RESEARCH & DEVELOPMENT

Development and Validation of Pavement Deterioration Models and Analysis Weight Factors for the NCDOT Pavement Management System (Phase II: Automated Data)

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Development and Validation of Pavement Deterioration Models and Analysis Weight Factors for the NCDOT Pavement Management System
Part II: Automated Survey Data

Final Report
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16. Abstract

The North Carolina Department of Transportation (NCDOT) Pavement Management Unit (PMU) has recently begun collecting pavement distress data using automated data collection techniques. Automated distress data differ from manual distress data in that there is more detail, greater quantity, better quality, and higher repeatability. The NCDOT PMU is charged with effectively conducting performance and funding analysis of the state’s pavements using a Pavement Management System (PMS). Differences between manual and automated data create a need to develop a new set of performance models and distress indices based on the automated data. This study was conducted to identify an appropriate composite distress index development method and develop performance and distress models for Primary and Interstate roadways that can be used by the NCDOT Pavement Management System (PMS).

17. Key Words
Pavement Management System, Automated Data, Performance Model, Distress Model

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EXECUTIVE SUMMARY

Automated pavement distress collection techniques have gained significant momentum in recent years. This is mainly due to the fact that, compared to manual survey methods, automated methods can collect more data, with better quality, in a safer manner, with reduced resources. In January 2012, NCDOT conducted the first round of automated data collection on pavements. Approximately 19,000 miles of Interstate and Primary roadways were surveyed. In November 2012, the second round of automated data collection was performed. This collected automated data allowed a longitudinal study of pavement distress and performance of North Carolina routes.

The existing performance and distress models in the NCDOT Pavement Management System (PMS) were developed from manually collected data. The model development process has been documented in FHWA/NC/2011-01. Now that automated data is available, there is a need to update the NCDOT PMS with new performance and distress models. This study was conducted to fulfill this need. In this study, Analytical Hierarchy Process (AHP) was used to develop composite distress and performance indices for asphalt and JCP pavements, and nonlinear regression analysis was conducted to develop sigmoidal distress and performance models using automated data.

Primary findings of this study include:

- The process of developing distress and performance models for the automated data was established. In this study, only two years' worth of data (2012 and 2013) were collected because the NCDOT had recently began automated data collection efforts. Consequently pavement age was not reset because condition data collected over three consecutive years are needed for the analysis algorithm. Despite these limitations, the process of model development has been successfully developed, which allows quick future updates of existing models once new automated condition data are collected.
- An approach to derive composite indices was developed and successfully used to develop distress and performance models. The automated data usually contain several severity ratings for each distress. These ratings need to be consolidated into one index (i.e., a composite index) in order to be used as the dependent variable for developing the distress model. Similarly, various distresses in both asphalt and JCP pavements were surveyed. The composite indices of these distresses need to be consolidated into another single composite index (i.e., PCR) in order to develop performance models. The approach involved the following steps:
    - For composite indices of distresses, the MAE method used by the NCDOT PMU to calculate the composite index of alligator cracking based on windshield survey data was modified and applied to the automated data. The 98th percentiles of distresses were calculated and averaged, entered into the MAE functions, and then composite distress indices of asphalt and JCP pavements were calculated and used to develop distress models.

    - For composite indices of the overall performance, deduction values used by the NCDOT PMU were analyzed to calculate the relative importance between pavement distresses, the Analytical Hierarchy Process (AHP) was used to obtain the weight factor of each distress, and then PCR values were calculated and used to develop performance models for asphalt and JCP pavements. AHP has proven to be an effective method because the magnitudes of weight factors match with NCDOT engineers' experience regarding the extent of impact of individual distress on pavement performance.
- The newly developed models from the automated data performed reasonably well. A direct visual comparison of pavement deterioration models developed using manual data and automated data indicated that alligator cracking curves are comparable except for the US 15kplus curve, asphalt performance curves are comparable, and JCP performance curves are not comparable possibly because of the small sample size of the automated data. In addition, a separate observation of the automated data distress model curves indicated that these curves start showing a decreasing trend at around 10~13 years. This concurred with the NCDOT's maintenance practice that is documented in "Proposed Life Cycle Cost Analysis Procedure Summary [18]." Based on these observations, it can be concluded that the newly developed models are robust.

