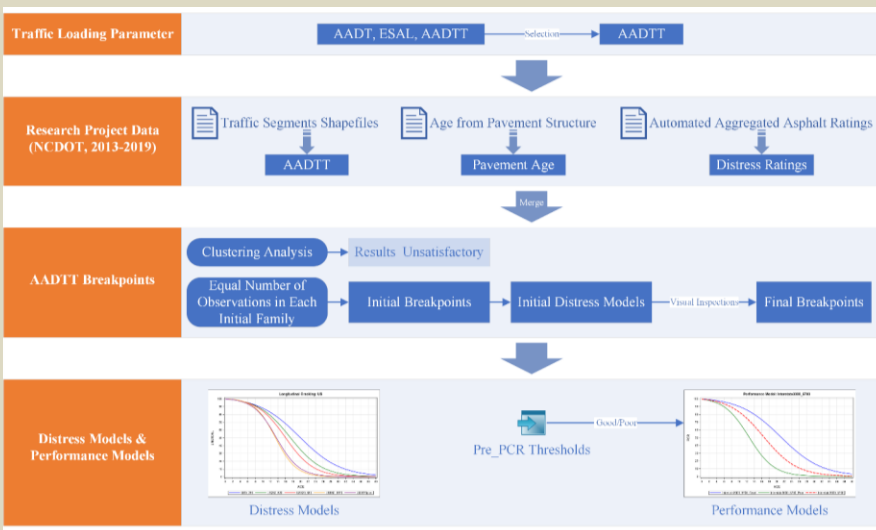
RESEARCH & DEVELOPMENT

Development of Pavement Performance Models using New Breakpoints and Pretreatment Conditions



Flow Chart for the Research Project

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Development of Pavement Performance Models using New Breakpoints and Pretreatment Conditions

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(Research Project No. RP 2020-14)

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16. Abstract

Previous studies indicated that two factors, traffic loading parameter and pre-treatment pavement condition, can have significantly impact on pavement performance and should be considered when developing pavement performance models. This study was conducted to use these two factors to develop new pavement performance models for the NCDOT Pavement Management System (PMS). A new traffic load indicator, AADTT, was selected and then its breakpoints were determined. These breakpoints, together with thresholds of pre-treatment pavement conditions, were used to define new pavement families; the corresponding distress and performance models were also developed. In addition, a pilot study was conducted to use ESAL as an alternative traffic loading parameter to develop distress and performance models for Interstate routes. These new models are expected to be more accurate and robust in predicting pavement deterioration trends because of the inclusion of additional pertinent factors; once the existing somewhat obsolete performance models developed using AADT are replaced by these new models, the performance of the NCDOT PMS will be improved and more informed maintenance and rehabilitation decisions can be made.

17. Key Words
AADTT, pre-treatment conditions, distress model, performance model, sigmoidal curve

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EXECUTIVE SUMMARY

This study was conducted to develop new pavement distress and performance models that will help NCDOT accurately predict pavement performance and maintain all state-owned roadways in a cost-effective manner. To this end, a more appropriate traffic loading parameter, Annual Average Daily Truck Traffic (AADTT), was selected and its breakpoints were determined to group roadways in North Carolina into new pavement families, then distress models and performance models (*Roadway*_Good and *Roadway*_Poor) were developed. Lastly, these newly developed models were compared with the ones developed previously using Annual Average Daily Traffic (AADT) as the traffic loading parameter, and findings and conclusions were provided, as follows:

- Data availability. Research data needed for this research project, e.g., AADTT, Pavement Age, Pavement Distress Ratings, etc., have been frequently updated and made available to the research team by NCDOT engineers. These raw data are either published on a website that can be accessed publicly or provided to researchers upon request on a timely basis.
- Development of pavement families. Clustering analysis and the equal number of observations method were used to determine the AADTT breakpoints, which were then used to group roadways into new pavement families. It was observed that clustering analysis used in this project did not provide sufficient accuracy because its resolution of is not sufficient to capture intermediate AADTT values as final breakpoints.
- Distress models. A comparison of distress model curves developed using AADT (referring to as AADT distress curves) with the model curves developed in this project using AADTT (referring to as AADTT distress curves) indicates the following:
    - Load Related Distresses (LDRs): Alligator Cracking AADTT distress curves are flatter than those of AADT model curves. Wheel Path Patching, Non-wheel Path Patching, and Rutting AADTT distress curves are quite flat. One possible reason is that these three types of distresses are not severe in asphalt pavements in North Carolina. The possible reason for the flatter curvature is that the data collection vendor has recently changed. It is reasonable to assume that algorithms used to process raw images are different, which can lead to distress ratings that are different than the ones provided by the previous vendor. If this is the case, it is necessary to conduct a detailed comparison between AADT distress curves and AADTT distress curves, and then update the NCDOT PMS Decision Trees accordingly.

    - Non-Load Related Distresses (NDRs): Transverse Cracking and Longitudinal Cracking curves are quite consistent, other than transverse cracking curves for Interstate roadways.
- Performance models. The curvature of performance models developed using AADTT breakpoints (referring to as the AADTT performance models) is as expected. A comparison of AADT and AADTT performance curves indicates that in general, AADTT curves are flatter, which might be the result of a different vendor's processing algorithms. A further comparison of AADT performance curves and AADTT Roadway_Poor performance curves indicates that they share the same deterioration trends.
- A pilot study was conducted to use Equivalent Single Axle Load (ESAL) as an alternative traffic loading parameter. Due to the time constraint, only Interstate routes were analyzed, and corresponding distress and performance models were developed. In this pilot study, ESAL values were calculated using a simplified equation. The resulting distress model curves lay between the AADT curves and AADTT curves, indicating that ESAL distress curves reflect NCDOT preventive maintenance practices closer than AADTT curves.

The following recommendations are provided for future research endeavors:

- Comparing to clustering analysis, the same number of observations per family method is more appropriate to be used to create pavement families, mainly because pavement distress data is variable in nature. The latter method is sufficiently accurate to capture reasonable intermediate AADTT values as family breakpoints.
- A subsequent research project is recommended to quantify the differences between AADT and AADTT distress and performance curves. Current Decision Trees in the NCDOT PMS are using the critical thresholds derived from previously developed AADT models. With the use of a new data collection vendor and the newly developed AADTT models, current Decision Trees should be updated to achieve PMS' maximum level of performance.
- Two sub-distress models, *Roadway*_Good and *Roadway*_Poor, should be developed for each distress type. The corresponding sub-performance models were developed in this research project, and these model curves provide additionally useful information such as the ranges of PCR values at a given age. The similar procedure can be implemented to distress models to provide the ranges of distress index values, which can be used to fine tune the NCDOT PMS' Decision Trees.
- ESAL should be further studied as the alternative traffic loading parameter to develop

distress and performance models for US and NC routes, and a comparison of ESAL and AADTT model curves should be conducted to study the differences between these two traffic loading parameters, and the results can assist NCDOT with an enhanced ability to update the decision trees, and thus make informative pavement management decisions.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1 INTRODUCTION AND OBJECTIVES

1.1 Background

The principal goal of this study is to develop new pavement distress and performance models that will help NCDOT accurately predict pavement performance and maintain all state-owned roadways in a cost-effective manner. For Interstate, US, and NC highways, this goal is directly related to the need to identify a new traffic loading parameter that can better explain pavement performance, determine breakpoints of this parameter, use these breakpoints and pre-treatment pavement conditions to define roadway families, and perform nonlinear statistical analysis to develop distress and performance models.

Traffic loading is an important factor used in the pavement analysis and design process and is critical to estimate the possible damage of existing roadways. It is typically quantified by parameters such as Annual Average Daily Traffic (AADT), Equivalent Single Axle Load (ESAL), and Annual Average Daily Truck Traffic (AADTT). AADT is a composite parameter that comprises of light, medium, and heavy traffic volumes, whereas ESAL and AADTT mainly represents traffic volume of heavy vehicles.

In this study, pre-treatment pavement condition is determined by the Pavement Condition Rating (PCR) value before pavement needs to be treated, i.e., the Pre_PCR value. Once treated, pavements with higher Pre_PCR values are expected to have longer service lives than those of with lower Pre_PCR values. Accurate prediction of pavement performance for both cases is essential for NCDOT engineers to make cost-effective pavement management decisions.

1.2 Research Needs and Significance

In the NCDOT PMS, AADT is used as the traffic loading parameter. Roadway sections are grouped into pavement families based on their AADT values, and then corresponding family performance models are developed. This method has limitations. Firstly, AADT breakpoints (e.g., 50k in the Interstate 0-50k family) are arbitrary. During recent NCDOT research projects [1] [2] [3], it has been observed that several roadway family curves are close to each other. This indicates that these roadway families should be combined into one family. In other words, the breakpoints of these families need to be adjusted. Secondly, PCR is largely determined by load-related distresses which are caused mainly by heavy traffic volumes. This necessitates the need for a different traffic loading parameter other than AADT, as AADT is not a good traffic loading indicator for heavy traffic.

Pre-treatment pavement condition has not been adopted in the NCDOT PMS because this information is not available until the completion of a recent NCDOT research project [4]. From that research project, thresholds of pretreatment pavement conditions, represented by the averages of Pre_PCR values of Interstate, US, and NC roadways, were determined. These thresholds were used to classify a pavement's pretreatment pavement condition as Good or Poor in this study, and then pavement families were further divided into two sub-families, i.e., Good and Poor, and corresponding performance models were developed. Compared to existing roadway family models, these new models are expected to be more accurate and robust because of the inclusion of additional pertinent pre-treatment pavement condition information, and once implemented, they can lead to improved performance of the NCDOT's PMS.

1.3 Research Objectives

To select breakpoints to define new pavement performance families and develop new pavement performance models, the following research objectives are proposed in this study:

- Selection of a new traffic load parameter
- Determination of new breakpoints and formation of new pavement families
- Development of pavement family models

1.4 Report Organization

An introduction to the research project, research needs, and objectives are presented in Chapter 1. A comprehensive literature review is provided in Chapter 2. The research methodology is described in Chapter 3. Chapter 4 summarizes the findings of a pilot study using ESAL as the alternative traffic loading parameter. Chapter 5 focuses on findings and conclusions. Chapter 6 provides recommendations for future research.

Appendix A includes plots of distress model curves. Appendix B presents performance model curves. Comparison plots of AADT and AADTT distress model curves are included in Appendix C, and comparison plots of AADT and AADTT performance model curves are included in Appendix D. Appendix E includes AADT and AADTT *Roadway*_Poor performance model curves. Distress model curves developed using ESAL for Interstate routes are included in Appendix F, and corresponding performance curves developed using ESAL for Interstate routes are included in Appendix G.

CHAPTER 2 LITERATURE REVIEW

2.1 Traffic Loading Parameters

Traffic loading parameters have been studied by many researchers and their findings are summarized below.

Madanat et al. [5] investigated impact of several predictors on the performance (in terms of IRI) of asphalt pavements and overlays. The most relevant predictors are the IRI value in the previous year, the ESAL value in the subject year, and the cumulative ESAL value (from the most recent treatment to the previous year). Serigos et al. [6] indicated that higher ESAL values significantly reduced preventive maintenance treatment's effective life. In this study, the sum of all annual ESAL values of a pavement section, weighted by a time factor, was used to reflect traffic values during the life of the treatment. The missing annual number of ESALs was replaced with the average of the set of annual ESALs for the corresponding roadway section. In another study [7], three traffic load levels (Low, Medium, and Heavy), in terms of predicted 20 years of ESALs, were used as factors to develop pavement prediction models for the TXDOT PMS. It was concluded that the new system "can serve as an effective tool in support for decision makers, pavement engineers, budget planners, and administrators."

In 2006 [8], Federal Highway Administration (FHWA) elaborated on how AADTT can be an impactful traffic indicator in pavement design, analysis and management systems. In 2018 Raheel et al. [9] quantified the impact of heavy traffic on pavement performance and concluded that the truck volume caused 47% more damage in asphalt pavement than other types of traffic volumes. Llopis-Castelló et al. [10] evaluated pavement distresses and conditions using AADT, AADTT, ESAL, and KESAL (ESAL in thousands). They recommended that AADTT and KESAL, rather than AADT, to be considered as prevalent traffic factors for pavement distress analysis. Onayev et al. [11] concluded that cumulative equivalent single axial load (CESAL) can be replaced by AADTT which can better describe the impact of heavy traffic loading on pavement deterioration in cracking predictability model. In another study, Yamany and Abraham [12] developed pavement performance models using probabilistic function to predict pavement condition. Cumulative

AADTT used to develop the models were retrieved from LTPP database. The results were satisfactory as they showed an 87% accuracy in terms of performance prediction.

2.2 Pre-treatment Pavement Conditions

Previous studies concluded that pre-treatment pavement conditions directly affect pavement performance after pavements are treated.

A study of asphalt pavements sections in Tennessee [13] indicated that pre-treatment pavement conditions can significantly impact effectiveness and cost-effectiveness of pavement preventive maintenance treatments. In 2016, effectiveness analyses of flexible pavement treatments using LTPP SPS-3 data [14] indicated that long-term roughness change and rutting can be significantly affected by pre-treatment surface condition, and that treatments applied to pavement sections that had poor pre-treatment conditions are more likely to develop severer rutting than the corresponding control sections. A study presented at the 2018 NCAT Test Track Conference [15] and several other studies [16] [17] [18] concluded that pavements' post-treatment performance is highly dependent on pavements' pre-treatment condition.

2.3 Grouping Roadway Families

Grouping roadways into families and managing these families using corresponding family performance models has proven to be an effective pavement management practice. Various family grouping methods have been studied by researchers elsewhere in the United States and internationally.

Shahin et al. [19] provided guidance on how pavement sections can be grouped into families based on pavement types, application aspects and other factors. In another study [20], IRI, PSI (Pavement Serviceability Index), PCR (Pavement Condition Rating) and AADT thresholds were used to group roadways into families to allow consistent implementation of family-based treatment strategies.

Statistical methods such as the clustering approach have been used to group roadway families. In a relevant study [21], AADT collected by Automatic Traffic Recorder Stations (ATRs) was used as input to a clustering approach to identify roadway attributes and traffic patterns, then corresponding roadway families were created. This study, however, has two limitations: firstly, traffic data collected by ATRs differed from year to year and was too variable to be considered logical; secondly, it was challenging to obtain reasonable roadway families. In 2001, Rossi et al. [22] used several clustering methods to group roadways using AADT collected from 50 ATR sites in the Province of Venice. They concluded that the performance of clustering methods used in this study was depending on data sets and traffic patterns.

CHAPTER 3 RESEARCH METHODOLOGY

This chapter describes the procedures used to develop pavement performance models using the newly selected traffic loading parameter and its breakpoints, as well as pre-treatment conditions of Interstate, US, and NC roadways. The main steps are included in the flow chart below (Figure 1).

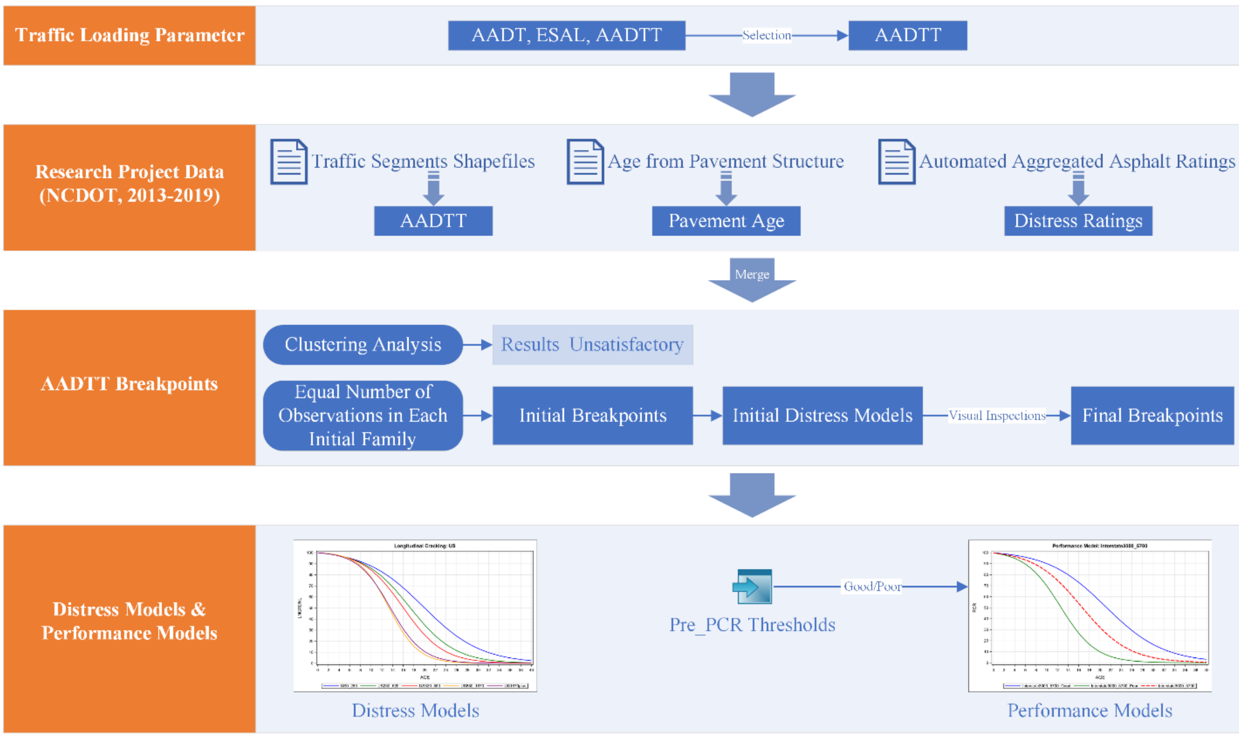


Figure 1. Flow Chart for the Research Project

3.1 Traffic Loading Parameter

As indicated by the literature review, both ESAL and AADTT are better traffic loading parameters than AADT. In this study, AADTT was selected to be the traffic loading parameter because NCDOT has collected AADTT data since 2013, whereas ESAL for each roadway section is not readily available. From NCDOT's "Traffic Survey GIS Data Products & Documents" webpage [23], Traffic Segments Shapefiles from 2013 to 2019 (highlighted in Figure 2) were downloaded and then imported into ArcGIS to generate Excel spreadsheet outputs. An excerpt of the generated Excel spreadsheets is shown in Figure 3.

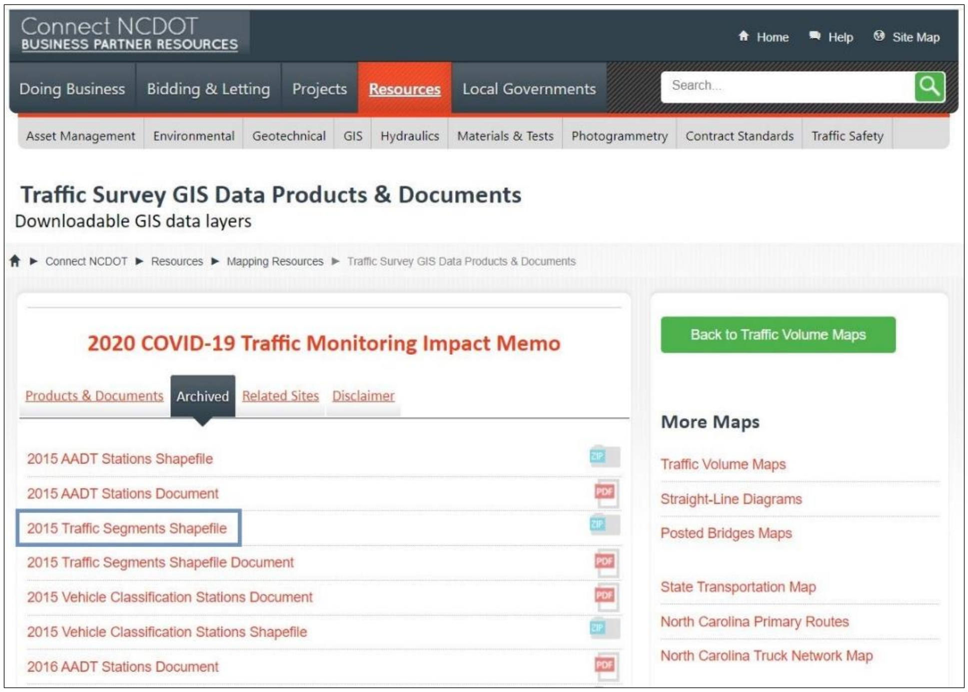


Figure 2. NCDOT Traffic Segments Shapefile

FID	Rte_ID	BegMP1	EndMP1	AADT2015	SU_PCT	MU_PCT	SU_AADT	MU_AADT	AADTT2015	SOURCE
0	1000002610	0	0.567	22000	0.028317218	0.03920533	650	900	1550	MAINT
1	1000002610	25.114	28.244	72000	0.03670694	0.072655041	2750	5440	8190	MAINT
2	1000002610	18.744	20.495	81000	0.03670694	0.072655041	3150	6230	9380	MAINT
3	1000002610	20.495	25.114	78000	0.03670694	0.072655041	3020	5970	8990	MAINT
4	1000002610	28.574	29.167	52000	0.031624567	0.094039567	1850	5490	7340	MAINT
5	1000002644	0	0.01	72000	0.03670694	0.072655041	2750	5440	8190	MAINT
6	1000002644	0.01	3.288	52000	0.031624567	0.094039567	1850	5490	7340	MAINT
7	1000002644	3.288	9.014	53000	0.031624567	0.094039567	1710	5100	6810	MAINT
8	1000002644	9.014	12.571	51000	0.027627065	0.09602649	1420	4930	6350	MAINT
9	1000002644	13.656	17.46	35000	0.022393642	0.094389902	810	3400	4210	MAINT
10	1000002644	12.571	13.656	48000	0.027627065	0.09602649	1310	4560	5870	MAINT
11	1000002656	10.776	12.606	22000	0.028317218	0.03920533	650	900	1550	MAINT
12	1000002656	9.066	10.776	19000	0.028317218	0.03920533	570	790	1360	MAINT
13	1000002656	0	3.351	8800	0.031330949	0.112125324	300	1080	1380	MAINT
14	1000002656	3.351	9.066	10000	0.031330949	0.112125324	340	1230	1570	MAINT
15	1000002674	0	1.305	35000	0.022393642	0.094389902	810	3400	4210	MAINT
16	1000002674	1.305	7.818	34000	0.022393642	0.094389902	790	3310	4100	MAINT
17	1000002674	7.818	13.121	27000	0.025171887	0.126928953	730	3670	4400	MAINT
18	1000004000	1.335	2.316	119000	0.023403194	0.061194126	2610	6810	9420	MAINT
19	1000004000	4.026	6.166	123000	0.023403194	0.061194126	2710	7080	9790	MAINT
20	1000004000	2.316	4.026	124000	0.023403194	0.061194126	2750	7180	9930	MAINT
21	1000004000	7.926	8.886	117000	0.023403194	0.061194126	2600	6790	9390	MAINT
22	1000004000	6.166	7.926	120000	0.023403194	0.061194126	2680	7020	9700	MAINT

Figure 3. NCDOT Segments Output (2015)

In Figure 3, **AADTT2015** is estimated annual average daily total trucks for 2015. AADTT is one of the most important data in this study. As described in subsequent sections, it is used to determine breakpoints which are thresholds for grouping roadway families. In addition, the following are the index variables that are used later to merge with other raw data obtained from NCDOT:

- **Rte_Id**: GIS 10 digit unique route identifier

- **BegMP1**: Route milepost at the beginning of the reference
- **EndMP1**: Route milepost at the end of the reference

3.2 Research Project Data

3.2.1 Pavement Age Data

Pavement age, as the independent variable, is an essential component of pavement distress models and performance models. Pavement age data was obtained from the NCDOT Pavement Management Section. In this study, pavement age is defined as:

$$Age = EFF\_YEAR - YEAR\_LAST\_REHAB \quad (1)$$

where:

EFF_YEAR: year the roadway section was surveyed

YEAR_LAST_REHAB: year the roadway section was last rehabilitated

An excerpt of the pavement age data file is shown in Figure 4. The following are the index variables that are used later to merge with other raw data obtained from NCDOT:

- **COUNTY**: unique county number identifier
- **ROUTE1**: unique route number identifier
- **OFFSET_FROM**: Route milepost at the beginning of the reference
- **OFFSET_TO**: Route milepost at the end of the reference

COUNTY	ROUTE1	OFFSET_FROM	OFFSET_TO	LENGTH	EFF_YEAR	YEAR_LAST_REHAB	YEAR_CONSTR	TOTAL_THICK
96	10000795	1.997	2.042	0.045	2015	2010	2005	19.5
96	10000795	2.042	9.994	7.952	2015	2010	2005	26.5
96	10000795	9.994	11.047	1.053	2015	2010	2005	26.5
96	10000795	11.047	13.351	2.304	2015	2010	2005	26.5
96	10000795	1.997	2.042	0.045	2015	2010	2005	19.5
96	10000795	2.042	9.994	7.952	2015	2010	2005	26.5
96	10000795	9.994	11.047	1.053	2015	2010	2005	26.5
96	10000795	11.047	13.351	2.304	2015	2010	2005	26.5
96	10000795	13.351	13.551	0.2	2015	2005	2005	23
96	10400795	0	2.492	2.492	2015	2010	2005	26.5
96	10400795	2.492	3.556	1.064	2015	2010	2005	26.5
96	10400795	3.556	11.501	7.945	2015	2010	2005	26.5
96	10400795	11.501	11.544	0.043	2015	2010	2005	19.5
96	10400795	0	2.492	2.492	2015	2010	2005	26.5
96	10400795	2.492	3.556	1.064	2015	2010	2005	26.5
96	10400795	3.556	11.501	7.945	2015	2010	2005	26.5
96	10400795	11.501	11.544	0.043	2015	2010	2005	19.5
96	10400795	11.544	12.763	1.219	2015	2005	2005	16
96	10400795	12.763	13.537	0.774	2015	2005	2005	16.5
96	37000581	0	0.62	0.62	2015	2005	2005	16.5
96	37400581	0	0.641	0.641	2015	2005	2005	16.5

Figure 4. NCDOT Pavement Age Data

3.2.2 Asphalt Pavement Distress Data

Asphalt pavement distress data was also obtained from the NCDOT Pavement Management Section. As shown in the excerpt below (Figure 5), this data includes distress ratings, e.g., TRNSVRS_LOW_LF, which represents Low severity Transverse Cracking ratings measured in LF. In addition, the following index variables that are used later to merge with other raw data obtained from NCDOT are included:

- **ROUTE1**: unique route number identifier
- **COUNTY**: unique county number identifier
- **OFFSET_FROM**: Route milepost at the beginning of the reference
- **OFFSET_TO**: Route milepost at the end of the reference

ROUTE1	COUNTY	OFFSET_FROM	OFFSET_TO	TRNSVRS_LOW_LF	TRNSVRS_MDRT_LF	TRNSVRS_HGH_LF
10000074	86	4.565	6.565	624	221	63
10000074	86	6.565	8.565	731	304	43
10000074	86	8.565	10.565	198	81	16
10000074	86	10.565	12.565	282	150	67
10000074	86	12.565	14.565	232	50	39
10000074	86	14.565	16.565	367	107	53
10000074	86	16.565	17.413	228	243	57
10000077	86	0	0.938	401	111	178
10000077	86	4.493	6.493	596	246	74
10000077	86	6.493	8.493	803	385	91
10000077	86	12.493	14.493	2969	315	106
10000077	86	14.493	16.493	2635	197	58
10000077	99	0	2	55	0	3
10000077	99	2	3.132	61	40	39
10000077	99	9.654	11.654	2099	417	270
10000077	99	11.654	13.757	860	431	514
10400077	86	6.359	8.359	3766	685	150
10400077	86	8.359	10.359	3104	579	276
10400077	86	14.359	16.359	564	213	138
10400077	86	16.359	18.359	582	278	146
10400077	86	22.359	22.881	368	102	55

Figure 5. Asphalt Pavement Distress Data

3.2.3 Data Merging

The abovementioned three types of data were merged using the same shared unique index variables. The merged data file includes 59,430 individual roadway sections.

The following spatial conditions were used when merging data i and data i+1:

- if MP_FROM_i >= MP_TO_i+1 *then* DELETE

- if MP_TO_i <= MP_FROM_i+1 *then* DELETE
- if MP_FROM_i >= MP_FROM_i+1 and MP_TO_i <= MP_TO_i+1 *then* KEEP
- if MP_FROM_i+1 <= MP_FROM_i <= MP_TO_i+1 and MP_TO_i >= MP_TO_i+1 *then* KEEP
- if MP_FROM_i+1 <= MP_TO_i <= MP_TO_i+1 and MP_FROM_i <= MP_FROM_i+1 *then* KEEP
- if MP_FROM_i <= MP_FROM_i+1 and MP_TO_i >= MP_TO_i+1 *then* KEEP

where:

- MP_FROM: Route milepost at the beginning of the reference
- MP_TO: Route milepost at the end of the reference
- i: Research data, i = 1, 2, 3.

3.2.3 Distress Normalization

Pavement distress ratings (Figure 5) need to be normalized so they are unitless and become percentages over section length or area. Normalized distress ratings are later used to calculate distress index values. Normalization equations are:

Transverse Cracking and Reflection Transverse Cracking

$$TRNSVRS\_LOW = (TRNSVRS\_LOW\_LF + REFLCT\_TRNSVRS\_LOW\_LF)/(LENGTH \times 5280) \quad (2)$$

$$TRNSVRS\_MDRT = (TRNSVRS\_MDRT\_LF + REFLCT\_TRNSVRS\_MDRT\_LF)/(LENGTH \times 5280) \quad (3)$$

$$TRNSVRS\_HGH = (TRNSVRS\_HGH\_LF + REFLCT\_TRNSVRS\_HGH\_LF)/(LENGTH \times 5280) \quad (4)$$

Alligator Cracking

$$ALGTR\_LOW = ALGTR\_LOW\_SF/(LENGTH \times 5280 \times 7) \times 100 \quad (5)$$

$$ALGTR\_MDRT = ALGTR\_MDRT\_SF/(LENGTH \times 5280 \times 7) \times 100 \quad (6)$$

$$ALGTR\_HGH = ALGTR\_HGH\_SF/(LENGTH \times 5280 \times 7) \times 100 \quad (7)$$

Raveling

$$RVL\_LOW = RVL\_LOW\_SF/(LENGTH \times 5280 \times LANE\_WIDTH) \times 100 \quad (8)$$

$$RVL\_MDRT = RVL\_MDRT\_SF/(LENGTH \times 5280 \times LANE\_WIDTH) \times 100 \quad (9)$$

$$RVL\_HGH = RVL\_HGH\_SF/(LENGTH \times 5280 \times LANE\_WIDTH) \times 100 \quad (10)$$

Longitudinal Cracking

$$LNGTDNL\_LOW = LNGTDNL\_LOW\_LF/(LENGTH \times 5280) \quad (11)$$

$$LNGTDNL\_HGH = LNGTDNL\_HGH\_LF/(LENGTH \times 5280) \quad (12)$$

Longitudinal Lane Joint Cracking

$$LNGTDNL\_LANE\_JNT\_LOW = LNGTDNL\_LANE\_JNT\_LOW\_LF/(LENGTH \times 5280) \quad (13)$$

$$LNGTDNL\_LANE\_JNT\_HGH = LNGTDNL\_LANE\_JNT\_HGH\_LF/(LENGTH \times 5280) \quad (14)$$

Patching Area - Wheel Path

$$WP\_PTCH = WP\_PTCH\_SF/(LENGTH \times 7 \times 5280) \times 100 \quad (15)$$

Patching Area – Non-Wheel Path

$$NWP\_PTCH = NWP\_PTCH\_SF/(LENGTH \times 5280 \times (LANE\_WIDTH - 7 + 0.0001)) \times 100 \quad (16)$$

Rutting

$$MAX\_RUT = 100 - 100 \times (MAX\_RUT\_AVG)^2 \quad (17)$$

$$if\ MAX\_RUT\_AVG < 0.05\ then\ MAX\_RUT = 100 \quad (18)$$

It was decided to combine Transverse Cracking and Reflection Transverse Cracking due to their similarities in terms of pavement management practices. In Equation (16), 0.0001 is added to avoid a zero denominator.

3.2.3 Distress Index Calculation

Pavement distress index values are calculated using the Excel spreadsheet tool developed by NCDOT (Figure 6). In this spreadsheet, normalized distress ratings are entered into the orange cells as low_sev_in, med_sev_in, or high_sev_in. Based on a previous study [24], 99^{th} percentiles of normalized distress ratings are entered into the tool as Maximum Allowable Extent (MAE) values, i.e., low_sev_mae_in, med_sev_mae_in, and high_sev_mae_in; Threshold Amounts for distress that has three severity levels (L/M/H) are 60, 30, and 0; 60 and 0 for distress that has two severity levels (L/H); and 0 for distress that has one severity level (L). After entering these parameters and normalized distress ratings, the distress index value is calculated and shown at the bottom of the spreadsheet tool.

f_mae(a.ALGTR_LOW_PCT,a.ALGTR_MDRT_PCT, a.ALGTR_HGH_PCT,null,100, 80, 50,75,40,0,0,0,0)				
INPUTS				
OUTPUT				
Distress Values passed into the function. Distresses with less than three severities should pass null to low then med in that order. Function return MAE index with 100 as good 0 as bad				
low_sev_in	**0**			
med_sev_in	**20**	*OK* - Sum distress total is 100 or less		
high_sev_in	**40**			
The normalizing factor will normalize absolute distress amounts null indicates no normailzation required				
normalizing_in	null			
MAE Amounts (Low Med and High) are the Extent amounts that maximize deduction for that severity				
low_sev_mae_in	100			
med_sev_mae_in	80			
high_sev_mae_in	50			
Threshold Amounts are lowest possible score for that severity when it occurs alone				
low_sev_threshold_in	75			
med_sev_threshold_in	40			
high_sev_threshold_in	0			
Begin deduct scores are the extent value when point deductions begin for each severity level				
low_sev_begin	0		distr_low	0
med_sev_begin	0		distr_med	20
high_sev_begin	0		distr_high	40
d1	0			
d2	15		d2c	15
d3	80		d3c	83
Alligator Cracking Index Value	**17**			

Figure 6. Distress Index Value Calculation Tool

3.3 AADTT Breakpoints

3.3.1 Initial AADTT Breakpoints

AADTT breakpoints are AADTT threshold values that are used to group roadways into pavement families. Two methods were used to determine initial breakpoints: (1) clustering analysis and (2) equal number of observations in each initial family.

(1) Clustering Analysis

In clustering analysis, distress index values were standardized, then the hierarchical clustering technique was used to determine number of clusters. The results indicated that Interstate should have 3 clusters, with 4,470 and 8,820 as AADTT breakpoints; US should have 4 clusters, with 830, 1,860, and 3,440 as AADTT breakpoints; and NC should have 4 clusters, with 390, 900, and 1,790 as AADTT breakpoints. Initial results are included in Table 1. Based on resulting AADTT breakpoints, either 3 or 4 families were created for Interstate, US, and NC roadways. *Error! Reference source not found.*It was observed that the sizes of families are not balanced. For example, Family #1 of Interstate, US, and NC roadways comprises 46.9%, 61.1%, and 62.7% of the total number of roadway sections in each respective roadway classification. Therefore, it is logical to assume that the first AADTT breakpoint of each classification is too large to capture some reasonable intermediate breakpoints, which necessitates further breakdown of the sizes of roadway families. This leads to the next method.

Table 1. Clustering Analysis Results

		Family #1	**Family #2**	**Family #3**	**Family #4**
Interstate	AADTT Breakpoints	(0 - 4,740)	(4,740 - 8,820)	> 8,820	
	Number of Sections	1,837	1,531	547	
	Percentage	46.9%	39.1%	14.0%	
US	AADTT Breakpoints	(0 - 830)	(830 - 1,860)	(1,860 - 3,440)	> 3,440
	Number of Sections	14,140	5,718	2,656	634
	Percentage	61.1%	24.7%	11.5%	2.7%
NC	AADTT Breakpoints	(0 - 390)	(390 - 900)	(900 - 1,790)	> 1,790
	Number of Sections	20,306	8,491	2,993	577
	Percentage	62.7%	26.2%	9.2%	1.8%

(2) Equal Number of Observations in Each Initial Family

After studying the total numbers of roadway sections of Interstate, US, and NC, it was decided to develop 7 initial Interstate families of 500 roadway sections, 10 initial US families of 2,000 sections, and 10 initial NC families of 3,000 sections. It is expected that this breakdown allows the identification of all reasonable AADTT breakpoints. Corresponding initial AADTT breakpoints are:

- Interstate: ***2,000, 3,000, 4,200, 5,700, 6,700, 8,000***
- US: ***160, 280, 400, 520, 660, 880, 1,200, 1,670, 2,460***
- NC***: 80, 140, 190, 250, 320, 420, 570, 850, 1,900***

Scatterplots of Transverse Cracking index vs. Age for Interstate, US, and NC are shown in Figure 7, Figure 8, and Figure 9. As indicated by these figures, outliers need to be removed before these raw data can be used to develop distress and performance models.

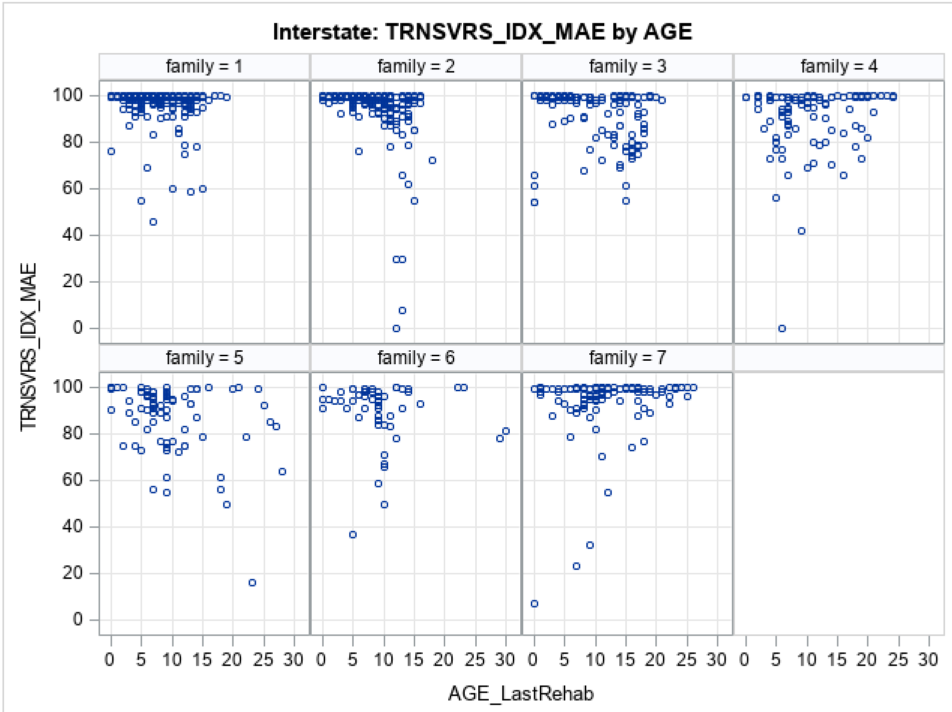


Figure 7. Transverse Cracking vs. Age for Initial Interstate Families

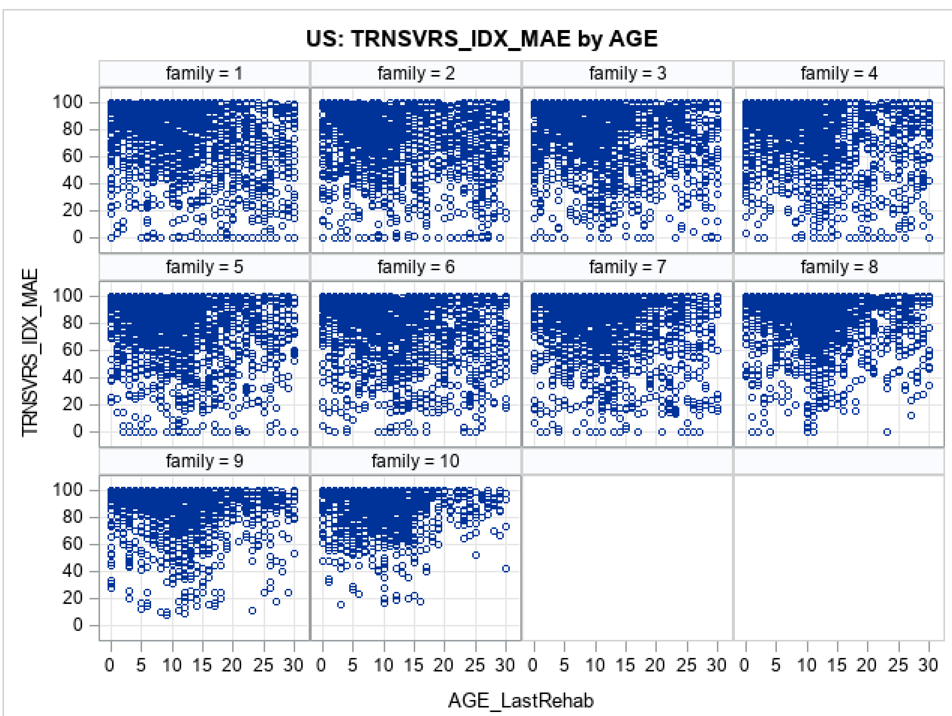


Figure 8. Transverse Cracking vs. Age for Initial US Families

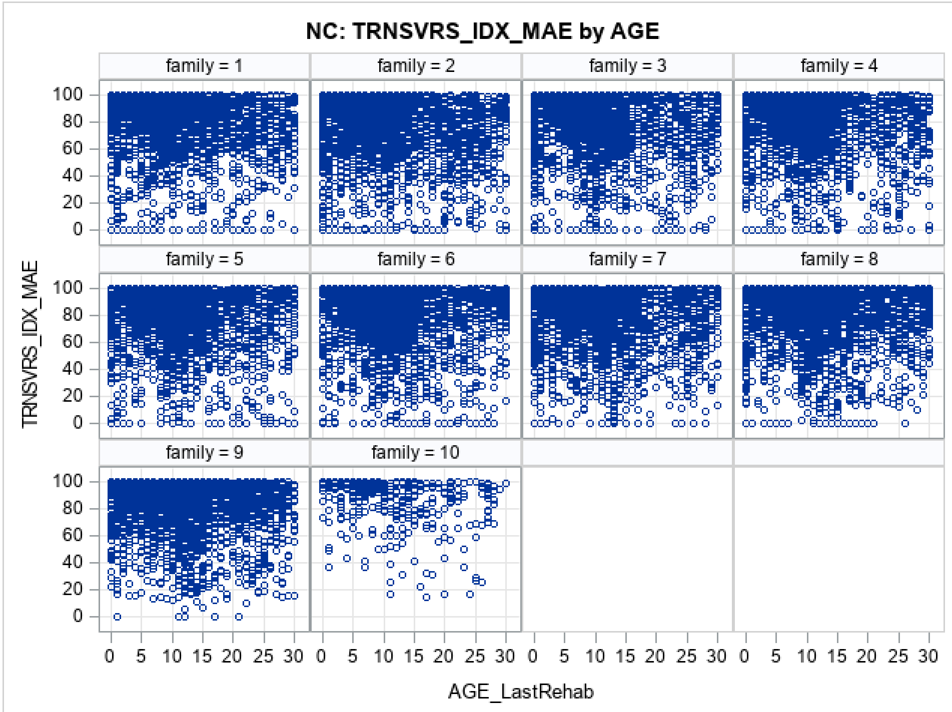


Figure 9. Transverse Cracking vs. Age for Initial NC Families

3.3.2 Initial Distress Models

Outliers in the raw distress data needs to be cleaned before distress models can be developed. Interquartile range (IQR) of each distress at each age was calculated and the following equations were used to remove outliers:

$$IQR = Q_1 - Q_3 \tag{19}$$

$$Bottom\ Boundary = Q_1 - 1.5 * IQR \tag{20}$$

$$Upper\ Boundary = Q_3 + 1.5 * IQR \tag{21}$$

where:

$\boldsymbol{Q_1}$: The 25th percentile

$\boldsymbol{Q_3}$: The 75th percentile

Individual observations at each age beyond the corresponding bottom and upper boundaries were considered as outliers and remove. Additionally, the following steps were used to further remove outliers:

- if AGE = 0 and DISTRESS INDEX VALUE < 100 then DELETE
- if AGE = 1 and DISTRESS INDEX VALUE < 95 then DELETE
- if AGE = 2 and DISTRESS INDEX VALUE < 90 then DELETE
- if AGE = 3 and DISTRESS INDEX VALUE < 85 then DELETE

Initial distress models, i.e., Distress Index Value vs. Age, were then developed using the following sigmoidal equation [1] [2] [3] for Transverse Cracking, Alligator Cracking, Raveling, Longitudinal Cracking, Longitudinal Lane Joint Cracking, Wheel Path Patching, Non-wheel Path Patching, and Rutting:

$$\text{Distress\_Index\_Value} = a/(1 + e\hat{}((-\text{Pavement\_}Age + b)/c)) \tag{22}$$

where a, b, and c are Model parameters.

