MODEL REVIEW AND UPDATES

This chapter describes the work done to revise the calculation models to add some of the over- and underemphasized distresses. A review of the calculated CRS and its distribution to designated functional and structural categories will also be discussed to provide guidance on potential revisions.

5.1 MOTIVATION AND BACKGROUND

IDOT has regularly updated the CRS calculation models as more data has been collected from the network since the 1970s. A transition from manual rating to automated rating, with the use of calculation models as a function of distresses, took place in 1994 (Darter et al. 1994).

Ratings are conducted by experts. As experts gain more experience and additional data are collected, two distinct needs must be addressed while data is being collected and models are updated. First, there is a sufficient number of new distress observations not originally in the CRS equation. Second, certain distresses seem to be under- or overemphasized. In other words, some distresses affect CRS in a way that is not consistent with the experience of experts in the field. Moreover, it seems that not all distresses affect the CRS in a consistent way with their weight (coefficient) in the model. It is expected that distresses related to the structural performance of the pavement will notably affect the pavement CRS, whereas distresses related to the functional performance of the pavement will have less influence on the CRS. Thus, the objectives of the work explained in this chapter are as follow:

- Identify missing distresses that can be added to the current models and update the model coefficients accordingly.
- Identify, additional (if any) under- or overemphasized distresses, using expert opinions or through decomposition of the CRS into structural vs. functional distresses.

5.2 CRS CALCULATION MODEL FORMS

CRS is a subjective measure in which expert ratings are correlated with different distresses, their severities, and more objective measures like IRI and rutting, to develop objective, regression-based models. Thus, the model form consists of determining CRS as a function of roughness, rutting, faulting (where appropriate), and recorded distresses and severities:

$$CRS = Intercept - x \times IRI - y \times Rutting - z \times Faulting - a \times A - b \times B - c \times C \ldots$$

where,

Intercept is the starting point for the calculation

x, y, and *z* are coefficients for the sensor data (as applicable)

IRI, Rutting, and *Faulting* are the values obtained from the sensor data

a, b, c … are the coefficients for the distresses

A, B, C … are the values of distresses recorded by the raters

A multiple-regression method had been employed in the past to estimate the model parameters for each pavement type. Manually rated pavements were correlated to the CRS calculated using the data collected via automated pavement data collection vehicles to reach the current form of models. Therefore, the CRS calculation model is a subjective index, developed originally by expert rankings. Over the years, raters established familiarity with the system, resulting in a consistent and representative overall condition of the pavement. When the raters thought that the model was either overestimating or underestimating the current condition or the model was missing a distress present, the CRS records were overridden. In general, models have worked so far to represent the overall condition of the pavement and the timing for maintenance and rehabilitation. However, some minor revisions can reduce the occurrences of overriding by addressing the rater's expert opinions. It is important to note that any modification to the model should also be supported by expert opinion.

5.3 CURRENT MODELS

The original CRS calculation models were revised through research in 2007. Distress code definitions are provided in Table 5.1. Tables 5.2 and 5.3 show the parameters of the existing models for asphalt- and concrete-surfaced types, respectively.

Table 5.1. Distress Code Definition

Asphalt Distress Code	Definition	Concrete Distress Code	Definition
IRI	International Roughness Index	IRI	International Roughness Index
L	Alligator cracking	A	D-cracking
M	Block cracking	B	Transverse cracking
O	Trans. cracking/Joint reflection cracks	C	Joint deterioration
P	Overlaid patch reflective cracking	D	Centerline deterioration
Q	Long./Center-of-lane cracking	E	Longitudinal cracking
R	Reflective widening crack	F	Edge punchouts
S	Centerline deterioration	H	Corner breaks
T	Edge cracking	I	Map cracking/Scaling
U	Permanent-patch deterioration	J	Popouts/High steel
V	Shoving, bumps, sags, and corrug.	K	Permanent-patch deterioration
W	Weathering/Raveling/Segregation/Oxidation		
X	Reflective D-cracking		

Table 5.2. 2007 Model Coefficients for Asphalt-Surfaced Pavements

Distress Code	ACP		AC/JRCP	AC/CRCP		AC/PCC	AC/Other
	Interstate	Non-Interstate	Interstate	Interstate	Non-Interstate	Non-Interstate	Non-Interstate
Intercept	9.0	9.0	9.0	9.0	9.182	9.0	9.0
IRI	-0.007	-0.002	-0.005	-0.006	-0.001	-0.002	-0.002
Rutting	-2.589	-1.403	-1.829	-1.605	-1.068	-0.430	-0.998
L		-0.236			-.207	-0.203	
M	-0.544	-0.271	-0.326	-0.356	-0.209	-0.210	-0.204
O	-0.091	-0.378	-0.142	-0.115	-0.483	-0.444	-0.485
P	-0.301		-0.214	-0.235		-0.036	
Q	-0.118	-0.199	-0.189	-0.139	-0.184	-0.175	-0.250
R		-0.088				-0.063	-0.113
S	-0.234	-0.252	-0.350	-0.387	-0.290	-0.237	-0.123
T		-0.208		-0.171	-0.178	-0.176	-0.182
U		-0.146	-0.112	-0.064	-0.604	-0.610	
V		-0.253				-0.114	
W		-0.311	-0.383		-0.264	-0.316	-0.283
X			-0.326	-0.351		-0.074	

Table 5.3. 2007 Model Coefficients for Concrete-Surfaced Pavements

Distress Code	JRCP	CRCP		PCC
	Interstate	Interstate	Non-Interstate	Non-Interstate
Intercept	8.66	9.0	8.204	8.254
IRI	-0.0019	-0.007	-0.003	-0.001
Faulting	-6.08			
A	-0.428	-0.225	-0.334	
B	-0.318	-0.317	-0.226	-0.274
C	-0.299			-0.453
D	-0.178	-0.342	-0.318	-0.292
E	-0.1	-0.254		-0.076
F		-0.085	-0.049	
H	-0.194			-0.119
I				-0.134
J		-0.103	-0.165	-0.141
K	-0.081	-0.322		

5.4 UPDATED MODELS

Tables 5.4, 5.5, 5.6, and 5.7 show the revised model for Interstate sections. Details of model updating are explained in Appendix C. Bolded rows show the new distresses added to the models based on the expert comments provided in Appendix B. Also, a 95% reliability range for each parameter is provided. To validate the model accuracy, CRS was calculated for the sections that do not contain new distresses using the revised models and comparing them to that of the 2007 model. Scatter plot results of the revised versus 2007 model are presented in Figure 5.1. The results show that the revised models are sufficiently accurate in calculating the CRS for the sections that do not contain new distresses.

Table 5.4. Interstate ACP Calculation Model Revision

Distress Code	Definition	2007 Model	Revised Model	95% Reliability Range
Intercept		9	9	
IRI	International Roughness Index	-0.007	-0.007	[0.004–0.006]
Rutting	Rutting depth	-2.589	-2.589	[1.441–2.563]
L	**Alligator cracking**		**-0.141**	
M	Block cracking	-0.544	-0.544	[0.464–0.527]
O	Trans. cracking/Joint reflection cracks	-0.091	-0.091	[0.092–0.138]
P	Overlaid patch reflective cracking	-0.301	-0.301	[0.159–0.240]
Q	Long./Center-of-lane cracking	-0.118	-0.118	[0.104–0.147]
R	Reflective Widening Crack			
S	Centerline deterioration	-0.234	-0.234	[0.300–0.396]
T	Edge cracking			
U	Permanent-patch deterioration			
V	Shoving, bumps, sags, and corrugation			
W	**Weathering/Raveling/Segregation/Oxidation**		**-0.133**	
X	Reflective D-cracking			