The following recommendations are proposed for future research:

- It is recommended to update the newly developed models after new condition data are collected. With three years' worth of data, pavement age can be reset, and more accurate pavement distress and performance models are expected.
- To improve data quality for increased PMS performance, it is recommended that 1) raters should record maintenance activities when observed. This allows pavement age to be accurately reset instead of judging from the magnitudes of PCR jumps; and 2) a centralized database should be developed that contains both pavement performance ratings and pavement construction history. This database eliminates the need to merge multiple databases, and more importantly preserves pavement sections presenting valuable pavement performance information that otherwise are purged during the database merging process.
- This research project focused on asphalt and JCP pavements, and composite pavements are considered as a part of asphalt pavements, even though they perform differently. It is recommended that deterioration models for composite pavements be developed in future efforts.
- It is recommended to further subdivide the current 18 roadway families into three regions. The reason is that, for example, Interstate 0-50k routes in the Mountains region perform differently than the ones in the Piedmont region, and similarly roadways belong to other families perform differently in different regions. Therefore, additional models (e.g., Interstate 0-50k_Mountains, Interstate 0-50k_Piedmont, and Interstate 0-

50k_Coastal) should be developed, if possible, to enhance functionality of the NCDOT PMS.

- It is recommended that additional weight factors be developed that consider highway use categories such as Statewide (National Highway System), Regional and Subregional (local) roads.

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CHAPTER 1 INTRODUCTION AND OBJECTIVES

1.1 Background

Automated pavement distress collection techniques have gained significant momentum in recent years. This is mainly due to the fact that, compared to manual survey methods, automated methods can collect more data, with better quality, in a safer manner, with reduced resources [1]. Pavement condition data collected using these techniques are referred to as automated data in this research project.

In 2008, the North Carolina Department of Transportation (NCDOT) sponsored a study [2] to evaluate automated survey methods for asset management inventory. Asset data of four infrastructure areas, including pavements, bridges, geotechnical features, and roadside appurtenances, were collected by three automated surveyors. The results were compared with data collected using the existing NCDOT survey protocols. In January 2012, NCDOT conducted the first round of automated data collection on pavements. Approximately 19,000 miles of Interstate and Primary roadways were surveyed. In November 2012, the second round of automated data collection was performed. This collected automated data allowed a longitudinal study of pavement distress and performance of North Carolina routes.

The Phase I of this research project (Report No. FHWA/NC/2011-01) focused on the development of distress and performance models using the *windshield data* (also referred to as manual data). This research project, Phase II, focused on developing distress and performance models using the *automated data*.

The same terminologies, i.e., distress models and performance models, are used in the Phase II: *Performance models* estimate the average value of the dependent variable – Pavement Condition Rating (PCR), which is a pavement performance indicator that combines all visual distresses into one index. The independent variable is pavement age, which is determined from the time of construction, reconstruction, or overlay to the time of the last PCR survey. *Distress models* estimate individual distress index values (the dependent variable) from pavement age (the independent variable).

1.2 Research Needs and Significance

The existing performance and distress models in the NCDOT Pavement Management System (PMS) were developed from manually collected data. The model development process has been documented in FHWA/NC/2011-01. Now that automated data is available, there is a need to update the NCDOT PMS with new performance and distress models. The main reasons for this update are:

- Automated data are more consistent. Consequently, there will be a smaller number of outliers, different data cleaning strategies, and different performance and distress models; and
- Automated data are numerical, whereas some manual data are ordinal. Thus statistical analysis methods will be different, and the final model forms will be different.

The research project provided the NCDOT with a new set of performance and distress models developed from automated data. Tangible benefits include: reliable predictions of pavement performance that allow the NCDOT to select appropriate maintenance activities, and accurate Cost-Benefit Analysis (CBA) results that enable the NCDOT to make efficient investment decisions.