Distress model curves belonging to each classification were plotted together and visual inspections were conducted to identify AADTT breakpoints by grouping model curves that are close to each other. Two examples, i.e., Interstate Transverse Cracking model curves (Figure 10) and US Alligator Cracking model curves (Figure 11), are shown below.

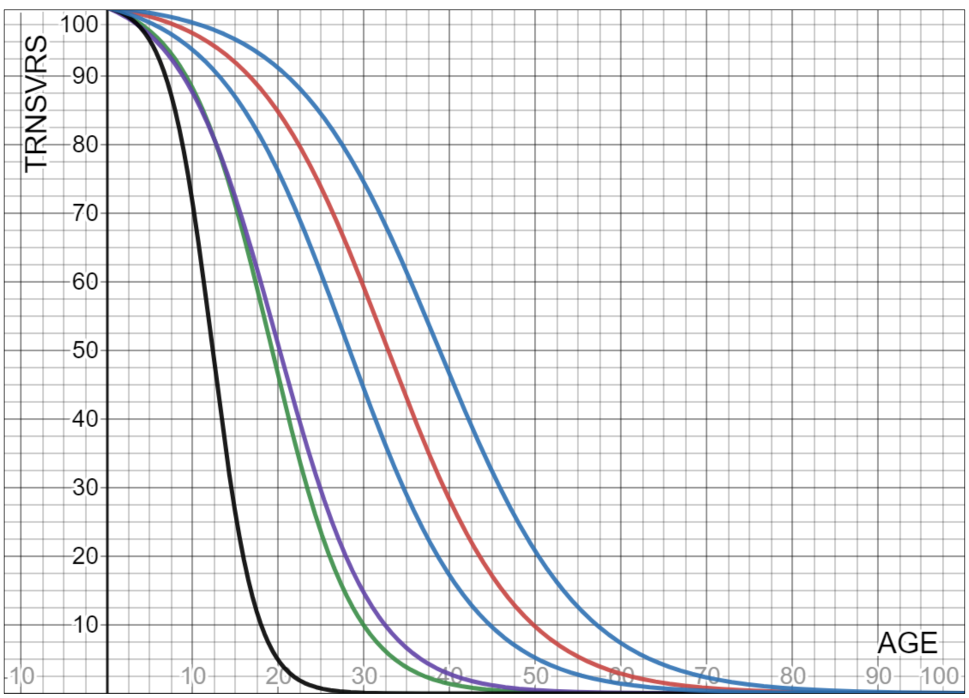


Figure 10. Initial Interstate Transverse Cracking model curves

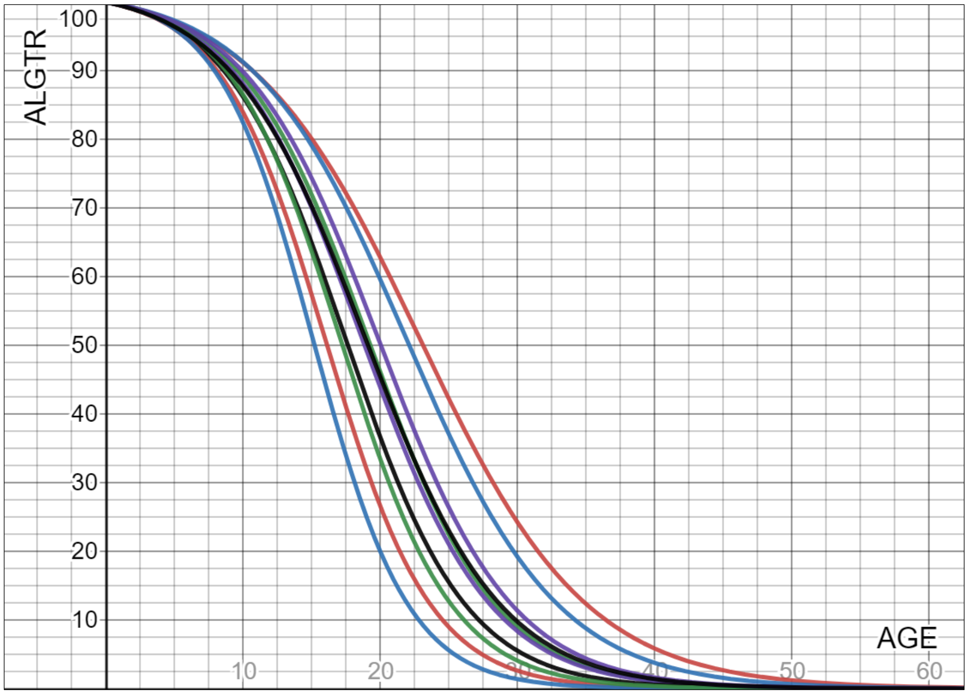


Figure 11. Initial US Alligator Cracking model curves

Visual inspection results are shown in Table 2. In this table, yellow, green, and blue color blocks in each column indicate that their corresponding initial family curves are close to each other and should be grouped together, and grey color blocks indicate that all initial family curves are close to each other, and it was challenging to distinguish between each other. The final AADTT breakpoints were determined by grouping as many blocks as possible with the same color across all the columns in the table. These breakpoints are included in the last column of the table. They are:

- Interstate: ***3,000, 5,700***
- US: ***280, 520, 880, 1,670***
- NC***: 250, 420, 850***

Therefore, the final pavement families are:

- Interstate0_3000, Interstate3000_5700, Interstate5700plus
- US0_280, US280_520, US520_880, US880_1670, US1670plus
- NC0_250, NC250_420, NC420_580, NC580plus

3.4 Final Distress Models

Final distress models for Transverse Cracking, Alligator Cracking, Raveling, Longitudinal Cracking, Longitudinal Lane Joint Cracking, Wheel Path Patching, Non-Wheel Path Patching, and Rutting were developed using Equation (22). The same data cleaning process described in Section 3.3.2 was used and resulting model parameters a, b, and c are included in

Table 3 below. It should be noted that the Longitudinal Lane Joint Cracking model for NC250_420 is not reasonable and thus is not included in the table. Transverse Cracking model curves of US roadways are included in Figure 12 as an example. All distress model curves are included in Appendix A.

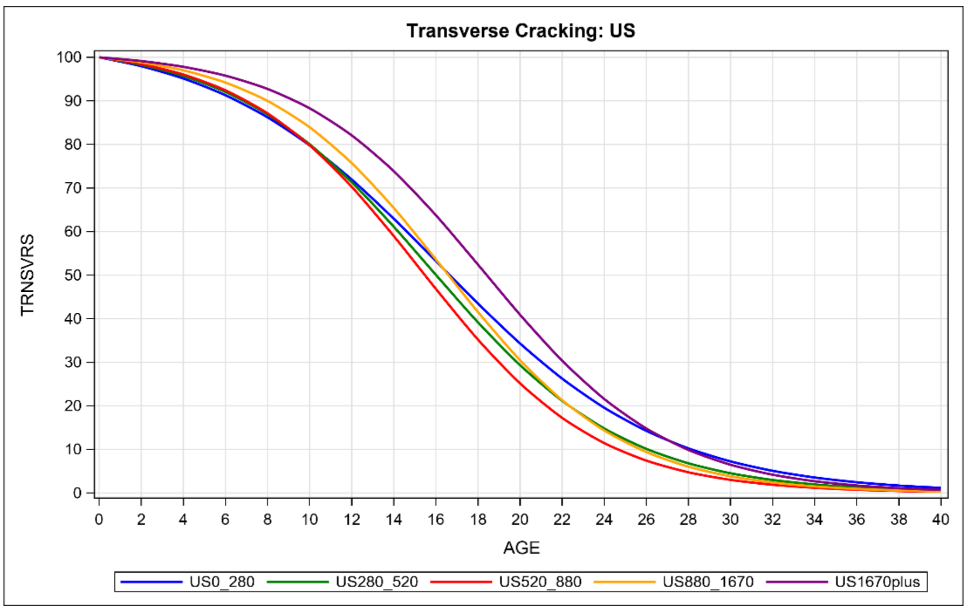


Figure 12. Transverse Cracking Model curves for US Roadways

Table 2. Final AADTT Breakpoints

System	AADTT	TRNSVRS	ALGTR	LNGTDNL	LNGTDNL_LANE_JNT	RVL	WP_PTCH	NWP_PTCH	RUT	Break Points
Interstate	0_2000									0_3000
	2000_3000									
	3000_4200									3000_5700
	4200_5700									
	5700_6700									5700 plus
	6700_8000									
	8000 plus									
US	0_160									0_280
	160_280									
	280_400									280_520
	400_520									
	520_660									520_880
	660_880									
	880_1200									880_1670
	1200_1670									
	1670_2460									1670 plus
	2460 plus									
NC	0_80									0_250
	80_140									
	140_190									
	190_250									
	250_320									250_420
	320_420									
	420_570									420_850
	570_850									
	850 plus									850 plus

Table 3. Final Distress Models

Distress		Interstate0_3000	Interstate3000_5700	Interstate5700plus	US0_280	US280_520	US520_880	US880_1670	US1670plus	NC0_250	NC250_420	NC420_850	NC850plus
TRNSVRS	a	101.15	102.36	103.22	104.78	103.37	102.66	101.96	101.51	102.73	102.53	102.00	101.77
	b	34.49	19.25	36.36	16.17	15.71	15.26	16.43	18.29	14.58	14.65	14.65	16.93
	c	-7.73	-5.14	-10.58	-5.32	-4.63	-4.21	-4.18	-4.36	-4.05	-3.98	-3.75	-4.20
ALGTR	a	100.76	100.78	101.85	102.13	101.80	101.85	101.50	101.83	101.44	101.53	101.54	101.44
	b	32.84	24.23	32.36	22.48	19.11	17.39	16.44	19.47	19.93	20.07	19.16	18.55
	c	-6.73	-4.99	-8.10	-5.84	-4.75	-4.36	-3.92	-4.87	-4.70	-4.80	-4.59	-4.37
LNGTDNL	a	101.27	101.18	102.60	102.65	101.78	101.41	100.75	101.13	101.47	101.34	101.43	101.33
	b	18.53	14.02	16.43	19.74	17.21	15.95	13.33	13.55	20.52	18.48	17.72	16.43
	c	-4.25	-3.16	-4.50	-5.44	-4.27	-3.74	-2.72	-3.02	-4.87	-4.28	-4.17	-3.80
LNGTDNL-LANE-JNT	a	100.68	101.75	100.66	100.03	101.27	100.04	100.05	100.16	100.36		100.01	100.07
	b	39.88	36.65	80.14	708.48	18.53	697.63	251.84	96.83	46.02		801.11	205.77
	c	-7.99	-9.05	-15.94	-87.75	-4.25	-88.07	-33.17	-14.98	-8.17		-88.10	-28.29
RVL	a	100.99	102.23	103.65	101.62	101.36	101.64	101.54	101.57	102.25	101.88	102.05	102.00
	b	16.24	30.63	41.45	24.51	24.75	24.86	28.81	27.84	21.27	22.95	22.61	24.26
	c	-3.52	-8.06	-12.52	-5.94	-5.76	-6.05	-6.90	-6.70	-5.60	-5.78	-5.82	-6.20
WP-PTCH	a	100.03	100.28	100.14	100.18	100.16	100.21	100.22	100.14	100.11	100.17	100.23	100.26
	b	234.45	45.66	76.32	151.75	112.54	241.49	185.65	99.63	87.76	86.64	210.29	77.21
	c	-29.26	-7.75	-11.65	-24.04	-17.49	-39.05	-30.37	-15.12	-12.95	-13.56	-34.70	-13.01
NWP-PTCH	a	100.04	100.30	100.11	100.17	100.13	100.15	100.19	100.10	100.11	100.14	100.20	100.25
	b	228.48	46.68	73.32	189.40	128.03	150.29	292.45	104.36	93.19	101.69	150.01	83.30
	c	-28.89	-8.04	-10.72	-29.83	-19.22	-23.18	-46.76	-15.15	-13.72	-15.56	-24.05	-13.86
RUT	a	102.08	101.11	101.34	101.25	101.43	101.87	101.76	102.31	100.81	101.07	101.43	101.69
	b	86.68	117.99	74.23	207.56	84.48	103.24	70.03	90.82	83.29	61.88	69.37	75.66
	c	-22.37	-26.20	-17.21	-47.35	-19.89	-25.95	-17.34	-24.10	-17.29	-13.64	-16.34	-18.54

3.4 Final Performance Models

Since pavement's pre-treatment condition can greatly impact the performance of pavement after it is treated, it was decided to include this information when developing pavement performance models. As concluded by a previous study [4], the average PCR values before Interstate, US, and NC roadways were treated, i.e., Pre_PCR values, are summarized in Table 4 below.

Table 4. Pre_PCR Values

Pavement Classification	**Pre_PCR**
Interstate	69
US	61
NC	58

Using these Pre_PCR values, each of the roadway family can be further divided into two sub-families. For example, Interstate0_3000 is divided into Interstate0_3000_Poor (when roadways' Pre_PCR values are less than 69) and Interstate0_3000_Good (when roadways' Pre_PCR values are greater than 69). Therefore, the new pavement families are listed below and performance models were developed for all these families:

- Interstate0_3000_Poor, Interstate0_3000_Good,
  Interstate3000_5700_Poor, Interstate3000_5700_Good,
  Interstate5700plus_Poor, Interstate5700plus_Good
- US0_280_Poor, US0_280_Good,
  US280_520_Poor, US280_520_Good,
  US520_880_Poor, US520_880_Good,
  US880_1670_Poor, US880_1670_Good,
  US1670plus_Poor, US1670plus_Good
- NC0_250_Poor, NC0_250_Good,
  NC250_420_Poor, NC250_420_Good,
  NC420_580_Poor, NC420_580_Good,
  NC580plus_Poor, NC580plus_Good

These performance models were developed using the following model equation:

$$\text{PCR} = a/(1 + e\hat{}((-\text{Pavement\_}Age + b)/c)) \quad (23)$$

where a, b, c are model parameters.

Based on findings from a previous study [3], PCR values of asphalt pavements can be calculated as shown in equations below:

$$\text{NDR} = 0.5152640 \times \text{TRA} + 0.2729290 \times \text{LNG} + 0.2118080 \times \text{LNG\_JNT} \quad (24)$$

$$\text{LDR} = 0.5316370 \times \text{ALGTR} + 0.1520450 \times \text{WP} + 0.0887566 \times \text{NWP} + 0.2275610 \times \text{RUT} \quad (25)$$

$$\text{PCR} = \min\,(\text{LDR}, \text{NDR}) \quad (26)$$

where:

- **NDR**: Non-Load Related Distress Rating
- **LDR**: Load Related Distress Rating
- **PCR**: Pavement Condition Rating
- **TRA**: Transverse Cracking index value
- **LNG**: Longitudinal Cracking index value
- **ALGTR**: Alligator Cracking index value
- **WP**: Wheel Path Patching index value
- **NWP**: Non Wheel Path Patching index value
- **RUT**: Rutting index value

The same data cleaning process described in Section 3.3.2 was used and resulting model parameters a, b, and c are included in Table 5 below.

Table 5. Final Performance Models

Family	a	b	c
Interstate0_3000_good	101.2	23.25	-5.35
Interstate0_3000_poor	104.5	14.70	-4.79
Interstate3000_5700_good	102.0	21.05	-5.45
Interstate3000_5700_poor	102.0	12.59	-3.32
Interstate5700plus_good	104.5	48.81	-15.94
Interstate5700plus_poor	117.0	12.46	-7.09
US0_280_good	103.2	22.73	-6.73
US0_280_poor	103.2	11.50	-3.41
US280_520_good	103.0	21.97	-6.23
US280_520_poor	105.0	13.02	-4.42
US520_880_good	102.5	22.23	-6.17
US520_880_poor	109.0	12.99	-5.47
US880_1670_good	101.6	19.96	-5.08
US880_1670_poor	105.0	12.96	-4.44
US1670plus_good	102.0	21.01	-5.37
US1670plus_poor	104.5	12.98	-4.21
NC0_250_good	102.5	23.76	-6.61
NC0_250_poor	102.5	12.84	-3.65
NC250_420_good	102.0	21.43	-5.61
NC250_420_poor	102.0	12.52	-3.36
NC420_850_good	102.0	22.40	-5.99
NC420_850_poor	103.0	12.72	-3.76
NC850plus_good	101.7	23.11	-5.94
NC850plus_poor	103.0	12.72	-3.62

Performance model curves of Interstate0_3000 and US520_850 roadways are included in Figure 13 and Figure 14 below as examples. In these figures, the blue solid line represents the model curve that was developed using roadway sections that have greater Pre_PCR values than the corresponding Pre_PCR threshold, i.e., the *Roadway*_Good curve, the green solid line represents the *Roadway*_Poor curve, and the red dash line represent the overall model curve, *Roadway*_Combined curve, that was developed using the combined *Roadway*_Good and *Roadway*_Poor data. All performance model curves are included in Appendix B.

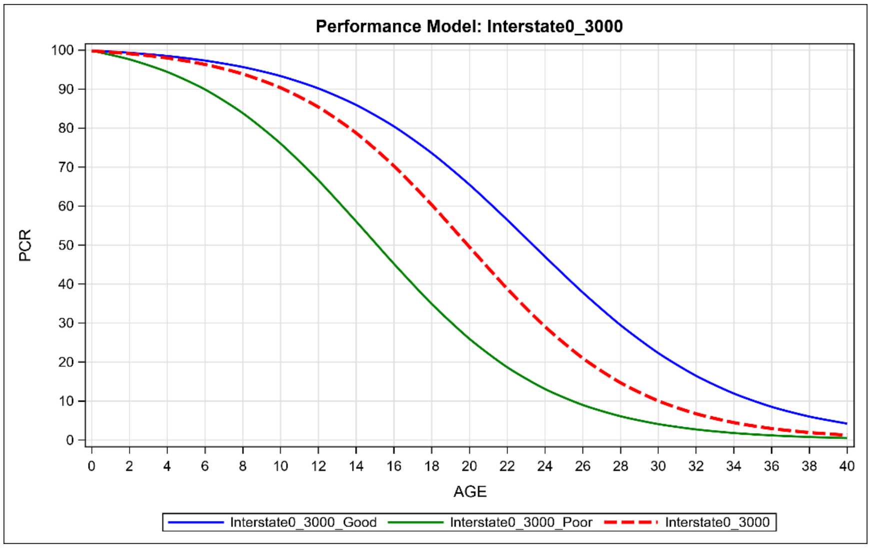


Figure 13. Performance Model Curves for Interstate0-3000

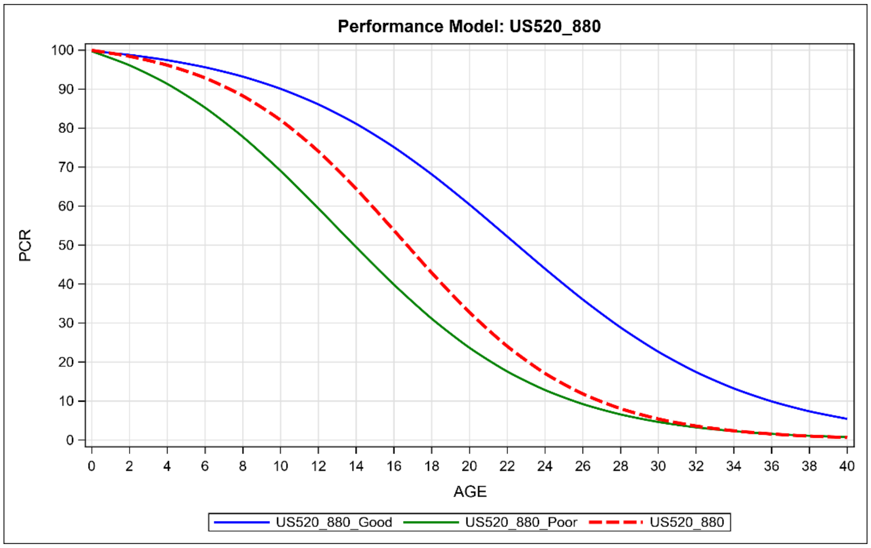


Figure 14. Performance Model Curves for US520-850

CHAPTER 4 A Pilot Study on ESAL

This chapter describes the procedures used to develop pavement distress and performance models for Interstate routes using an alternative traffic loading parameter, ESAL, and its breakpoints as well as pre-treatment pavement conditions. The flow chart is the same as the procedure used for AADTT except for AADTT being replaced with ESAL (the red box in Figure 15 below).

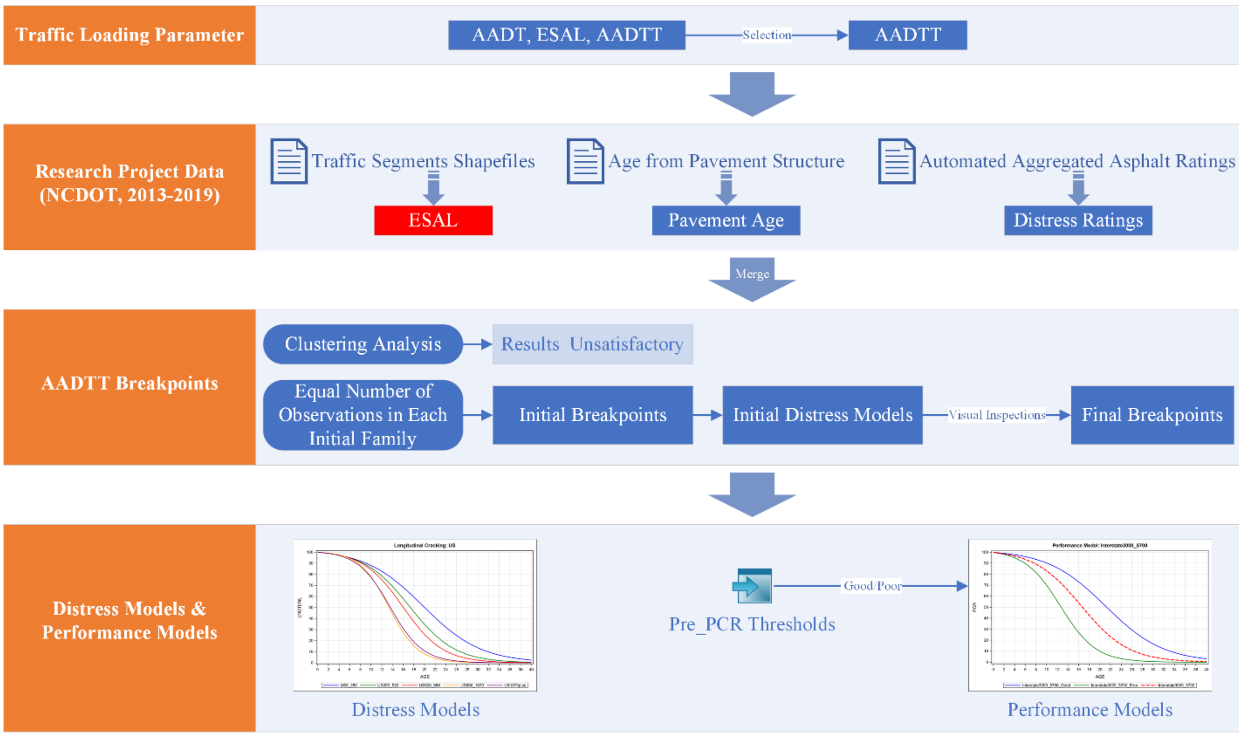


Figure 15. Flow Chart for ESAL

As described in Chapter 3, ESAL was not initially selected as the new traffic loading parameter because quite some additional information is required for each roadway section to calculate ESAL values (equations below), whereas AADTT values are included in the segment shapefiles for this research project to use directly.

According to the NCDOT Pavement Design Procedure [25], ESAL can be calculated using the following equations:

$$\boldsymbol{ESALS_{Total}} = \frac{\left(\left(1+\frac{\%Growth}{100+365.25}\right)^{(365.25\times N_D)}-1\right)\times\left(ADT_C\times\frac{\%TTST}{100}\times TTST_F\times\frac{\%Duals}{100}\times Duals_F\right)\times\frac{\%Direction}{100}\times L_D}{\ln\left(1+\frac{\%Growth}{100+365.25}\right)} \tag{27}$$

where,

$$\%\boldsymbol{Growth} = \left(10^{\left(\frac{\log_{10}\frac{ADT_{Future}}{ADT_{Initial}}}{(Year_{Future}-Year_{Initial})\times 365.25}\right)} \times 365.25 - 365.25 \right) \times 100 \qquad (28)$$

$$\boldsymbol{ADT_C} = ADT_{Initial} \times \left(1 + \frac{\%Growth}{100\times 365.25}\right)^{((Year_{Construction}-Year_{Initial})\times 365.25)} \qquad (29)$$

N_D = Design Number of Years

ADT_C = Average Annual Daily Traffic in the year of construction

$TTST_F$ = Tractor Trailor Semi Truck (TTST) Loading Factor

$Dual_F$ = Duals Factor

L_D = Lane Distribution Factors (a lane distribution factor of 0.50 will be used for the design of inside (median) lane widening of existing facilities with 2 or more lanes per direction):

No. of Lanes In One Direction	Lane Distribution Factor
1	1.0
2	0.9
3 or more	0.8

Truck Loading Factors (Flexible Pavement, 18-kip ESALs):

	DUALS	TTST
Rural Freeway & Interstates	0.30	1.15
Rural Other	0.30	0.95
Urban Freeway & Interstates	0.30	0.85
Urban Other	0.25	0.80

% Direction: a direction spilt of 50% is typically used in all designs.

For this pilot study, a simplified equation was suggested by NCDOT to calculate ESAL:

$$ESAL = 0.3 \times SU\_AADT + 1.05 \times MU\_AADT \qquad (30)$$

where,

SU_AADT = Annual average daily traffic of single unit single axle trucks, “Duals”

MU_AADT = Annual average daily traffic of various combinations of multiple unit and multiple axle trucks, "TTST"

Calculated ESAL values were then used as the new alternative traffic loading parameter to develop distress and performance models for Interstate routes only.

4.1 Initial ESAL Breakpoints

Using the equal number of observations in each initial family method, it was decided to develop 7 initial Interstate families of 500 roadway sections, 10 initial US families of 2,000 sections, and 10 initial NC families of 3,000 sections. Corresponding initial ESAL breakpoints are:

- Interstate: ***1,500, 2,300, 3,700, 5,200, 6,400, 7,700***
- US: ***50, 110, 180, 250, 340, 450, 600, 820, 1,200***
- NC***: 30, 60, 100, 130, 170, 220, 300, 410, 660***

4.2 Initial Distress Models

After outliers were removed using the same process described in Chapter 3, initial distress models were developed, and model curves were visually inspected to group similar curves. One example, Interstate Transverse Cracking model curves, are shown below (Figure 16).

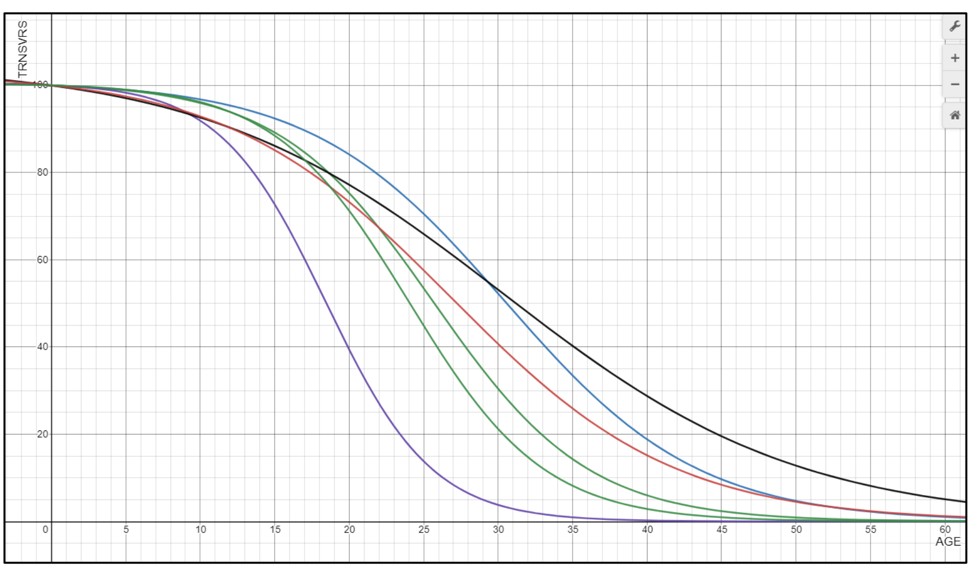


Figure 16. Initial Interstate Transverse Cracking model curves

Visual inspection results are shown in Table 6. In this table, differing color blocks in each column indicate that their corresponding initial family curves are close to each other and should be grouped together.

Table 6. Final ESAL Breakpoint (Interstate Routes)

System	ESAL	TRNSVRS	ALGTR	LNGTDNL	LNGTDNL_LANE_JNT	RVL	WP_PTCH	NWP_PTCH	RUT	Break Points
Interstate	0-1500									0-1500
	1500-2300									1500-2300
	2300-3700									2300-5200
	3700-5200									
	5200-6400									5200-7700
	6400-7700									
	7700 plus									7700 plus

The final ESAL breakpoints were determined by grouping as many blocks as possible with the same color across all the columns in the table. These breakpoints are included in the last column of the table. They are:

- Interstate: ***1,500, 2,300, 5,200, 7,700***

Therefore, the final Interstate pavement families are:

- Interstate0_1500, Interstate1500_2300, Interstate2300_5200, Interstate5200_7700, Interstate7700plus

4.3 Final Distress Models

Final distress models for Transverse Cracking, Alligator Cracking, Raveling, Longitudinal Cracking, Longitudinal Lane Joint Cracking, Wheel Path Patching, Non-Wheel Path Patching, and Rutting were developed using Equation (22). The same data cleaning process described in Section 3.3.2 was used and resulting model parameters a, b, and c are included in Table 7 below. Transverse Cracking model curves of Interstate roadways are included in Figure 17 as an example. All distress model curves are included in Appendix F.

Table 7. Final Distress Models for Interstate Routes (ESAL)

Distress		Interstate_E_0_1500	Interstate_E_1500_2300	Interstate_E_2300_5200	Interstate_E_5200_7700	Interstate_E_7700plus
TRNSVRS	a	100.9	100.7	101.7	104	100.5
	b	30.46200818	25.64414652	21.101897	370.985241	24.02716255
	c	-6.48155643	-5.203086327	-5.134310916	-115.5202975	-4.530896571
ALGTR	a	100.5	100.3	100.5	101.5	100.4
	b	29.79158571	23.96676485	41.00879646	118.541268	23.26348119
	c	-5.567784068	-4.022073291	-7.760868368	-28.49631158	-4.124833706
LNGTDNL	a	100.4	100.2	100.5	104.3	100.8
	b	18.00055101	15.81804042	17.01757405	52.05476974	17.88383666
	c	-3.301935126	-2.572078442	-3.20114607	-16.46921987	-3.743364604
LNGTDNL-LANE-JNT	a	101.9	100.1	100.6	100.8	100.5
	b	24.74019771	12.50137132	15.19824058	15.01003277	16.62965384
	c	-6.185674379	-1.808939741	-3.014184853	-3.148038624	-3.095278283
RVL	a	101.1	100.8	102.6	107.5	101.3
	b	19.20674883	16.72243498	27.99596232	33.95666223	21.49364764
	c	-4.276868206	-3.482180236	-7.701692953	-13.08393945	-4.922031145
WP-PTCH	a	100.5	100.3	101.1	101	100.95
	b	167.271779	83.96452929	29.84304886	38.60612198	35.1711101
	c	-32.04710207	-14.16865825	-6.620403566	-8.33878383	-7.558877921
NWP-PTCH	a	100.5	100.3	101.05	101.05	101.05
	b	323.615484	81.07287713	28.38759874	39.43206828	36.50056583
	c	-61.77984868	-13.90167611	-6.240470472	-8.587812704	-7.992856132
RUT	a	101.4	102.05	101.65	101.6	101.12
	b	39.47051099	66.85133209	191.7035046	87.53173572	66.34072338
	c	-9.26547041	-17.19207189	-46.83488666	-21.22425491	-14.81575485

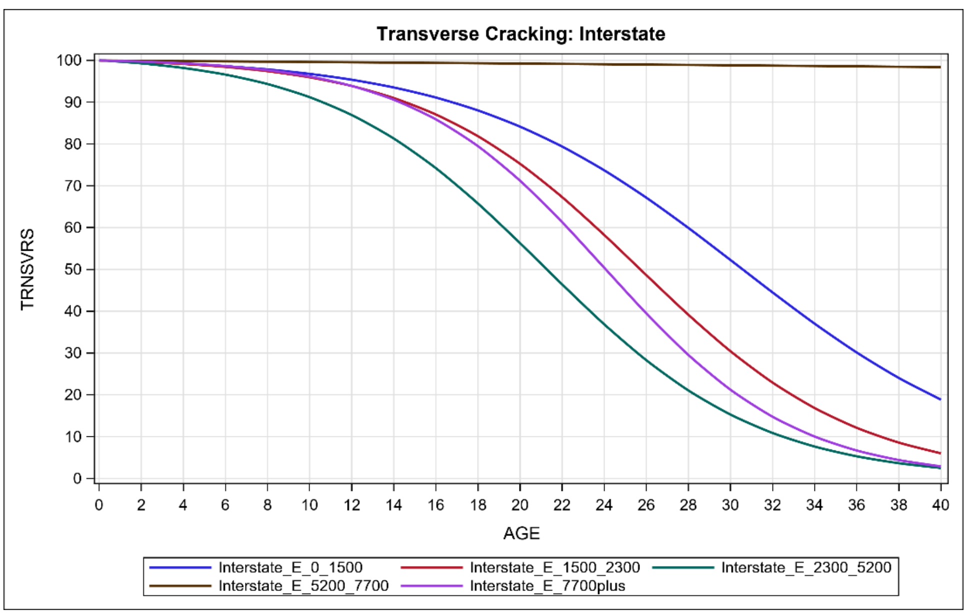


Figure 17. Transverse Cracking Model Curves for Interstate Routes (ESAL)

4.4 Final Performance Models

Using the same Pre_PCR values listed in Table 4, final performance models were developed for the following Interstate families:

- Interstate0_1500_Poor, Interstate0_1500_Good, Interstate1500_2300_Poor, Interstate1500_2300_Good, Interstate2300_5200_Poor, Interstate2300_5200_Good, Interstate5200_7700_Poor, Interstate5200_7700_Good, Interstate7700plus_Poor, Interstate7700plus_Good

Resulting model parameters, a, b, and c are included in Table 8 below.

Table 8. Final Performance Models for Interstate Routes (ESAL)

Family	a	b	c
Interstate_E_0_1500_good	101.63	25.146009659	-6.155948602
Interstate_E_0_1500_poor	100.00	-23.15220801	31.278934863
Interstate_E_1500_2300_good	100.90	19.333423522	-4.087873165
Interstate_E_1500_2300_poor	104.20	14.845647092	-4.694104871
Interstate_E_2300_5200_good	102.60	23.375366909	-6.418199513
Interstate_E_2300_5200_poor	113.40	15.838415118	-7.890229436
Interstate_E_5200_7700_good	105.70	58.249022104	-20.40296632
Interstate_E_5200_7700_poor	114.70	11.059762499	-5.773810448
Interstate_E_7700plus_good	102.20	26.578801103	-6.962505814
Interstate_E_7700plus_poor	100.00	5.4214545976	8.8478152996

Performance model curves of the Interstate1500_2300 family are included in Figure 18 below as an example. In this figure, the blue solid line represents the model curve that was developed using roadway sections that have greater Pre_PCR values than the corresponding Pre_PCR threshold, i.e., the *Roadway*_Good curve, the green solid line represents the *Roadway*_Poor curve. It should be noted that the Interstate0_1500_Poor model and the Interstate7700plus_Good models are not reasonable mainly because of the small sample size of these two families and thus are not included in the final plots. All performance model curves are included in Appendix G.

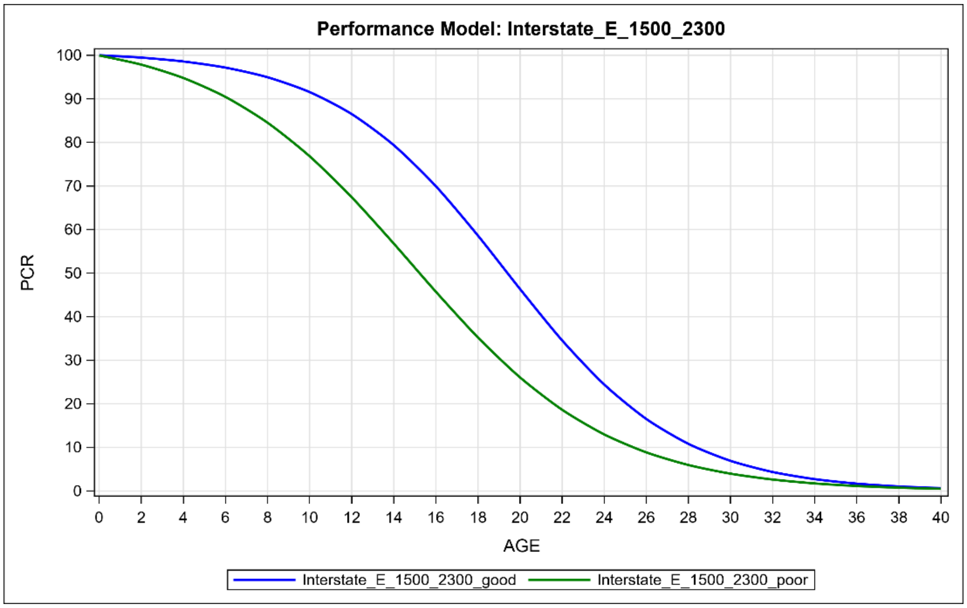


Figure 18. Performance Model Curves for Interstate1500-2300 (ESAL)

CHAPTER 5 FINDINGS AND CONCLUSIONS

This research project was conducted to develop pavement distress and performance models using a new traffic loading indicator, a new set of breakpoints for dividing roadway families, and pavement pre-treatment conditions. Several steps were involved in this study: (1) traffic segment shapefiles, pavement age files, and automated asphalt pavement rating files were obtained from NCDOT and merged to create a master data file; (2) distress ratings were normalized and distress index values were calculated, outliers were removed, and two different methods, clustering analysis and equal number of observations in each initial roadway family, were used to determine the initial breakpoints; (3) initial distress models were developed and visual inspections were conducted to group the model curves that are close to each other, then the final breakpoints were determined; (4) final distress models were developed, and final performance models were developed using Pre_PCR conditions. Findings and conclusions of this research project are provided below:

- Data availability. Research data needed for this research project, e.g., AADTT, Pavement Age, Pavement Distress Ratings, etc., have been frequently updated and made available to the research team by NCDOT engineers. These raw data are either published on a website that can be accessed publicly or provided to researchers upon request on a timely basis.
- Development of pavement families. Clustering analysis and the equal number of observations method were used to determine the AADTT breakpoints, which were then used to group new pavement families. It was observed that clustering analysis used in this project did not provide sufficient accuracy, as shown in Figure 19, Figure 20, and Figure 21. In these histograms, counts of AADTT are shown at the top of each bin, (a) includes color blocks that have boundaries ending at the AADTT values resulting from clustering analysis, (b) includes color blocks that have boundaries ending at pre-selected number of roadway sections in each initial pavement family, i.e., 500 for Interstate, 2,000 for US, and 3,000 for NC, and (c) includes color blocks that have boundaries ending at final AADTT breakpoints determined by visual inspections. It can be observed that the resolution of (a) is not sufficient to capture intermediate AADTT values as final breakpoints. It can be concluded that for a similar research project, it is recommended to use the equal number of observations method to determine breakpoints.