Table 5.5. Interstate AC/JRCP Calculation Model Revision

Distress Code	Definition	2007 Model	Revised Model	95% Reliability Range
Intercept		9	9	
IRI	International Roughness Index	-0.005	-0.005	[0.004–0.005]
Rutting	Rutting depth	-1.829	-1.829	[1.823–2.112]
L	**Alligator cracking**		**-0.207**	
M	Block cracking	-0.326	-0.326	[0.289–0.311]
O	Trans. cracking/Joint reflection cracks	-0.142	-0.142	[0.132–0.149]
P	Overlaid patch reflective cracking	-0.214	-0.214	[0.197–0.212]
Q	Long./Center-of-lane cracking	-0.189	-0.189	[0.197–0.211]
S	Centerline deterioration	-0.350	-0.350	[0.354–0.377]
U	Permanent-patch deterioration	-0.112	-0.112	[0.08–0.126]
V	Shoving, bumps, sags, and corrugation			
W	Weathering/Raveling/Segregation/Oxidation	-0.383	-0.383	[0.275–0.312]
X	Reflective D-cracking	-0.326	-0.326	[0.312–0.338]

Table 5.6. Interstate AC/CRCP Calculation Model Revision

Distress Code	Definition	2007 Model	Revised Model	95% Reliability Range
Intercept		9	9	
IRI	International Roughness Index	-0.006	-0.006	[0.006–0.006]
Rutting	Rutting depth	-1.605	-1.605	[1.508–1.610]
L	**Alligator cracking**		**-0.193**	
M	Block cracking	-0.356	-0.356	[0.351–0.357]
O	Trans. cracking/Joint re. cracks	-0.115	-0.115	[0.114–0.119]
P	Overlaid patch reflective cracking	-0.235	-0.235	[0.235–0.240]
Q	Long./Center-of-lane cracking	-0.139	-0.139	[0.138–0.144]
R	Reflective widening crack			
S	Centerline deterioration	-0.387	-0.387	[0.386–0.394]
T	Edge cracking	-0.171	-0.171	[0.159–0.168]
U	Permanent-patch deterioration	-0.064	-0.064	[0.049–0.061]
V	Shoving, bumps, sags, and corrugation			
W	**Weathering/Raveling/Segregation/Oxidation**		**-0.219**	
X	Reflective D-cracking	-0.351	-0.351	[0.349–0.355]

Table 5.7. Interstate CRCP Calculation Model Revision

Distress Code	Definition	2007 Model	Revised Model	95% Reliability Range
Intercept		9	9	
IRI	International Roughness Index	-0.007	-0.007	[0.006–0.007]
A	D-cracking	-0.225	-0.225	[0.213–0.239]
B	Transverse cracking	-0.317	-0.317	[0.326–0.356]
C	Joint deterioration			
D	Centerline deterioration	-0.342	-0.342	[0.376–0.431]
E	Longitudinal cracking	-0.254	-0.254	[0.249–0.280]
F	Edge punchouts	-0.085	-0.085	[0.083–0.147]
H	Corner breaks			
I	**Map cracking/Scaling**		**0.200**	
J	Popouts/High steel	-0.103	-0.103	[0.061–0.109]
K	Permanent-patch deterioration	-0.322	-0.322	[0.267–0.327]

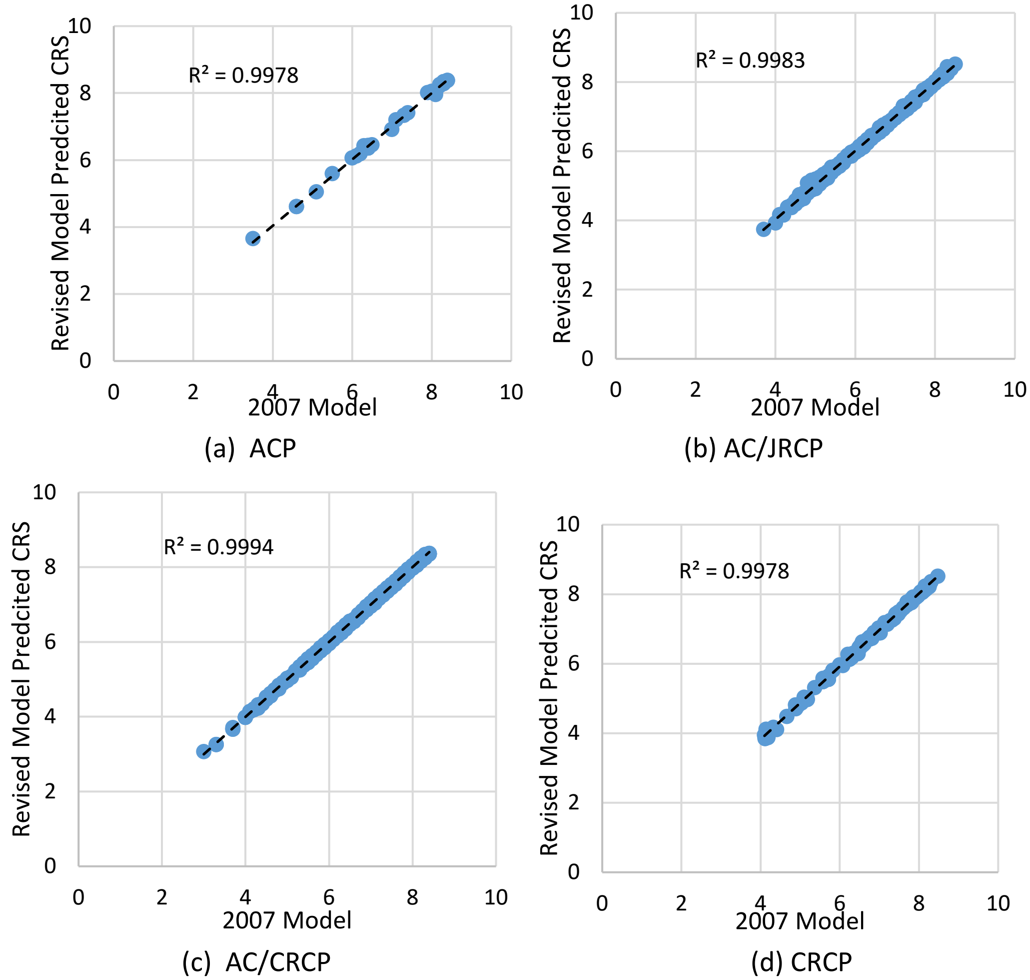


Figure 5.1. Revised model validation versus 2007 model for Interstate sections and different surface types.

5.5 AN EVALUATION OF UNDER- AND OVEREMPHASIZED DISTRESSES

An evaluation of under- and overemphasized distresses was made. The discussion and data analysis for this section can be found in Appendix C.

CHAPTER 6: SUMMARY AND CONCLUSIONS

6.1 SUMMARY AND REMARKS

Condition rating survey calculation and prediction models were revised using the dataset containing historical pavement-condition data from 2000–2014. Two datasets were utilized in developing the prediction models. The majority of the surface types were modeled using the data obtained from the IRIS system. The second dataset was obtained from the reports that the Illinois Department of Transportation (IDOT) has been conducting pavement performance monitoring surveys on mechanistically-designed pavements. A standard procedure was applied to the data prior to developing model coefficients. The first action taken was to consolidate data obtained from different years and repopulate them to monitor the progression of the CRS in each section. Since a section could be broken into different beginning and ending station numbering during the analysis period, it was critical to monitor the unique progression of CRS and distress records for each section.

Additional steps were taken in data preparation to check the data trends. Instead of removing flats and risers (the two consecutive data points remaining constant or increasing) from the dataset as it was done by the previous modeling efforts (Heckel and Ouyang, 2007a), a sensitivity analysis was conducted to check situations where the flats and risers remain in the datasets. An algorithm was developed to catch specific data trends and identify them with appropriate flags. These flags included negative slopes and various types of positive slopes (e.g. flats and risers). Positive slopes indicate potential rehabilitation (resurfacings), preservation, upstream, and downstream identifiers. The total percentage of positive slopes were around 20–30% for the Interstate system and 25–30% for the Non-Interstate system. There were consistent trends in the percentages of positive flags when there was enough data. The majority of the positive slopes indicated potential resurfacing events followed by potential preservation events which may include patching, centerline micro-surfacing, sealing, etc. There were also positive slopes either at the beginning of a pavement service life (upstream) or toward the end (downstream when the CRS is around 5.0). Retaining all the data in between two resurfacing events or original construction and resurfacing event stems allows for more realistic estimations of future CRS values. A similar approach was also followed by one of the previous modeling efforts to evaluate overlay performance (Wolters et al., 2008).