1.3 Research Objectives

The objectives of this research project are twofold: (a) to calculate pavement distress indices based on automated data sets for Asphalt pavements and Jointed Concrete Pavements (JCP); and (b) to develop pavement performance and distress models using these new distress indices.

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. Chapter 3 focuses on the pavement condition data. Chapter 4 presents development of pavement distress models. Chapter 6 presents development of pavement performance models. Chapter 6 provides conclusions drawn from this research and recommendations for future research.

The appendices present individual distress model curves and are organized as follows:
- Appendix A: Alligator cracking curves
- Appendix B: Raveling curves
- Appendix C: Transverse cracking curves
- Appendix D: longitudinal cracking curves
- Appendix E: longitudinal lane joint curves
- Appendix F: Rutting curves
- Appendix G: Wheel path patching curves
- Appendix H: Non-wheel path patching curves
- Appendix I: Asphalt performance curves
- Appendix J: JCP performance curves

CHAPTER 2 LITERATURE REVIEW

An extensive literature review was conducted to synthesize past and ongoing research related to this research project.

2.1 Manual Surveys and Automated Surveys

Recently, state DOT's have started collecting the condition data using high speed profiler vehicles equipped with cameras, lasers, and positioning sensors [3]. According to Wang [4], digital camera resolutions can capture cracks on the roadway surface with a width that is less than two millimeters. A study of analyzing 3D computer images of the roadway surfaces was conducted by Grinstead in 2006 [5]. In 2011, Sun concluded that lasers overcome the problems that occur with the limitation of 2D data recording systems by being able to differentiate between pavement distresses and debris on the roadway surface [6].

In 2001 [7], Wu investigated the compatibility between automated and manual data collection systems for pavements in North Carolina. Surface crack information on the US and NC roadways was collected using the automated method. A parallel manual survey was also conducted. It was observed that manual survey results were more variable than automated survey results.

In 2004, McGhee [1] indicated that when compared to manual survey methods, the automated survey methods can collect more data, with improved quality, while increasing safety, and reducing the amount of required resources.

Flintsch and Bryant [8] concluded that "manual surveys allow for very detailed data collection but are very labor intensive and require more time per asset than automated or semi-automated methods." A recent study [1] found out that in several states, automated data are more consistent.

A recent study [9] indicated that the automated data collection method allows for safer and more consistent collection of roadway surface data.

2.2 Pavement Condition Indices

The automated data collection method typically rates each type of distress at several severity levels, e.g., a roadway section can have 2,500 LF of light transverse cracking, 2,100 LF of moderate transverse cracking, and 750 LF of severe transverse cracking. These severity ratings need to be combined to obtain a composite condition index of transverse cracking which can be used to develop the distress model (e.g., transverse cracking index vs. pavement age). In addition, a composite condition index of overall pavement performance should be calculated in order to develop the performance model (i.e., PCR vs. pavement age).

In 2002, McGhee [10] developed three pavement condition indices for the Virginia DOT (VDOT). These three indices are: the Load Related Distress Index – LDR, the Non-Load Related Distress Index – NDR, and the Combined Condition Index – CCL. CCL is the lowest value of the LDR or NDR. These indices are calculated using a point deduction system which assigns a

value of 100 when the pavement being evaluated has no load or non-load related distress. VDOT deduction curves were developed based on PAVER [11] deduction curves.
New Jersey DOT also uses three pavement condition indices to quantify pavement performance [12]. They are: the Load Related Distress Index – LDI (0-5 scale), the Non-Load Related Distress Index – NDI (0-5 scale), and the Surface Distress Index – SDI (0-5 scale). NDI and LDI are calculated using the following equations:

- DV_NL = distress weight * severity * % occurrence → NDI=(500-Sum(DV_NL))/100
- DV_L = 350 * severity coefficient * % occurrence → LDI=(500-(Sum(DV_L)+DV_rut))/100
- For flexible pavements, SDI = (NDI*LDI)/5. For rigid pavement, SDI = NDI.