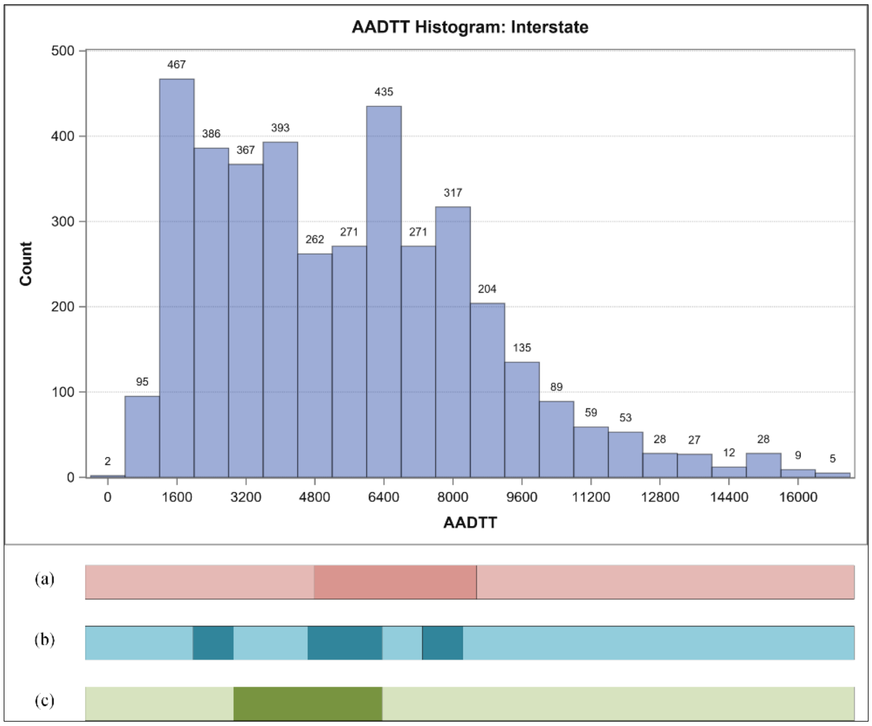


Figure 19. AADTT Breakpoints for Interstate

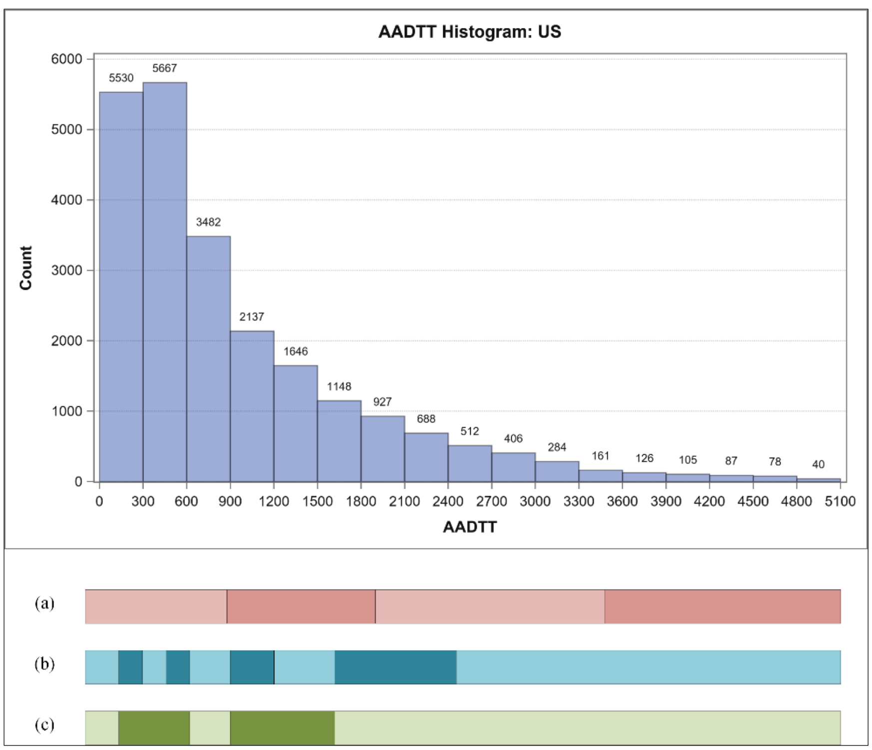


Figure 20. AADTT Breakpoints for US

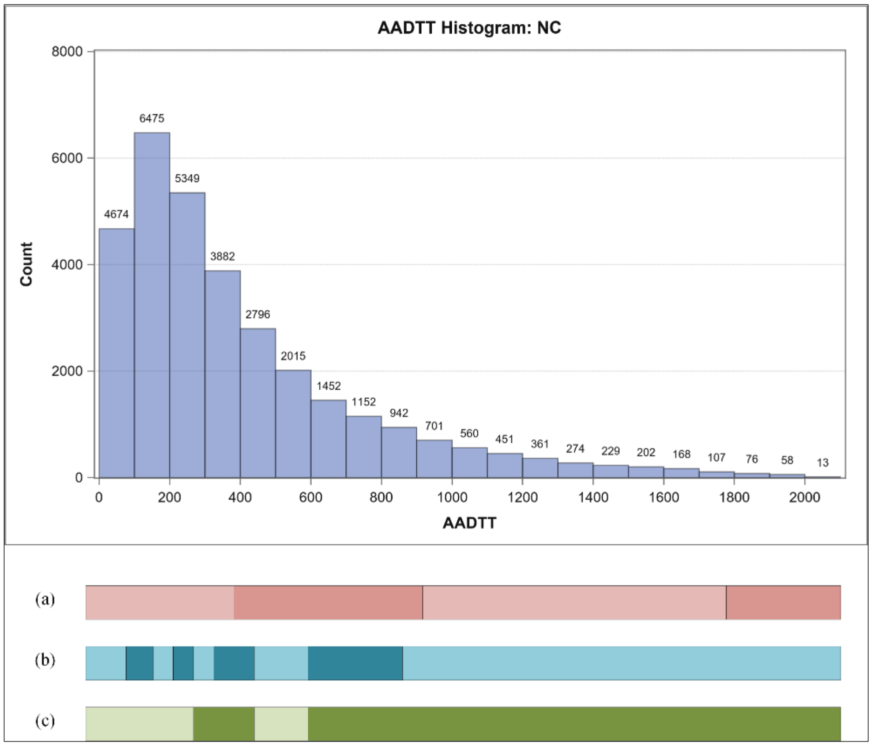


Figure 21. AADTT Breakpoints for NC

- Distress models. A comparison of distress model curves (Figure 22) developed using AADT [3] (referring to as AADT distress curves) with the model curves developed in this project using AADTT (referring to as AADTT distress curves) indicates the following:
  - The Wheel Path Patching, Non Wheel Path Patching, and Rutting AADTT distress curves are flat. One possible reason is that these three types of load related distresses (LDRs) are not severe in asphalt pavements in North Carolina. Another possible reason is that the data collection vendor has recently changed, and it is reasonable to assume that algorithms used to process raw images are different, which can lead to distress ratings that are different than the ones provided by the previous vendor. If the latter is true, it is necessary to conduct a detailed comparison between AADT distress curves and AADTT distress curves, and then update the NCDOT PMS Decision Trees accordingly.
  - Alligator Cracking AADTT distress curves are flatter than corresponding AADT distress curves. Alligator Cracking is another type of load related distress. This indicates that very likely the vendor's processing algorithms for LDRs are quite different, and special attention should be given to LDRs if the NCDOT PMS

Decision Trees need to be updated.

- Transverse Cracking and Longitudinal Cracking curves are quite consistent, other than transverse cracking curves for Interstate roadways, as shown in Figure 22 (all curves in Figure 22 are included in Appendix C).

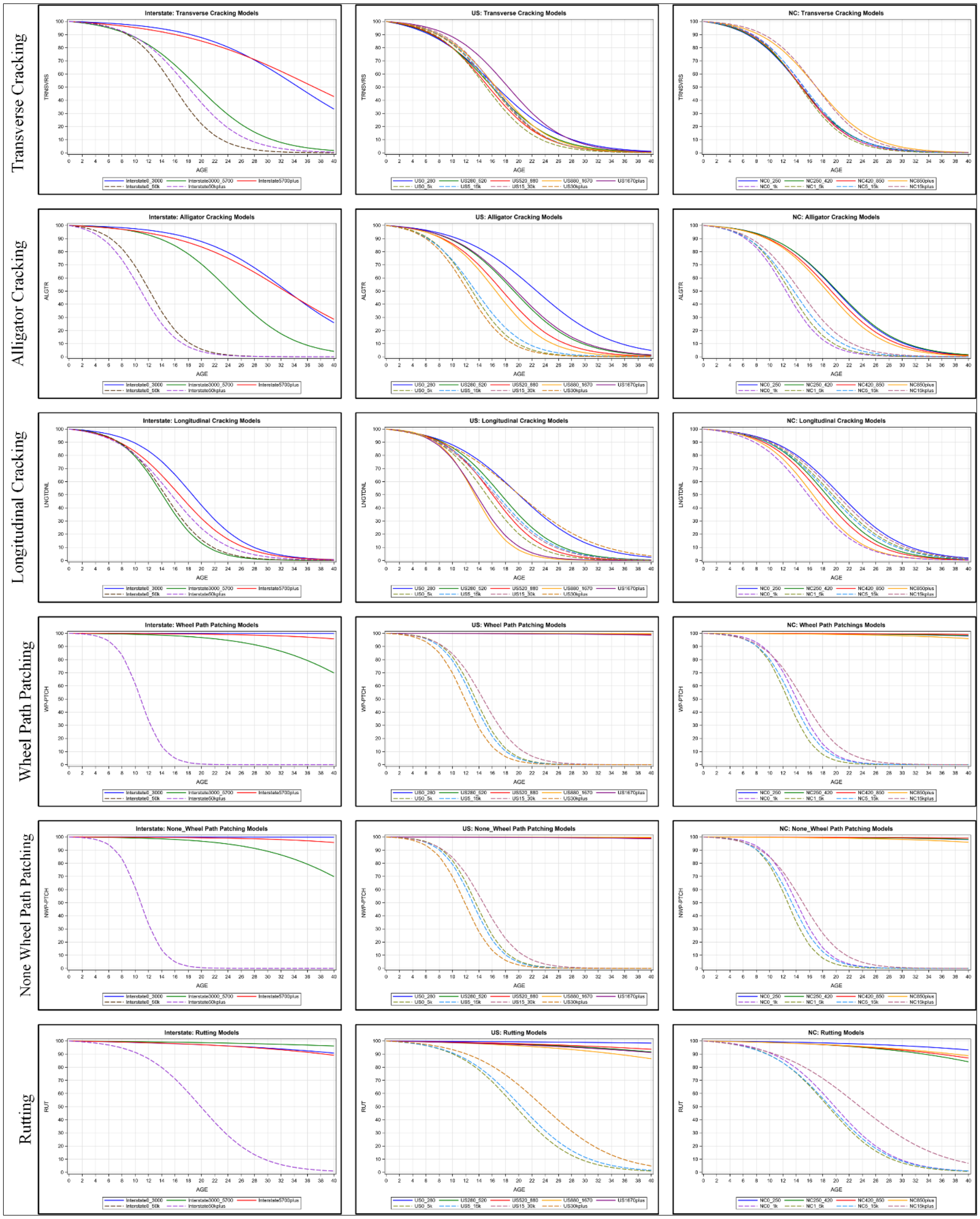


Figure 22. Comparison of Distress Model Curves

- Performance models. For performance models developed using AADTT breakpoints (referring to as the AADTT performance models), their curvature is as expected (Figure 23). The *Roadway*_Good curves (blue solid lines) are flatter than the *Roadway*_Combined curves, and the *Roadway*_Poor curves are steeper than the *Roadway*_Combined curves (green solid lines). A comparison of AADT and AADTT performance curves indicates that in general AADTT curves are flatter (Figure 24) (all curves are included in Appendix D). A further comparison of AADT performance curves (dash lines) and AADTT *Roadway*_Poor performance curves (solid lines), however, indicates that they share the same deterioration trends (Figure 25) (all curves are included in Appendix E).

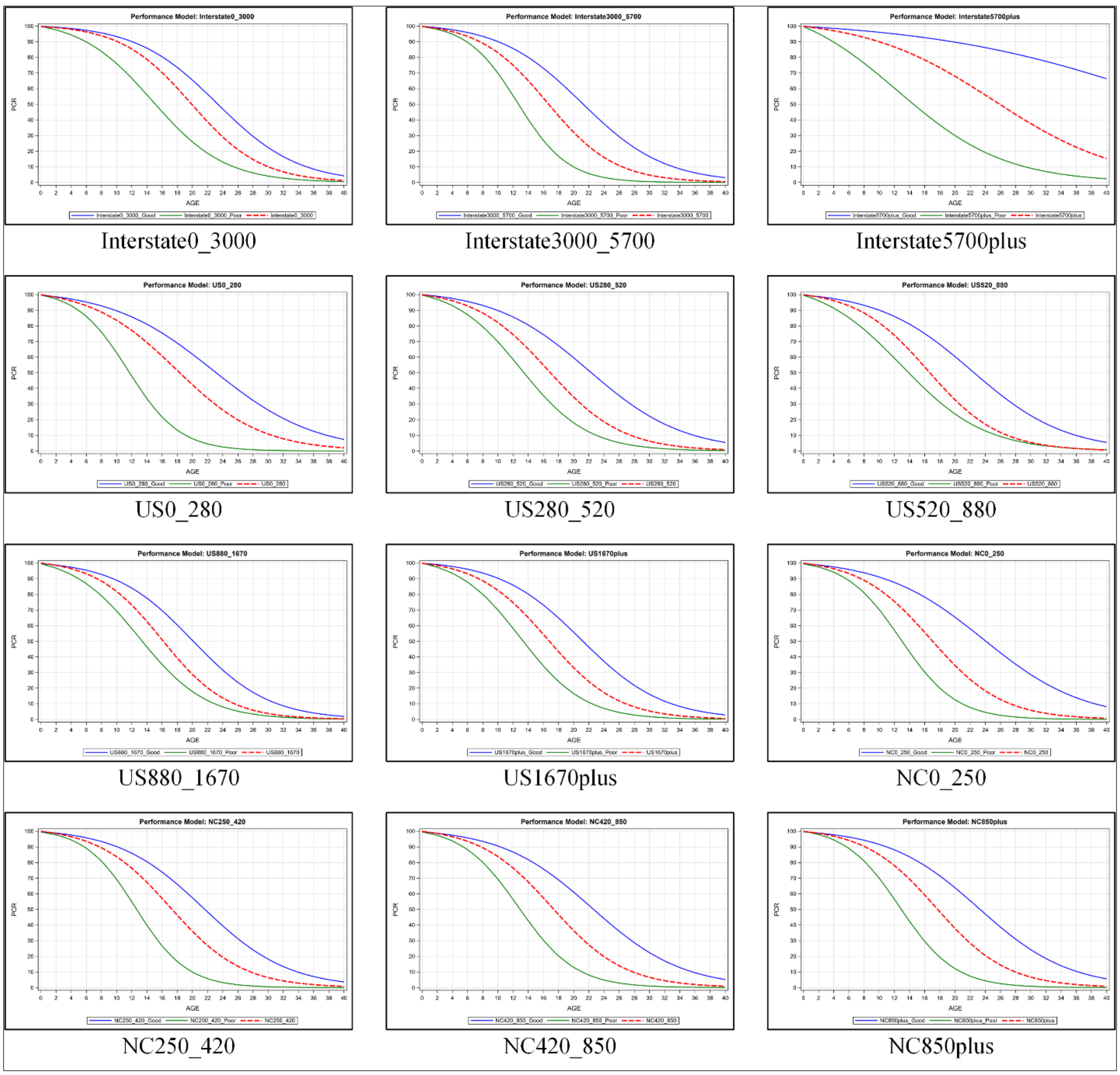
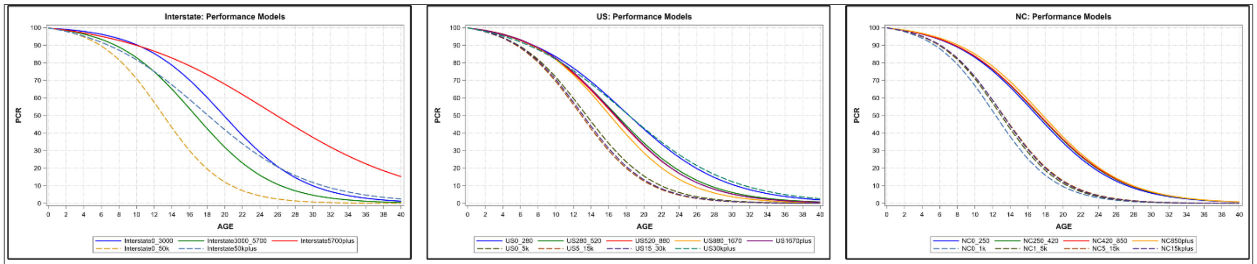
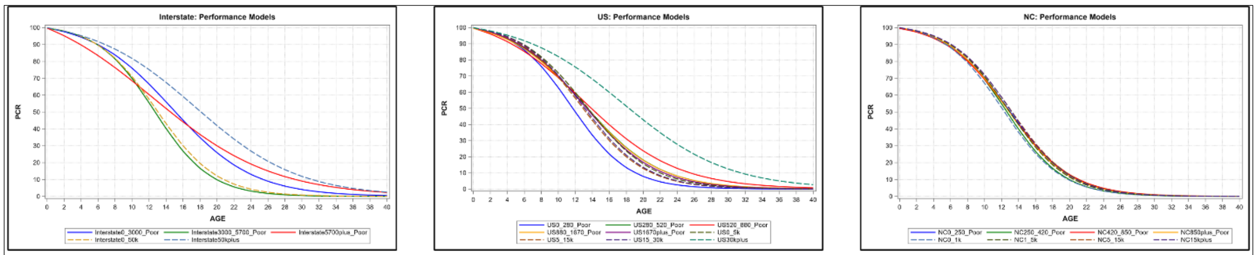


Figure 23. Performance Models: Combined, Good, and Poor



Interstate US NC

Figure 24. AADT Performance Models and AADTT Performance Models



Interstate US NC

Figure 25. AADT Performance Models and AADTT Roadway_Poor Performance Models

- A pilot study was conducted to use Equivalent Single Axle Load (ESAL) as an alternative new traffic loading parameter. Due to the time constraint, only Interstate routes were analyzed, and corresponding distress and performance models were developed. In this pilot study, ESAL values were calculated using a simplified equation. The resulting distress model curves lay between the AADT curves and AADTT curves, indicating that ESAL distress curves reflect NCDOT preventive maintenance practices closer than AADTT curves.

CHAPTER 6 RECOMMENDATIONS

Based on findings and conclusions obtained from this research project, the following recommendations are provided for future research endeavors:

- Comparing to clustering analysis, the same number of observations per family method is more appropriate to be used to create pavement families, mainly because pavement distress data is variable in nature. The latter method is sufficiently accurate to capture reasonable intermediate AADTT values as family breakpoints.
- A subsequent research project is recommended to quantify the differences between AADT and AADTT distress and performance curves. Current Decision Trees in the NCDOT PMS are using the critical thresholds derived from obsolete AADT models. With the use of a new data collection vendor and the newly developed AADTT models, current Decision Trees should be updated to achieve PMS' maximum level of performance.
- Two sub-distress models, *Roadway*_Good and *Roadway*_Poor, should be developed for each distress type. Sub-performance models were developed in this research project. The model curves provide the ranges of PCR values at a given age. The similar procedure should be implemented to distress models to provide the ranges of distress index values, which can be used to fine tune the NCDOT PMS' Decision Trees.
- ESAL should be further studied as the alternative traffic loading parameter to develop distress and performance models for US and NC routes, and a comparison of ESAL and AADTT model curves should be conducted to study the differences between these two traffic loading parameters, and the results can assist NCDOT with an enhanced ability to update the decision trees, and thus make informative pavement management decisions.

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25. NCDOT PAVEMENT DESIGN PROCEDURE AASHTO 1993 METHOD (2019), North Carolina Department of Transportation, Materials and Tests Unit – Pavement Section, January 4, 2019