Two modeling approaches were implemented. The traditional two-slope model was applied to AC overlays. An incremental survival-type model was developed for the first time and applied to concrete-surfaced pavements. Both methods followed an incremental approach, which does not require age information. It was decided to work the survival-type model with a nonlinear S-shaped curve commonly used in pavement damage progression. The S-shaped curve is defined by three distinctive regions with the initial slow damage initiation and progression followed by almost constant rate fast damage progression and finally the state where the pavement is saturated with damage. This type of model provides increased flexibility required for concrete pavements which had distinct deterioration trends (especially at the early stages) and service life compared to AC overlays. The S-shaped curve is determined by a coefficient to define its shape and terminal service life. Terminal service life was used as a constraint and selected based on the earlier modeling efforts in Illinois for similar pavement types. It also helps to determine if it fits with the existing data. There are two major advantages of this model type for concrete pavements. First, it captures the initial slow deterioration trends commonly observed in concrete pavements very successfully. Secondly, since the model is more consistent with the underlying physics of pavement damage progression, more consistent trends can be obtained in terms of terminal service life, even when there is not enough data available.

The following list summarizes the research findings for the prediction models developed for the Interstate and Non-Interstate systems:

Interstate System Asphalt-Surfaced Pavements (summarized in Table 6.1):

- Two-slope models were developed for all Interstate asphalt-surfaced pavements.
- Service life to reach a CRS of 5.5 varies from approximately 10 years (AC/JRCP type) to 16.7 years (ACP type) for Interstate asphalt-surfaced pavements.
- Service life predictions for AC/CRCP and overlays in full-depth HMA sections have comparable service lives (14–15 years to reach a CRS of 5.5 and approximately 21 years to reach a CRS of 4.5). Both types of pavements showed slower deterioration trends before and after the breakpoint and benefitted from the decision of not removing flats and risers.
- AC/JRCP type resulted in service lives considerably shorter than the AC/CRCP and ACP types by about 25–40% less than AC/CRCP and 50–60% less than the AC or AC/ACP types.
- Due to the lack of data, AC/JRCP model coefficients were assigned to AC/JPCP.
- The sections with D-cracked underlying concrete are predicted to result in service lives about 26-44% shorter than the standard types.
- The models developed for full-depth HMA pavement in Districts 5–9 for the Non-Interstate are currently assigned to the Interstate as AC/ACP type until there is enough data for this type on the Interstate system.
- The data did not reveal any consistent differences between northern and southern districts. This is consistent with the previous modeling efforts for overlay analysis (Wolters 2008).

Table 6.1. Summary of Service Life Predictions for Asphalt-Surfaced Pavements in the Interstate System

Type	Surface Type	Districts	Years to CRS = 5.5	Years to CRS = 4.5
Standard	AC/CRCP	1-4	14.3	21.2
		5-9	13.2	19.2
	AC/JRCP	1-4	10.2	14.7
		5-9	10.5	15.3
	AC/JPCP	1-4	10.2	14.7
		5-9	10.5	15.3
	AC/ACP	1-9	15.4	21.9
	ACP	1-9	16.7	25.0
D-cracked	Overlay on Jointed Rigid	1-9	7.5	10.7
	Overlay on CRCP	1-9	9.0	11.9

Interstate System Concrete-Surfaced Pavements (summarized in Table 6.2):

- Incremental survival-type models were developed for Interstate concrete-surfaced pavements.
- There was enough data to develop survival models only for standard and D-cracked CRCP sections on the Interstate system. The model developed for the Non-Interstate JPCP was assigned to the Interstate JPCP for standard and D-cracked types.
- As compared to the previous models developed in 1999 and 2007, the proposed models resulted in relatively longer service life estimates. This is due to using terminal service life as a constraint chosen from modeling efforts for similar pavements in Illinois. When there is more data available to indicate the terminal service life of concrete pavements, the models should be reviewed.
- The service life estimates assume an initial CRS of 9.0. Lower service life should be expected if the initial CRS is not 9.0.
- Accuracy of the models is much higher within the first 10-20 years after original construction where there was sufficient data. The model was applied to the data in the mechanistic database to verify its correlation to high quality performance data for mechanistically-designed pavements.
- It is recommended to fine-tune the model when there is enough data to make a better prediction to reach CRS values of 5.5 or 4.5. The models can also be improved if accurate age information can be obtained. This is the case for the concrete models developed for both Interstate and Non-Interstate systems.

Table 6.2. Summary of Service Life Predictions for Concrete-Surfaced Pavements in the Interstate System

Type	Surface Type	Districts	Years to CRS = 5.5	Years to CRS = 4.5
Standard	CRCP	1-9	40	45
	JPCP	1-9	36	40
D-cracked	CRCP	1-9	31	35
	JPCP	1-9	27	30

Non-Interstate System Asphalt-Surfaced Pavements (summarized in Table 6.3):

- A similar trend was observed in the service life comparison of overlays on jointed concrete pavements (AC/JPCP and AC/JRCP) against AC/CRCP. A reduction of service life by approximately 18–29% was observed for overlays on JPCP and JRCP types.
- The ACP models for full-depth HMA pavements were developed using the database containing only mechanistically-designed pavements. The mechanistic database was cleaned to develop the model for original full-depth HMA prior to first resurfacing. The models indicated the service life of 16.7 years and 25.0 years to reach CRS values of 5.5 and 4.5, respectively.
- The full-depth HMA sections available in the IRIS dataset were also analyzed which may include data before and after overlay. The models were developed for overlays in full-depth HMA using this data. There is considerable difference in the performance of these sections in northern and southern districts in favor of sections in the southern districts. Service life predictions for Districts 5–9 (15.4 and 21.9 years to reach CRS values of 5.5 and 4.5) are more consistent with the mechanistic database.
- AC overlays on PCCun surfaces in the northern districts outperformed overlays with JPCP and JRCP type and showed comparable performance with AC/CRCP and overlays in full-depth HMA. This is one of the surface types with the largest amount of data available. This overlay type can be studied more carefully with additional data from the districts and field to verify the trends.
- The service life to reach critical values of CRS in southern districts for standard and SMART surface types is 3–30% higher than those in northern districts, except for AC overlays of PCCun surfaces.
- SMART sections showed comparable service life with standard overlays on concrete pavement (AC/JRCP, AC/JPCP, AC/PCCun), except those on CRCP structures. This may indicate something about the (in-)effectiveness of policy overlays (only ¾ to 1 inch thicker than SMART overlays) when they are used with jointed concrete pavements underneath. However, it may be premature to reach such a conclusion as the data analyzed contains structures with many different existing HMA thicknesses. Comparable performance could also be attributed to the timing of SMART overlays that may have contributed to its performance despite the reduction in thickness.

- Overlays on the concrete pavements with D-cracking flag and “X” distress showed a similar reduction in service life within the range 19–33%. Data counts are low for these sections. Therefore, positive slopes were not added. This may also have skewed the outcome to yield shorter service lives. However, the predictions are consistent with the earlier modeling efforts (Gharaibeh et al., 1999 and Wolters et al. 2008) and expectations.