2.3 Development of Pavement Performance Models Using Automated Data

In 2004, Australia ARRB Transport Research (ARRB) [13] initiated a study to develop deterioration models using pavement data collected from 580 monitoring sites over 5 years. A multi-laser profiler was used to collect roughness, rutting and macro texture measurements, and a Falling Weight Deflectometer (FWD) was used to assess structural strength. Several models were developed, including roughness, rutting, strength, cracking for sealed roads, and roughness and gravel loss for unsealed roads.

Development and implementation of pavement performance models for the Arizona Department of Transportation (ADOT) [14] PMS were documented in a 2006 study. A roughness index termed Pavement Serviceability Rating (PSR) was calculated from the International Roughness Index (IRI). PSR was the main indicator of pavement performance in this study. Performance models in the sigmoidal form were developed to predict PSR as a function of pavement age. An overall Pavement Distress Index (PDI) was developed to represent the overall pavement surface distress condition. For flexible and composite pavements, distress models were developed to predict PDI as a function of cracking, rutting, flushing, and patching. For rigid pavements, PDI was predicted as a function of corner breaks, transverse cracking, and faulting.

In 2009, Mohammad et al. [15] developed pavement performance and treatment models for Louisiana Department of Transportation and Development (LADOTD). The pavement data that were used in this study were collected by the automatic road analyzer (ARAN) since 1995, and were shifted based on historical resurface year. The models developed followed the power function.

In 2010, the Pennsylvania Department of Transportation (PennDOT) initiated a study to synthesize performance modeling development activities used by five case study State DOT's: the Minnesota Department of Transportation (Mn/DOT), the North Dakota Department of Transportation (NDDOT), the Oklahoma Department of Transportation (OkDOT), the Oregon Department of Transportation (ODOT), and the Washington State Department of Transportation (WSDOT). The findings are summarized below [16]:

- NDDOT used a semi-automated survey method to collect pavement condition data, and used an overall index called the Distress Score. Its IRI models are simple linear models using the last rehabilitation treatment, the highway performance classifications, and the pavement types as independent variables.

- OkDOT used a semi-automated data collection method. Condition indices and the overall condition were calculated. Deterministic family performance models were then developed to predict the index as a function of pavement age. The models used the power function.
- ODOT used a semi-automated data collection method. AgileAssets was the PMS software used by the Department. An index factor was calculated for each severity level of each distress. A composite index factor was calculated for distresses with more than one severity level. Performance models were developed to predict Remaining Service Life (RSL).
- WSDOT also used a semi-automated data collection method. A pavement structural condition (PSC) index was calculated and modeled against pavement age for each individual pavement section using a power function.

CHAPTER 3 PAVEMENT CONDITION DATA

3.1 Data Sources

The NCDOT began collecting the first round of automated data in January 2012. These data were referred to as the 2012 data. The second round of automated data collection was initiated in November 2012, and were referred to as the 2013 data. These condition data contain various distress ratings collected from asphalt, composite, jointed concrete (JCP), and continuously reinforced concrete (CRC) pavements as well as shoulders. Three things that should be noted:

1) even though asphalt pavements perform differently from composite pavements, a decision was made by consulting NCDOT engineers that these two types of pavements were grouped together and referred to as "asphalt" pavements;
2) CRC pavements and shoulders were not studied because they make up a very small percentage of the NCDOT roadway system; and
3) the NCDOT only collected automated data from Interstate, US, and NC routes. Condition data of SR routes continue to be collected by windshield surveys.

Tables 1 and 2 list types of distresses and their severity levels for asphalt pavements and JCP pavements, respectively, that have been collected by the NCDOT automated data collection method.