Appendix A. Distress Model Curves

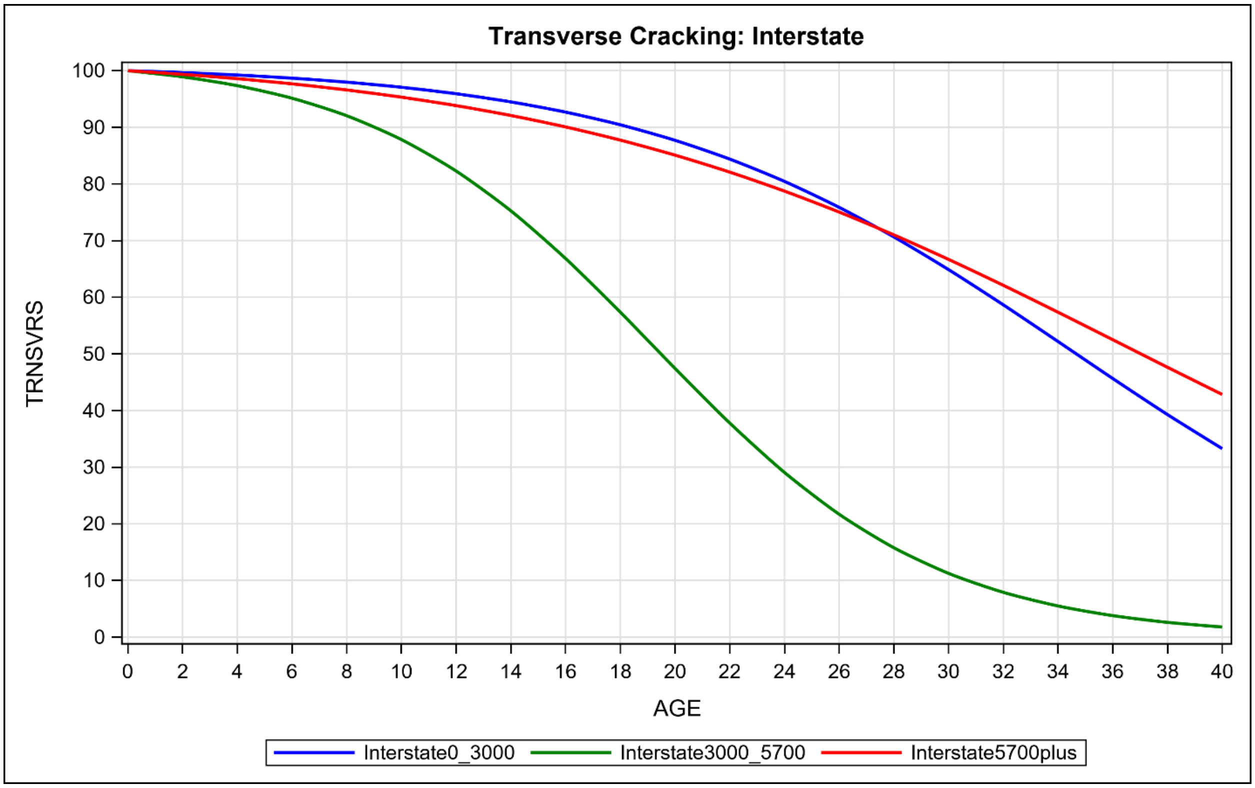

Figure A 1. Transverse Cracking: Interstate

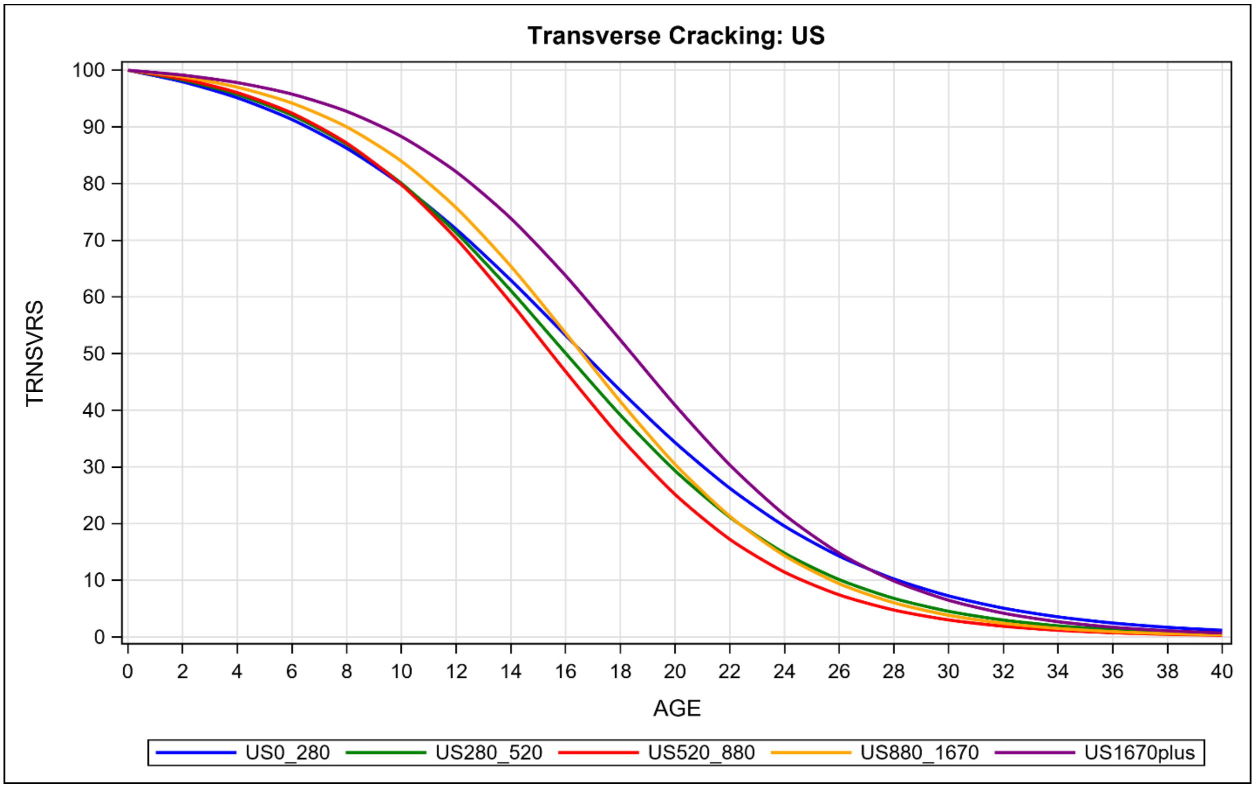

Figure A 2. Transverse Cracking: US

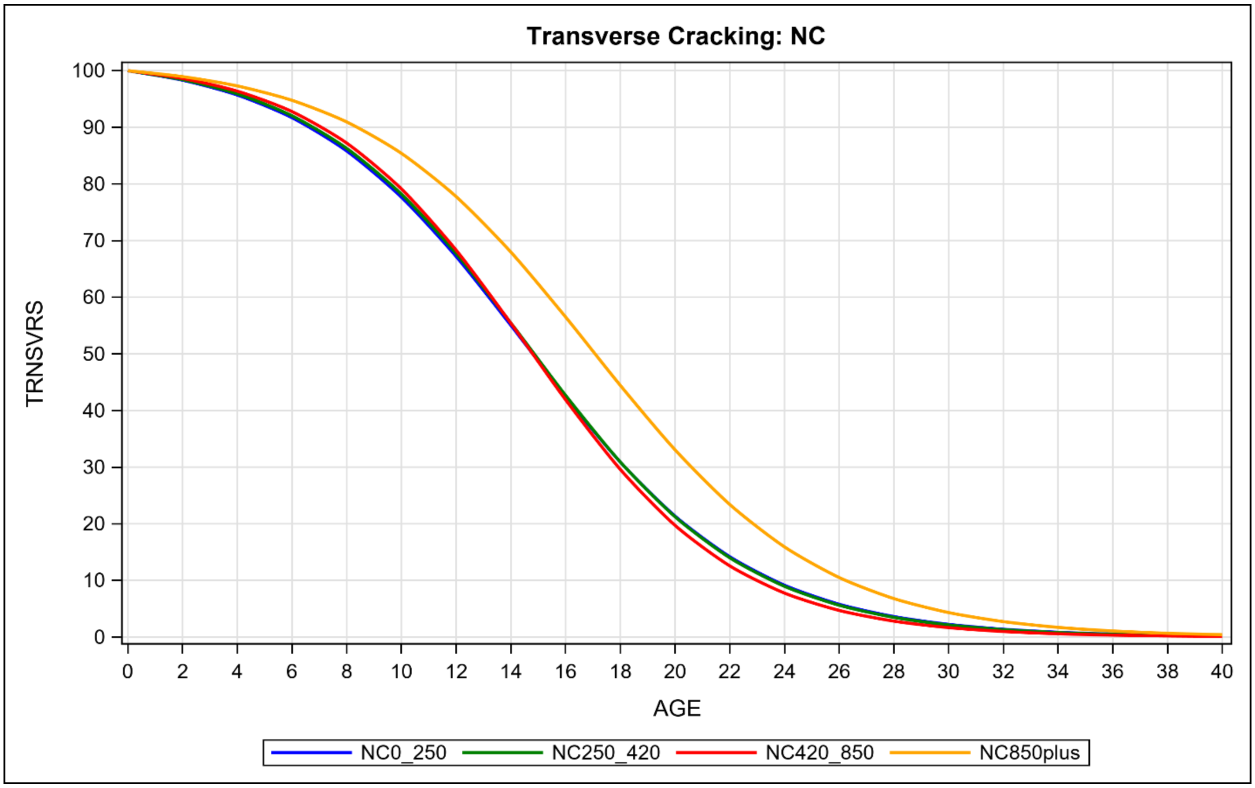

Figure A 3. Transverse Cracking: NC

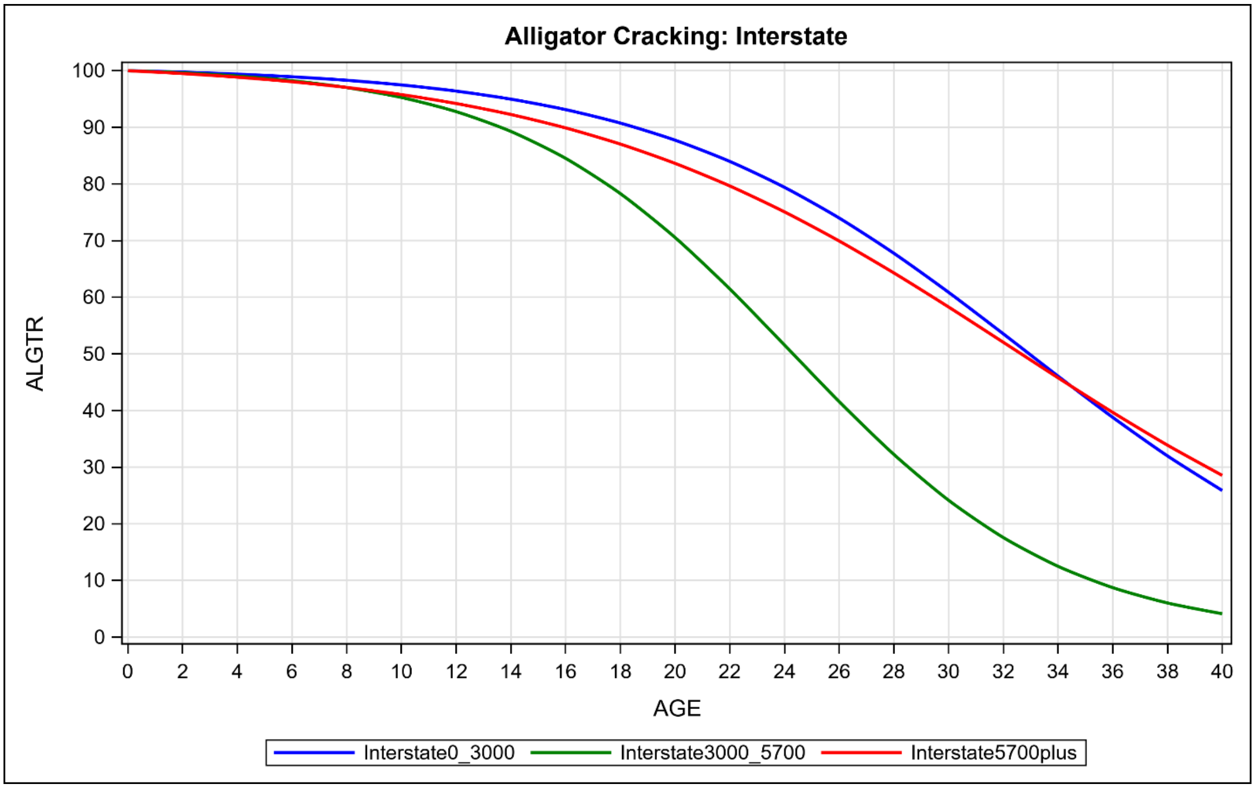

Figure A 4. Alligator Cracking: Interstate

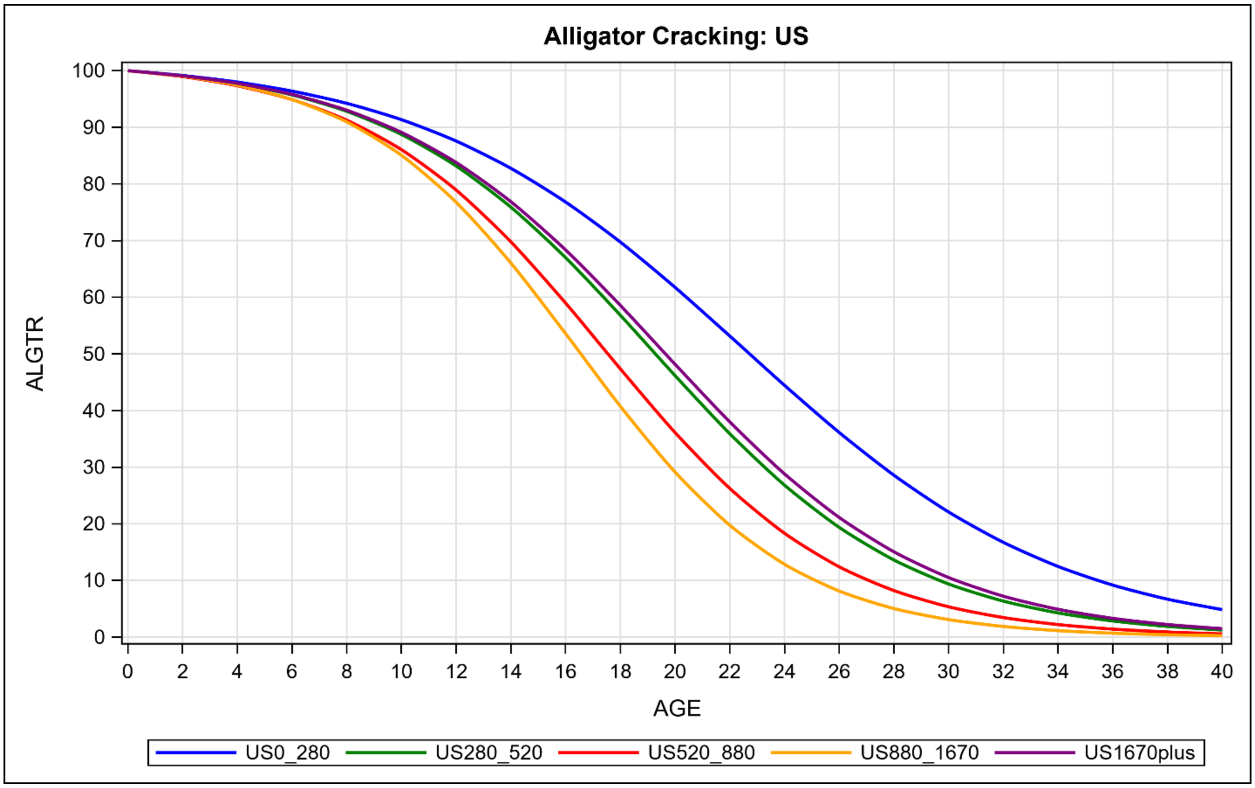

Figure A 5. Alligator Cracking: US

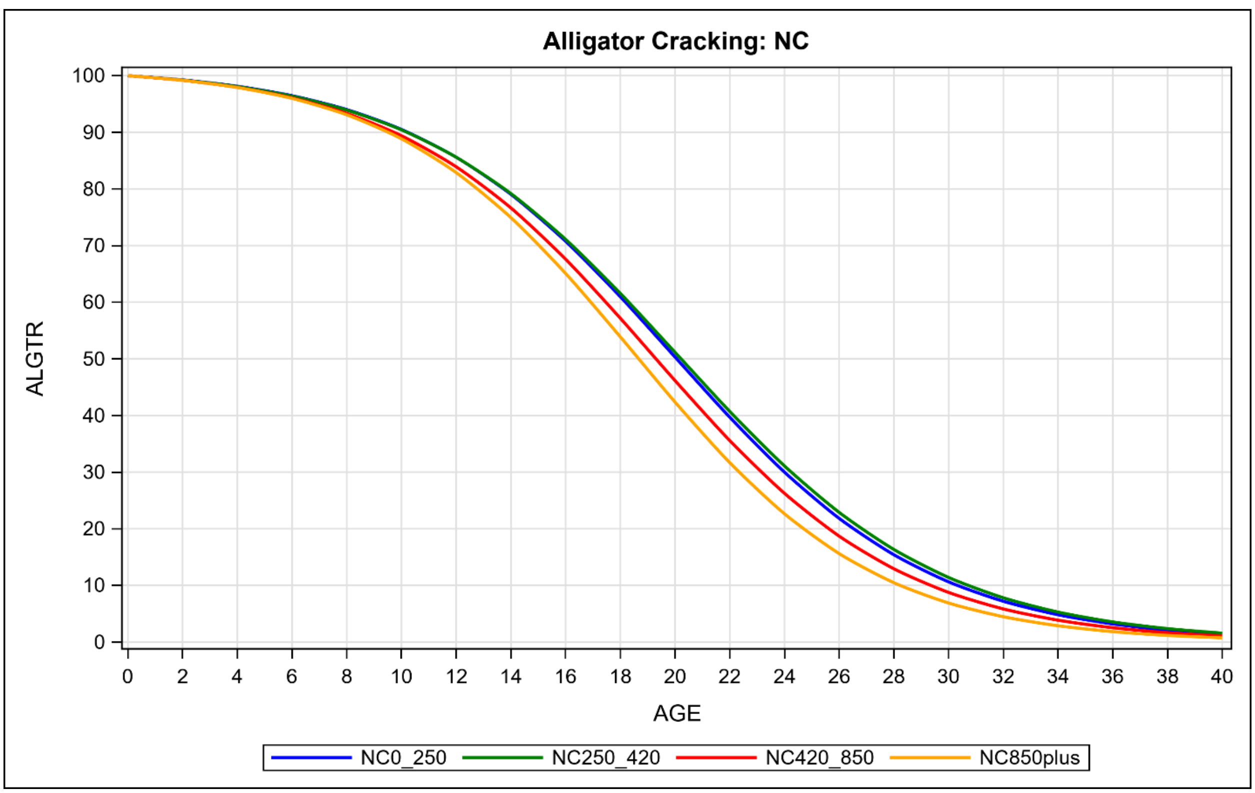

Figure A 6. Alligator Cracking: NC

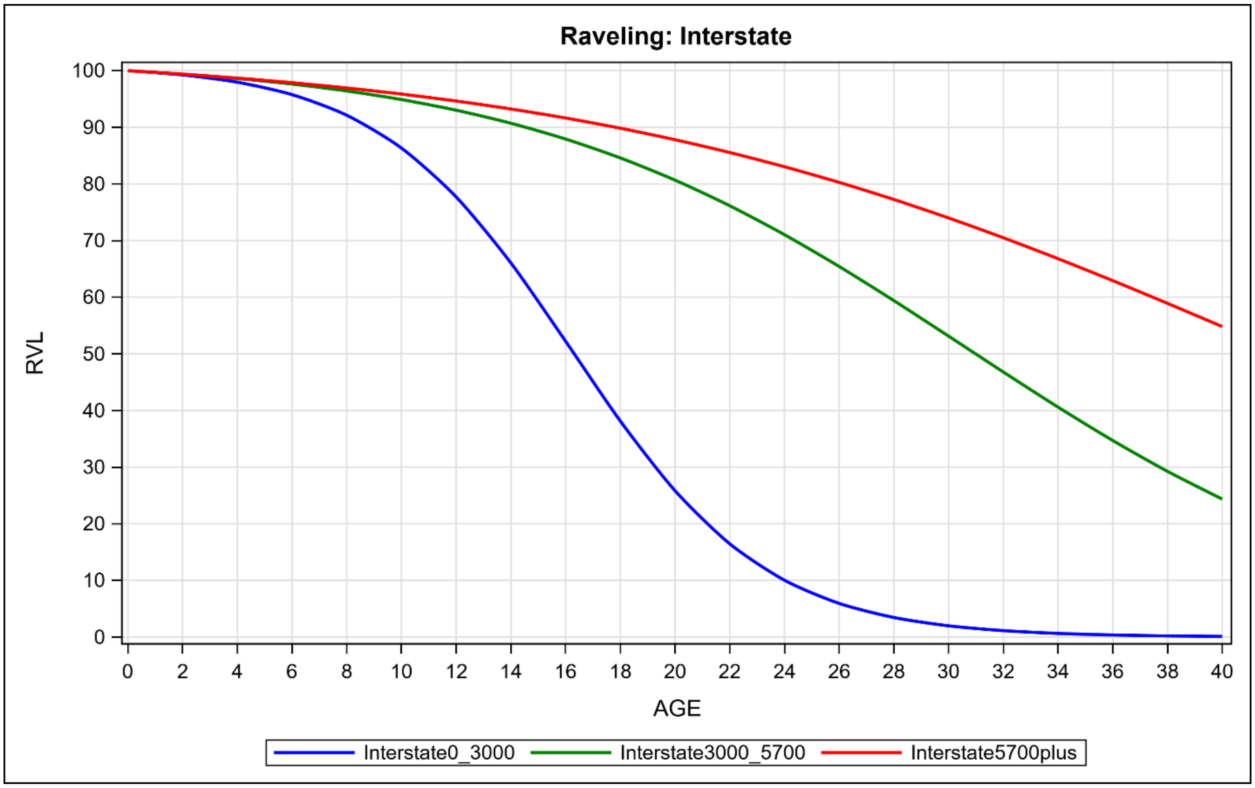

Figure A 7. Raveling: Interstate

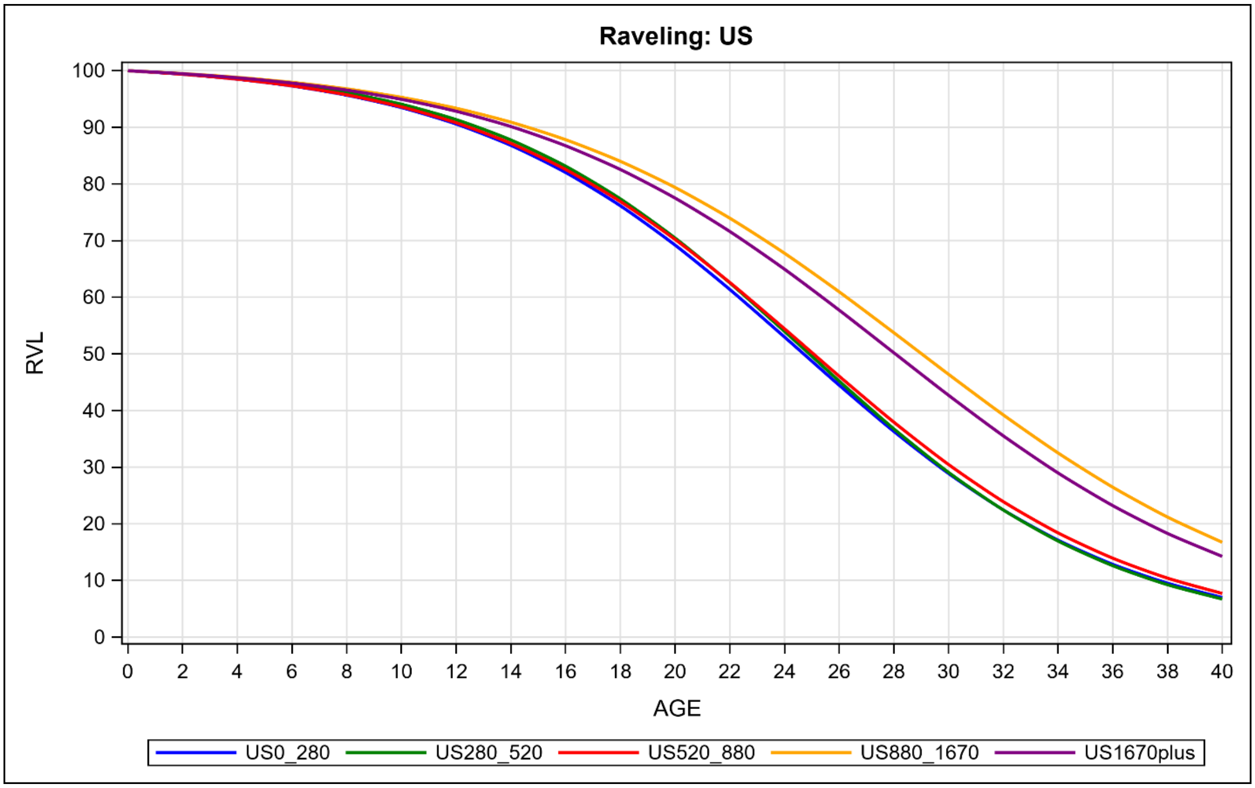

Figure A 8. Raveling: US

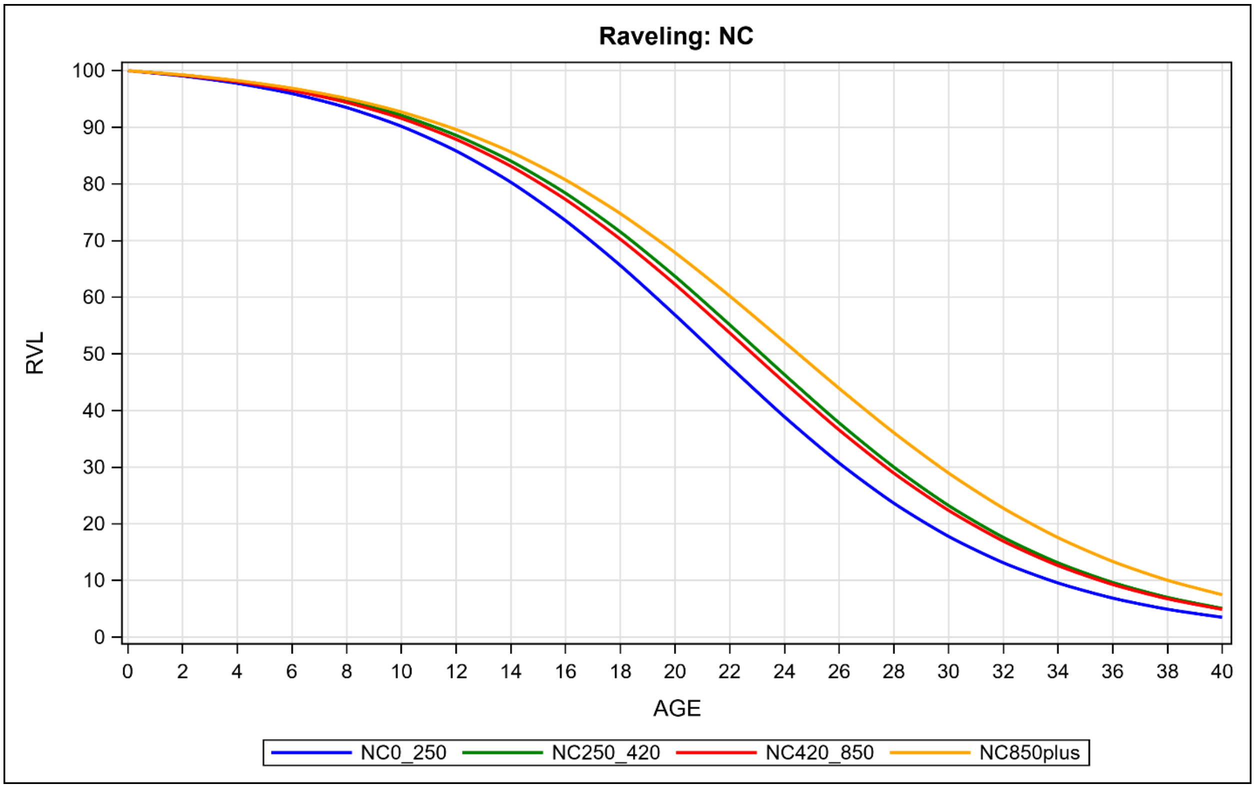

Figure A 9. Raveling: NC

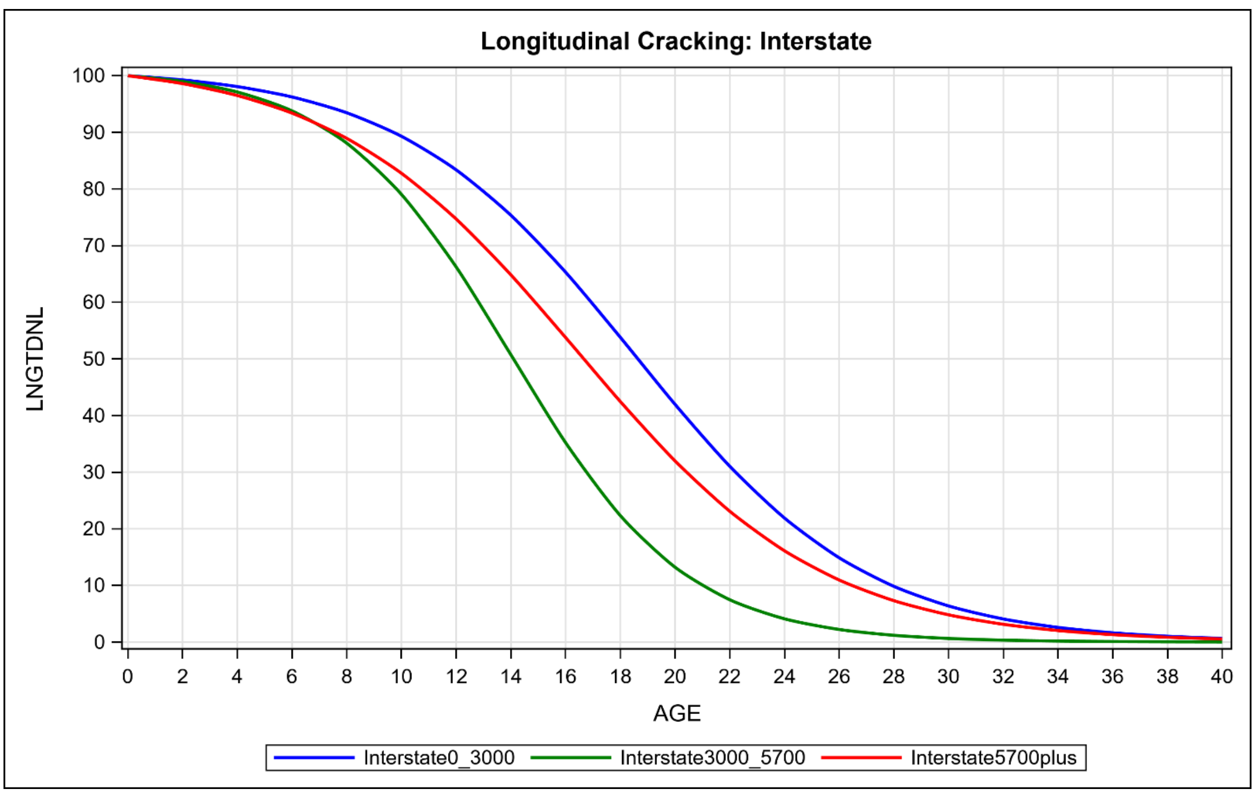

Figure A 10. Longitudinal Cracking: Interstate

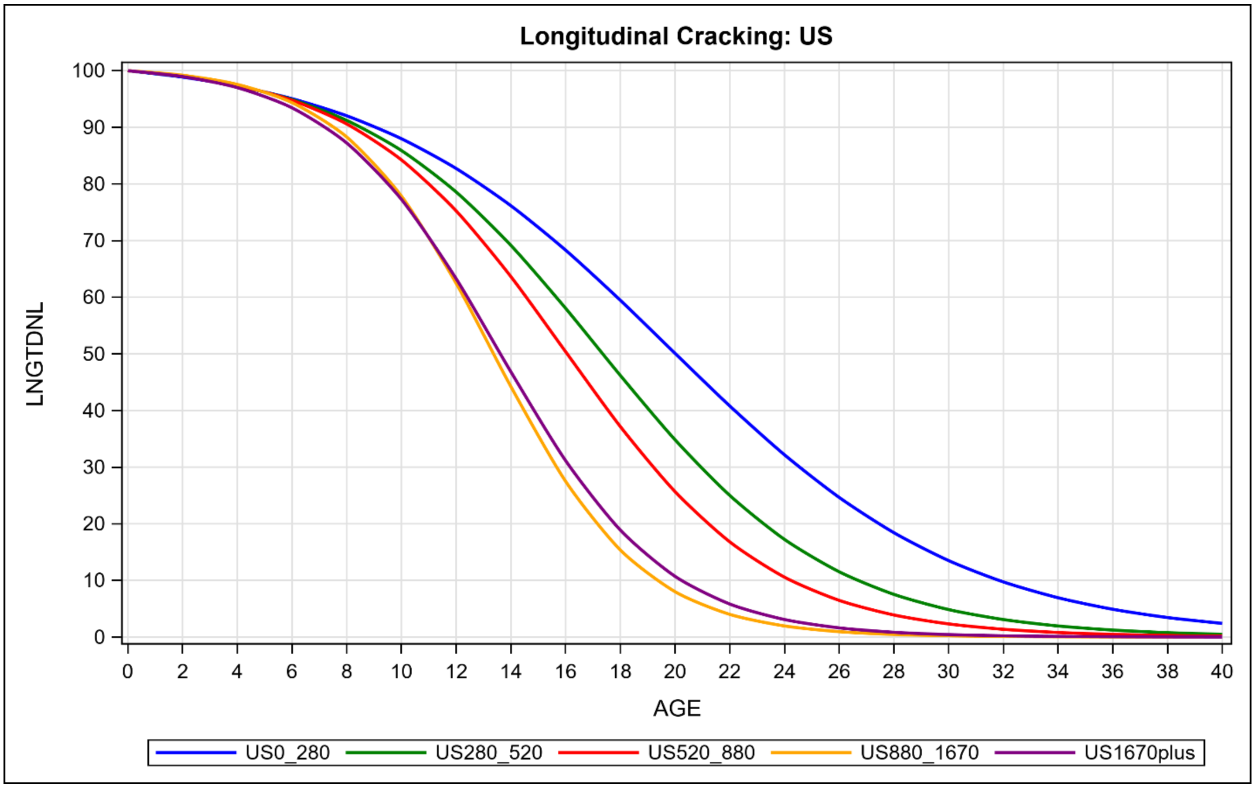

Figure A 11. Longitudinal Cracking: US

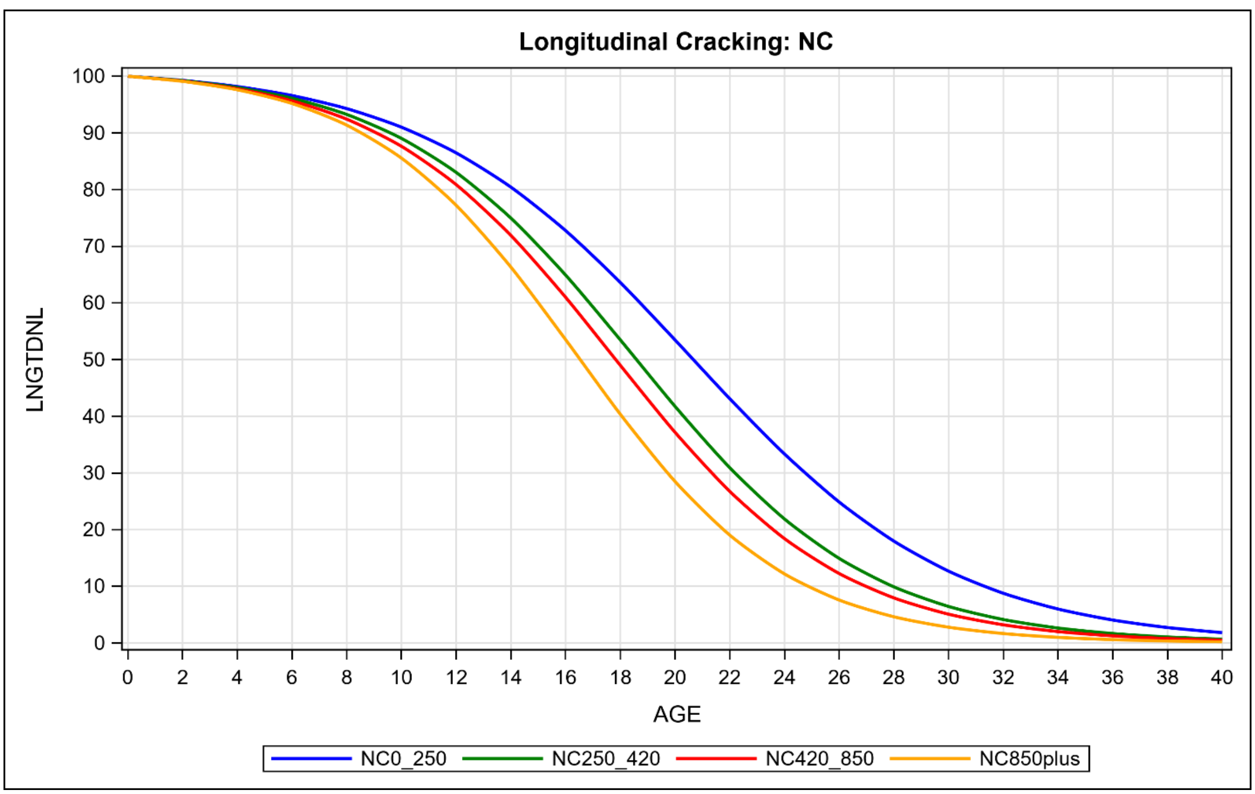

Figure A 12. Longitudinal Cracking: NC

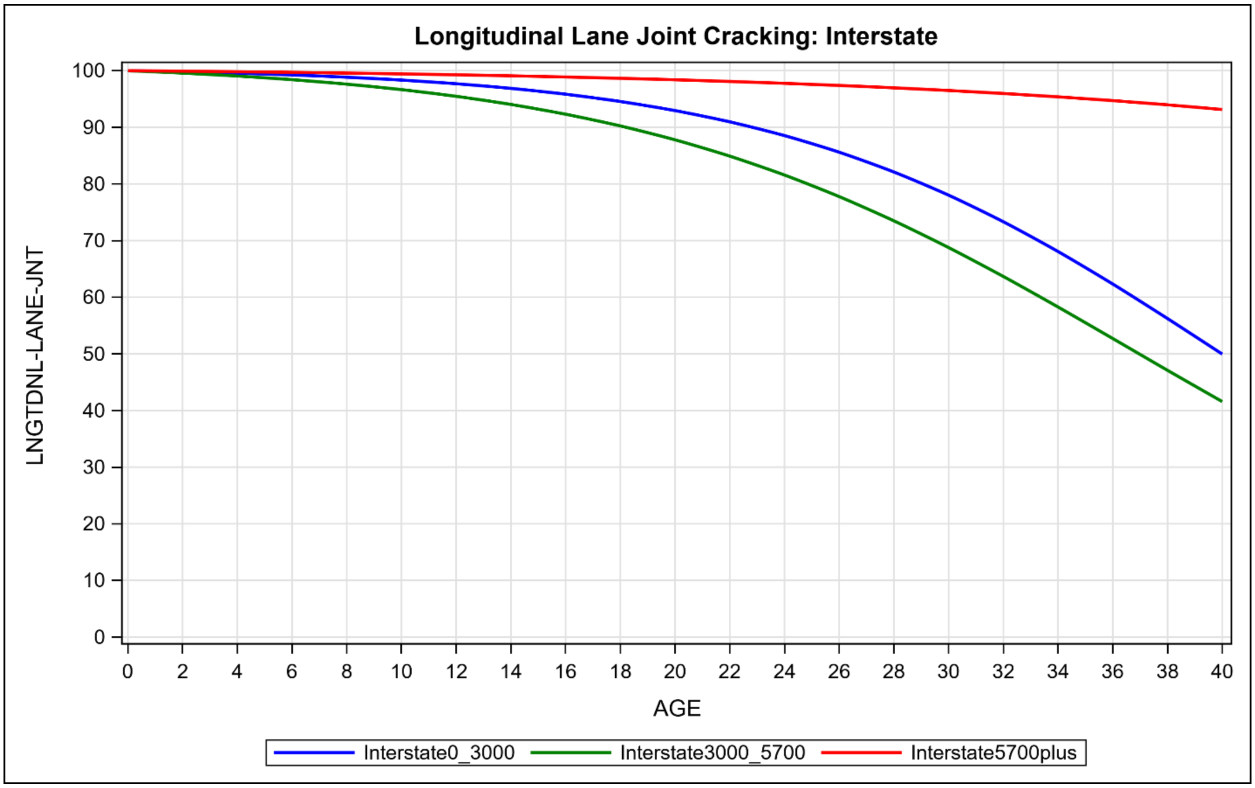

Figure A 13. Longitudinal Lane Joint Cracking: Interstate

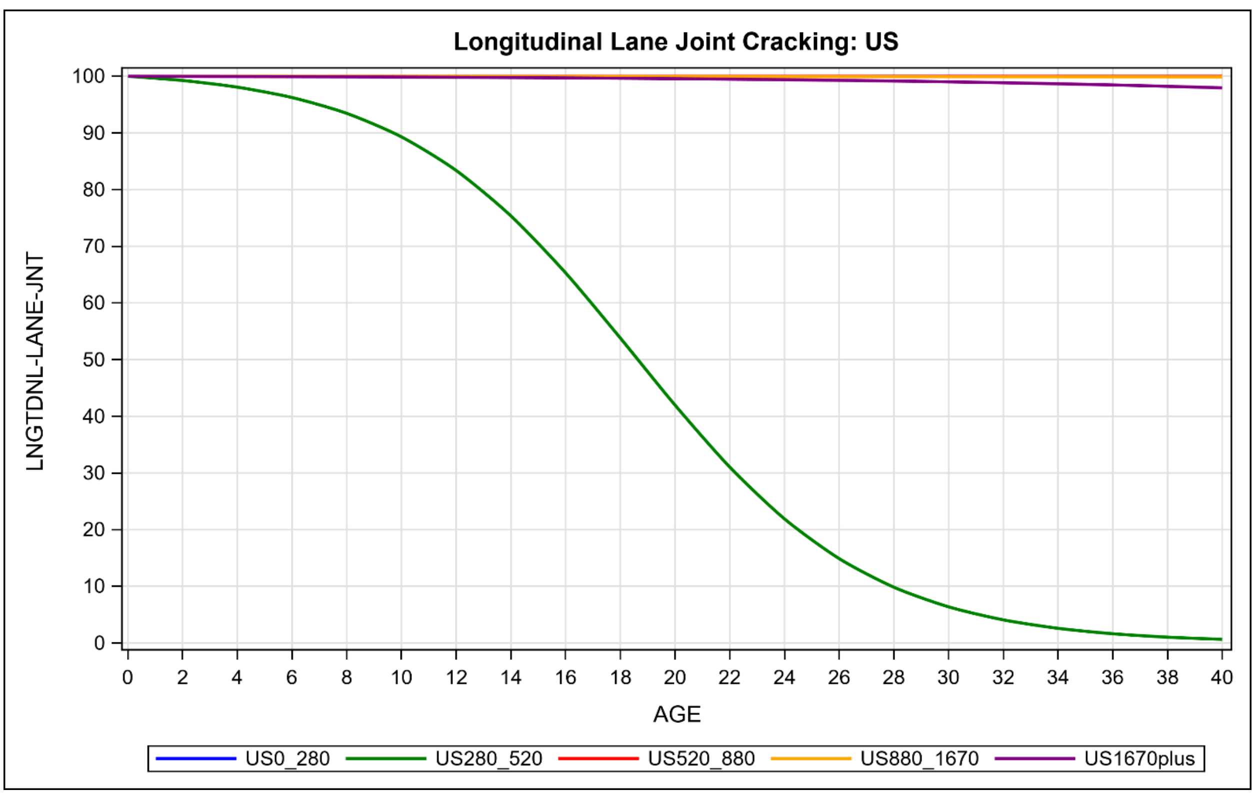

Figure A 14. Longitudinal Lane Joint Cracking: US

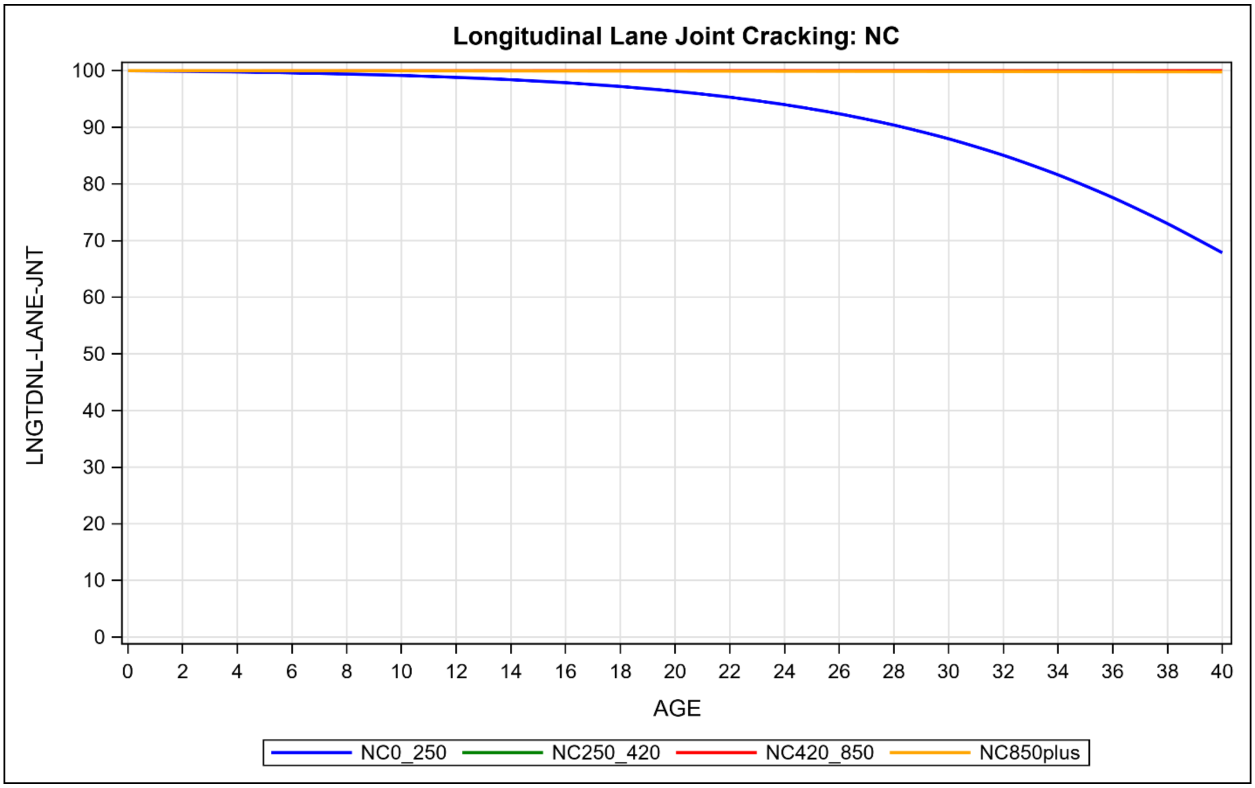

Figure A 15. Longitudinal Lane Joint Cracking: NC

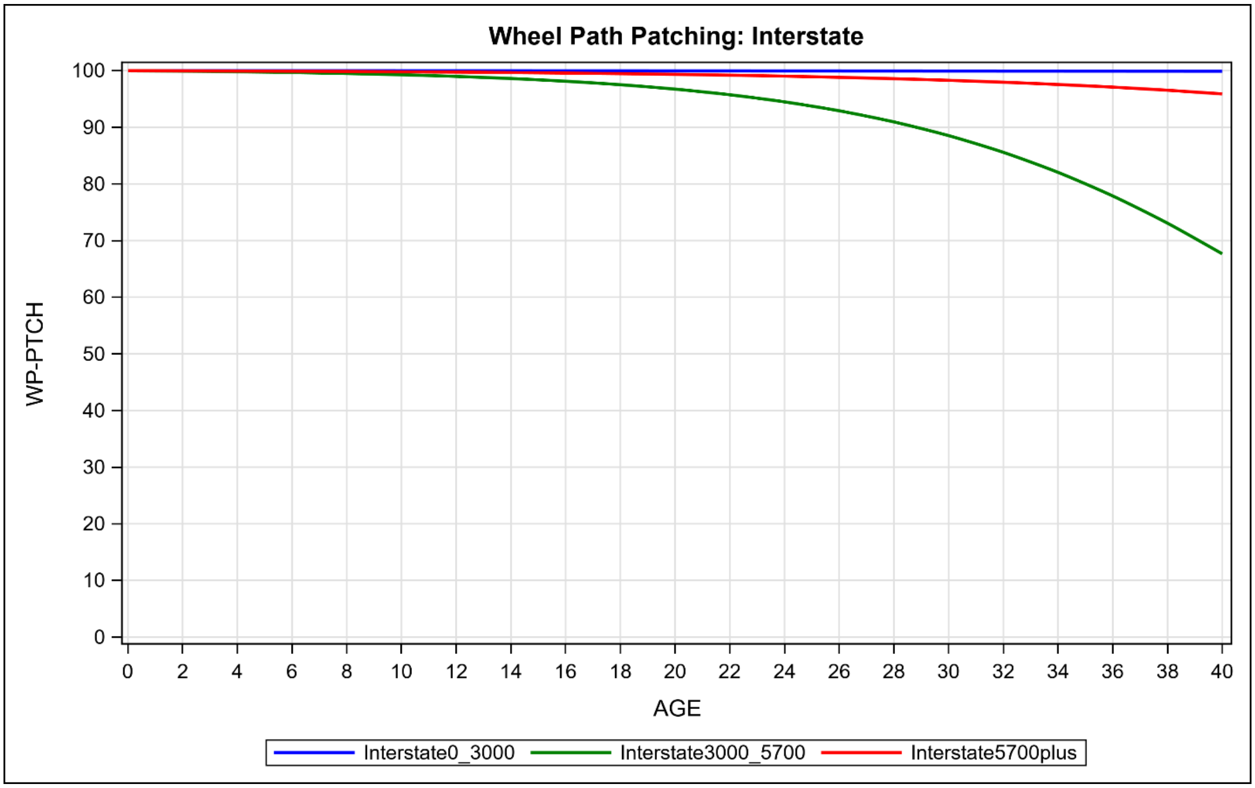

Figure A 16. Wheel Path Patching: Interstate