Table 6.3. Summary of Service Life Predictions for Asphalt-Surfaced Pavements in the Non-Interstate System

Type	Surface Type	Districts	Years to CRS = 5.5	Years to CRS = 4.5
Standard	AC/CRCP	1-4	12.1	17.7
		5-9	13.1	18.8
	AC/JRCP	1-4	9.8	14.6
		5-9	11.1	16.4
	AC/JPCP	1-4	9.6	14.6
		5-9	10.0	15.1
	AC/PCCun	1-4	13.2[1]	20.2[1]
		5-9	10.3	15.0
	AC/ACP	1-4	12.4	18.0
		5-9	15.4	21.9
	ACP	1-9	16.7	25.0
SMART[3]	AC/CRCP	1-9	10.3[2]	14.5[2]
	AC/JRCP	1-4	10.3	15.4
		5-9	10.8	16.3
	AC/JPCP	1-4	10.0	15.7
		5-9	10.9	16.7
	AC/PCCun	1-4	12.7[1]	18.7[1]
		5-9	11.1[1]	16.2[1]
	ACP	1-4	10.5	15.2
		5-9	13.7	19.2
D-cracked	Overlays on Jointed Rigid	1-9	8.2	12.2
	Overlays on CRCP	1-9	8.9	13.2

[1] Apparent increase in service life for the AC/PCCun surface type may be due to large percentage of positive downstream slopes contributing to the increase in service life until the next overlay.

[2] Limited number of data points may have caused the underestimation of service life for SMART overlays on CRCP system.

[3] SMART overlays are placed on pavements with a higher CRS value, which may explain the longer service life to the terminal CRS values compared to some standard overlays.

Non-Interstate System Concrete-Surfaced Pavements (summarized in Table 6.4):

- Survival-type models were developed when there was enough data available for concrete-surfaced pavements on the Non-Interstate system.
- Similar to the Interstate concrete-surfaced pavement predictions, the proposed model resulted in longer service life estimates compared to the estimates of previous models. This is due to using terminal service life as a constraint chosen from modeling efforts for similar pavements in Illinois. When there is enough data available to indicate terminal service life of concrete pavements, the models should be fine-tuned.
- The estimates assume an initial CRS of 9.0. Lower service life should be expected if initial CRS is not 9.0.

Table 6.4. Summary of Service Life Predictions for Concrete-Surfaced Pavements in the Non-Interstate System

Type	Surface Type	Districts	Years to CRS = 5.5	Years to CRS = 4.5
Standard	CRCP	1-9	36	40
	JPCP	1-9	36	40
	JRCP	1-9	36	40
	PCCun	1-9	31	35
	HJCP	1-9	31	35
D-cracked	CRCP	1-9	27	30
	JPCP	1-9	27	30
	JRCP	1-9	27	30
	PCCun	1-9	22	25
	HJCP	1-9	22	25

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APPENDIX A: CRS BASED ALGORITHM TO IDENTIFY VARIOUS TRENDS IN THE SLOPE

IF M >= 0 (%Flats and Risers)
    EXECUTE BLOCK A
ELSE (%for normal deterioration)
    Flag = Noflag

BLOCK A:

IF Two Records (CRS_t and CRS_{t+1}) are NOT from consecutive years
    IF CRS_{t+1} > 7.0
        FLAG = REHAB1
    ELSE
        FLAG = UNKNOWN1
ELSE
    1. IF CRS_t AND CRS_{t+1} > 7.5 (Two close records at the very early years after construction)
        FLAG = UPSTREAM1

    2. ELSE IF CRS_{t+1} >= 7.5 AND CRS_t <= 7.5

        IF m >= 0.5 (consider this rehab regardless of IRI drop)
            FLAG = REHAB2 (most likely indicating a jump from a lower CRS)

        ELSE IF m < 0.5 AND IRI drop < 30
            FLAG = PRESERVE1 (slope small and IRI drop insignificant)

        ELSE
            FLAG = UNKNOWN2 (large IRI drop and m < 0.5➔ could be suspicious IRI)

    3. ELSE IF CRS_{t+1} < 7.5 AND [7.5>= CRS_t >=6.5]

        IF IRI drop < 30
            FLAG = PRESERVE2 (distress record was not used here due to high CRS range)
        ELSE
            FLAG = REHAB3

    4. ELSE IF CRS_{t+1} < 7.5 AND [6.5> CRS_t >=5.0]

        IF CRS_t and CRS_{t+1} has 5 distress records AND m < 0.5
            FLAG = DOWNSTREAM1
        ELSE IF IRI drop < 30 AND there is at least 3 distress records with CRS_{t+1}
            FLAG = PRESERVE3

ELSE IF m < 0.5 (There may be still some records with suspicious IRI records)

FLAG = PRESERVE3

ELSE

FLAG = REHAB4

5. ELSE IF CRS_t < 5.0 and [7.5>CRS_{t+1} >= 5.0]

IF CRS_t and CRS_{t+1} has 5 distress records AND m < 0.5

FLAG = DOWNSTREAM2

ELSE IF IRI drop < 30 AND there is at least 3 distress records with CRS_{t+1}

FLAG = PRESERVE4

ELSE

FLAG = REHAB5

6. ELSE IF CRS_t and CRS_{t+1} < 5.0

IF CRS_t and CRS_{t+1} has 5 distress records AND m < 0.5

FLAG = DOWNSTREAM3

ELSE IF there is at least 3 distress records with CRS_{t+1}

FLAG = PRESERVE5

ELSE

FLAG = UNKNOWN3

7. ELSE

FLAG = UNKNOWN4

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APPENDIX B: SUMMARY OF EXPERT-COMMENTED INTERSTATE SECTIONS

Table B.1. Expert-Commented Sections and Overridden CRS for Interstate Sections

Type	Surface Code	Distress Not in the Model	Comment by Expert	Cal. CRS	Manual CRS	Record	Distresses
Asphalt concrete pavement (ACP)	550 and 560	Weathering (W)	W not in Int Model	6.0	5.6	W4	M2Q2S2W4
			W not in Int Model	6.2	5.6	W4	M2Q2S2W4
			Weathering	5.2	5	-	L2M2O3Q2S3
		Alligator cracking (L)	-	4.5	4.1	L3	L3M3O3Q3S2
			Block cracking close to Level 4.	4.8	4.6	L4	L4M3O2Q2S3
			Some transverse cracking.	4.7	4.5	L4	L4M3Q4S2T3
Asphalt overlays of jointed reinforced concrete pavements (AC/JRCP)	620 - 630	Edge cracking (T)	Edge Breakup	6.2	6	T2	L1M2O3Q2R3
			Edge distress as well.	5.0	4.6	T2	L3M3O3P5S4
			Edge Break up	4.7	4.5	T1	M3O3Q3S4W2
			R3	5.1	4.8	R3	M3O4P4Q3S2
			R4	5.2	4.7	R4	M2O4P5S2W2
			R4 present	5.4	4.6	R4	M2O4P4Q3S2
		Alligator cracking (L)	L Not in Int Model	5.4	4.8	L3	L3M2O4Q3S3
			large CL cracking	6.8	6.5	L2	L2M2O1S3
			Photo match	5.1	4.2	L3	L3M2O3Q3S3
			many cracks	5.5	5.3	L3	L3M3O2R2S3

APPENDIX C: CALCULATION MODEL UPDATES

C.1 MODEL UPDATING

Since the last update in 2007 and during the data collection and evaluation procedure, CRS values were manually modified for some sections, based on the existence of some of the distresses currently not included in the CRS calculation models. These modifications were applied directly by overriding the values by the raters. The magnitude of the deduction depended on the expert judgment of the distress type and severity and its influence on the current deterioration level of the section. Some of the overridden records have explanations in the database to guide the revisions. Using the expert-overridden values, these specific distresses can be manually incorporated into the CRS calculation models, followed by regression analysis to update the other distresses' coefficients. The database and procedure to carry out the model updating are presented in the following sections.

C.1.1 Database

Data from 2000 to 2014 were used for model updating. Manually overridden data was separated from the main database, and different data sets for Interstate and Non-Interstate sections were prepared. Using expert-overridden values, the model updating can be carried out. Calculated CRS values from current models were compared to those of reported (overridden) values. A database was prepared based on the expert comments on some of the sections where inconsistencies were observed or modifications were thought to be necessary. A summary of the database is shown in Appendix C, Table C1.