Table 1: List of Asphalt Pavement Distresses

Distress	**Unit**	**Low Severity**	**Moderate Severity**	**High Severity**
Alligator Cracking	Square Feet	✓	✓	✓
Bleeding	Square Feet	✓		✓
Delamination	Square Feet	Single Rating		
Longitudinal Cracking	Linear Feet	✓		✓
Longitudinal Lane Joint	Linear Feet	✓		✓
Patching Area - Non Wheel Path	Square Feet	Single Rating		
Patching Area - Wheel Path	Square Feet	Single Rating		
Ravelling	Square Feet	✓	✓	✓
Reflective Longitudinal Cracking	Linear Feet	✓	✓	✓
Reflective Transverse Cracking	Linear Feet	✓	✓	✓
Rutting - Maximum Average Depth	Inch	Single Rating		
Transverse Cracking	Linear Feet	✓	✓	✓

Table 2: List of JCP Pavement Distresses

Distress	**Unit**	**None**	**Low Severity**	**Moderate Severity**	**High Severity**
Asphalt Patch	# of Slabs	Single Rating			
Corner Break	# of Slabs		✓		✓
Joint Fault	# of Joints	✓	✓	✓	✓
Longitudinal Cracking	# of Slabs		✓		✓
Longitudinal Joint Spalled	# of Slabs	Single Rating			
PCC Patch	# of Slabs		✓	✓	✓
Transverse Cracking	# of Slabs		✓		✓
Transverse Joint Spalled	# of Slabs		✓	✓	✓

Automated data were collected by NCDOT Divisions. The NCDOT started using the automated data collection method in 2011. During this implementation phase, not all 14 divisions' data were available. Table 3 includes a list of division data that were used in this research project.

Table 3: List of Division Data Used in This Research Project

Division	**Asphalt Data**		**JCP Data**	
	2012	**2013**	**2012**	**2013**
D01		✓		✓
D02	✓	✓		
D03	✓	✓		
D04	✓	✓	✓	✓
D05	✓	✓	✓	✓
D06	✓	✓		
D07	✓	✓	✓	✓
D08	✓	✓	✓	✓
D09	✓	✓		✓
D10	✓	✓		
D11	✓	✓		✓
D12	✓	✓		✓
D13	✓	✓		✓
D14	✓	✓		✓

3.2 Data Cleansing

In the Phase I of this research project (Report No. FHWA/NC/2011-01), the windshield data were cleaned before statistical analyses were conducted mainly because: 1) there was variability in the data because of human raters' subjectivity; and 2) pavement age needed to be reset. In this phase, the automated data were not cleaned before statistical analyses because: 1) there were not enough longitudinal roadway condition data; and 2) data variability was no longer a major concern because of the consistency of the automated data collection method. Removing bogus data points and resetting pavement age require evaluating at least *three* consecutive condition ratings of each roadway section. However, the data that were available for this research project only provided *two* consecutive condition ratings of each roadway section. Without the third consecutive condition ratings, neither an ascending trend nor a descending trend can be justified. Therefore, bogus observations and pavement age cannot be corrected.

As in Phase I, outliers in the automated data were removed during the statistical analysis process.

3.3 Combination of Distress Data

Transverse Cracking and Reflective Transverse Cracking: these two distress data were collected for asphalt pavements – Transverse Cracking from both asphalt and composite pavements, and Reflective Transverse Cracking from composite pavements. Since both asphalt and composite pavements were treated as asphalt pavements in this research project, it was decided to combine two distress condition data and develop one distress model to predict transverse cracking in asphalt pavements.

3.4 Insufficient Distress Data

For some distresses in asphalt pavements, there was not sufficient information collected to develop meaningful models. This means that most likely these distresses are not common forms of distresses in North Carolina asphalt pavements. These distresses include:

- Bleeding: most of the ratings were 0’s.
- Delamination: most of the ratings were 0’s.
- Reflective Longitudinal Cracking: most of the ratings were 0’s.

CHAPTER 4 PAVEMENT DISTRESS MODELS

4.1 Normalization of the Condition Ratings

Tables 1 and 2 show that distress condition data were collected in different units: linear feet (LF), square feet (SF), inch, number of slabs, and number of joints. In order to obtain meaningful statistical analysis results, it is necessary to normalize these condition data such that the variables used in the analysis are unitless.

The equations that were used to convert individual distresses into normalized ratings are shown in Tables 4 and 5.