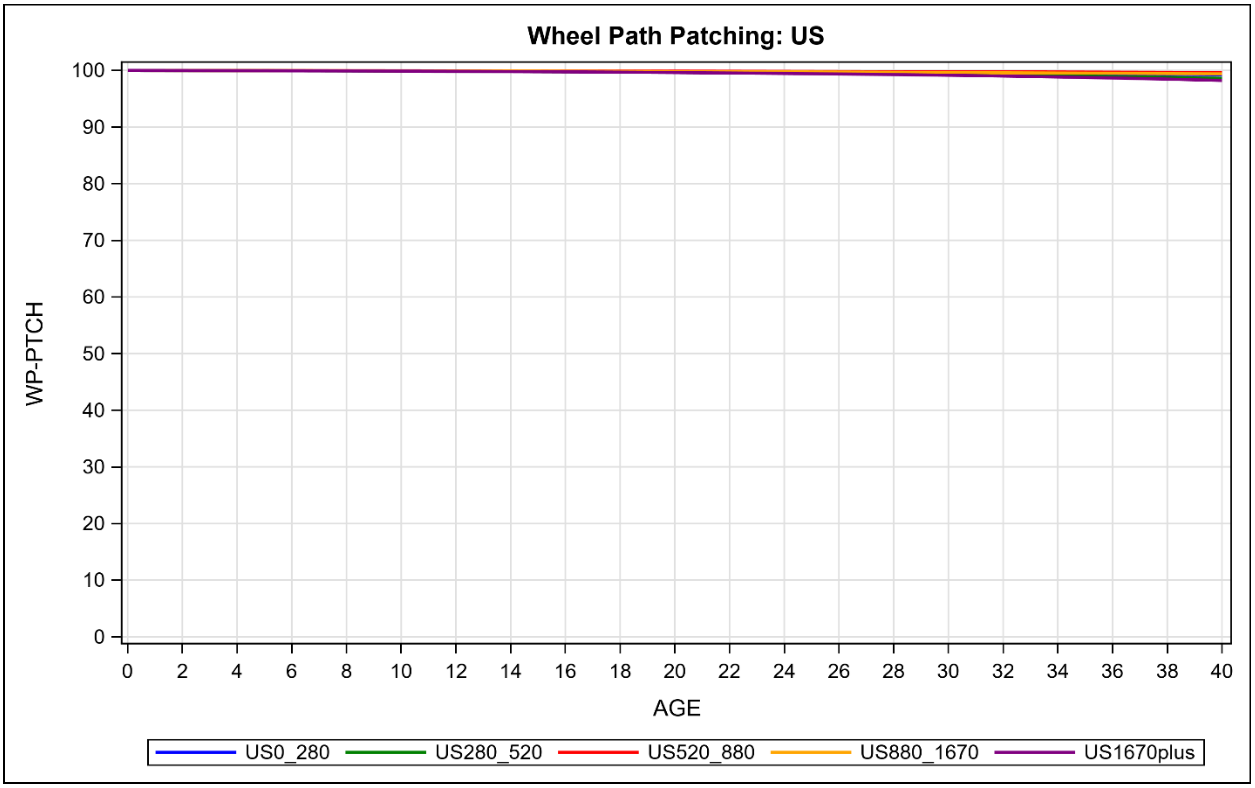

Figure A 17. Wheel Path Patching: US

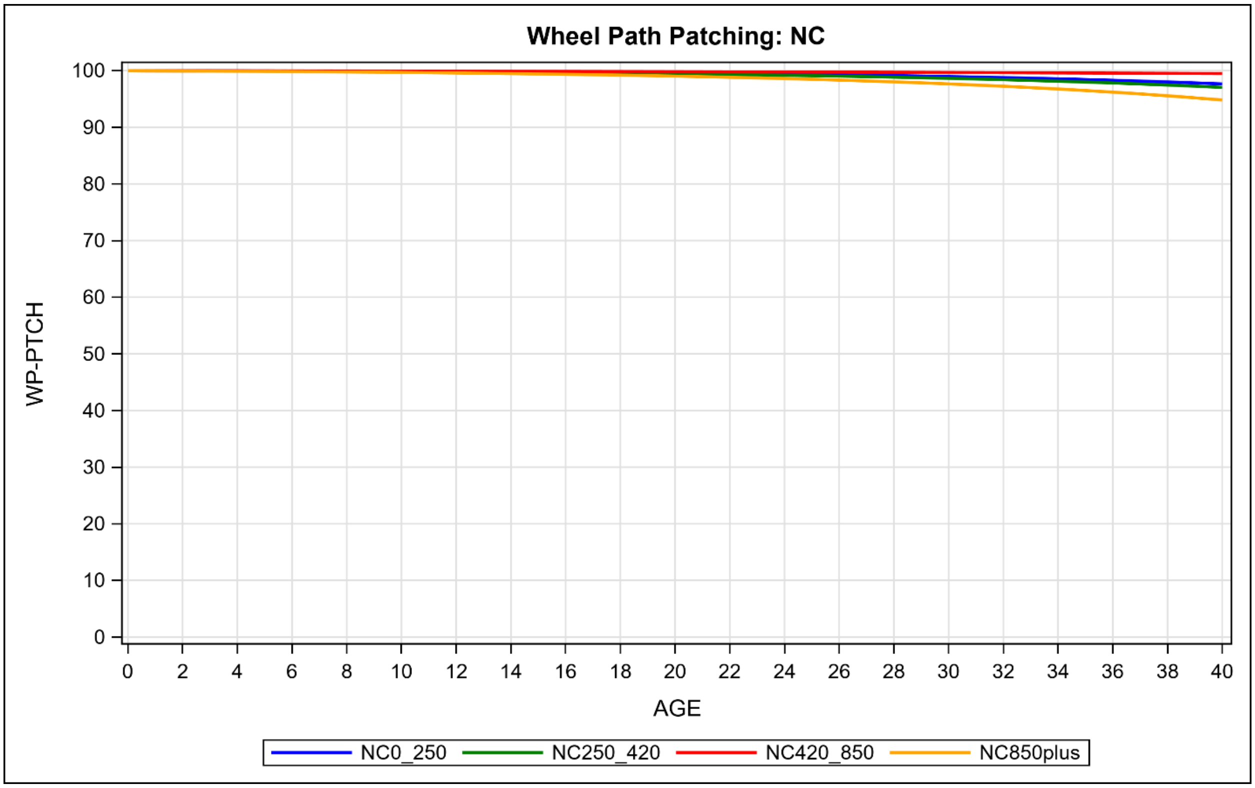

Figure A 18. Wheel Path Patching: NC

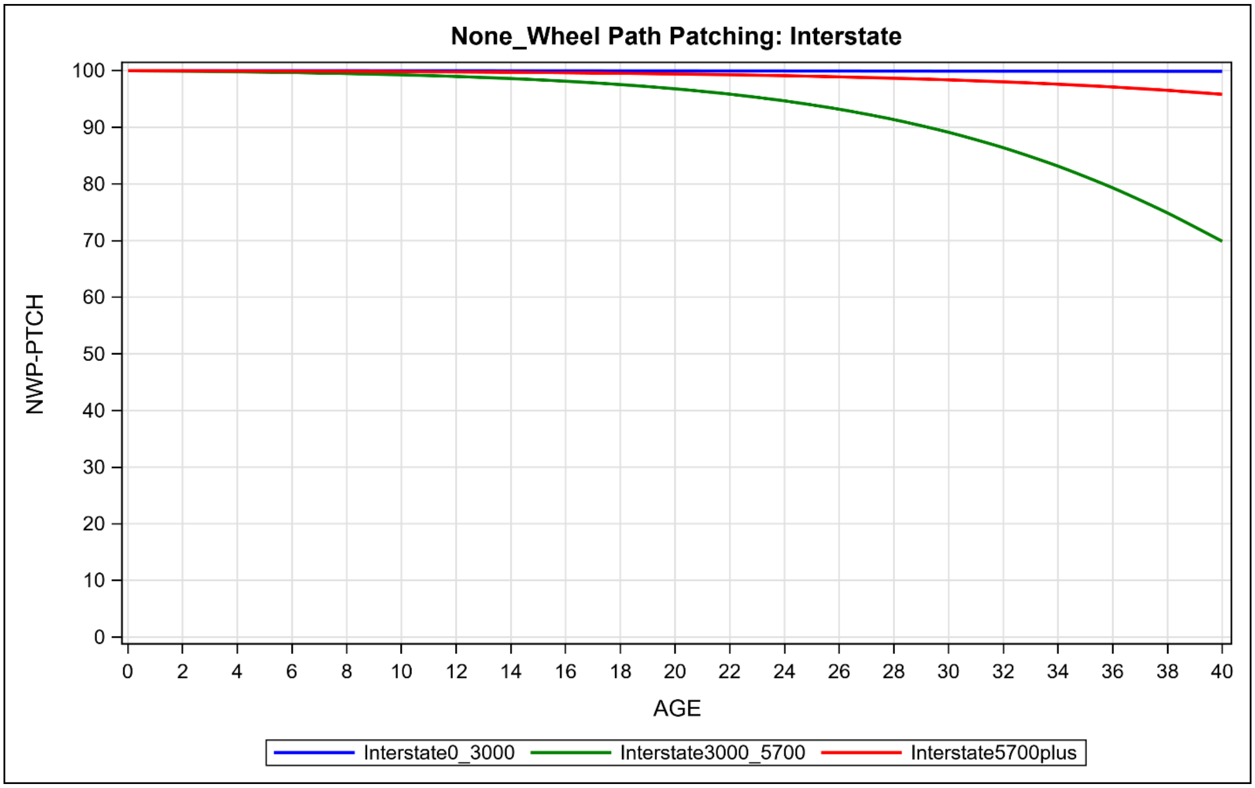

Figure A 19. Non-Wheel Path Patching: Interstate

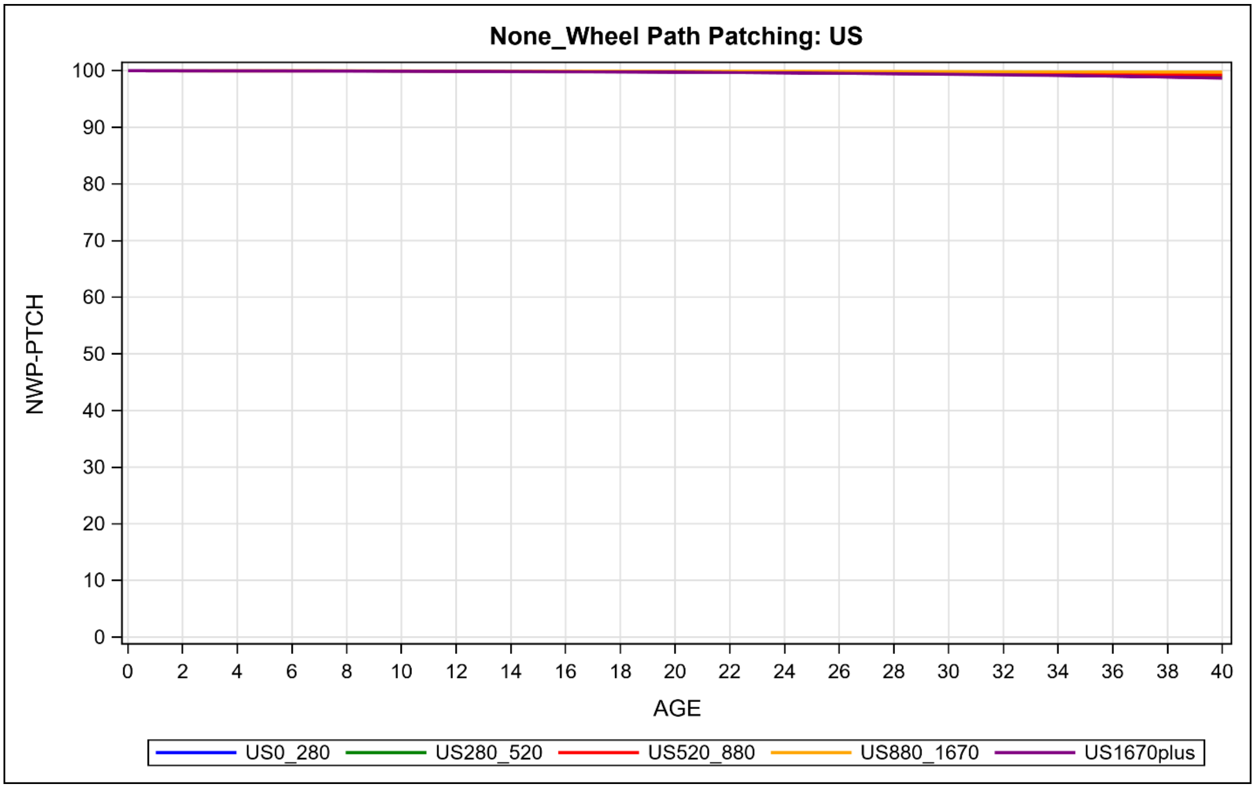

Figure A 20. Non-Wheel Path Patching: US

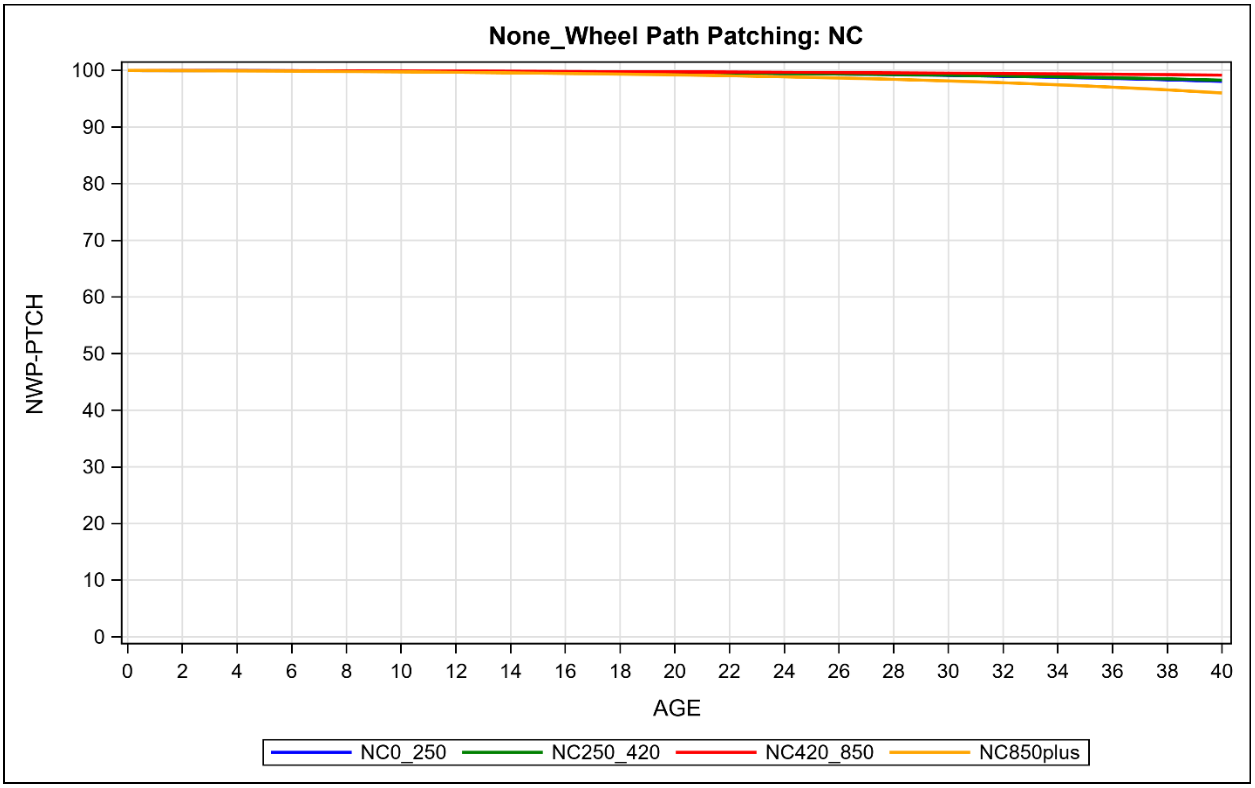

Figure A 21. Non-Wheel Path Patching: NC

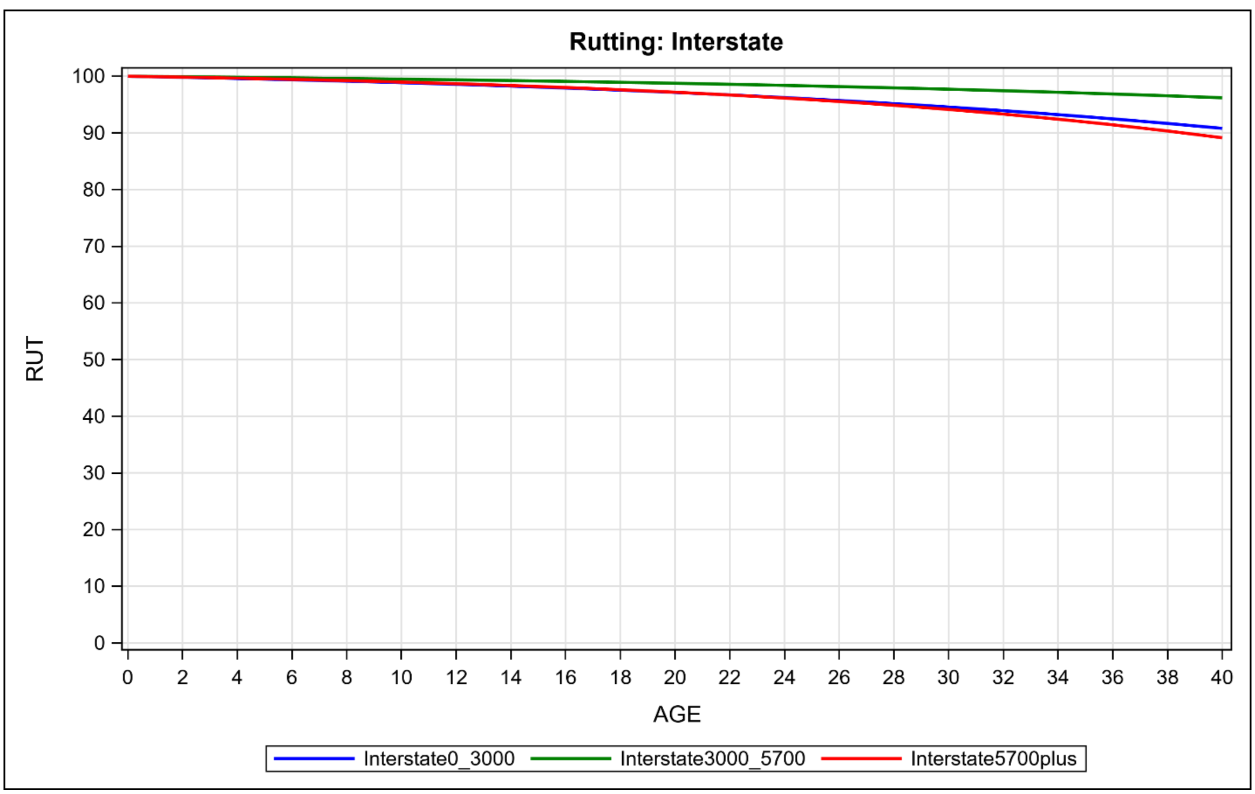

Figure A 22. Rutting: Interstate

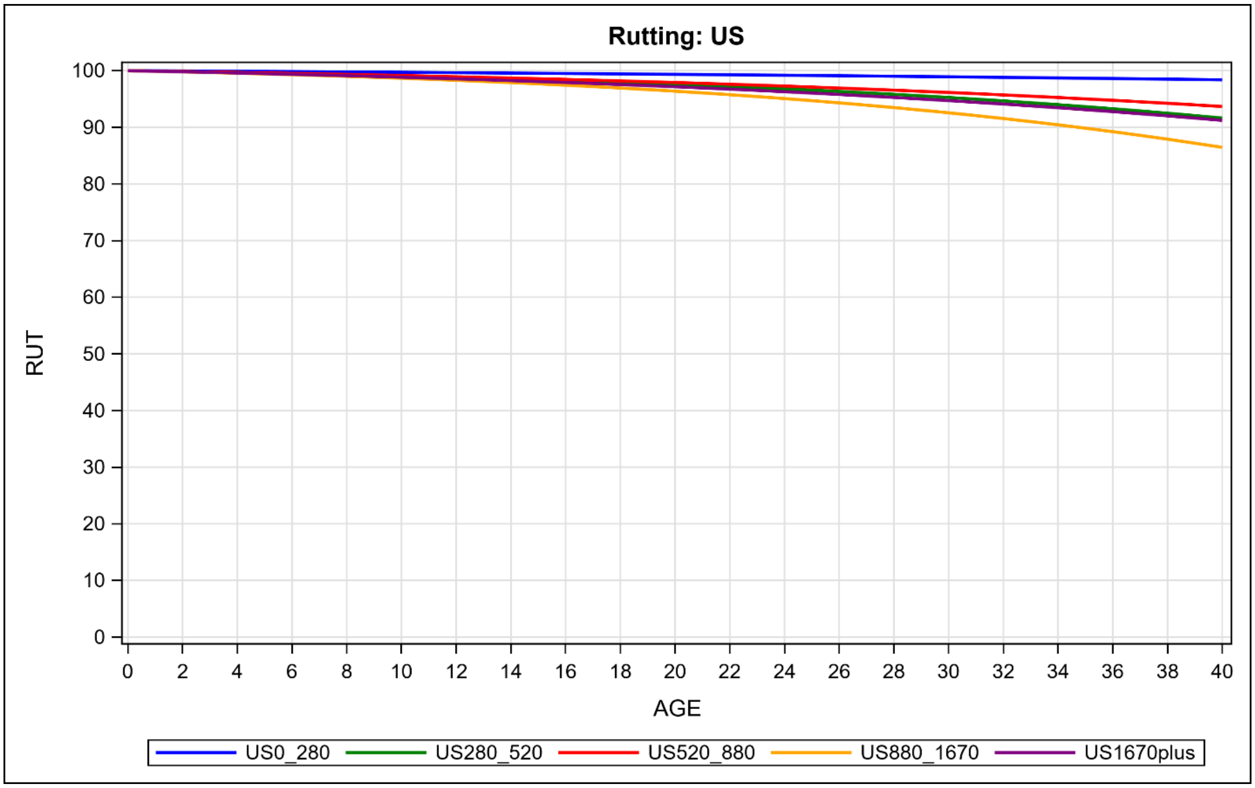

Figure A 23. Rutting: US

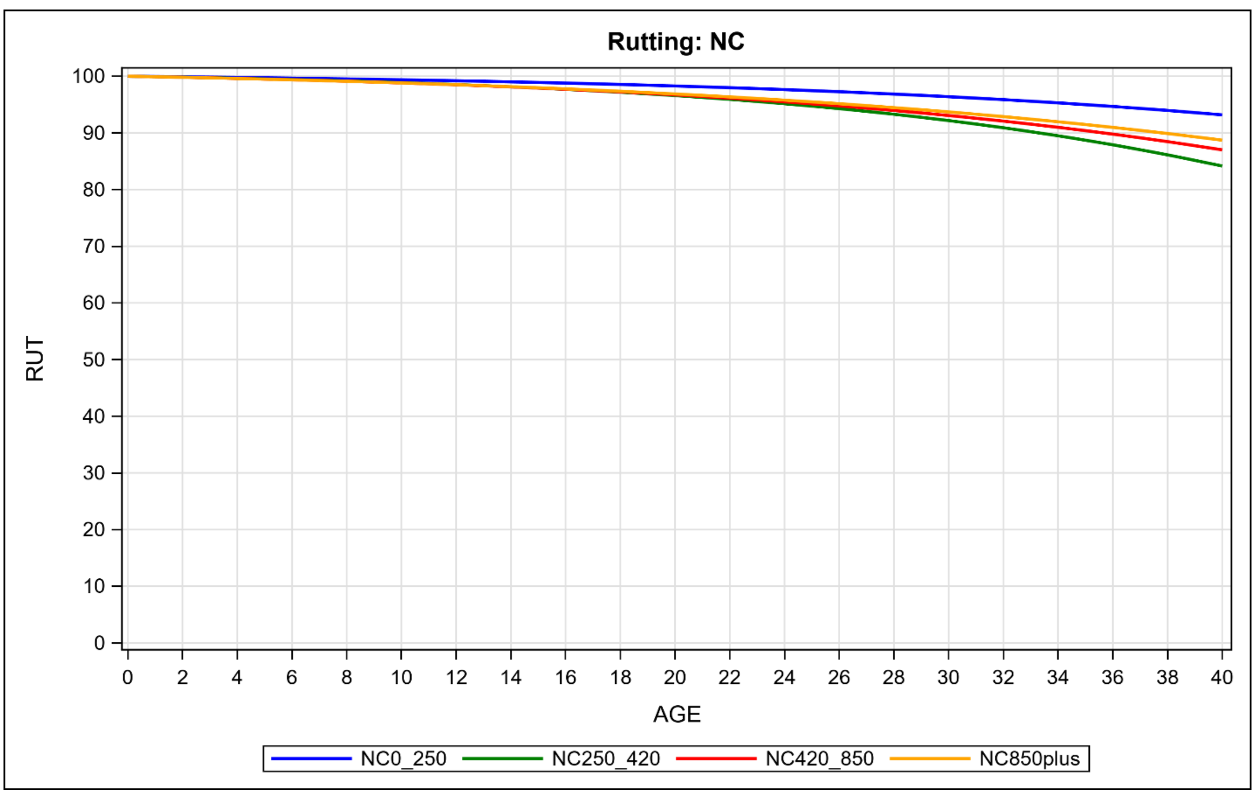

Figure A 24. Rutting: NC

Appendix B. Performance Model Curves

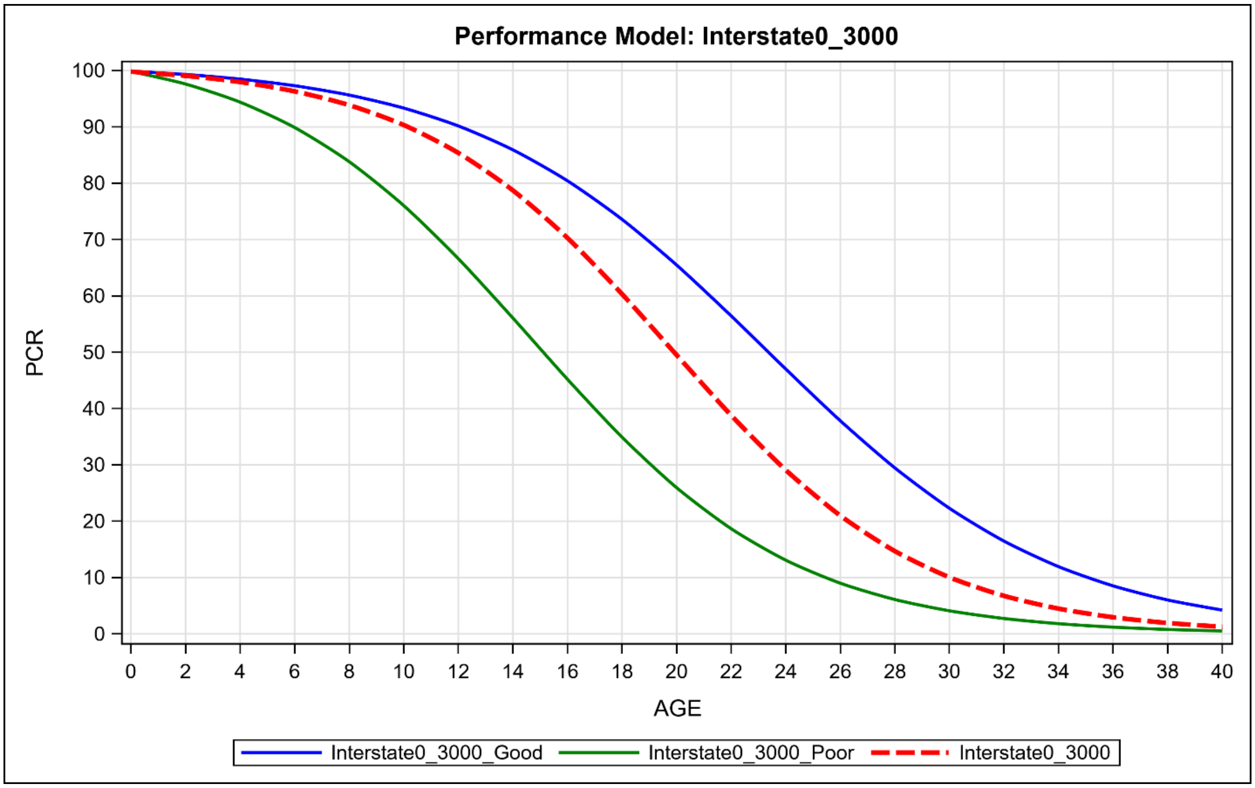

Figure B 1. Performance Model: Interstate0_3000

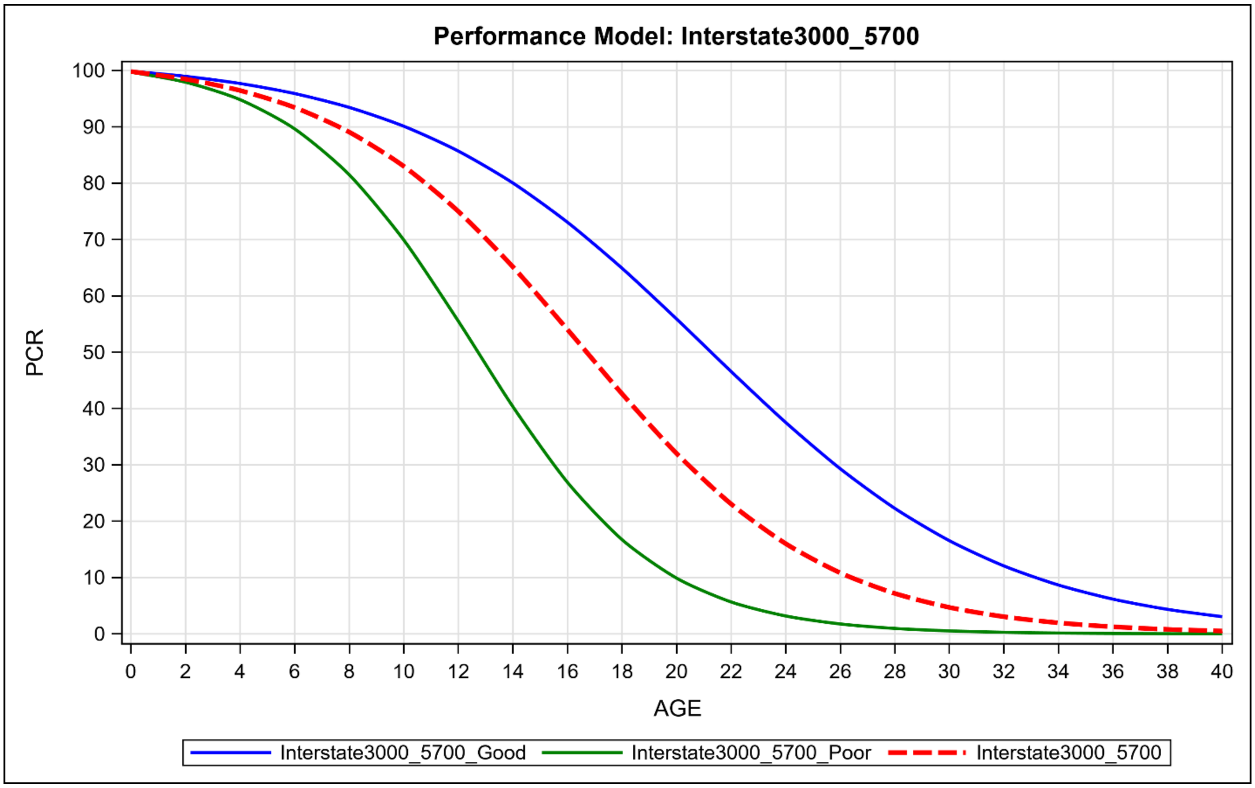

Figure B 2. Performance Model: Interstate3000_5700

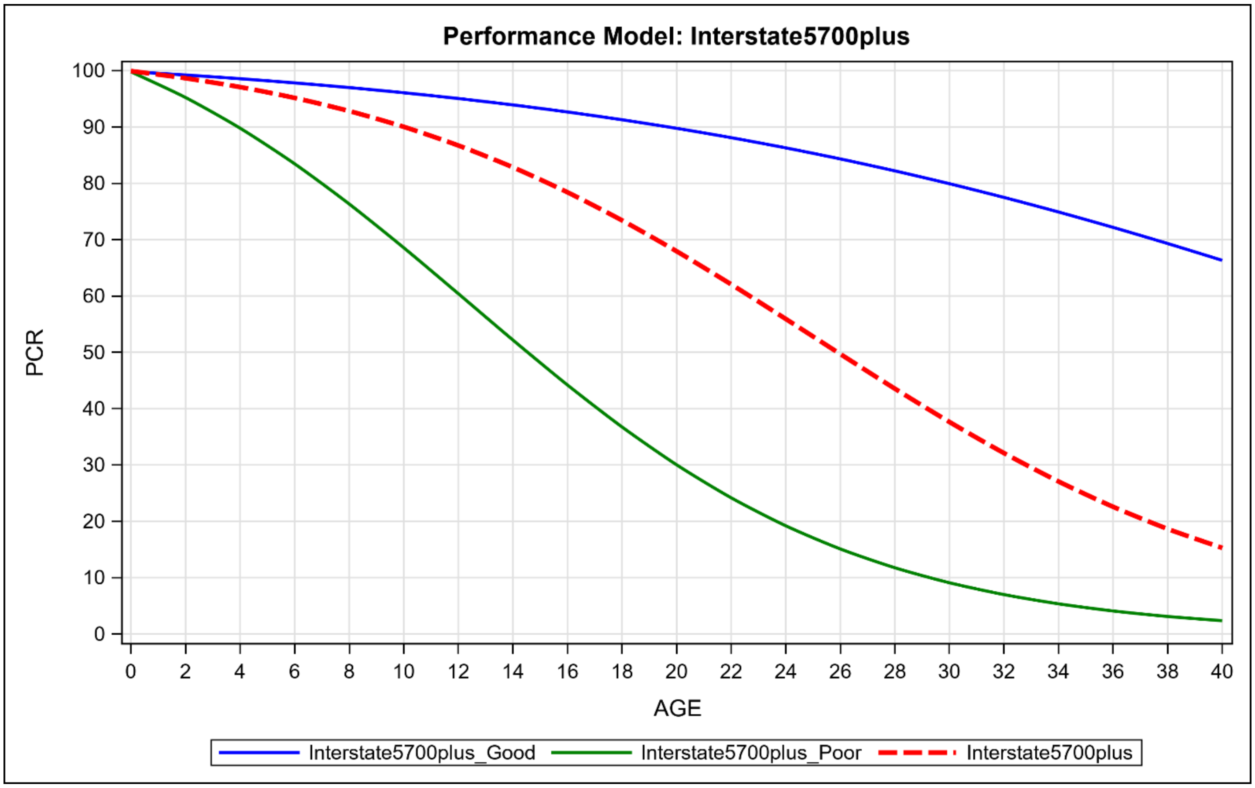

Figure B 3. Performance Model: Interstate5700plus

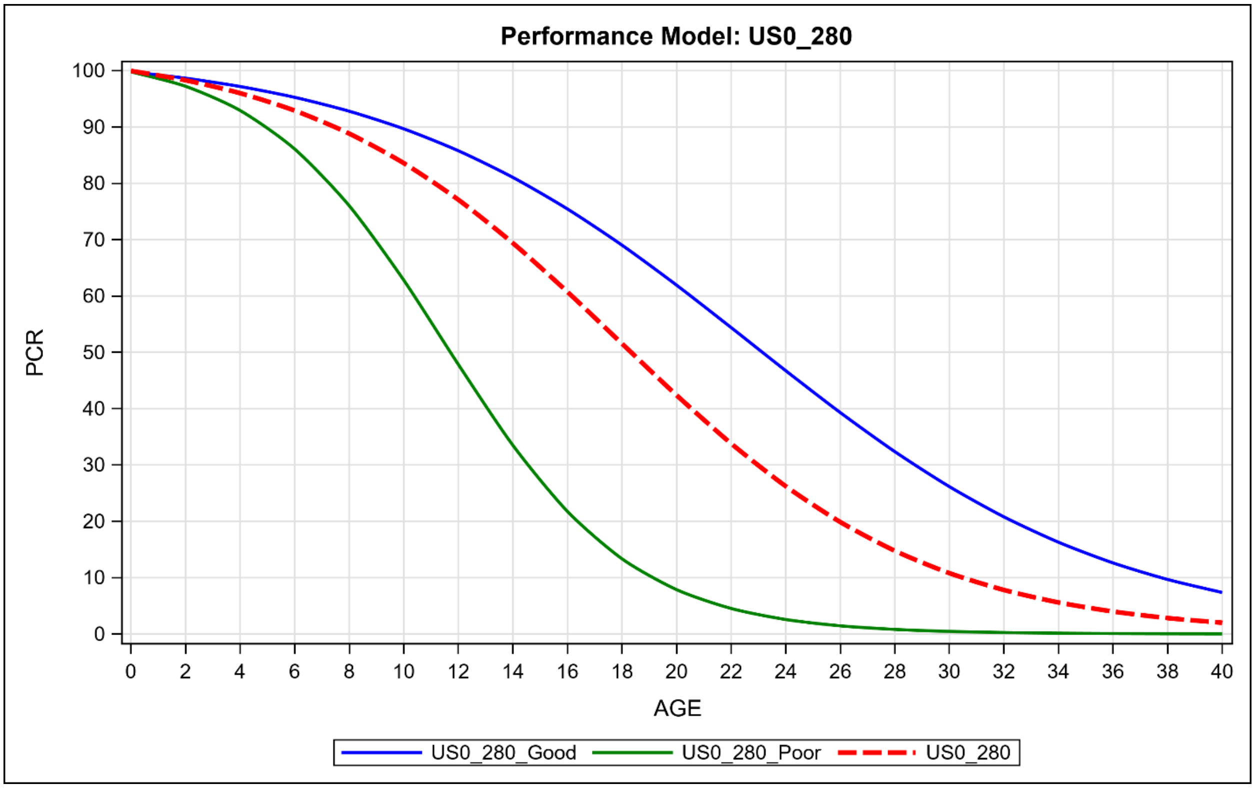

Figure B 4. Performance Model: US0_280

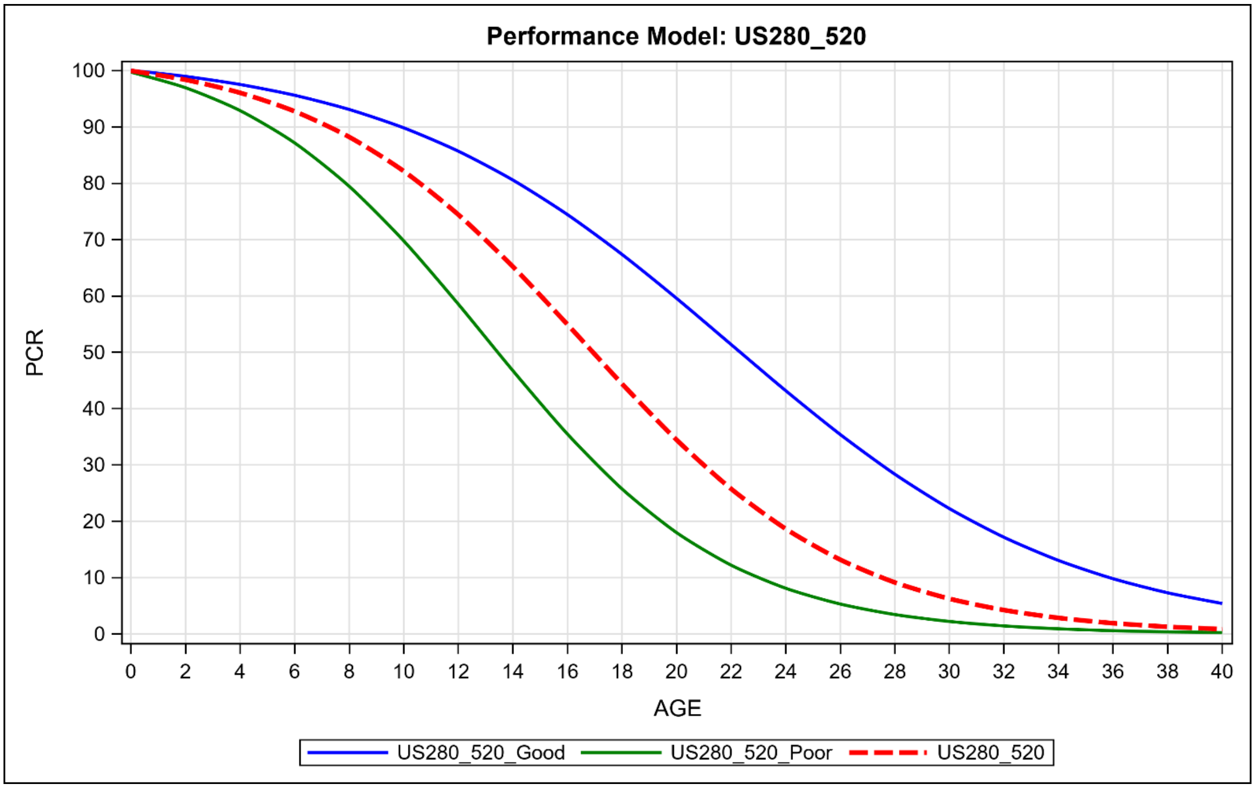

Figure B 5. Performance Model: US280_520

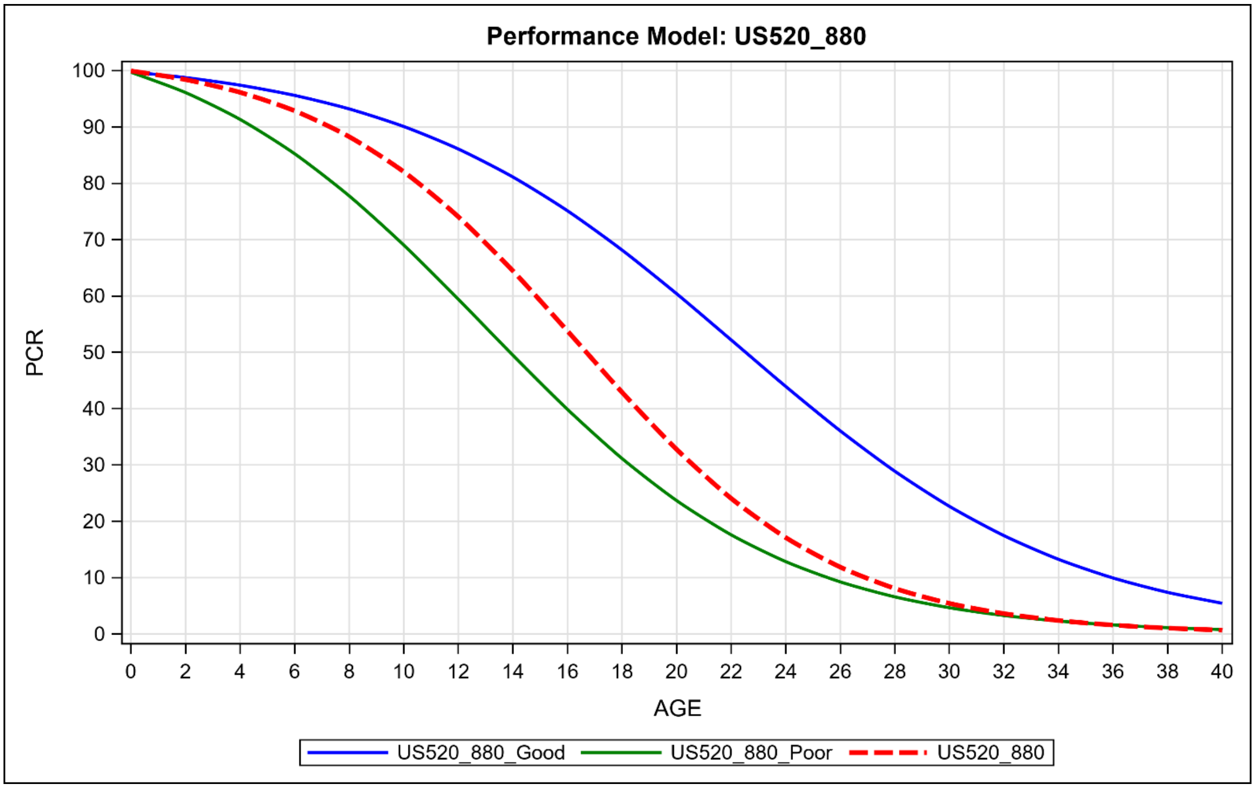

Figure B 6. Performance Model: US520_880

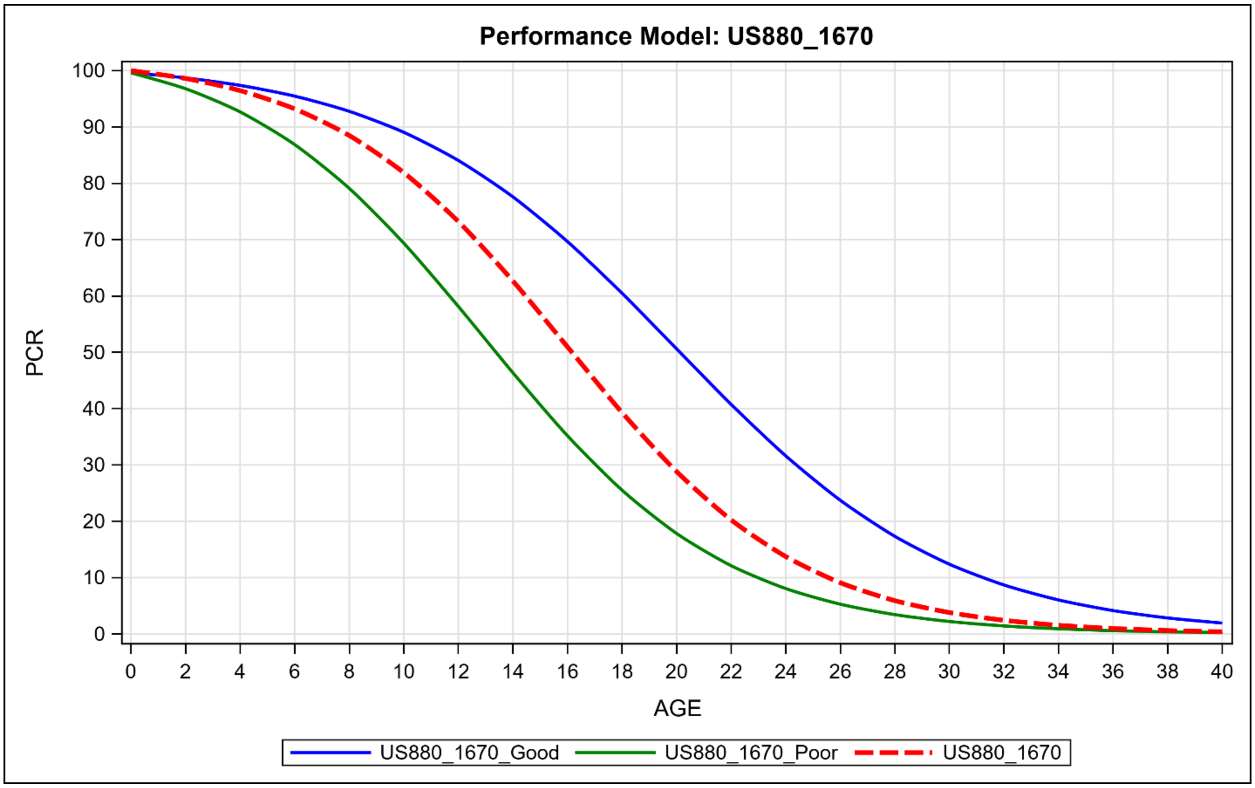

Figure B 7. Performance Model: US880_1670

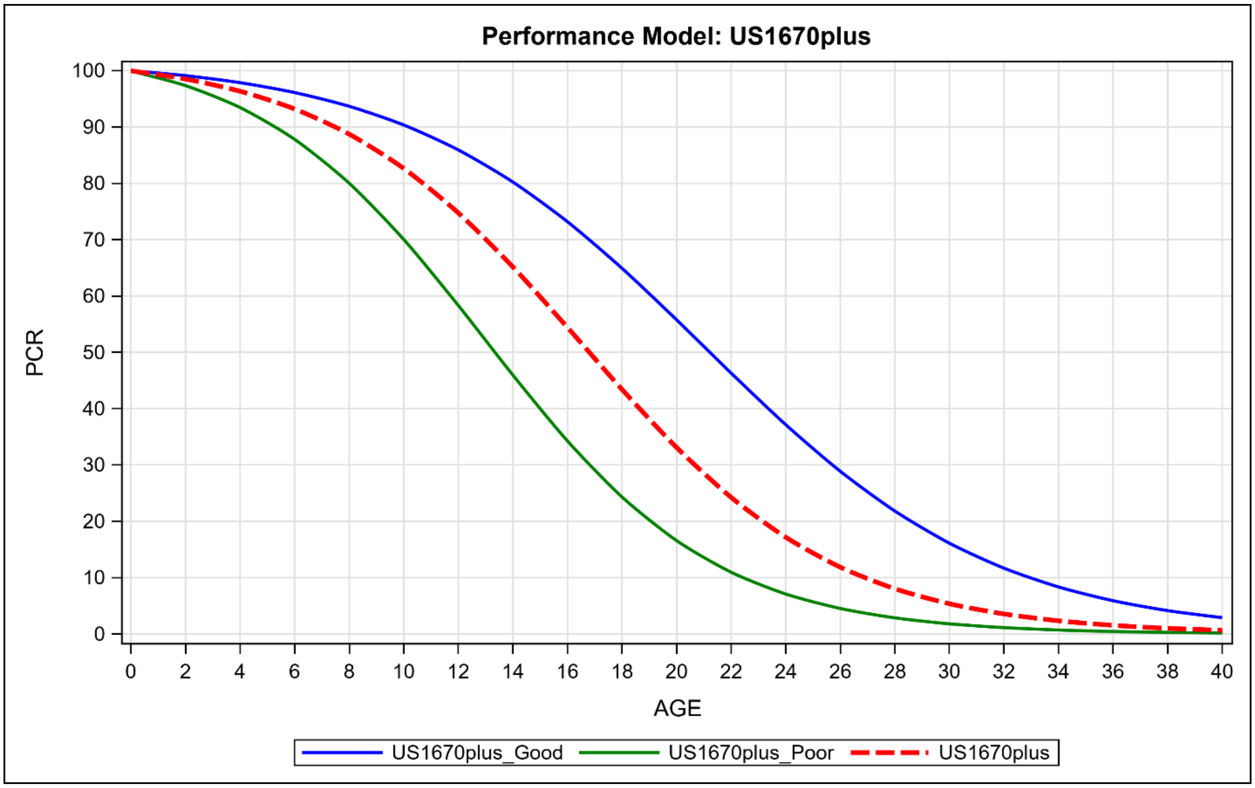

Figure B 8. Performance Model: US1670plus