Inconsistencies between the calculated and reported CRS values can be due to various reasons.

There are multiple reasons for the case when the reported CRS is less than calculated CRS. Some of them follow:

- New and old sections exist in the same evaluation, and the calculated CRS is determined based on the new section.
- It was observed that, where pavement was treated with micro-surfacing, the final CRS was rounded down to the nearest values of 7.5, 7.0, or 6.5.
- An expert thinks the distress is "progressing." An average CRS drop of 0.2 points was observed. Example: Progressing distress from O2 to O3, with a change from 7.5 to 7.2 or 7.1 to 7.0 was observed.
- Centerline issues, including "C. Line getting worse in spots" or "C. line issues in spots"; an average drop of 0.2 points was observed.
- If CRS > 6.5 and patching exists, reset the CRS to 6.5.
- When experts realize certain distresses that are underestimated by the equation, they may overwrite it to reflect that. However, experts may or may not leave comments on some of these sections in the database.

- If there are more than five distresses present, experts may manually deduct some points from the calculated CRS. An average drop of 0.25 points was observed.
- A new distress exists and the expert left a comment while deducting some points.

The last three cases, in which experts clearly indicate the existence of new distresses and deduct points accordingly, will be used for updating the models.

Two separate databases were developed. One database was used to incorporate new distresses into the CRS model, overriding CRS to reflect the new distresses. A second database was developed from the comment sections where experts thought there was an over- or underestimated distress. Although the first database is used to incorporate new distresses and accordingly update model coefficients, the second database is used only to address the over- or underestimated distresses.

Table C.1 shows example commented sections with more than five distresses where the new distress is the reason for additional deductions.

Table C.1. Expert-Commented Sections with More than 5 Distresses for Interstate Sections

Type	Code	Expert comment	Calculated CRS	Manual CRS	Difference	Distresses
Asphalt concrete pavement (ACP)	550, 560	C. Line distress.	4.4	4.1	0.3	L3M3O3Q3T3
Asphalt overlays of jointed reinforced concrete pavements (AC/JRCP)	620-630	P2	5.9	5.7	0.2	M1O4Q2R2S2
		W1	5.8	5.6	0.2	M2O3Q3R3S2
		W1	5.8	5.6	0.2	L2M2O3Q2S2
		P & Q Present	5.6	5.4	0.2	M2O3R2S2W2
		Q	5.6	5.4	0.2	M2O3S1T2W2
		P also present	5.2	5	0.2	M1O5Q3R3S2
		No room for Q distress	5.6	5	0.6	L3M1O3R4S3
		Weathering	5.1	4.8	0.3	L3M3O3Q3S2
Asphalt overlays of continuously reinforced concrete pavements (AC/CRCP)	640	W1(Startup)-S2 CL Patching Summer 14	6.2	5.9	0.3	M1O3Q3S2T2
		W1(Startup)-S2 CL Patching Summer 14	6.1	5.9	0.2	M1O3Q3S2T2

Table C.2 shows the potential distresses to be added to the Interstate CRS models and the number of expert-commented sections for each. It should be noted that most of the Non-Interstate sections are AC/PCC, and the current calculation model for this surface type includes all the distresses. Therefore, model updating was carried out only for Interstate sections.

Table C.2. Potential New Distresses for the Interstate CRS Models and the Number of Data Points for Each Surface Type

Type	Code	New distress	# of Expert-Commented Sections
ACP	550,560	Weathering (W)	2
		Alligator cracking (L)	1
AC/JRCP	620-630	Edge cracking (T)	2
		Reflective widening crack (R)	4
		Alligator cracking (L)	3
AC/CRCP	640	Weathering (W)	11
		Alligator cracking (L)	3
CRCP	740, 790, 792	Map cracking and scaling (I)	5

C.1.2 Model Updating Procedures

Using experts' comments indicating the existence of a specific distress not present in the model, one can carry out modifications to the model. Expert-modified CRS values were matched with the recorded severity level, and a deduction value was calculated accordingly. Then the new distress was added to the model. Other model coefficients were not modified because it may cause inconsistencies in future ratings when the new distress does not occur as part of the five measured distresses. This scenario is very likely because these new distresses are relatively less frequently observed.

There are two cases in which a deduction can be assigned to the new distress:

1 Apply a deduction when fewer than five distresses are present and one or more of the recorded distresses is not in the current model. For example, recorded distresses for a section includes A1, B2, C2, and D2, while the model includes only distresses A, B, and C. Assume the calculated CRS for this section is 7; however, the overridden CRS is 6.5. Thus, the 0.5 deduction is due to the distress D2, per expert opinion. Therefore, the weight of D would be approximately 0.5/2 = 0.25.

2 Apply a deduction when more than five distresses occur and the section is commented with an extra distress. For example, recorded distresses include A1, B2, C1, D2, E3, and F2. The calculated CRS is 7. However, F is neither in the model nor included within the five-distress record limit. So, the expert has deducted 0.5 point for the F distress (the overridden CRS is 6.5). Thus, a 0.5 deduction is due to the distress F2, per expert opinion. The weight of F then would be approximately 0.5/2 = 0.25.

It should be noted that the latter case is used only when there is a clear indication of a new distress not included within the five distresses but recorded in the comment section by experts.

In the next step, using the average deduction values from all commented sections, each distress was added to the model; and multiple-regression analysis was carried out to update the coefficients of all other distresses. Coefficients of the new distresses were kept constant during the regression modeling.

C.1.3 Results

Using the steps from the previous section, new distresses were added to the current models. Then a regression analysis was carried out to update current model coefficients. It should be noted that one may add new distresses to the equation without updating the current coefficients. However, because the new distress weights are averaged over expert opinions, all model coefficients were updated to better fit to all data. It should be noted that most of the Non-Interstate sections are AC/PCC, with the current calculation model for this surface type including all the distresses. Therefore, due to the lack of data, model updating was not conducted for other Non-Interstate models. Results were shown in the main body of report in Chapter 5.

C.2 AN EVALUATION OF UNDER- AND OVEREMPHASIZED DISTRESSES

C.2.1 Expert Comments

As noted by experts, during the data collection and rating process, some of the distresses were identified as under- or overemphasized. The confusion is partially because some of these distresses were not present at the time of data collection for model development purposes in the past, or there were not enough data collected for these distresses, or they were assumed to be insignificant. With time and as more data was collected, experts came to believe some the distresses were being either underemphasized or overemphasized. Table C.3 shows an example of an underemphasized distress commented upon by the raters. The overlay patch and reflective cracking distress (P) is the only distress recognized and commented upon by the experts. In the two cases, experts believed that “P should have a greater weight than a max of 0.2 deduction.”.

Table C.3. Underemphasized Distress Commented Upon by Experts

Type	Distress	Model Coefficient	Comment	Calculated CRS	Manual CRS	Record	Distresses
AC/JRCP	Overlay patch and reflective cracking (P)	0.214	It is believed that P should have a greater weight than a max of 0.2 deduction.	4.6	4.5	—	M3O4Q4S3T2
			It is believed that P should have a greater weight than a max of 0.2 deduction.	4.6	4.4	P5	M3O4P5Q3S4

Although clearly there is a need to update the P-distress coefficient to address these comments, there are no other records with similar comments where the CRS is manually modified according to the expert opinion. Therefore, updating the coefficient of distress “P” can be done in the future when there are enough observations for which experts manually modify the CRS to reflect the impact of P-distress and clearly identify these sections in the database. A sufficient number of observations is required to revise the model to reflect the representative condition of pavement so it won’t be overridden again. Alternatively, if a distress is chosen to be under- or overemphasized, new observations can be generated by re-rating a selected number of sections. Recommendations on how to revise calculation models will be discussed at the end of this chapter.