Table 5: Normalization of Asphalt Pavement Condition Data

Distress	**Unit**	**Normalization Equation**
Transverse/Reflective Transverse Cracking	Linear Feet	{(Transverse Cracking + Reflection Transverse Cracking) / (Length * 5280)}*10
Longitudinal Cracking	Linear Feet	{Longitudinal Cracking / (Length * 5280)}*10
Longitudinal Lane Joint	Linear Feet	{Longitudinal Lane Joint / (Length * 5280)}*10
Alligator Cracking	Square Feet	{Alligator Cracking / (Length * 7 * 5280)}*100
Ravelling	Square Feet	{Ravelling / (Length * 5280 * Section Width / Number of Lanes)}*100
Patching Area - Wheel Path	Square Feet	{Patching Area / (Length * 7 * 5280)}*100
Patching Area - Non Wheel Path	Square Feet	{Patching Area / (Length * 5280 * (Section width / Number of Lanes - 7))}*100
Maximum Average Rut Depth	Inch	100 - 100 * (Maximum Average Rut Depth) ^ 2

Table 4: Normalization of JCP Pavement Condition Data

Distress	**Unit**	**Normalization Equation**
Transverse Cracking	No. of Slabs	Transverse Cracking / Length
Longitudinal Cracking	No. of Slabs	Longitudinal Cracking / Length
PCC Patch	No. of Slabs	PCC Patch / Length
Asphalt Patch	No. of Slabs	Asphalt Patch / Length
Transverse Joint Spalled	No. of Slabs	Transverse Joint Spalled / Length
Longitudinal Joint Spalled	No. of Slabs	Longitudinal Joint Spalled / Length
Corner Break	No. of Slabs	Corner Break / Length
Joint Fault	No. of Joints	Joint Fault / Length

In Tables 4 and 5, "Length" represents the length of the roadway section. The NCDOT High Speed Distress Manual [17] specifies that "each wheel path should always be 3.5 feet wide." Therefore, "7" in Table 4 represents the overall width of the wheel path (7 feet, which is the total of two 3.5 feet wide wheel paths) in one travel lane. The normalization equation for maximum average rut depth in Table 4 was obtained by consulting the NCDOT engineers.

4.2 Development of Composite Indices

As shown in Tables 1 and 2, most of the distresses were rated at more than one severity level. Since only one distress model was developed for each type of distress, it was necessary to develop a composite index that can represent the overall condition of these distresses.

The NCDOT PMU has used a Maximum Allowable Extent (MAE) spreadsheet (Figure 1) to compute a composite index for alligator cracking. The application of the MAE method has been documented in the Phase I report (Report No. FHWA/NC/2011-01, Chapter 5). The MAE method has proven effective because the alligator cracking models developed in Phase I accurately described the deterioration trend of alligator cracking over time. Therefore, it was decided to continue using this method to develop composite distress indices in this research project.

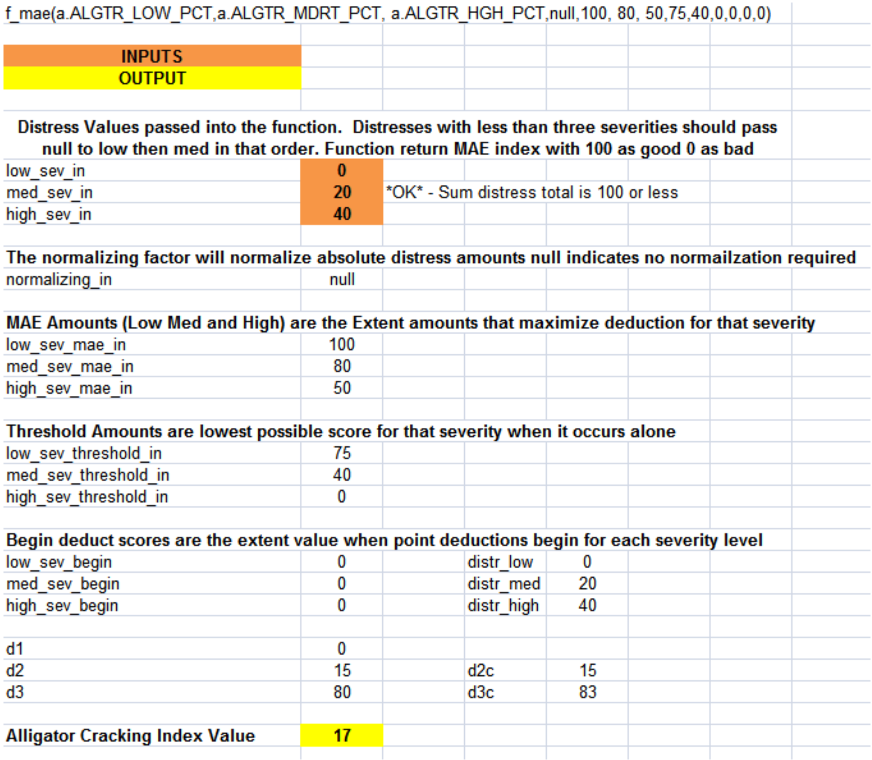
For readers' convenience, the description of the MAE method in the Phase I report is presented in the following section.