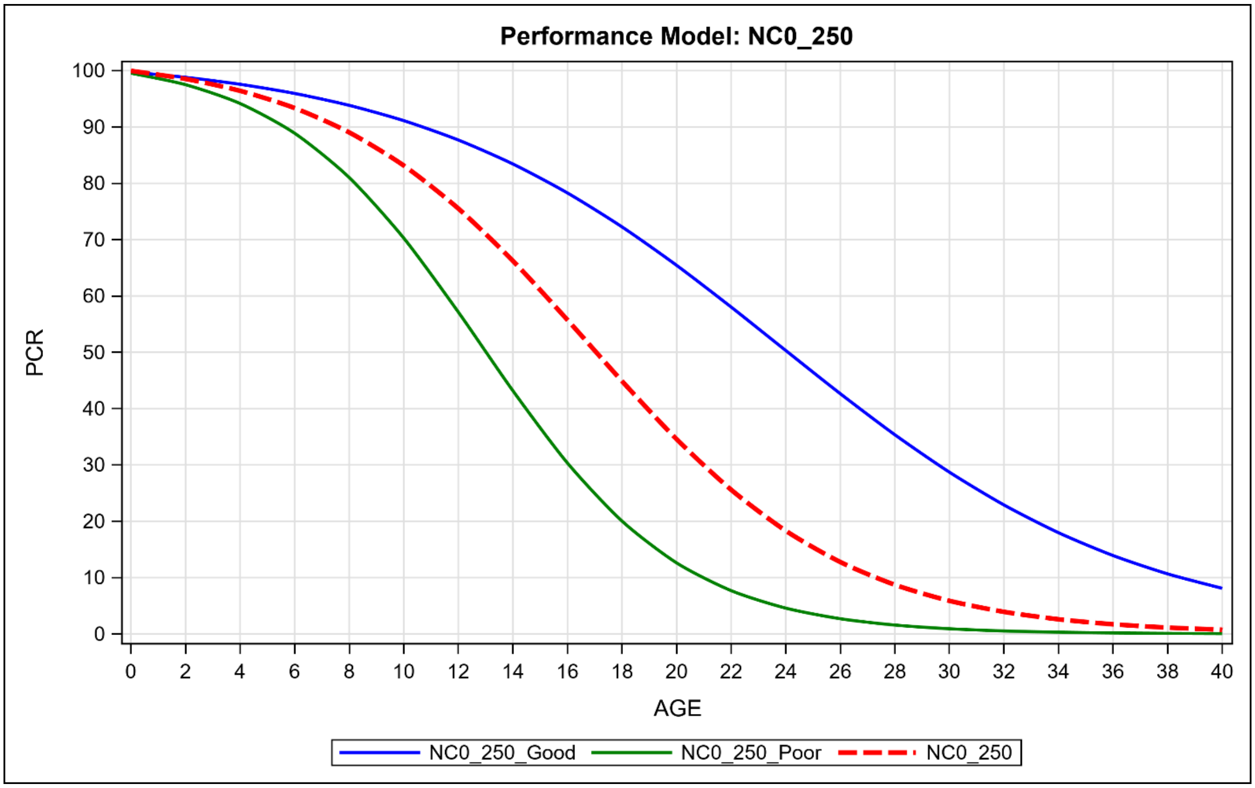

Figure B 9. Performance Model: NC0_250

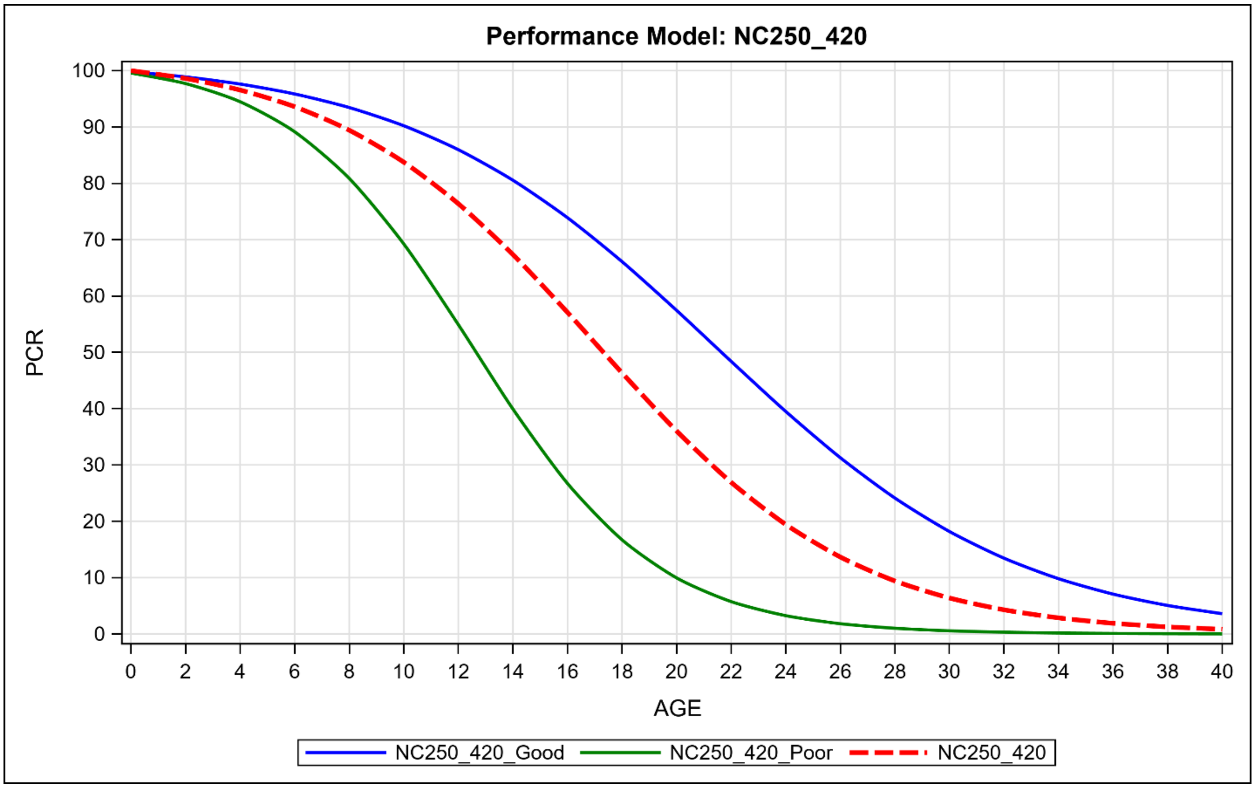

Figure B 10. Performance Model: NC250_420

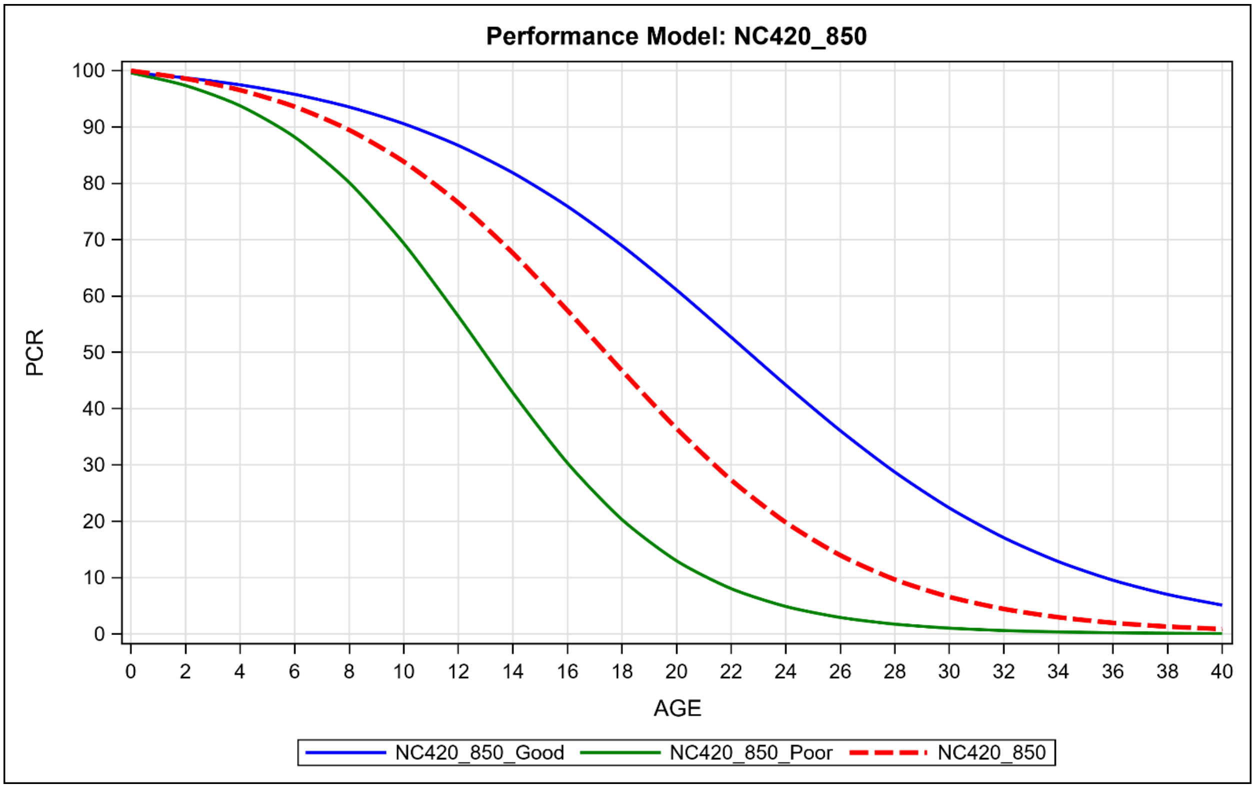

Figure B 11. Performance Model: NC420_850

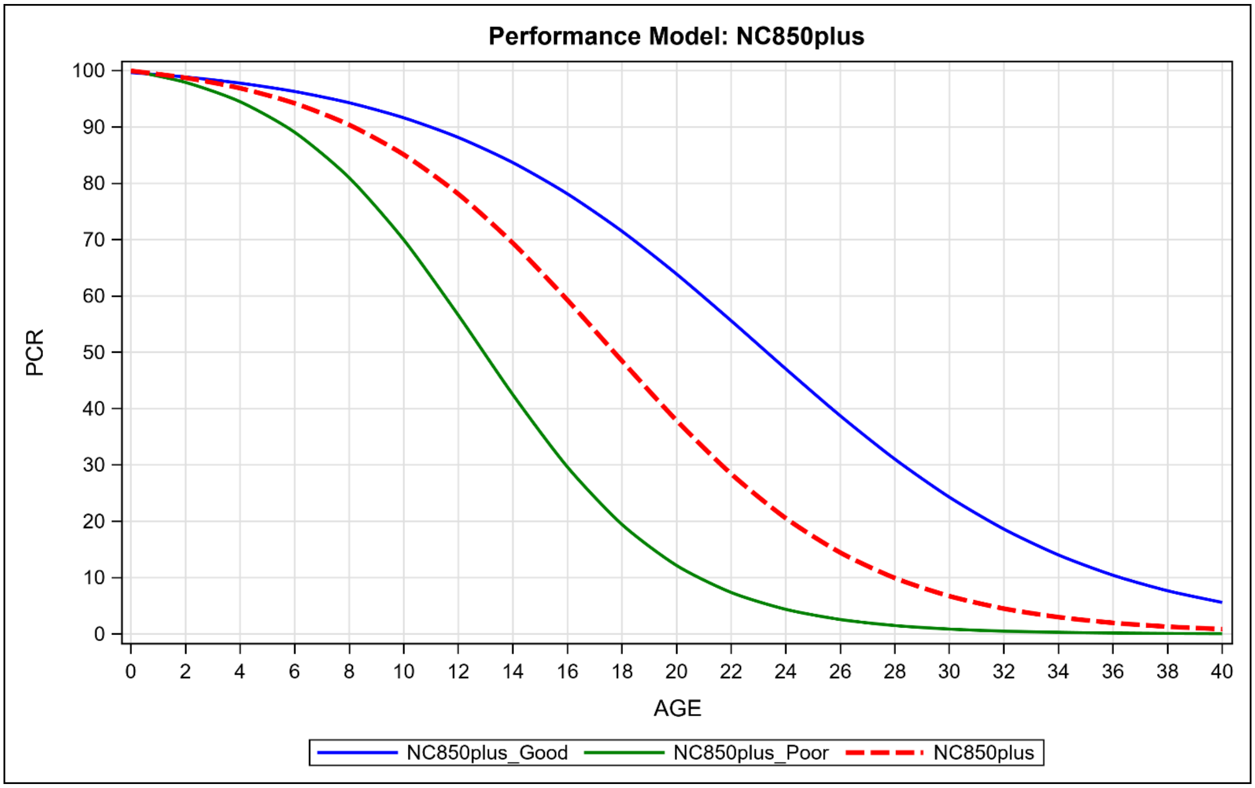

Figure B 12. Performance Model: NC850plus

Appendix C. AADT vs. AADTT Distress Model Curves

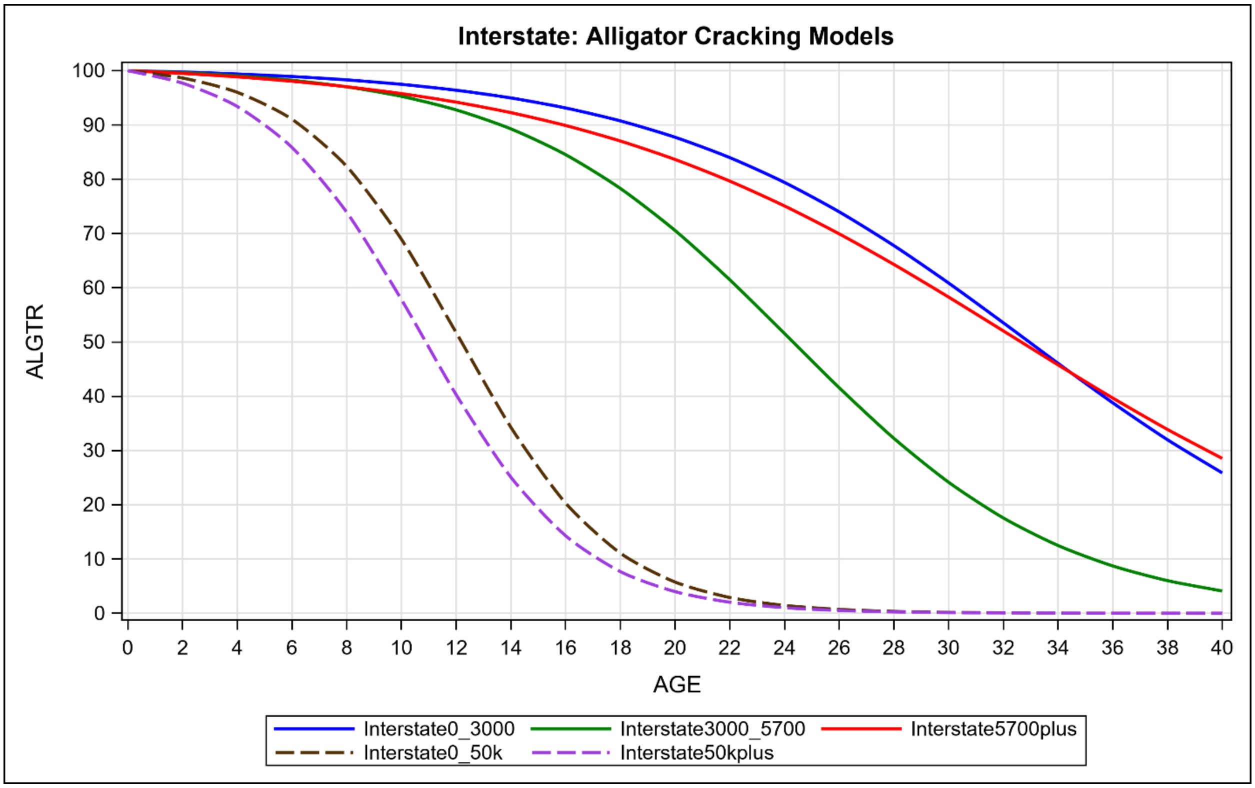

Figure C 1. Interstate: Alligator Cracking Models

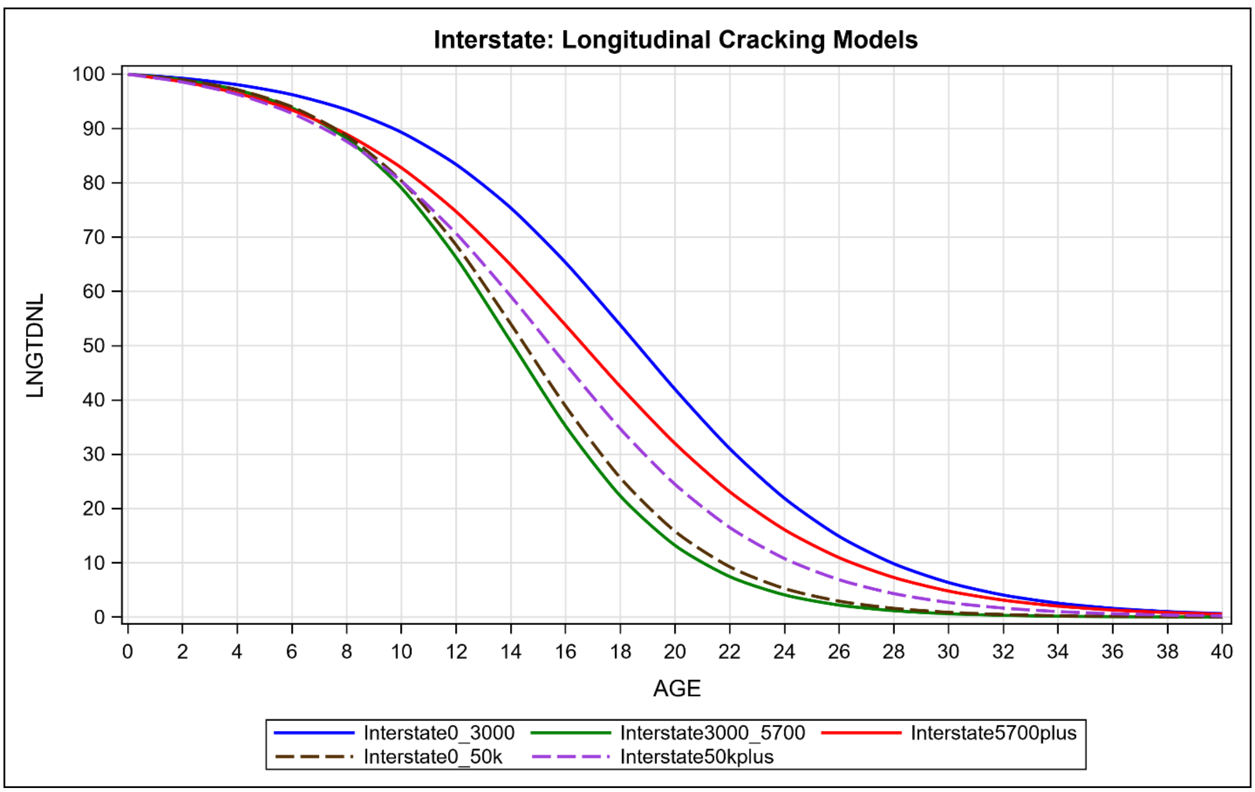

Figure C 2. Interstate: Longitudinal Cracking Models

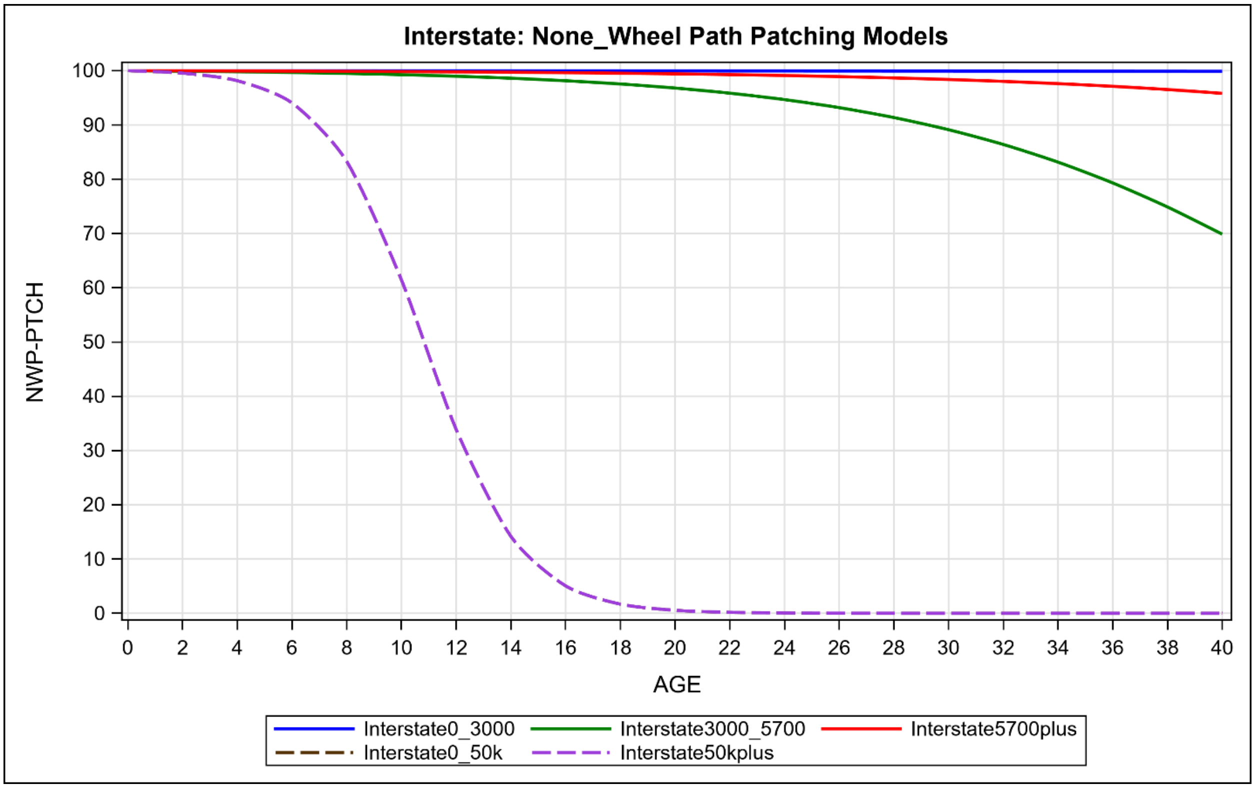

Figure C 3. Interstate: Non _ Wheel Path Practicing Models

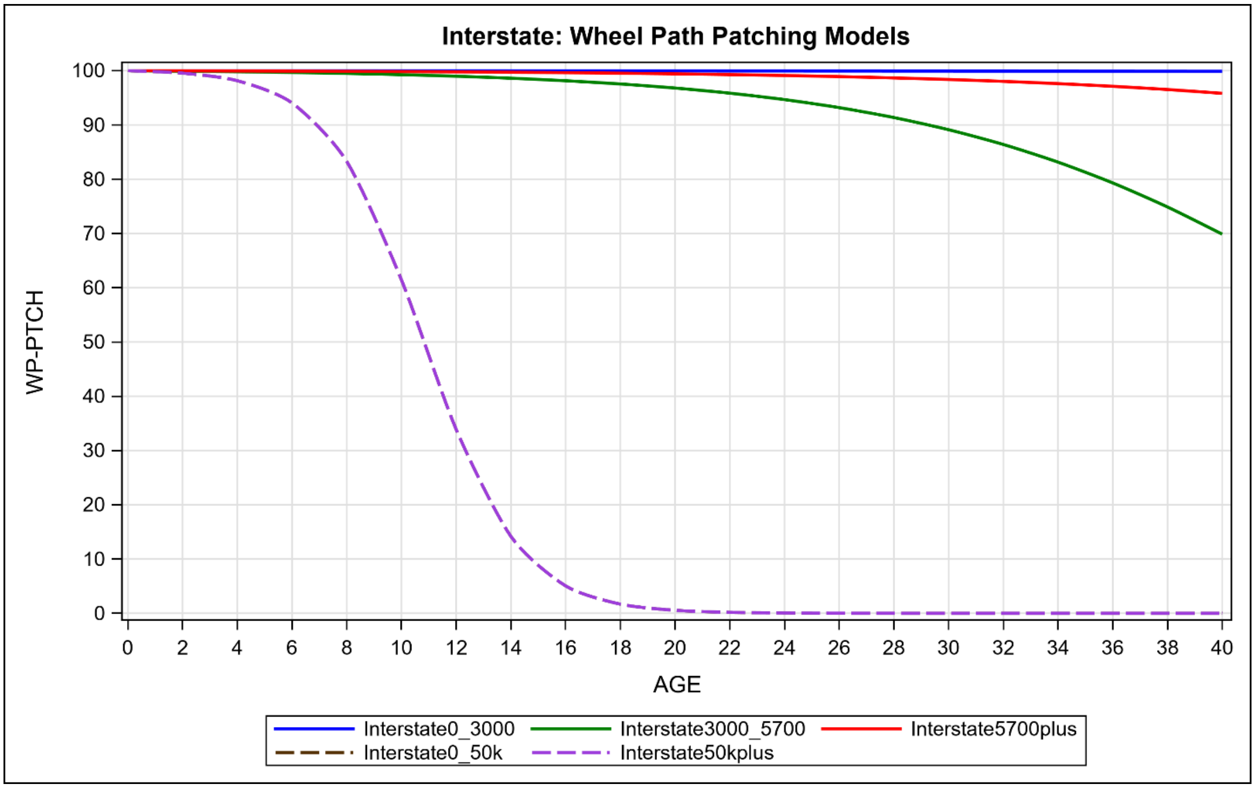

Figure C 4. Interstate: Wheel Path Practicing Models

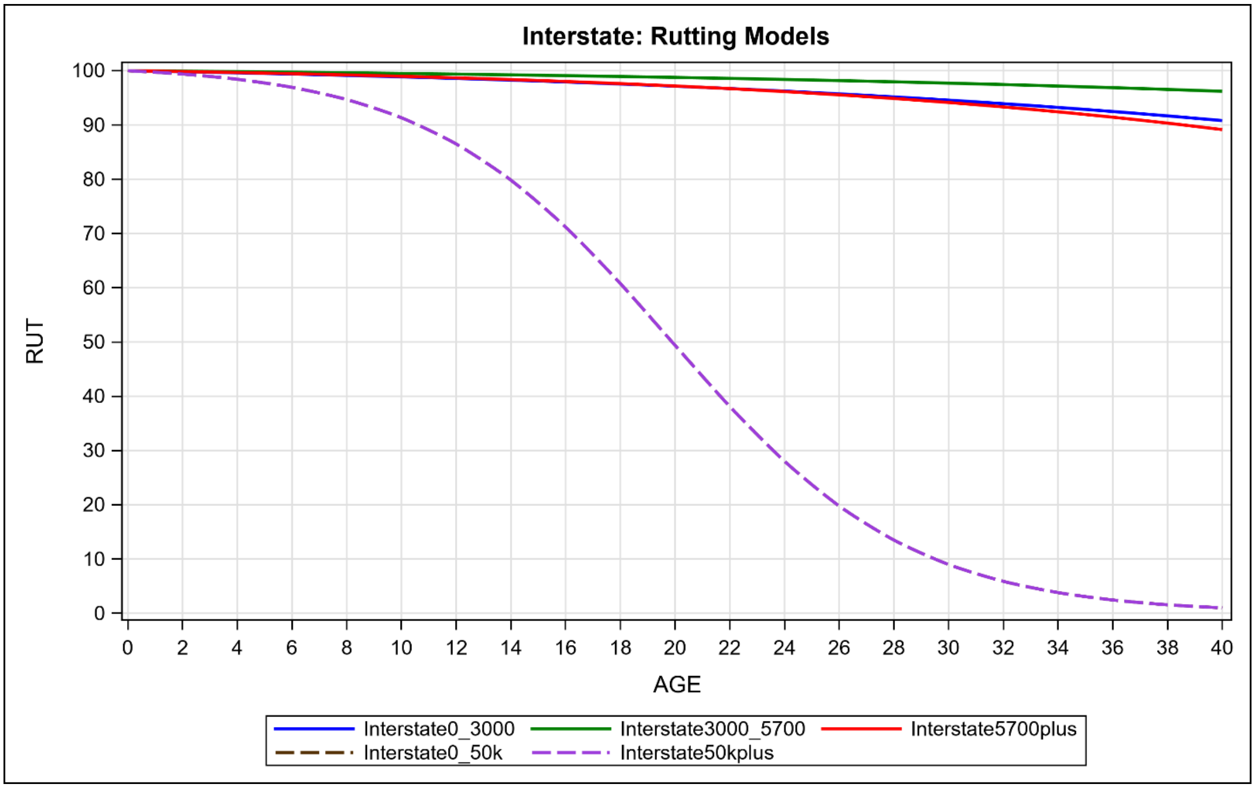

Figure C 5. Interstate: Rutting Models: Interstate: Rutting Models

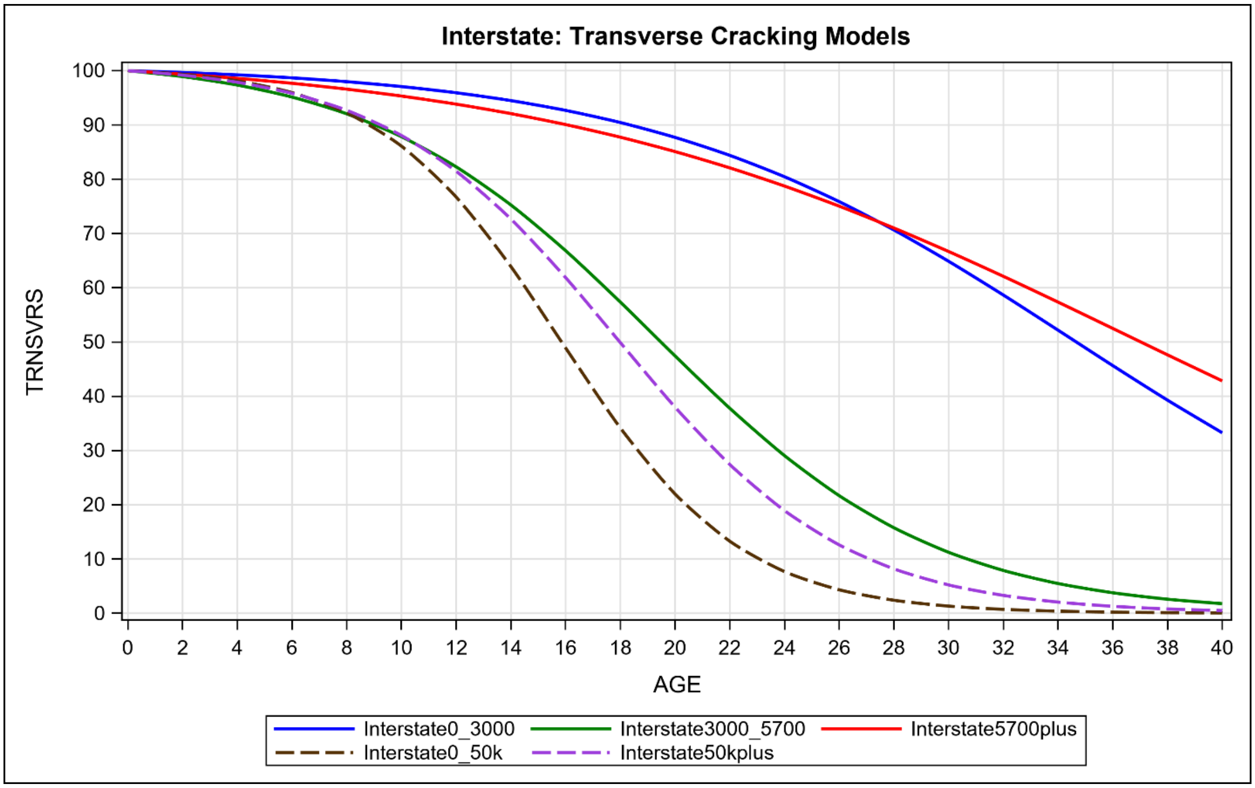

Figure C 6. Interstate: Transverse Cracking Models

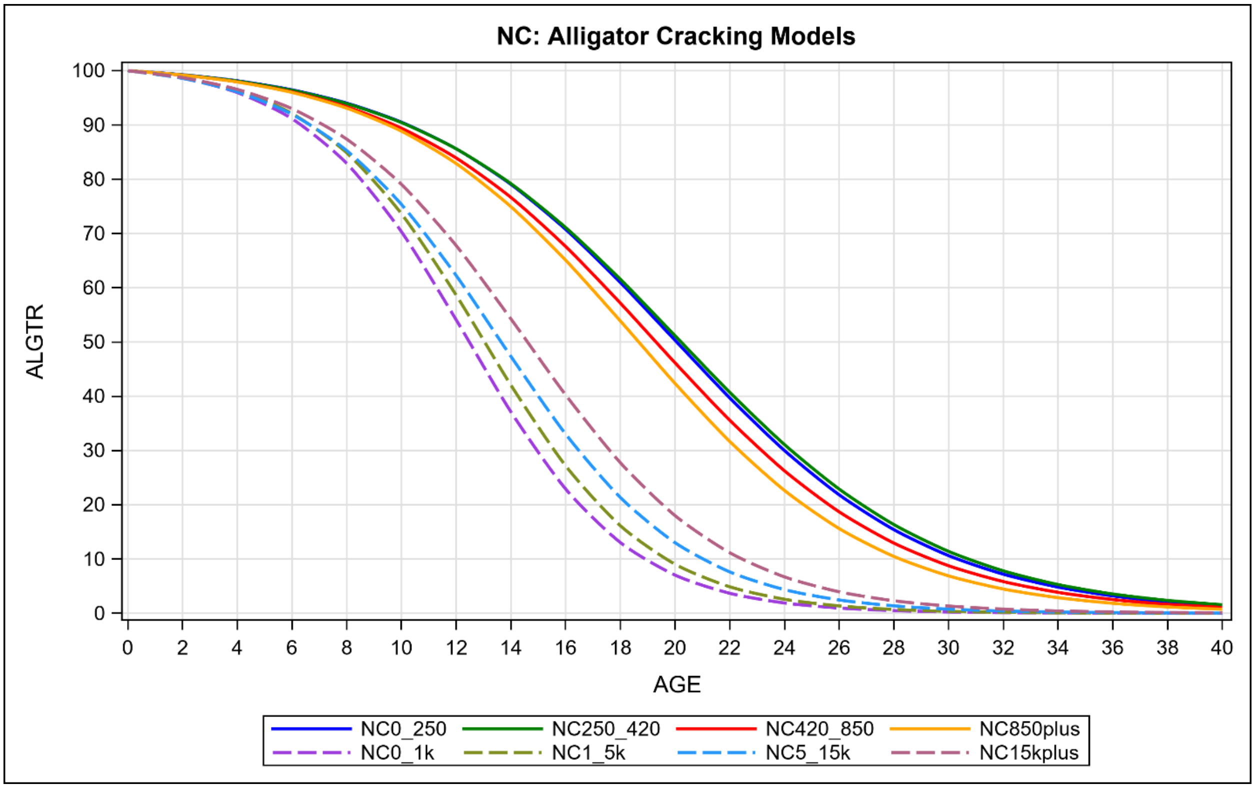

Figure C 7. NC: Alligator Cracking Models

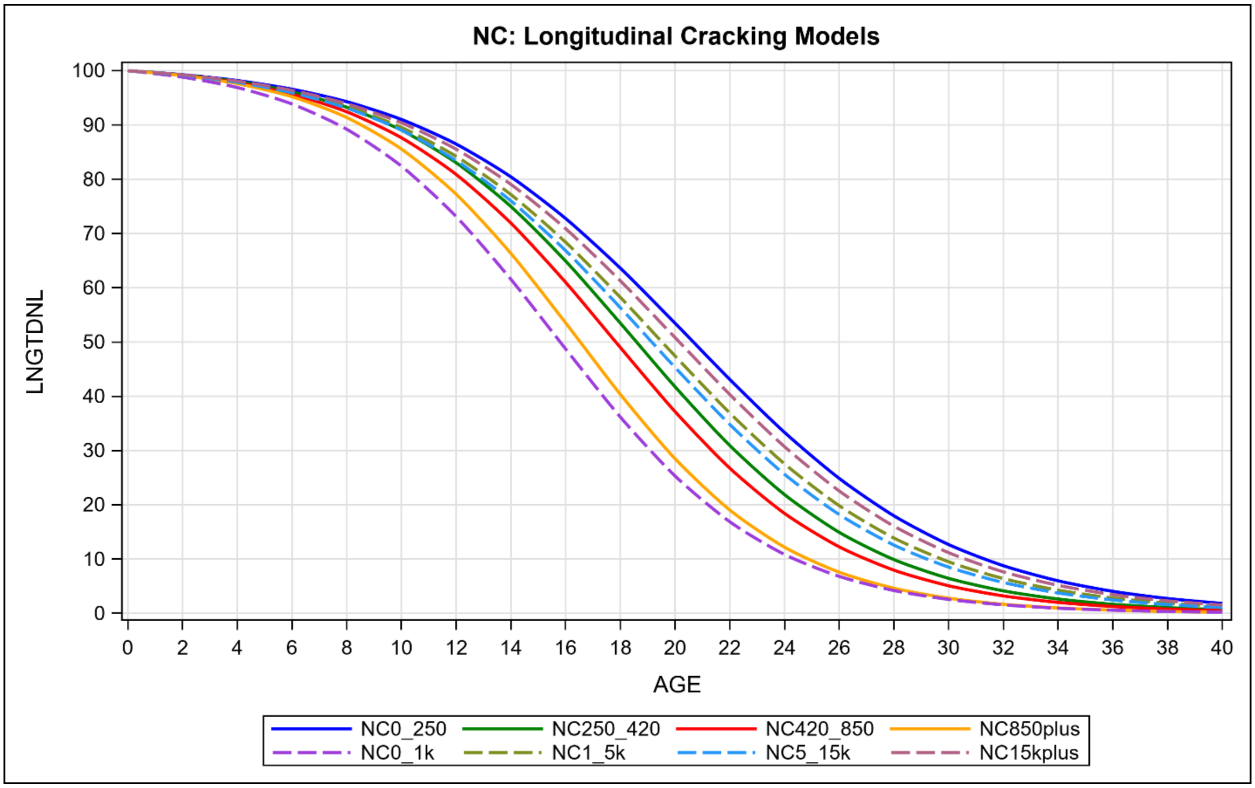

Figure C 8. NC: Longitudinal Cracking Models

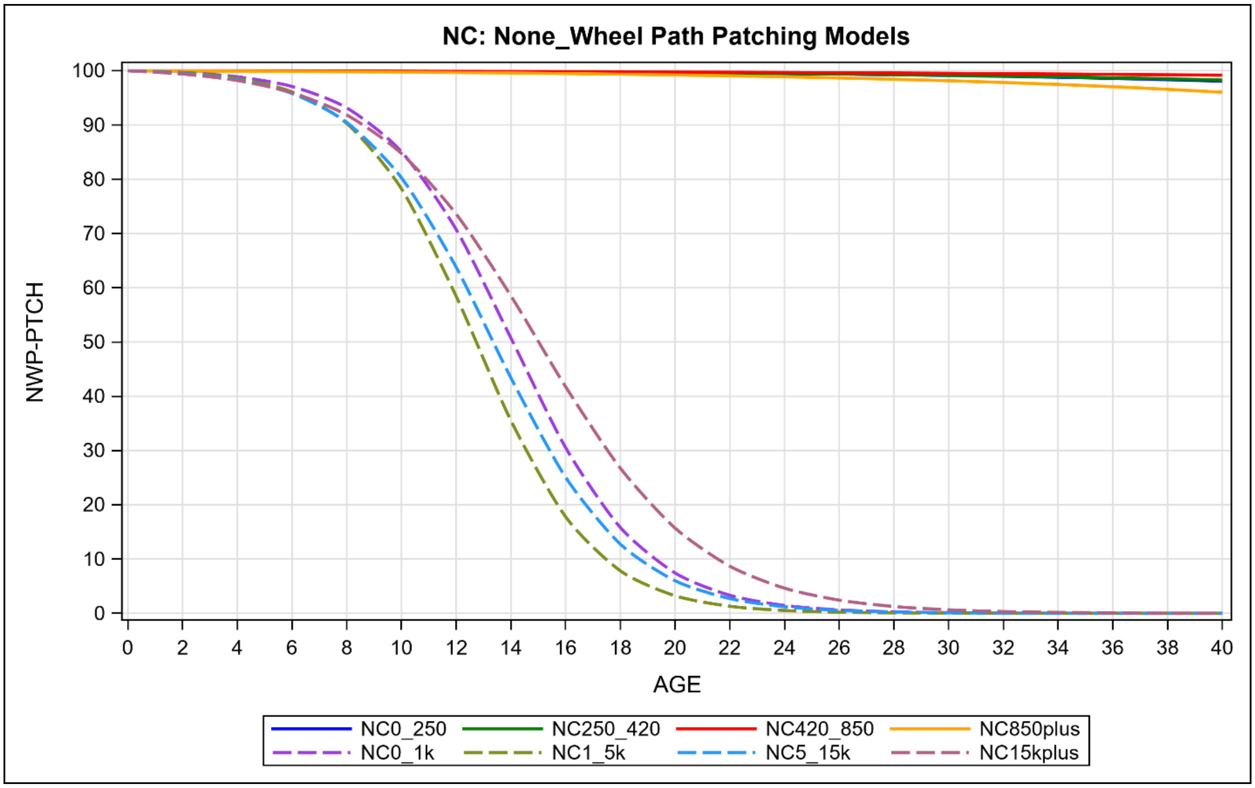

Figure C 9. NC: Non _Wheel Path Patching Models

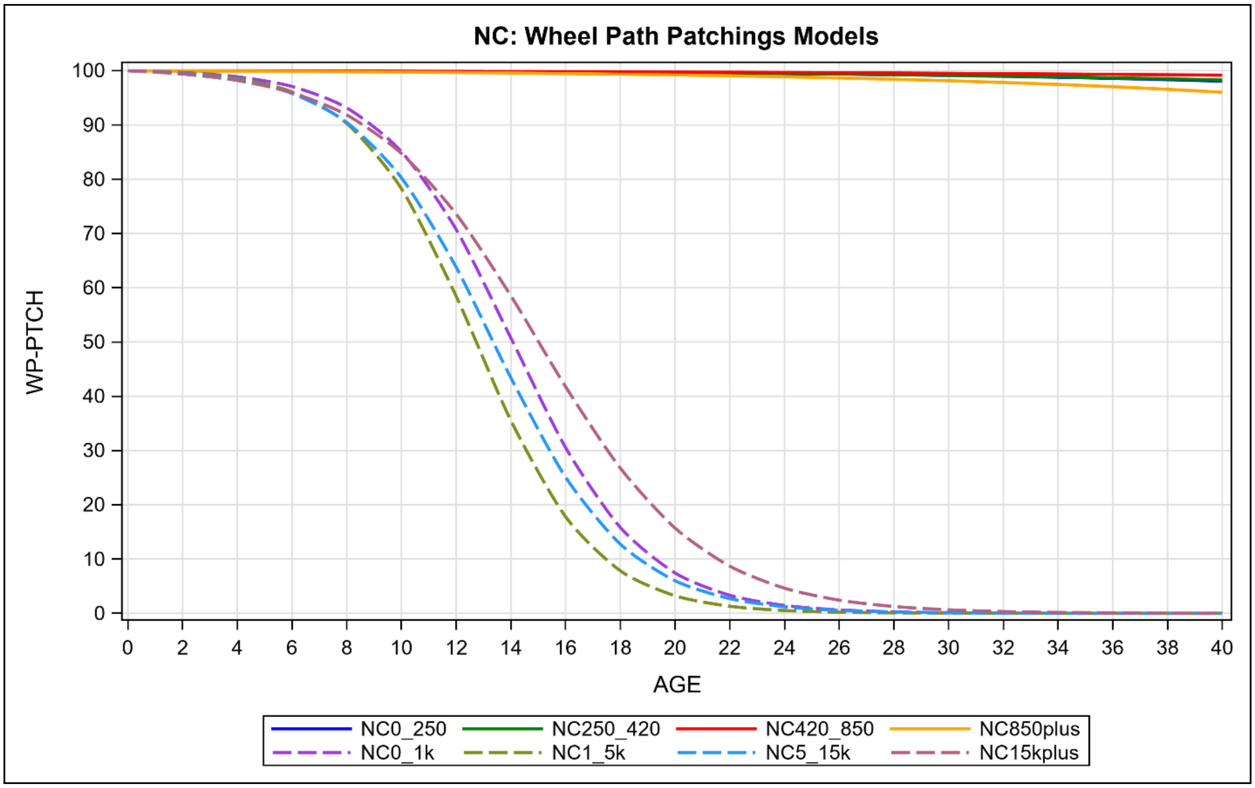

Figure C 10. NC: Wheel Path Patching Models

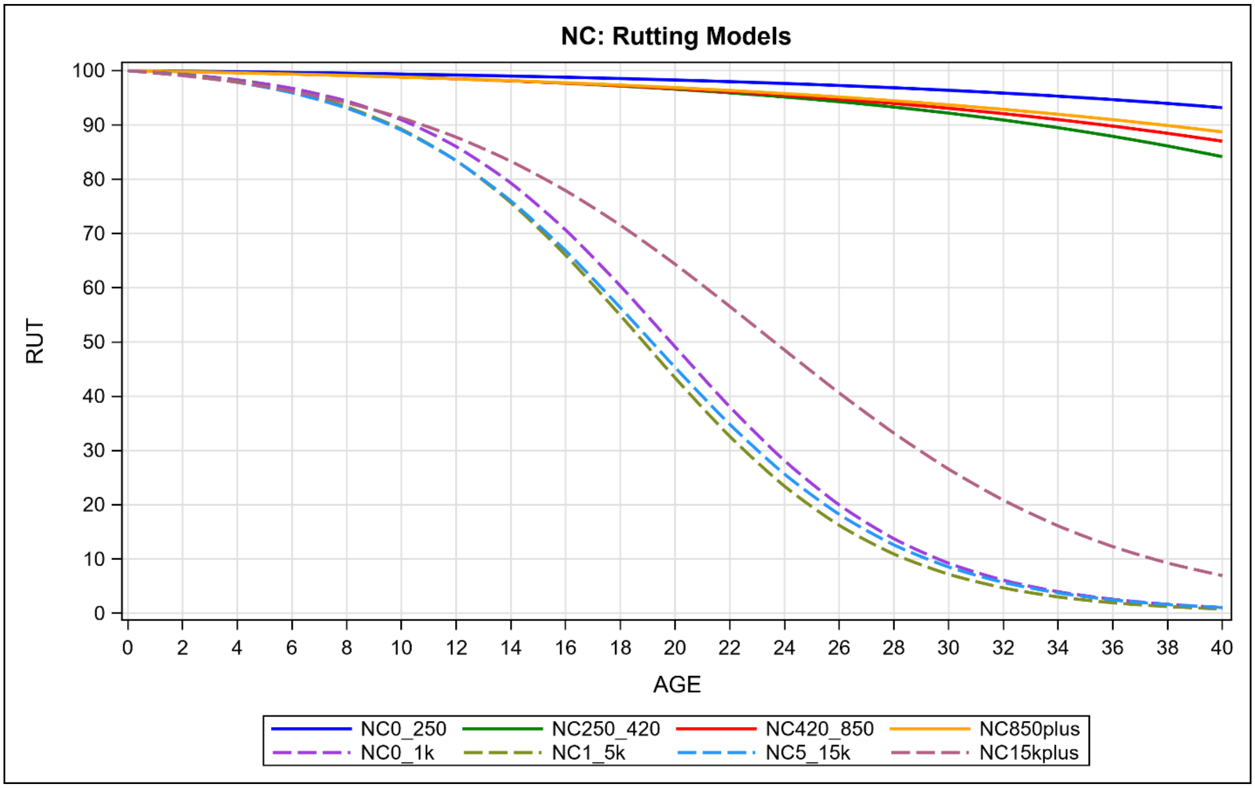