C.2.2 Structural and Functional Distresses

In addition to reviewing the raters' comments, an analysis of the data was conducted to investigate under- and overemphasized distresses. The significance of structural distresses has been recognized to estimate the remaining representative service life of pavements. In this regard, distresses can be categorized into two classes, functional and structural. Functional distresses affect ride quality, usually can be treated using less costly surface treatments, and are not critical in overall long-term performance of the pavement. By contrast, structural distresses are indications of a weak structure that may require more in-depth structural treatment and are crucial for overall performance of the pavement. Structural distresses are usually costly to repair, and in-time treatments of these distresses are of high importance for long-lasting pavements.

The approach to identify these distresses is as follows:

- Filter data and prepare a database with a time series of each distress showing progression.
- Understand distress decomposition to structural and functional types of distresses.
- Investigate possible correlation of each distress frequency and deduction in CRS. This should ideally correlate with individual distress coefficient (deduct value) in the models.
- Investigate the rate of deterioration of each distress with the rate of change in CRS. A high correlation between the rate of deterioration of a specific distress and CRS would potentially indicate the importance of that specific distress. Accordingly, the deduct value for that distress should be representative of its importance; otherwise, the distress is underemphasized.
- Similarly, a low rate of change of a distress with CRS change with time would potentially mean that specific distress is not significantly affecting the CRS. Accordingly, the coefficient of the distress (deduct value) in the model should be consistent with its importance, otherwise the distress is "overemphasized."
- Investigating and correlating the frequency of a distress and its deduction from total CRS can reveal the current significance of the distress.

All distresses defined by the CRS methodology were categorized into the functional and structural categories, according to the distress definition and the cause of the distress. Table C.4 shows these distress categories. IRI and rutting were categorized in neither of the categories because they can have both structural and functional causes. Some of these distresses can be categorized as both structural and functional, depending on the severity level. For example, block cracking can be considered a functional distress at low severity levels; however, as it progresses, it is usually considered a structural distress. The analysis of distress hereafter will be done using the following categorization of distresses.

Table C.4. Structural and Functional Distress Categories for Asphalt-Surfaced Pavements

Structural distresses	Functional distresses
Alligator cracking (L)	Longitudinal/Center-of-lane cracking (Q)
Trans. cracking/Joint ref. cracks (O)	Centerline deterioration (S)
Overlaid patch reflective cracking (P)	Weathering/Raveling/Segregation/Oxidation (W)
Edge cracking (T)	Block cracking (M)
Permanent-patch deterioration (U)	
Reflective widening crack (R)	
Shoving, bumps, sags, and corrugation (V)	
Reflective D-cracking (X)	

C.2.3 Distress Frequency Analysis

Frequency analysis of each distress category at different CRS levels can be a primary analysis to show the occurrence of each distress category. Distress frequency analysis was conducted at different CRS values. A weighted frequency was used to combine frequencies at different severity levels, according to the following equation. The higher the severity level of a distress, the higher the weight assigned to it:

$$Weighted\ Frequency = Freq_1 \times 1 + Freq_2 \times 2 + \ Freq_3 \times 3 + \cdots \qquad 5.1$$

where, $Freq_i$ is the frequency of appearance of a specific distress at severity level *i*.

Figures C.1 (a) and (b) show examples of a weighted frequency analysis for each distress, as well as distresses combined into two categories for Interstate AC/CRCP sections. A similar analysis can be conducted for each surface type.

Functional distresses are more frequent when pavement is in good condition. In contrast, structural distresses are the main contributors at lower CRS values. However, at the critical CRS level (CRS of 5.5), functional distresses govern pavement-condition, constituting more than half of the share. Among the distresses, centerline deterioration (S) and center-of-lane cracking (Q) are governing the deterioration at almost all levels of CRS. Structural distresses become more prominent when CRS levels are lower than 5.0. However, it is important to note that it is most likely that the limit of five distresses is achieved at low CRS levels, and the share analysis may not completely reflect all the existing distresses.

According to the distress frequency share analysis, one may think that functional distresses are overemphasized, as they are governing a significant part of CRS reduction. However, this is due to the way CRS was developed and interpreted to evaluate surface distresses. Regardless of structural or functional distresses, when critical levels of CRS are reached, this is a good indication of poor ride quality and indicates the time for some sort of maintenance and rehabilitation. The share of structural distresses within the overall distress composition dictates the remaining service life and the type of treatment required.

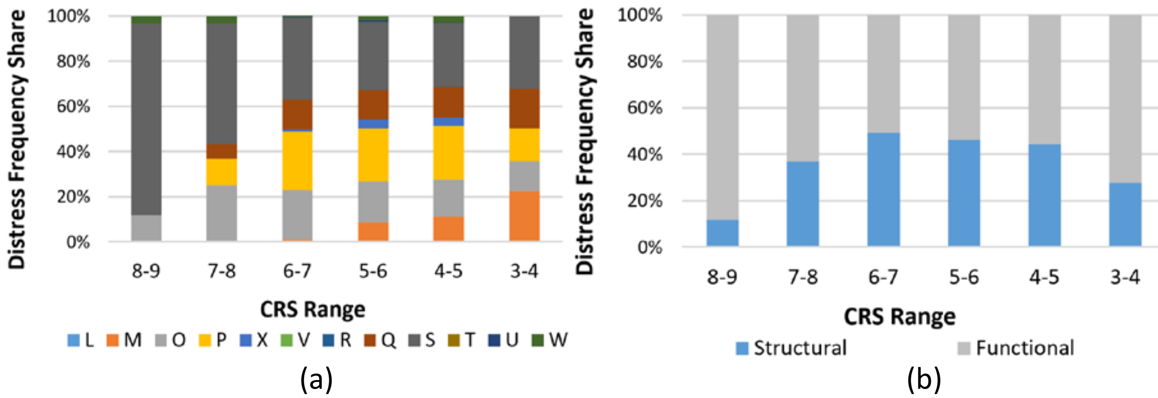


Figure C.1. Weighted frequency analysis for the interstate AC/JRCP section for (a) all distress and (b) distress categories.

C.2.4 CRS Rate of Change Analysis (or Remaining-Service-Life Analysis)

Distress composition and the CRS index can also be analyzed as to rate of deterioration from the presence of individual distresses. The goal would be to ascertain if the existence of a distress accelerates the rate of deterioration—hence reducing the remaining service life, indicating a structural problem. Such a distress, if it can be identified and supported by the data, can be revised to deduct more from the CRS.

The data was analyzed to ascertain if any trends between the rate of CRS and distresses can be captured. The average rate of deterioration was calculated for each distress at different CRS levels, compared, and plotted against the rate of change of CRS (Figure C.2)

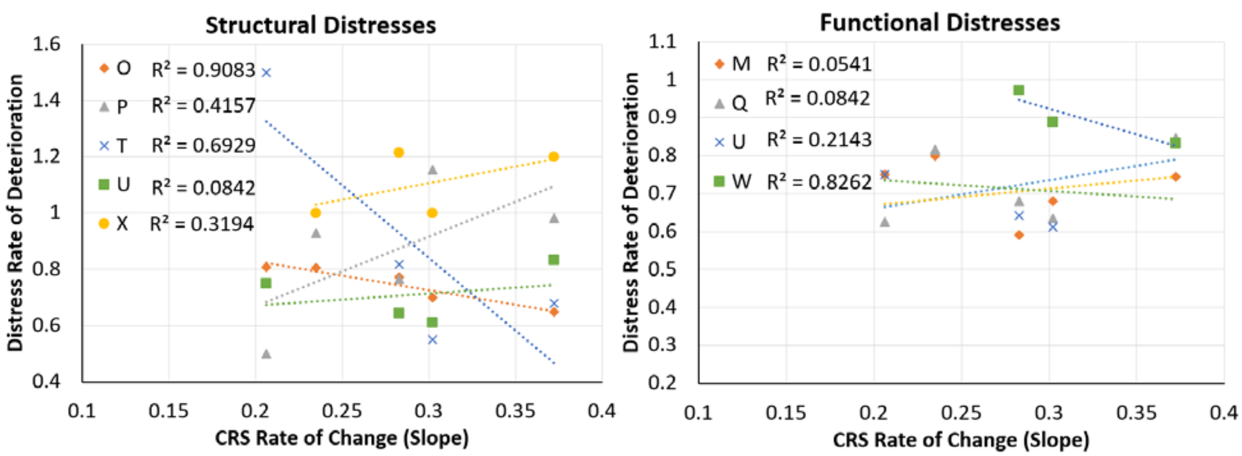


Figure C.2. Scatter plot showing the distress rate of deterioration versus the CRS rate of change for structural (left) and functional (right) distresses for an AC/CRCP section.