The MAE Method

> The NCDOT PMU uses a Maximum Allowable Extent (MAE) spreadsheet (Figure 1) to perform test computations of alligator cracking index values. In this spreadsheet, L/M/S ratings are entered into the orange cells (i.e., low_sev_in, med_sev_in, and high_sev_in), and the composite index value is calculated and displayed in the yellow cell. In the example below (Figure 1), L/M/S ratings are 0, 20%, and 40%, respectively. The alligator cracking index value is calculated as 17.
>
> MAE Amounts and Threshold Amounts are two sets of crucial thresholds. By definitions from the spreadsheet (Figure 1), MAE Amounts include low_sev_mae_in, med_sev_mae_in, and high_sev_mae_in, and these parameters are "the extent amounts that maximize deduction for that severity"; Threshold Amounts include low_sev_threshold_in, med_sev_threshold_in, and high_sev_threshold_in, and these parameters are "lowest possible score for that severity when it occurs alone."
>
> In the example below (Figure 1), low_sev_mae_in, med_sev_mae_in, and high_sev_mae_in are 100, 80, and 50, respectively; low_sev_threshold_in, med_sev_threshold_in, and high_sev_threshold_in are 75, 40, and 0, respectively.

> It means that Light alligator cracking can be present up to 100% of the roadway section being surveyed, Moderate alligator cracking can be rated up to 80% (cracking exists in more than 80% of the roadway section should use 80%), and Severe alligator cracking can be rated up to 50% (cracking exists in more than 50% of the roadway section should use 50%). It should be noted that the rating in this section refers to as the percentage of observed cracking at the particular severity level. When a roadway section only has Light alligator cracking, and the rating is 100%, the composite index value is 75. Similarly, when a roadway section only has Moderate alligator cracking, and the rating is 80%, the composite index value is 40; and when a roadway section only has Severe alligator cracking, and the rating is 50%, the composite index value is 0.

From the Phase I project, the appropriate MAE Threshold Amounts are determined to be 60, 30, and 0 for low_sev_threshold_in, med_sev_threshold_in, and high_sev_threshold_in, respectively. These same threshold amounts were used in this research project. However, different MAE Amounts were used in Phase II for each type of distress. The method to calculate MAE Amounts is described in the following section.



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 1: The MAE Spreadsheet

4.3 Calculation of MAE Amounts

MAE Amounts vary based on type of distress. This is to ensure that a composite index can accurately represent the overall condition of the corresponding type of distress. Scatterplots of normalized distress ratings showed that there were outliers in each plot. This was expected when analyzing field data. To avoid the impact of outliers, percentiles were used to determine MAE Amounts, and the method involved three steps, as follows:

1. Calculate the 98th percentiles of each type of distress' ratings;
2. Average these percentiles; and
3. Assign these averages as MAE Amounts.

The method is also illustrated in the flow chart below (Figure 2). It was observed from the scatterplots that the 98th percentile was an appropriate threshold to remove outliers, meanwhile preserving the majority of valid data points. In Figure 2, P_98 represents the 98th percentile.