Figure C 11. NC: Rutting Models

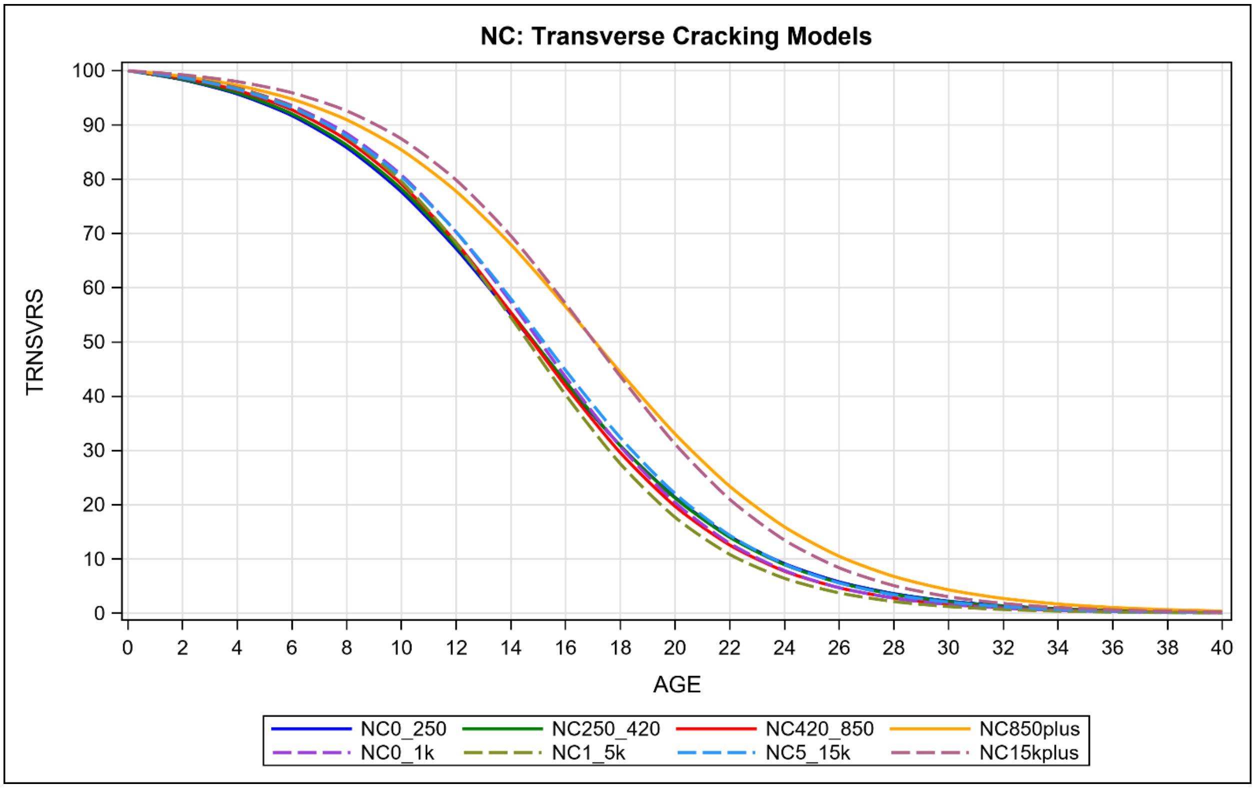

Figure C 12. NC: Transverse Cracking Models

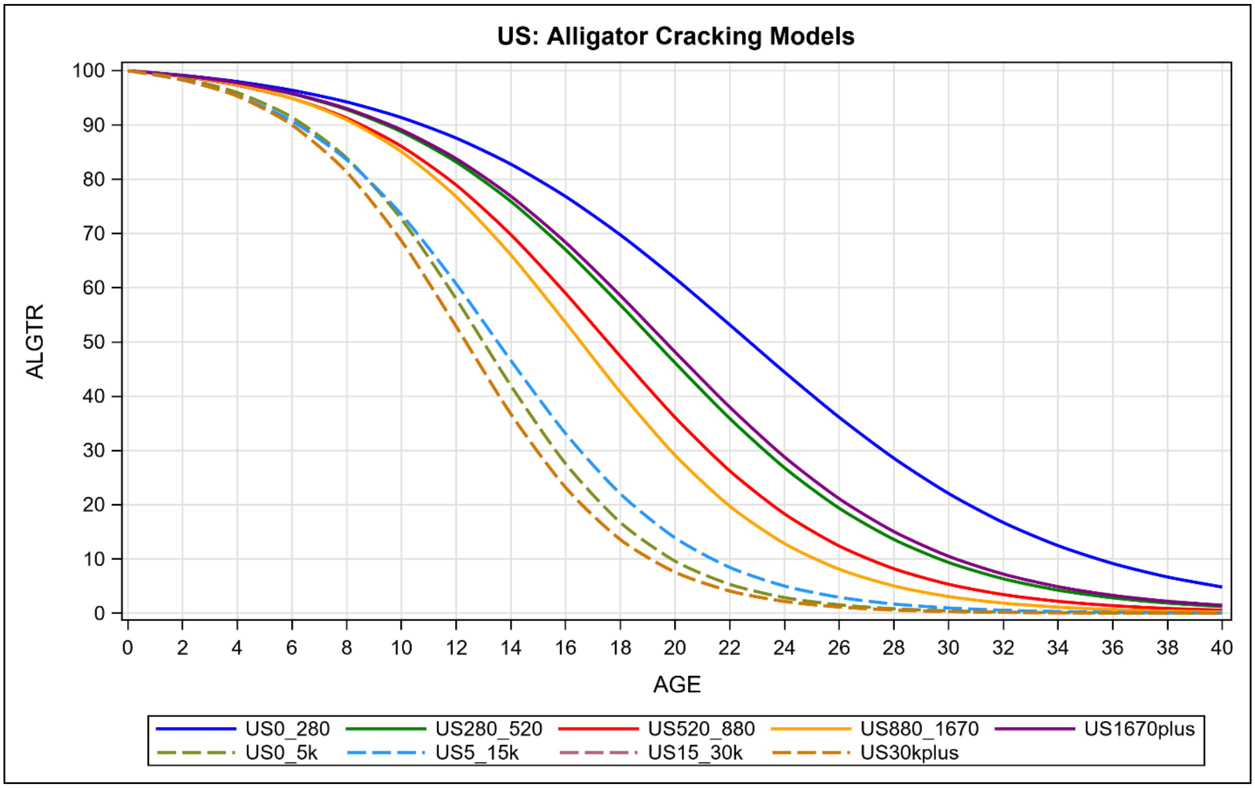

Figure C 13. US: Alligator Cracking Models

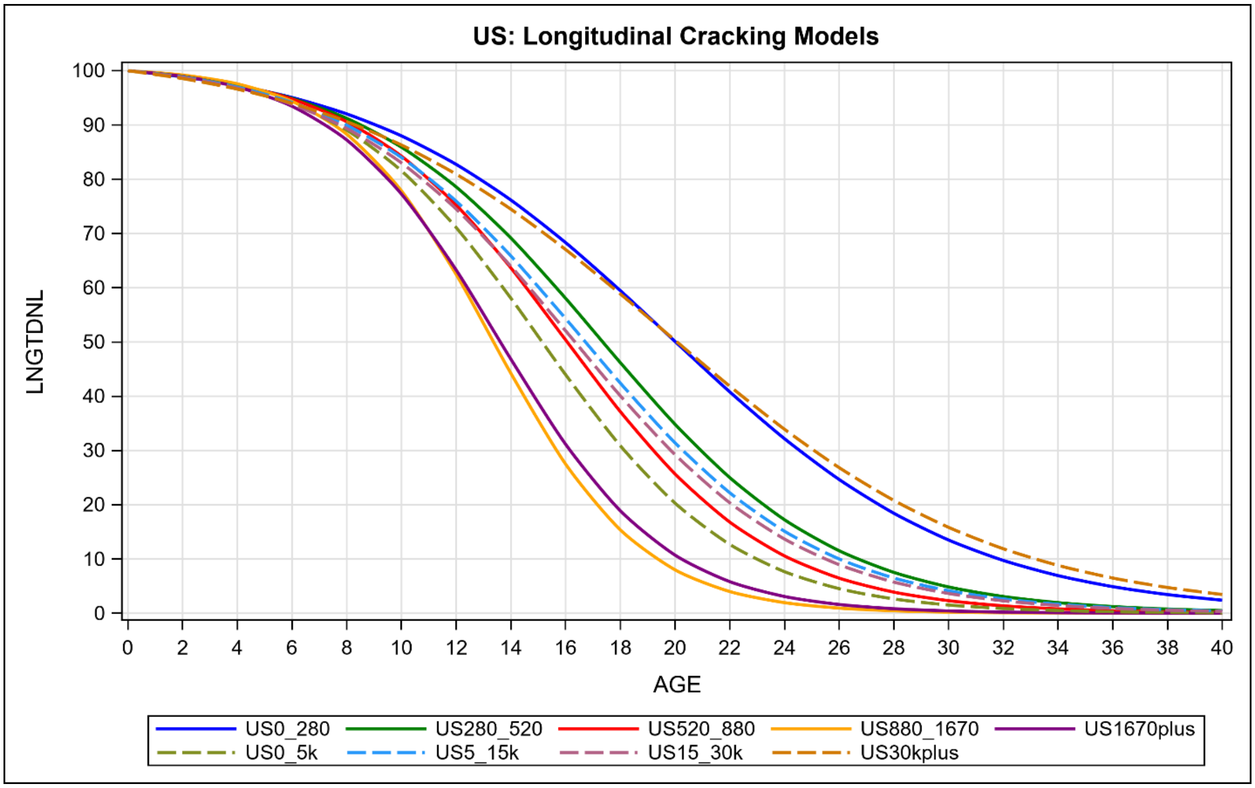

Figure C 14. US: Longitudinal Cracking Models

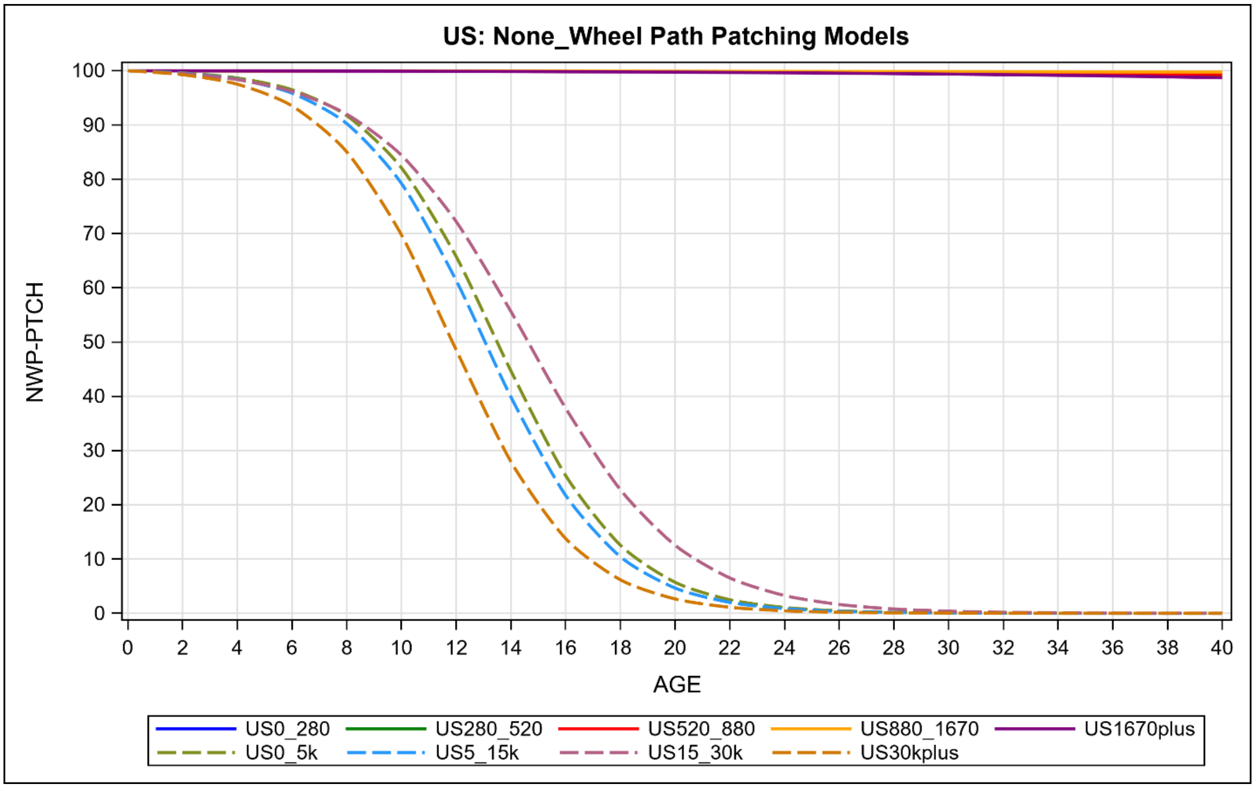

Figure C 15. US: Non _Wheel Path Patching Models

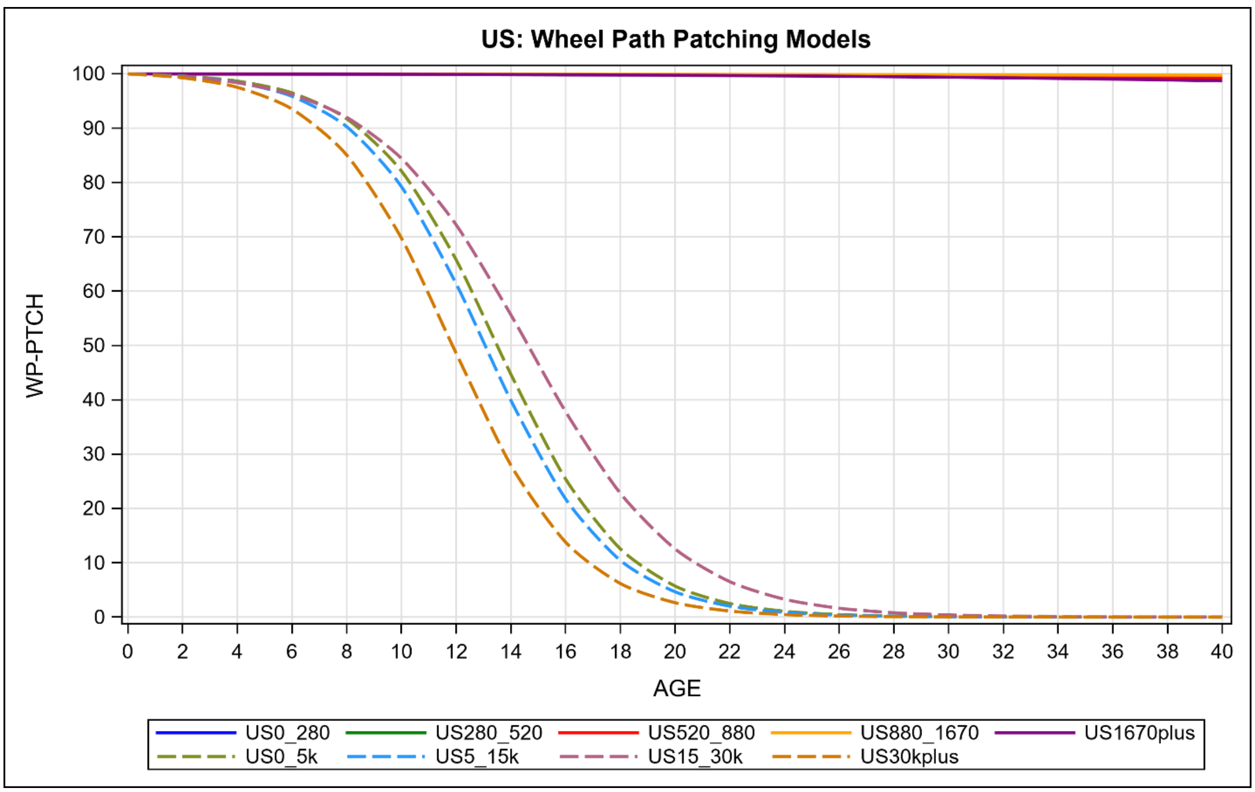

Figure C 16. US: Wheel Path Patching Models

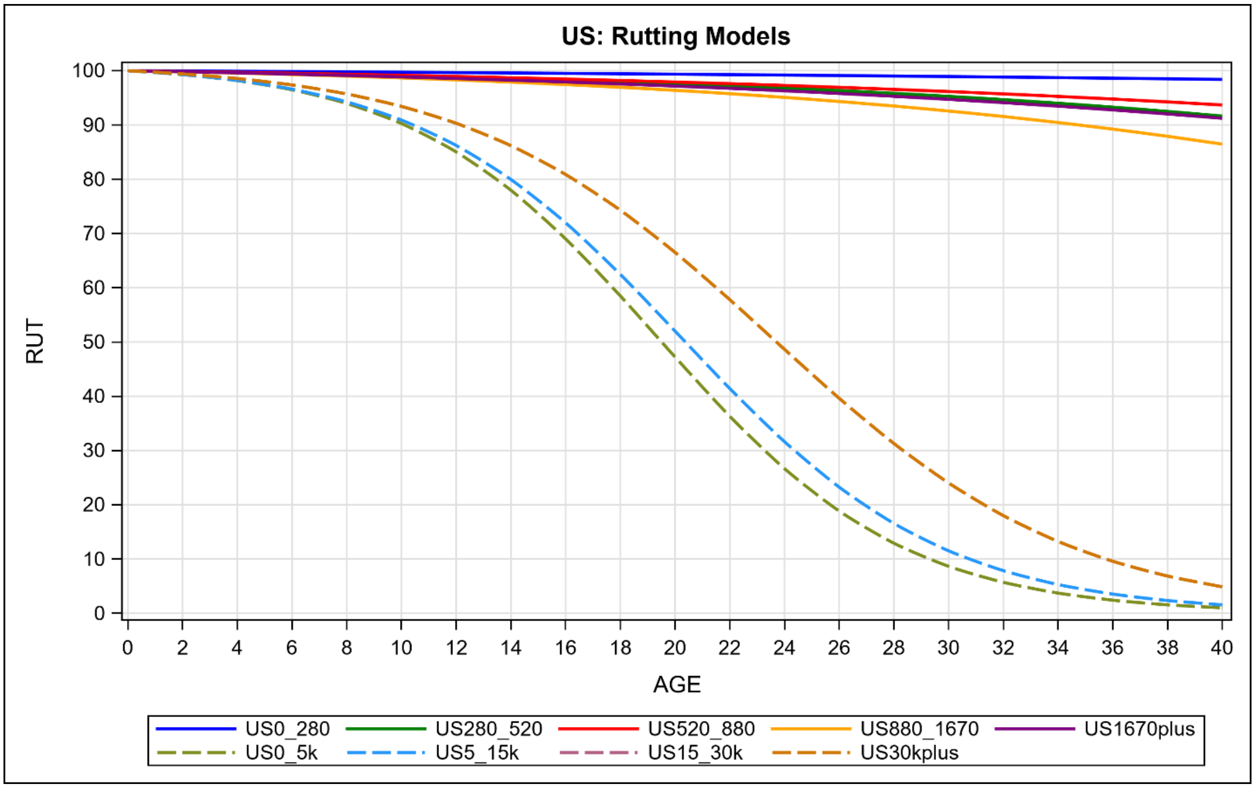

Figure C 17. US: Rutting Models

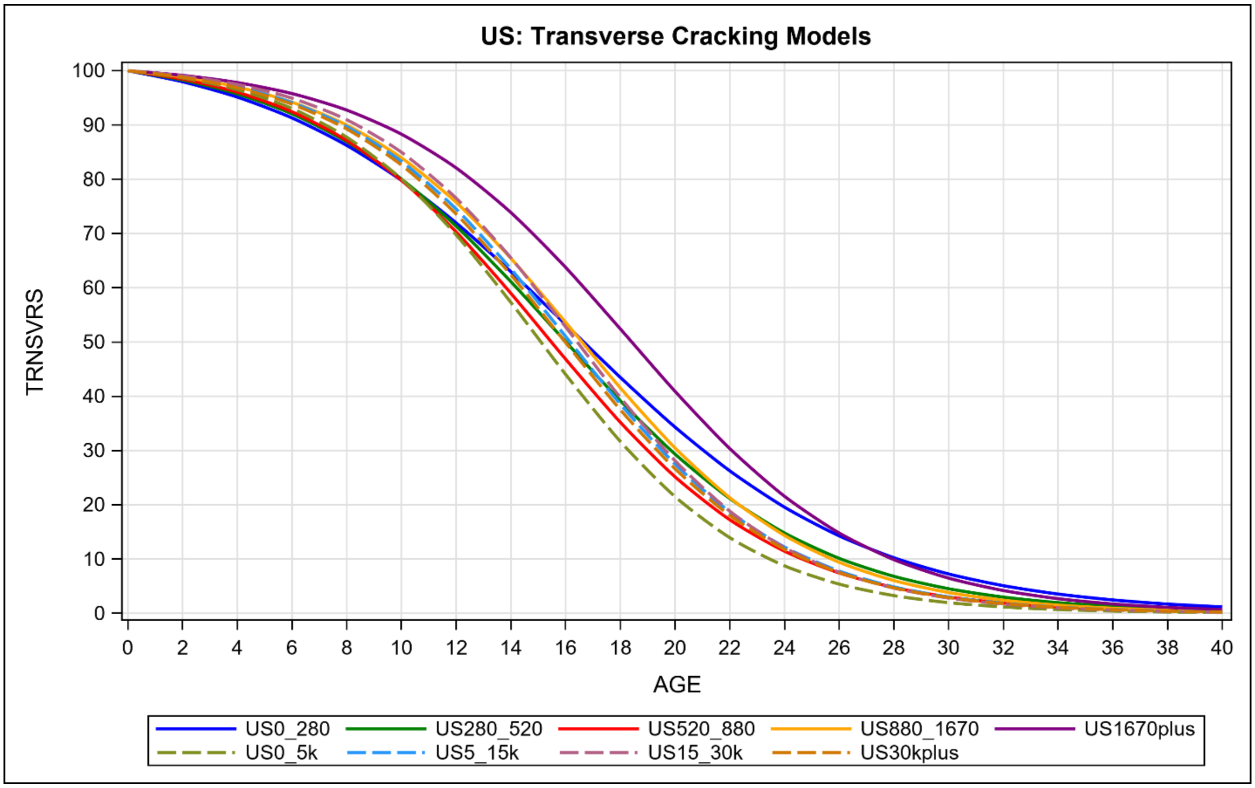

Figure C 18. US: Transverse Cracking Models

Appendix D. AADT vs. AADTT Performance Model Curves

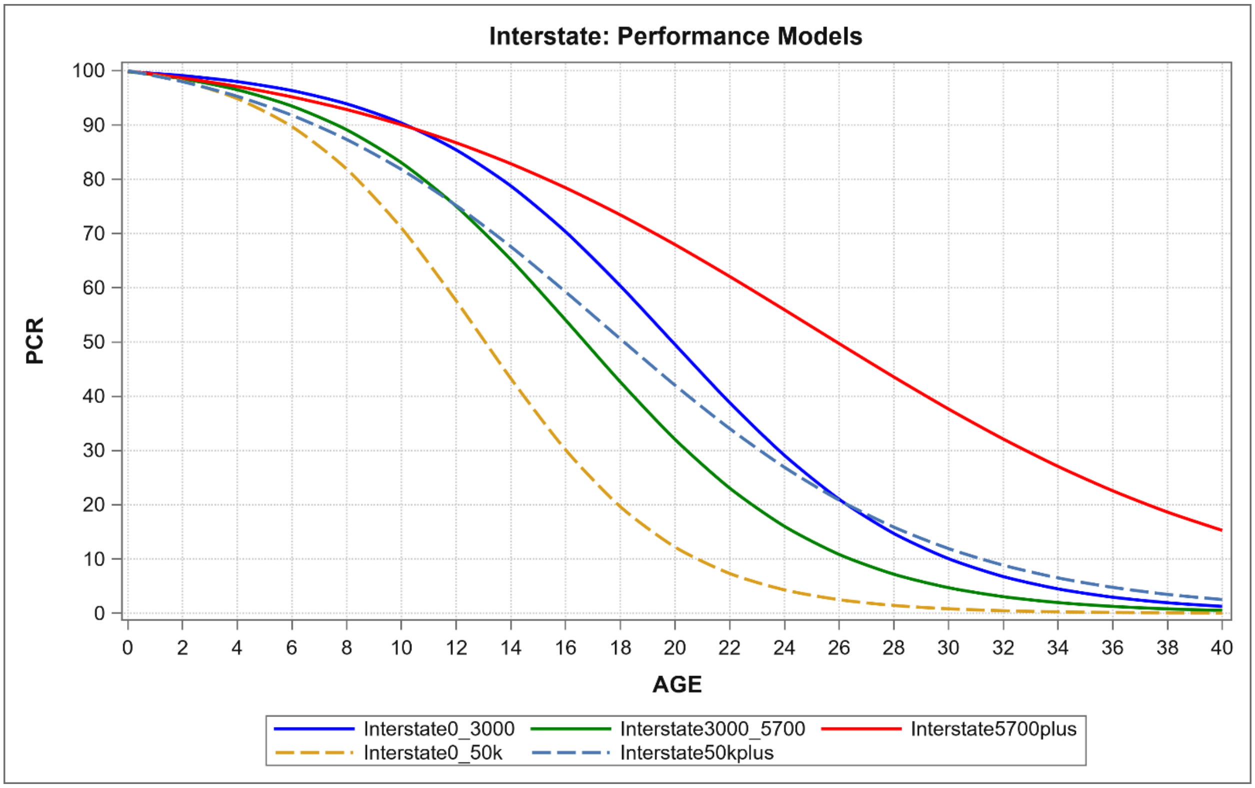

Figure D 1. Interstate: Performance Models

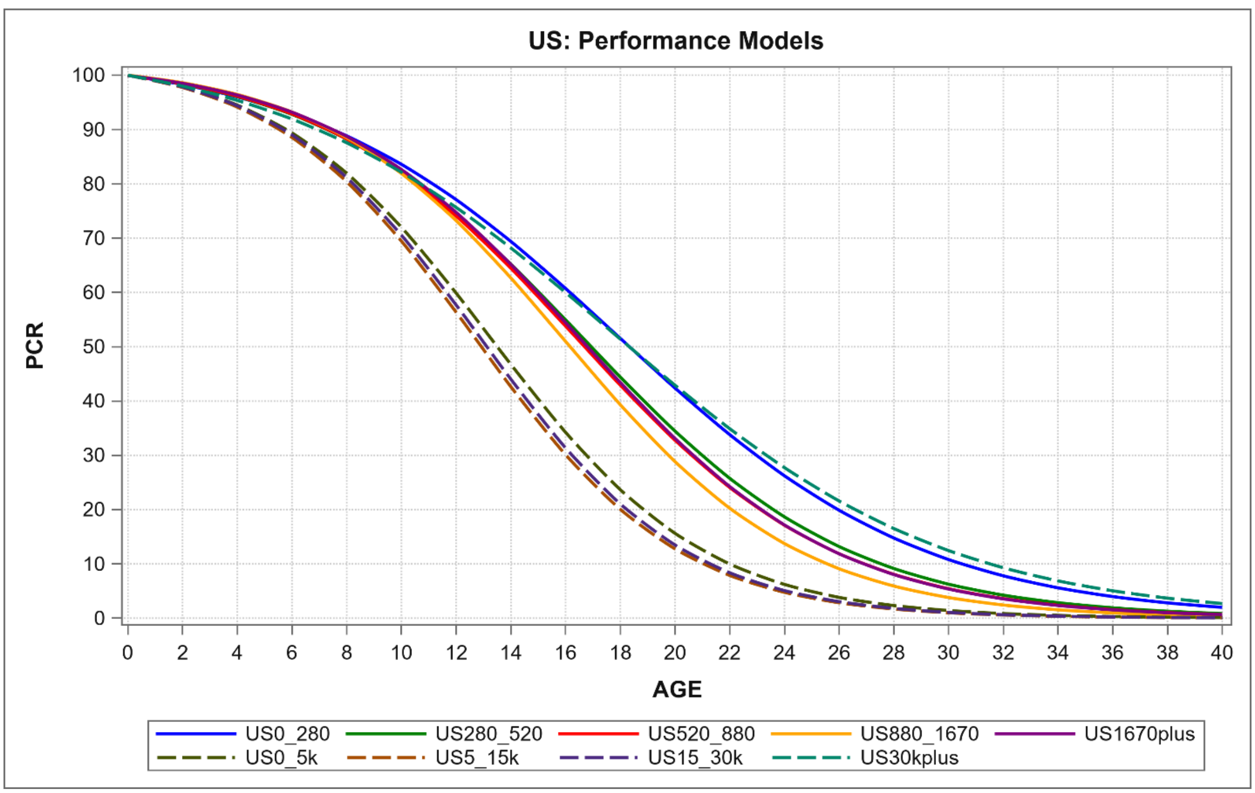

Figure D 2. US: Performance Models

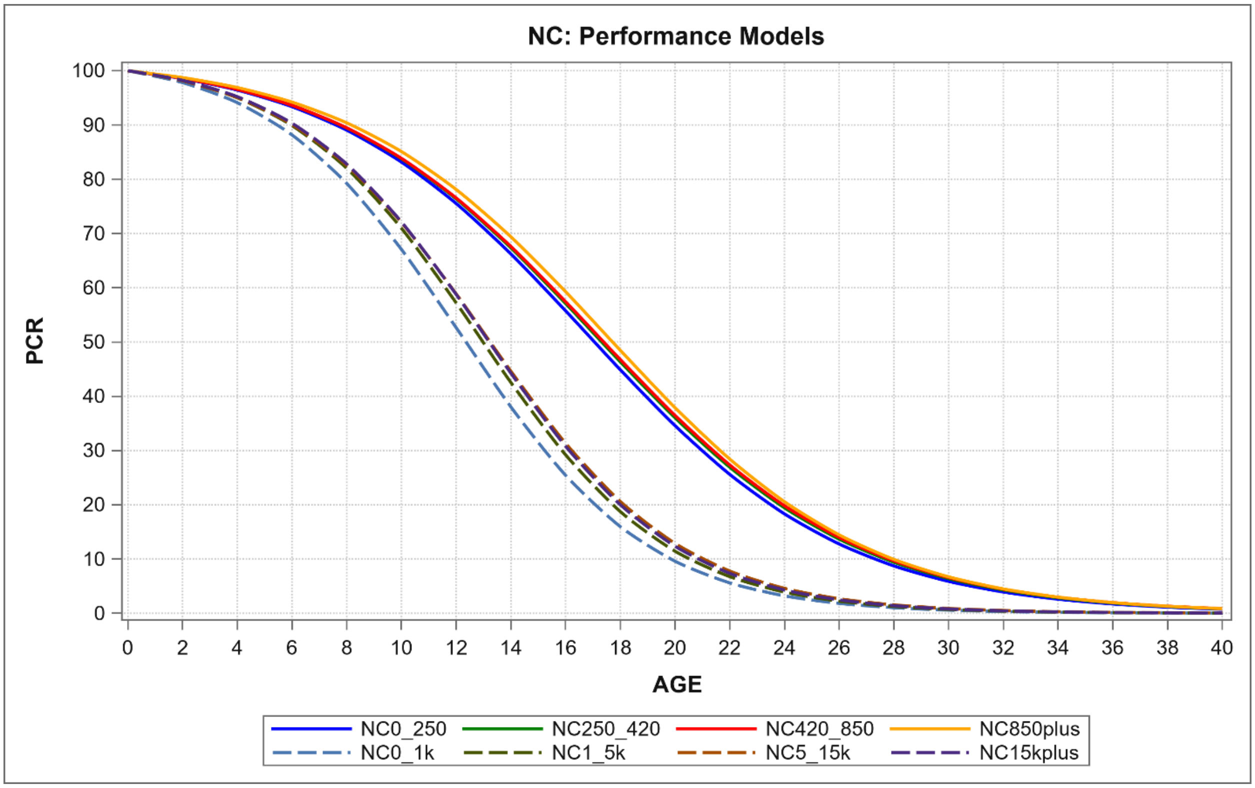

Figure D 3. NC: Performance Models

Appendix E. AADT vs. AADTT Roadway_Poor Performance Model Curves

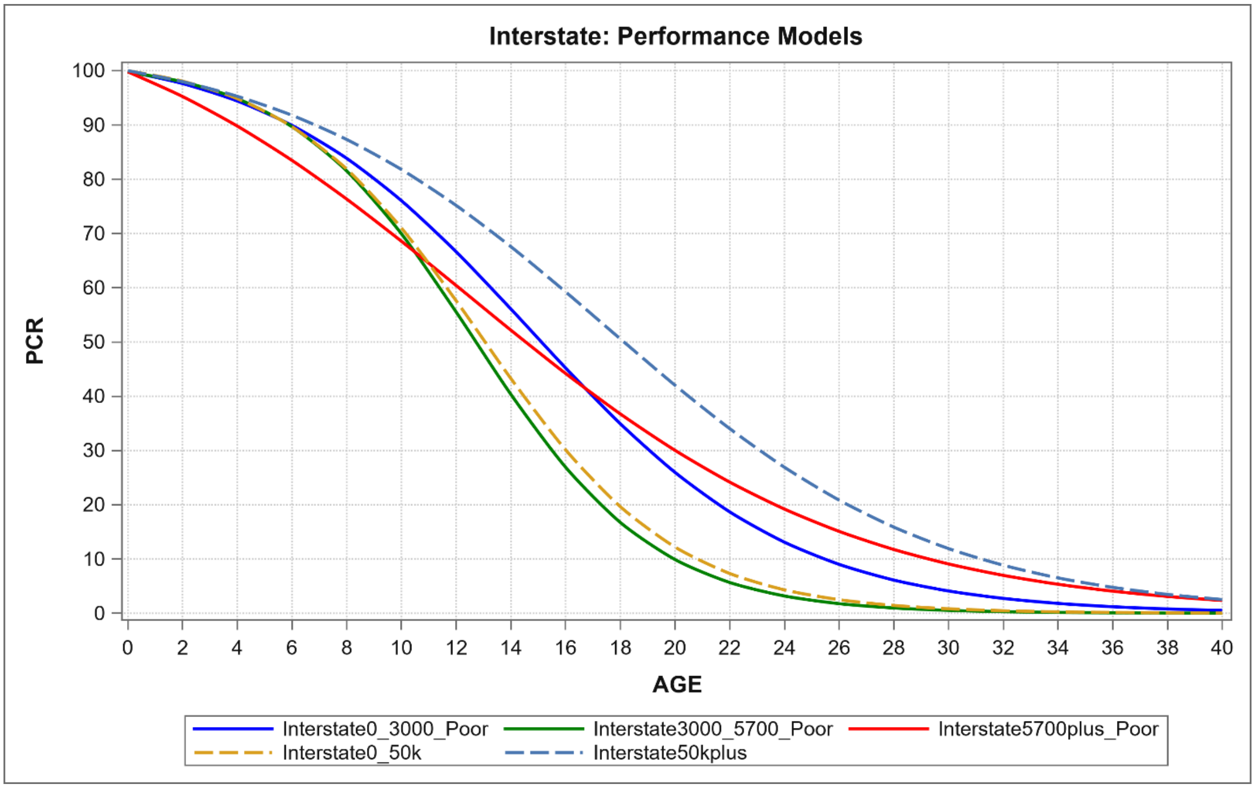

Figure E 1. Interstate Performance Models: AADT vs. AADTT Roadway_Poor

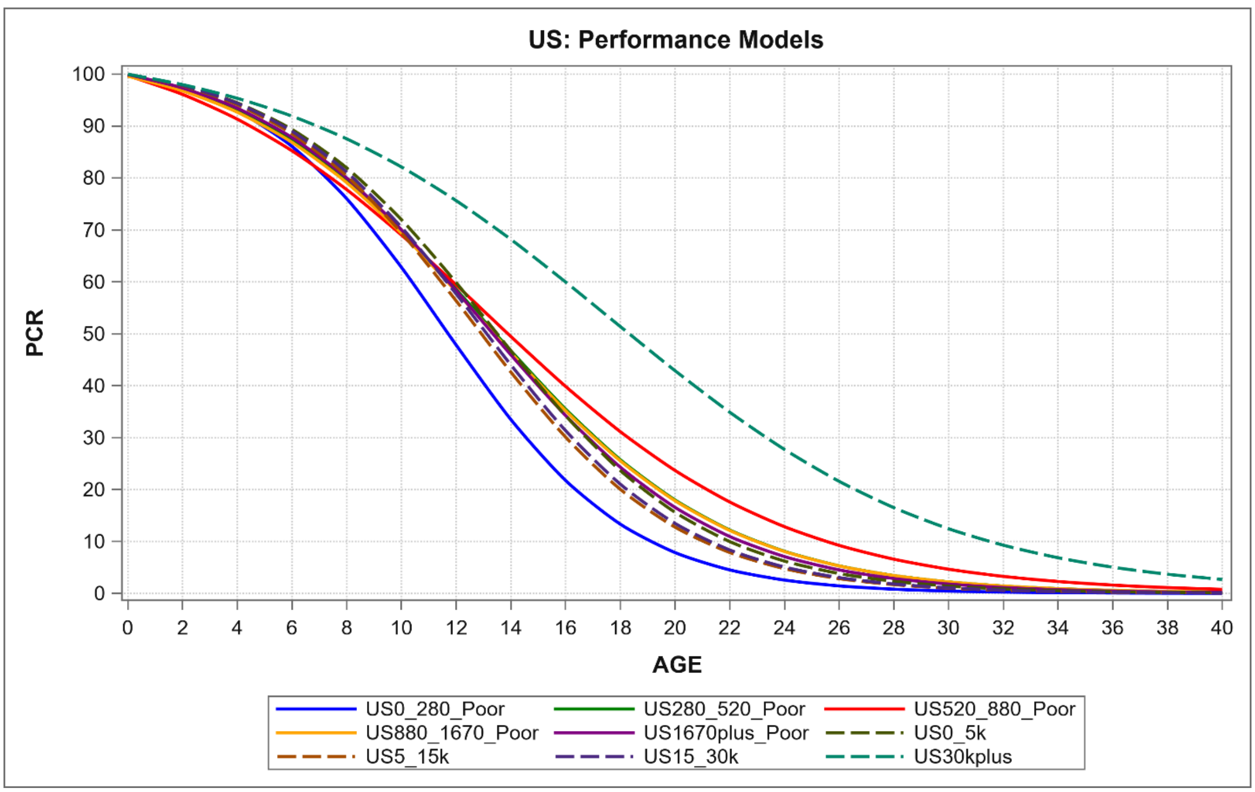

Figure E 2. US Performance Models: AADT vs. AADTT Roadway_Poor

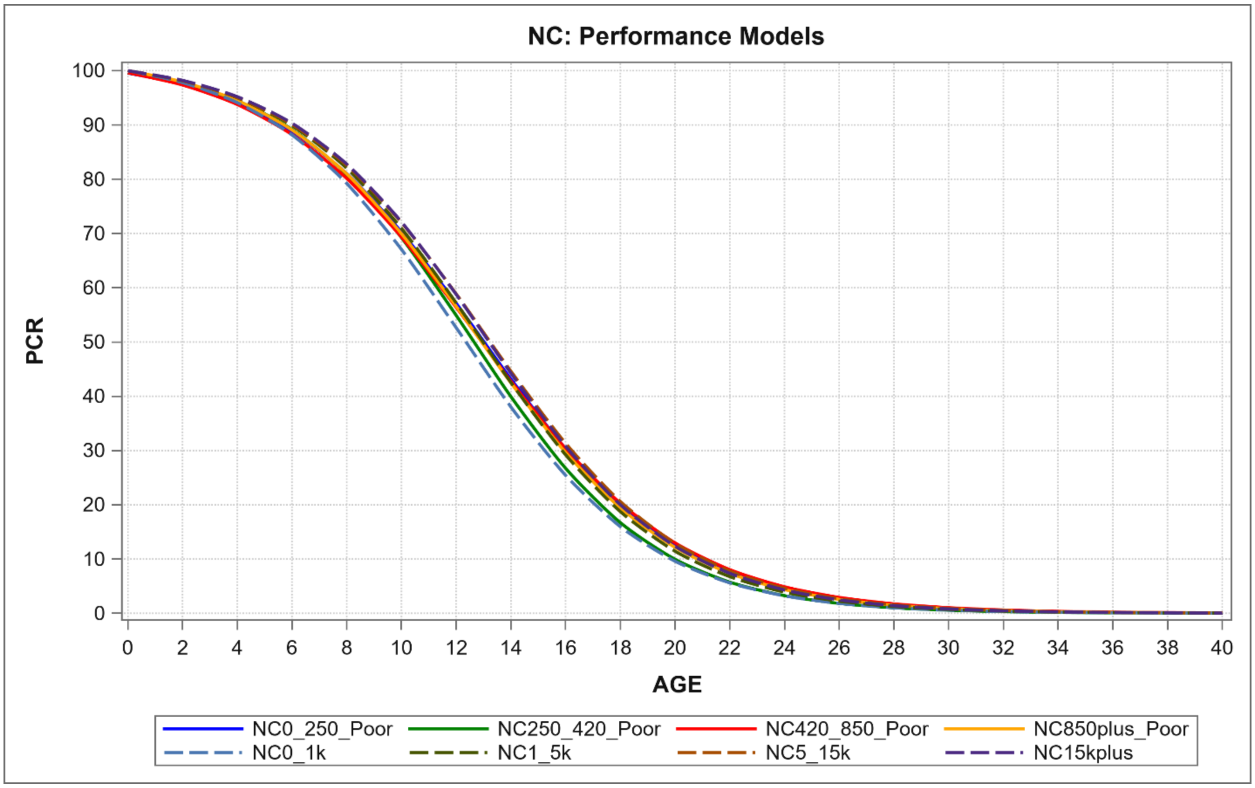

Figure E 3. NC Performance Models: AADT vs. AADTT Roadway_Poor

Appendix F. Distress Model Curves for Interstate Routes (ESAL)