It is expected that correlation between the distress rate of deterioration and the CRS rate of change (slope) would be positive and stronger for structural distresses than for functional distresses. However, according to the results, no specific trend was observed based on individual distress correlation within each structural and functional category. Furthermore, all structural and functional distresses were combined; and the share of each category from the CRS slope determined. Figure C.3 shows the share of each structural and functional distress in total CRS rate of change.

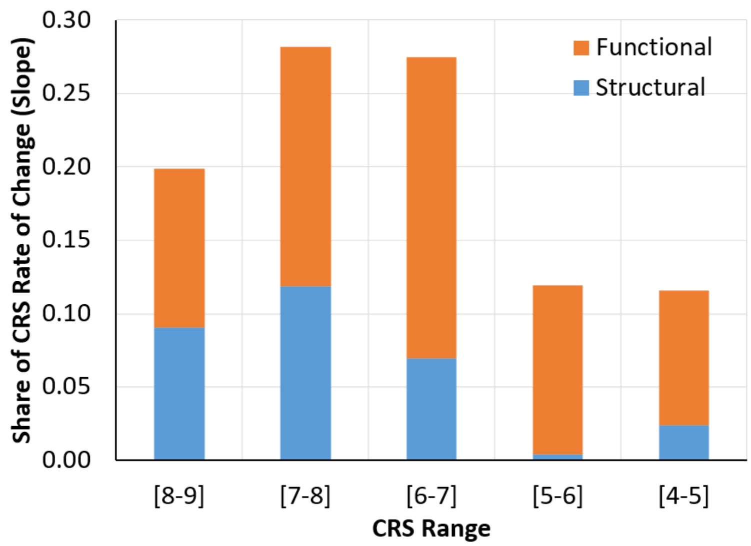


Figure C.3. Share of the rate of change (slope) for each distress category for an AC/CRCP section.

It can be noted that functional distresses play a significant role in all CRS ranges, indicating overemphasizing of the functional distresses.

Overall, the analysis did not result in meaningful conclusions because with the current system of distress recording and CRS ranking, which does not differentiate between functional and structural distresses, most emphasis will be on the surface distresses that are apparent. It is also clear from distress weights from the calculation models, in which functional distresses sometimes have higher weight than structural distresses. Decomposing distresses into distinct structural and functional categories and developing separate models for each category seem a viable remedy for the current CRS evaluation-system deficiency.

Recently, a dual pavement condition rating system was developed by FHWA (Elkins et al. 2013 and Yan, 2016). The balanced condition rating system was developed based on the structural and functional condition of pavement. The method decomposes pavement condition evaluation into functional and structural distress groups and estimates the remaining service period, using the dual prediction system: the remaining functional period and the remaining structural period. In order to develop a dual condition index based on structural and functional distresses and to estimate remaining life, one must have comprehensive and reliable records of the individual distresses.

C.3 SUMMARY AND RECOMMENDATIONS

The weight of each distress in the calculation model should reflect the importance of that distress on overall performance of the pavement. The CRS calculation model has been used by IDOT for many years, and a consistency was established in relating the pavement's condition to the CRS value. CRS has been the common language of the pavement management system at IDOT. Any revisions to the CRS calculation model must be made very cautiously. Otherwise, inconsistencies between calculated CRS and what is perceived by raters as the condition of the pavement surface will increase, resulting in more frequent overriding of the calculated CRS value.

CRS calculation models were updated to incorporate new distresses. A database of expert-commented sections and recorded distresses were used for each Interstate section. Updating Non-Interstate sections can be carried out similarly in the future when enough data is available.

Since there are multiple ways of identifying underemphasized or overemphasized distresses, three alternative approaches were introduced. Raters' comments, functional vs. structural distress analysis, and remaining service life analysis are various ways to help identify distresses that are contributing to the CRS more or less than expected. Any revisions to address over- or underemphasized distresses must be done very cautiously. For example, some of the structural distresses could be given higher deduction values if it can be shown that remaining service life is reduced due to reduction in structural capacity. However, doing so will result in a change in the deduction coefficients of other distresses, such as some of the functional distresses, if the overall CRS is to remain the same. Because some of these distresses (e.g., centerline deterioration, weathering) are occurring very frequently, especially in the early years of pavement life, CRS values will appear to be inflated. Therefore, when making any revisions to the calculation models, the following steps are recommended:

- Determine the underemphasized or overemphasized distresses, to revise the coefficients.
- Collect a sample of sections where the specific distress is present.
- Rate the sections according to the new interpretation of CRS. In addition, overridden and commented sections can also be used in this pool. For example, if there is an underemphasized distress, it will result in a reduction in the CRS or vice versa.
- Change only the coefficient of the distress of interest to address the gap. The other coefficients will remain the same.
- Train the raters with an emphasis on the change of CRS interpretation when the over- or underemphasized distress is present. It is possible that overriding cases will increase dramatically because CRS interpretation associated with some of these distresses will change. Such overridden data records should be sought and revised in the database until a consistency among the raters is achieved.

This approach is making some structural changes in how the new CRS is interpreted. Successful implementation may take years and can cause increased inconsistency between surface condition of the pavement and the overall index. Therefore, alternatively, an approach can be developed to bypass any changes in the CRS calculation models. This approach will rely on developing additional indices, while keeping the CRS as is. The additional indices will derive from the distress decomposition and support the CRS. For example, the two indices that can stem from functional and structural distresses to predict remaining service life can allow a more balanced allocation of budgeting at the network and project level. The development and implementation of this method require reliable and comprehensive historical construction, cross-section, traffic, and distress data (not limited to five). Ideally, distress rating should be done using an objective measurement rather than a subjective severity and frequency rating. The following approach is recommended for development of a dual-condition index to support CRS:

- Compile a list of sections with different surface types where reliable and consistent historical information can be obtained.
- Collect historical construction data, cross-sections, subgrade condition, construction quality information, traffic history, and measured distresses.
- Categorize a group of distresses potentially included in the structural and functional condition index. This group may not necessarily include all of the distresses used in the CRS calculation. An analysis will be performed, and the distresses with the highest correlation to the remaining service life will be determined.
- Investigate the suitability of survival-type models for possible development of dual indices.
- Develop simple survival curves to probabilistically determine failure times and remaining service lives.
- Investigate the possibility of including explanatory variables (i.e., structure information, subgrade condition, construction quality, traffic) into survival models.
- Implement a remaining service life analysis based on the survival models developed, including sensitivity analysis.
- Develop a recommendation system for possible future improvements in both data collection and model updating.

APPENDIX D: IMPLEMENTATION EXAMPLES FOR THE NEW CONCRETE MODELS

This section describes the use of proposed survival-type performance prediction models for concrete pavements. Different variations of the model were derived for the following use-case scenarios of the model.

Service life Prediction for New Pavements:

The first scenario is service life prediction for planning and programming purposes for new concrete pavements with a known or assumed initial CRS. Use the following formula (it was also given in Chapter 3 as Equation 3.9) and assign the initial CRS for new construction (this could be the measurement right after construction or next CRS measurement or an assigned CRS for a possible future construction).