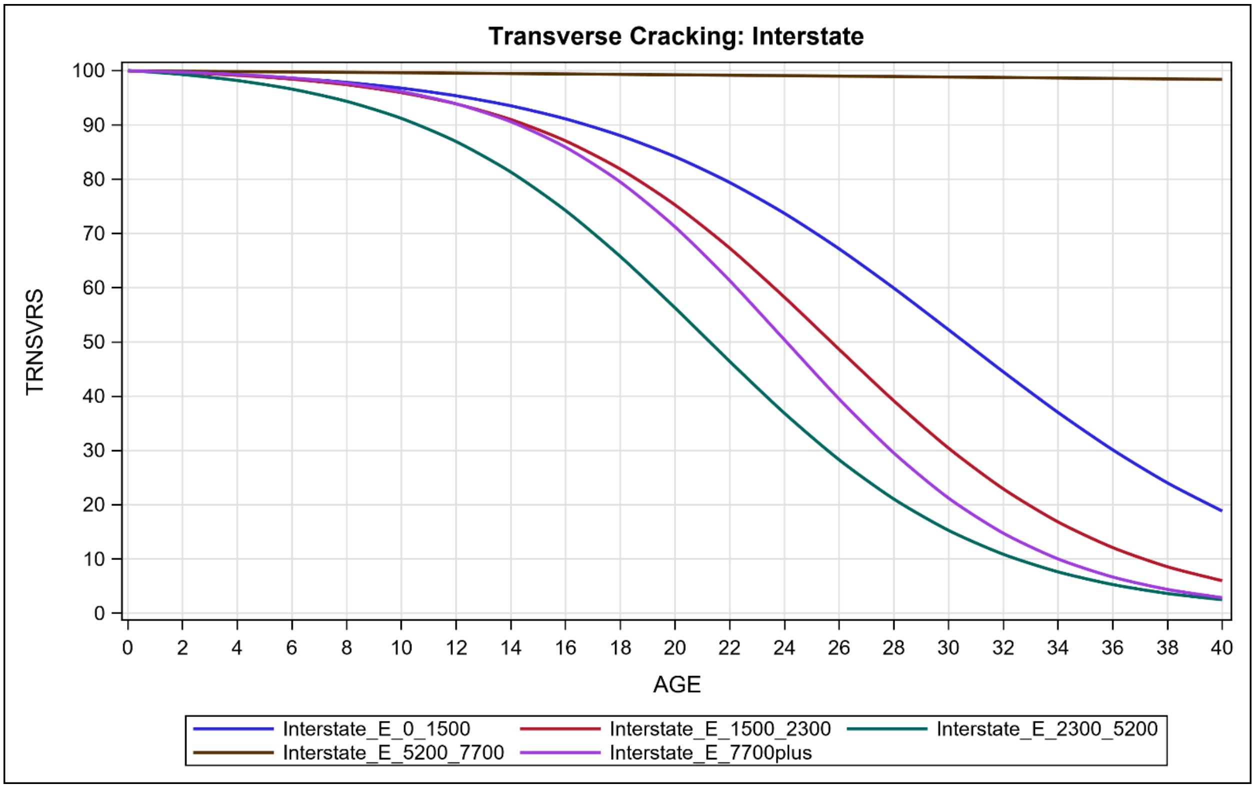

Figure F 1. Transverse Cracking: Interstate (ESAL)

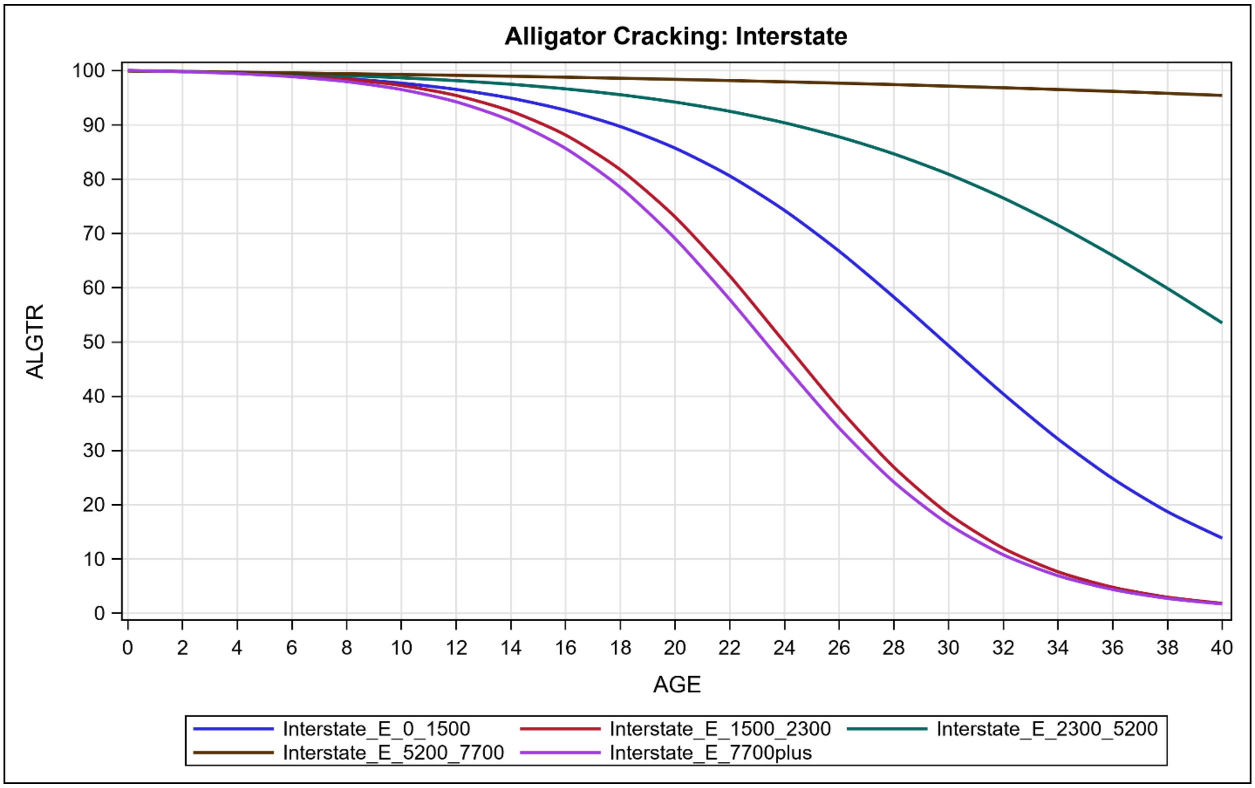

Figure F 2. Alligator Cracking: Interstate (ESAL)

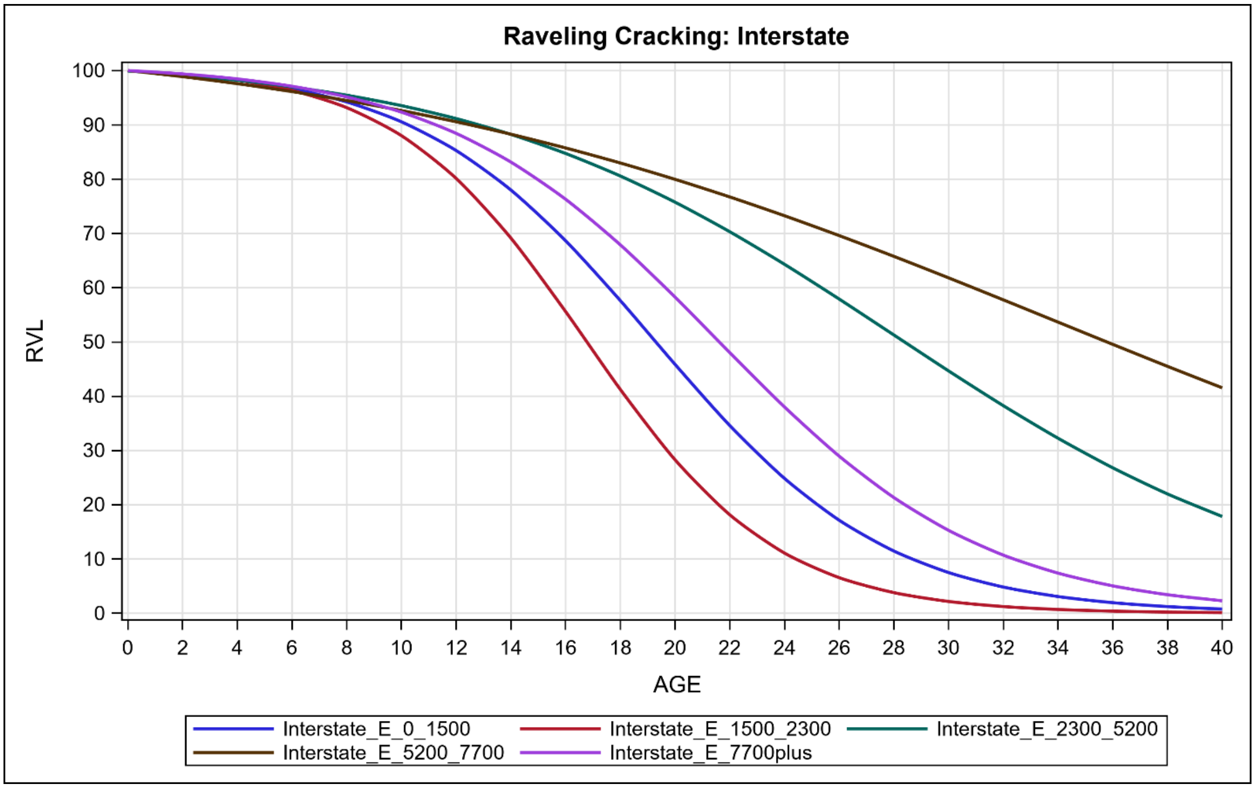

Figure F 3. Raveling: Interstate (ESAL)

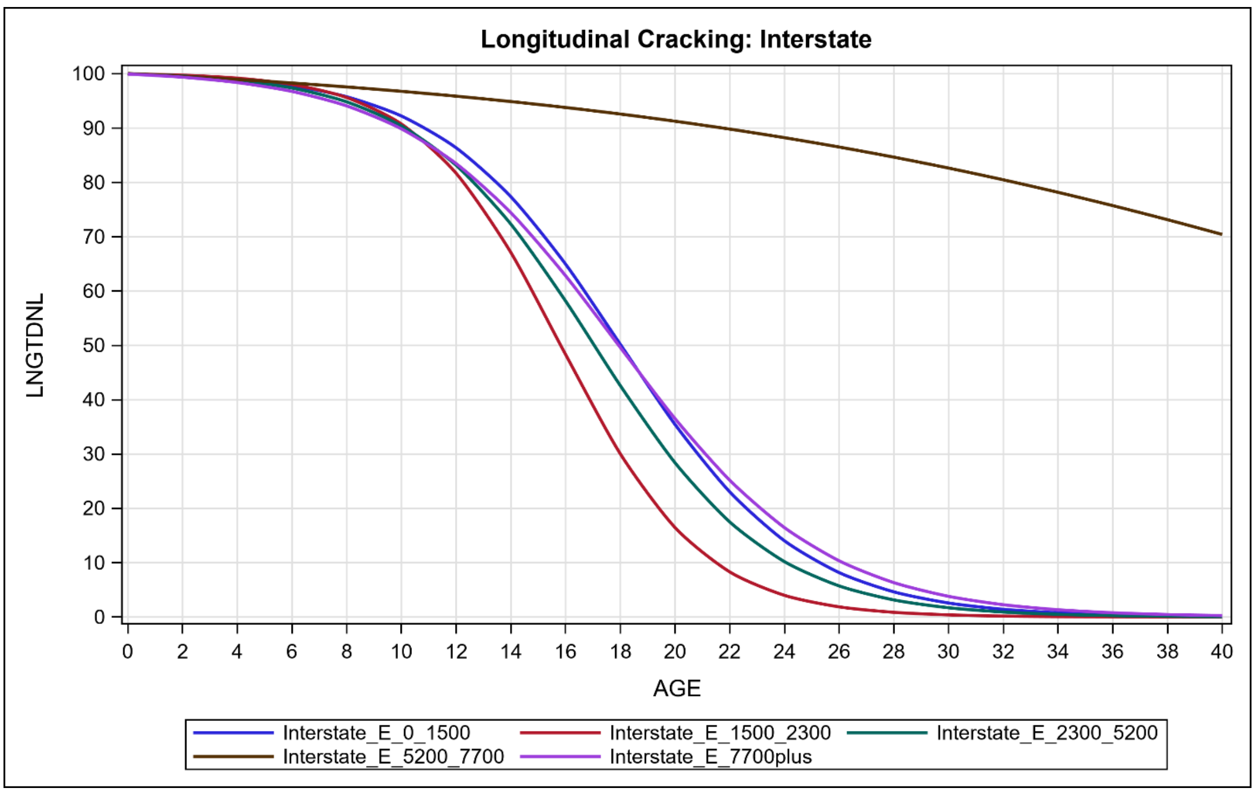

Figure F 4. Longitudinal Cracking: Interstate (ESAL)

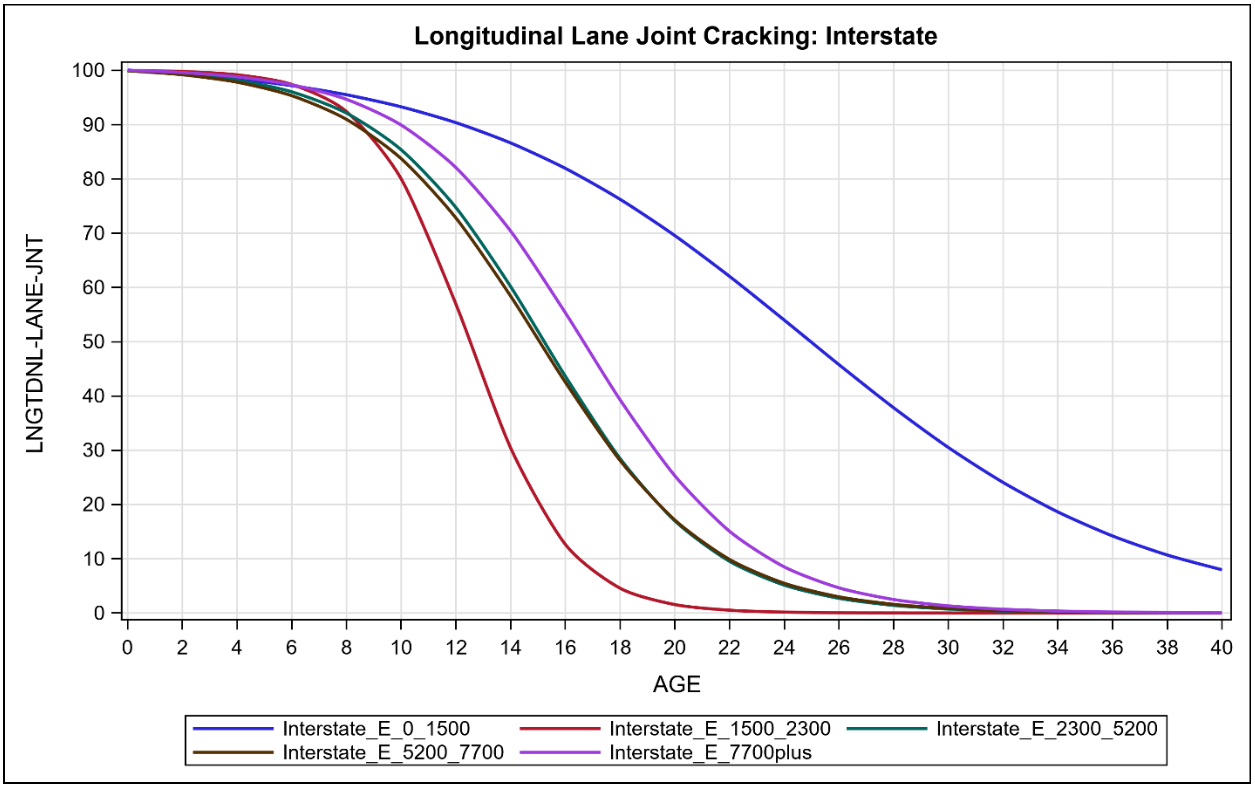

Figure F 5. Longitudinal Lane Joint Cracking: Interstate (ESAL)

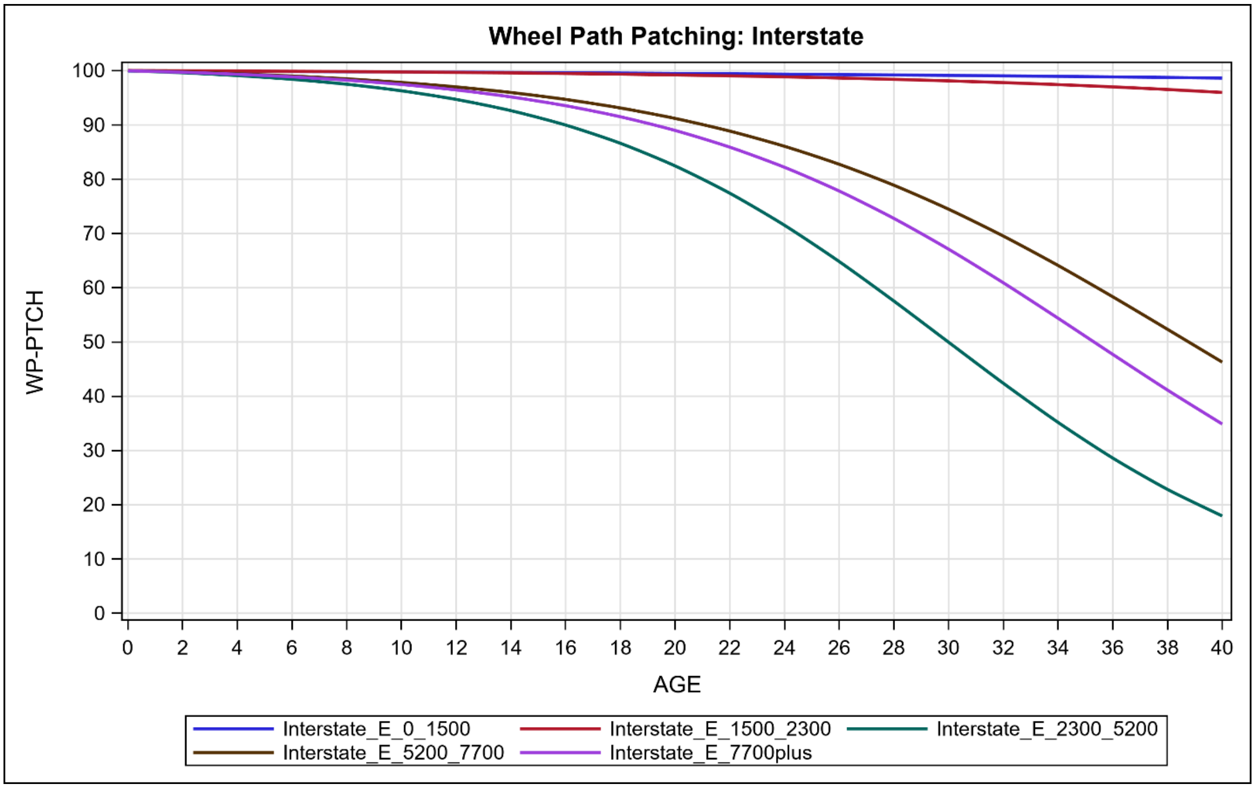

Figure F 6. Wheel Path Patching: Interstate (ESAL)

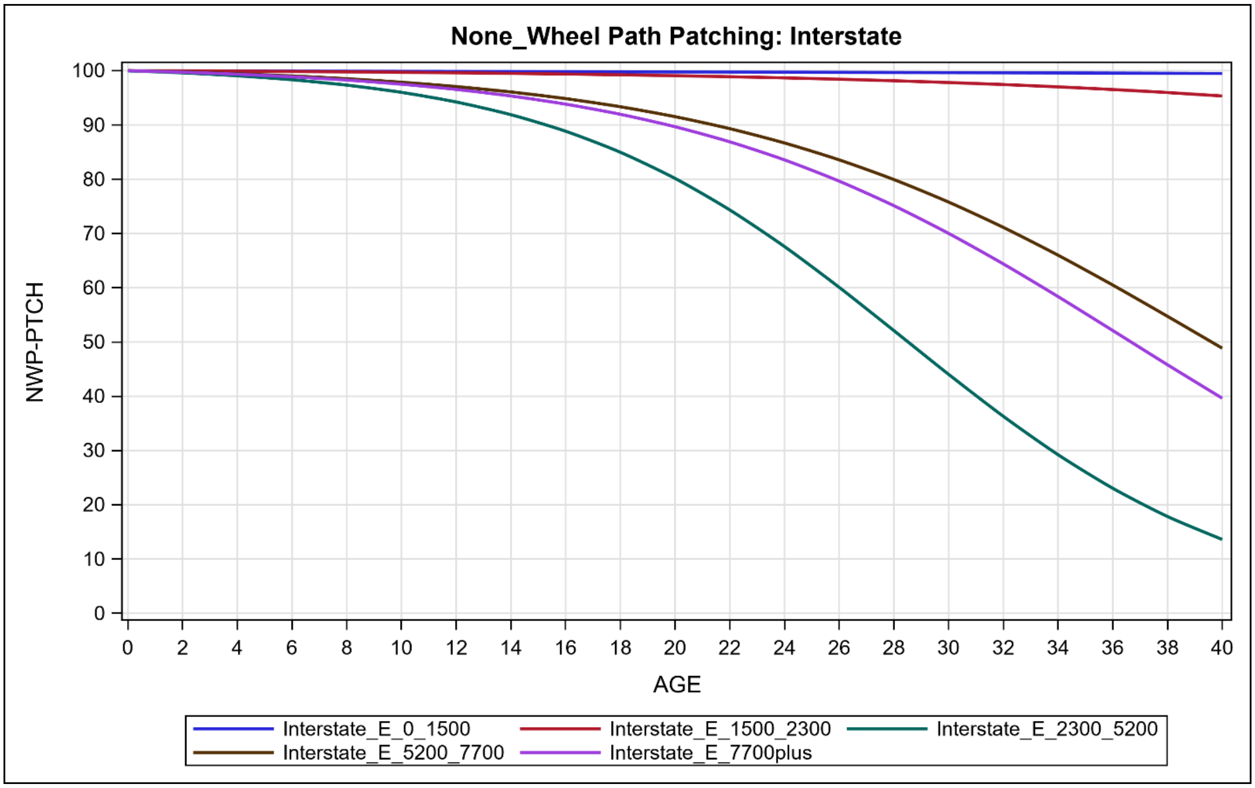

Figure F 7. Non-Wheel Path Patching: Interstate (ESAL)

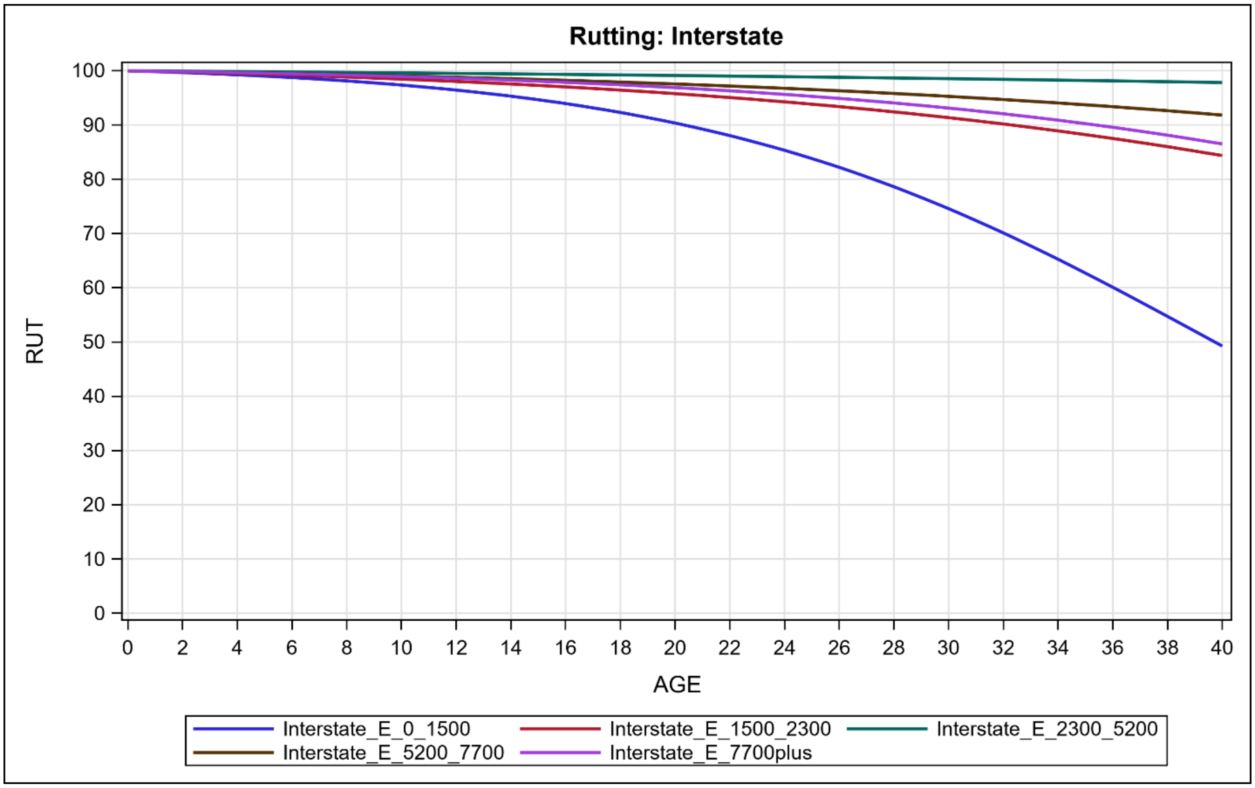

Figure F 8. Rutting: Interstate (ESAL)

Appendix G. Performance Model Curves for Interstate Routes (ESAL)

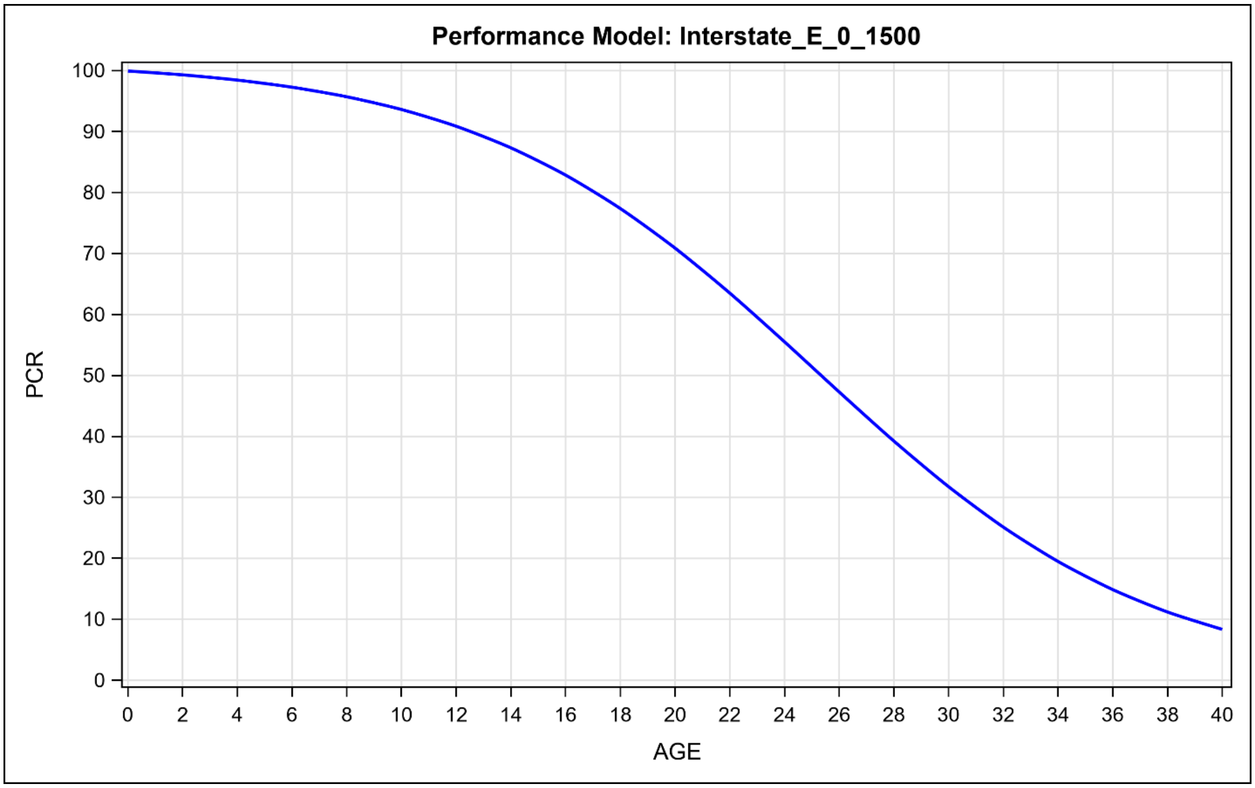

Figure G 1. Performance Model: Interstate0_1500 (ESAL)

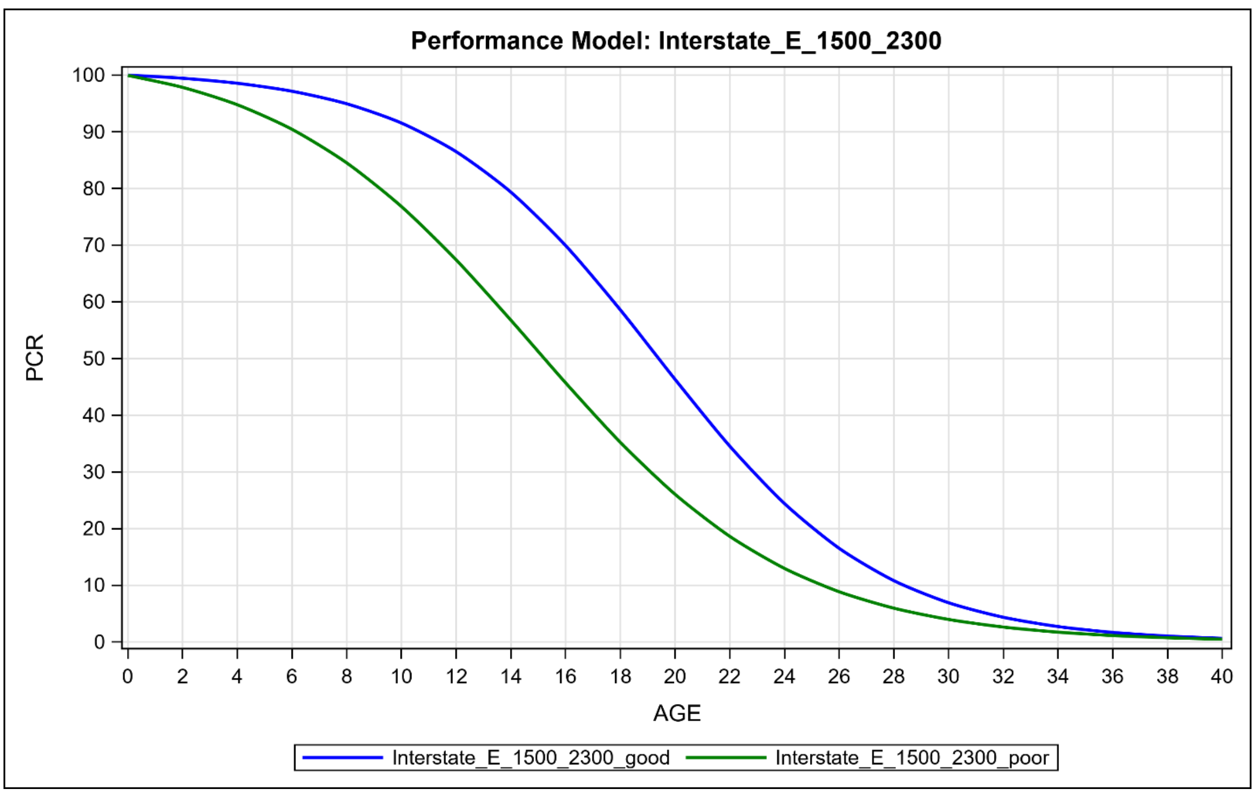

Figure G 2. Performance Model: Interstate1500_2300 (ESAL)

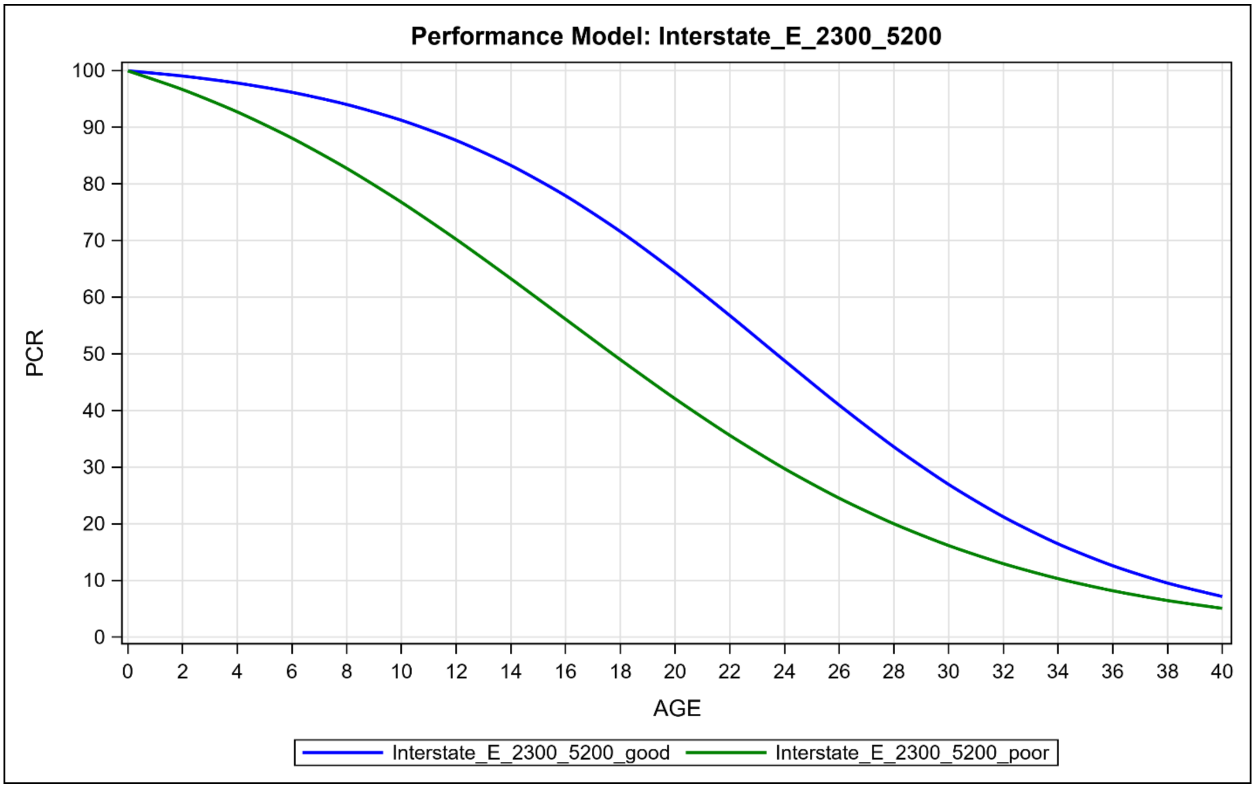

Figure G 3. Performance Model: Interstate2300_5200 (ESAL)

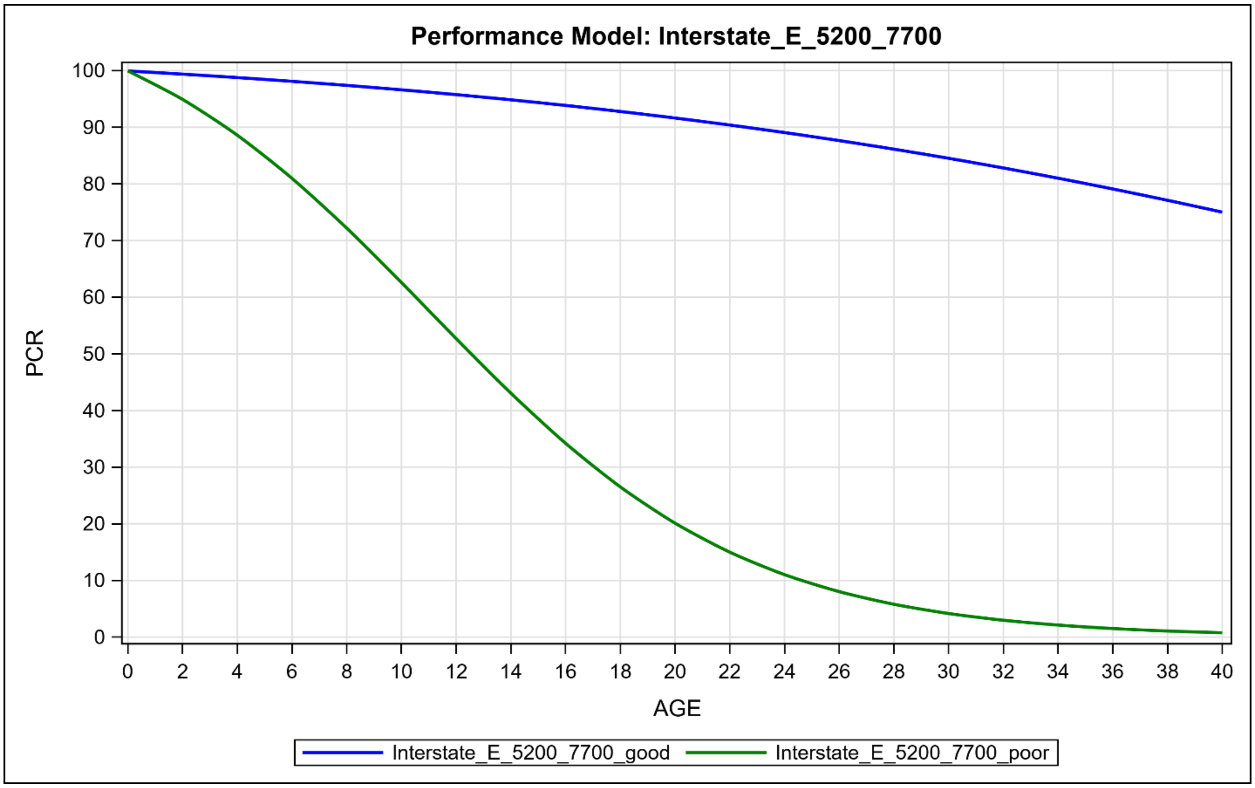

Figure G 4. Performance Model: Interstate5200_7700 (ESAL)

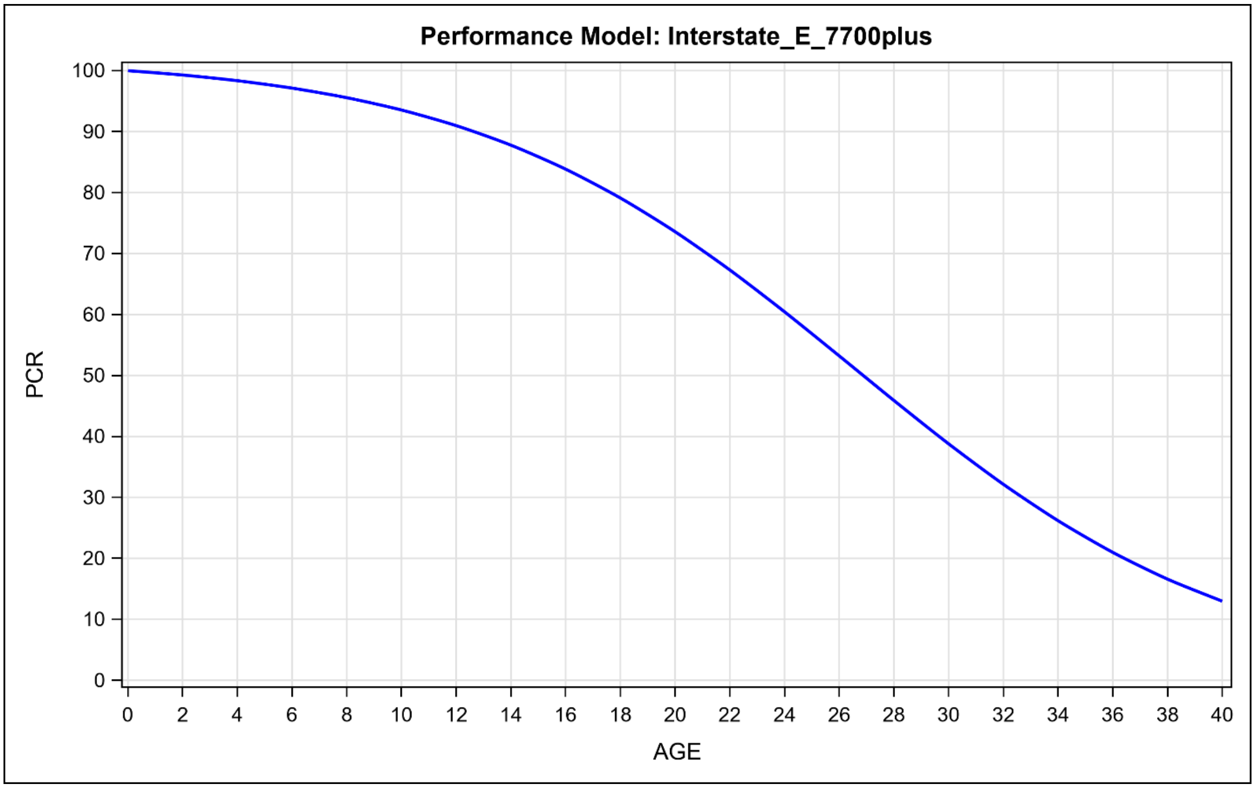

Figure G 5. Performance Model: Interstate7700plus (ESAL)