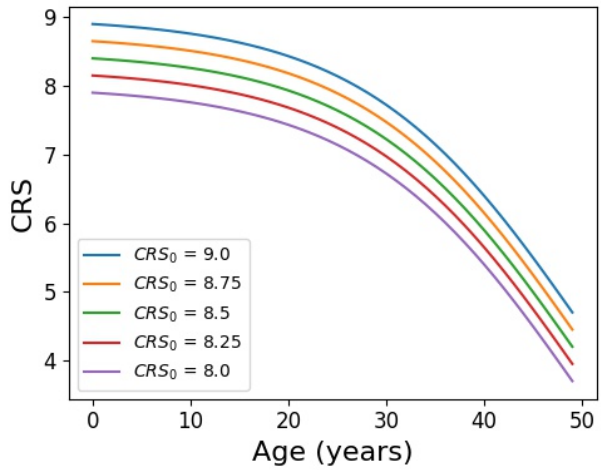
$$CRS_t = CRS_0 - \frac{0.1e^{\alpha t}}{1 + \left(\frac{9.1}{9.0} - 1\right) e^{\alpha t}} \quad 1$$

Sensitivity of this model was investigated when initial CRS changes from 8.0 to 9.0. Results are shown below in Table D.1 and Figure D.1.

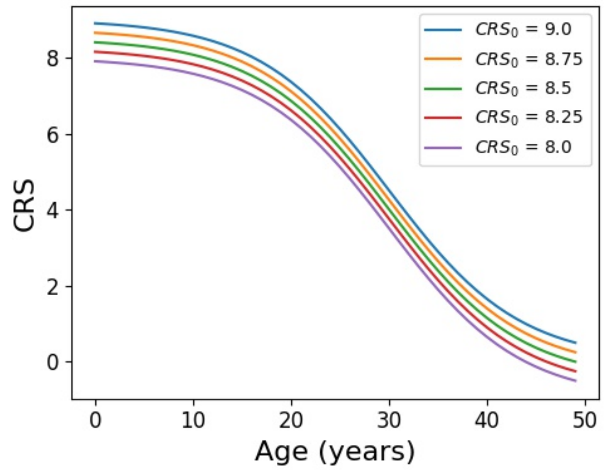
Table D.2. Sensitivity of Survival Model to Initial CRS.

Type	System	Failure CRS	α	Time to failure at CRS_0=9.0	Time to failure at CRS_0=8.75	Time to failure at CRS_0=8.5	Time to failure at CRS_0=8.25	Time to failure at CRS_0=8.0
CRCP (standard)	Non-Interstate	4.5	0.100	45	44	43	42	40
CRCP (D-cracked)	Non-Interstate	4.5	0.128	35	34	33	32	31
PCCun (standard)	Non-Interstate	4.5	0.100	45	44	43	42	40
PCCun (D-cracked)	Non-Interstate	4.5	0.128	35	34	33	32	31
JPCP (standard)	Non-Interstate	4.5	0.113	40	39	38	37	36
JPCP (D-cracked)	Non-Interstate	4.5	0.150	30	29	28	28	27
HJCP (standard)	Non-Interstate	4.5	0.100	45	44	43	42	40
HJCP (D-cracked)	Non-Interstate	4.5	0.113	40	39	38	37	36
JRCP (standard)	Non-Interstate	4.5	0.113	40	39	38	37	36

JRCP (D-cracked)	Non-Interstate	4.5	0.150	30	29	28	28	27



(a) Interstate CRCP (standard)



(b) Non-Interstate JRCP (standard)

Figure D.1 Example performance curves with different initial CRS (*CRS_0*) values.

Backlog Calculations for Pavement Sections in the Network:

In this case, it was assumed that the remaining service life will be calculated for an existing pavement. Remaining service life is defined as the time to reach a critical CRS for an existing pavement. Two different methods can be used for this.

First, Equation 1 can be used by assigning the initial CRS for new construction (this could be the measurement right after construction or next CRS measurement or an assigned CRS for a possible future construction). If the current condition of pavement at year *t* is known (CRS_t), then time elapsed to the current condition can be calculated using the same formula. Remaining service life can be found by subtracting time elapsed from the service life predicted for the pavement. An example is shown using the following illustration for a pavement with initial CRS 9.0 and alpha 0.15.

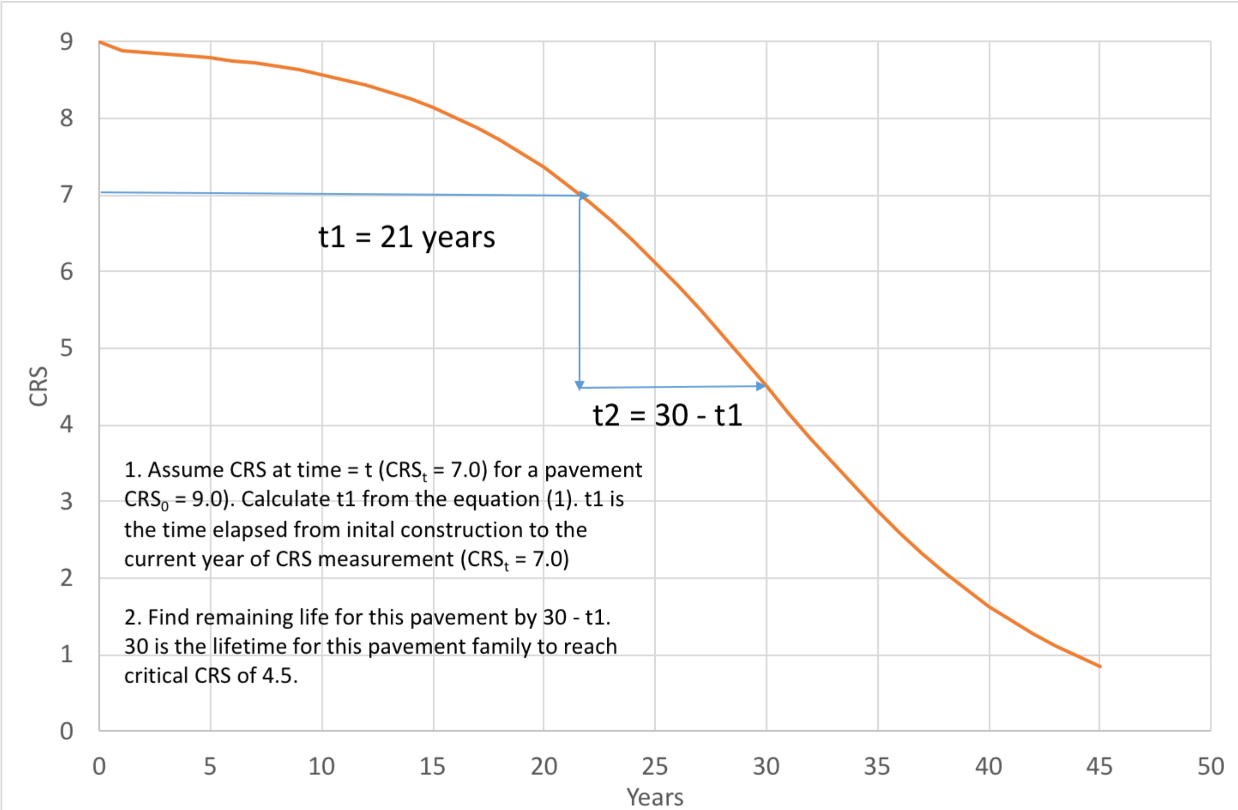


Figure D.2. An illustration of remaining service life calculation.

The second scenario assumes that the history of the pavement section is unknown, or that generic calculations are to be made for a pavement family. As a result, use Equation 2 to calculate remaining service life to critical CRS or backlog:

$$CRS_2 = \frac{9.0}{1 + \left(\frac{9.1}{CRS_1} - 1\right) e^{\alpha t}} \qquad 2$$

Where CRS_2 = Critical CRS or backlog CRS, and CRS_1 is CRS at the time you want to calculate remaining life, solving for t will give you the remaining life to from CRS_1 to CRS_2. The equation for that is:

$$\Delta t = \ln\left(\frac{CRS_1(CRS_2 - 9)}{CRS_2(CRS_1 - 9.1)}\right)/\alpha \qquad 3$$

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