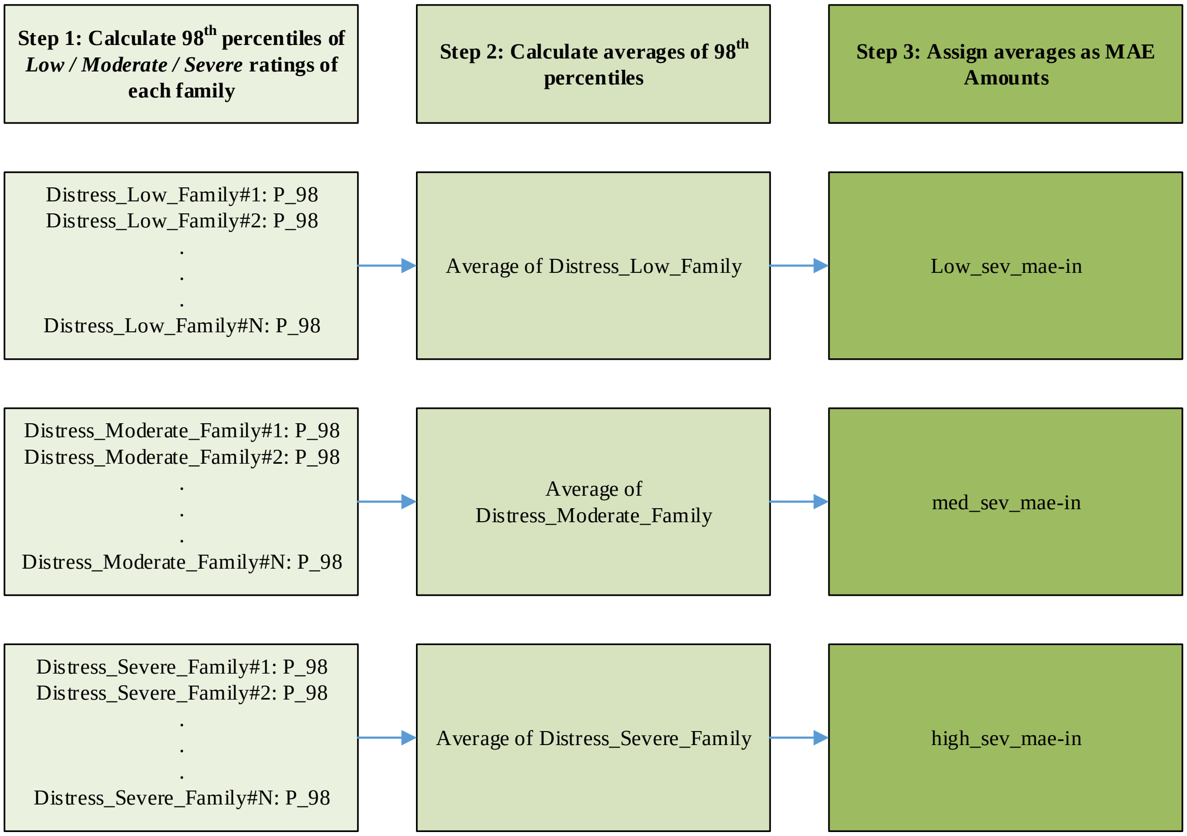


Figure 2: Flow Chart of the MAE Method

An example of how alligator cracking index values are calculated is described below. It is a four-step procedure, as follows:

Step 1. Normalizing the raw automated data

The alligator cracking ratings have three severity levels: Light (i.e., ALGTR_LOW_SF), Moderate (i.e., ALGTR_MDRT_SF), and Severe (i.e., ALGTR_HGH_SF). The following three equations are used to normalize the raw data:

- distr_low = ALGTR_LOW_SF/(LENGTH*5280*7)*100;
- distr_med = ALGTR_MDRT_SF/(LENGTH*5280*7)*100;
- distr_high = ALGTR_HGH_SF/(LENGTH*5280*7)*100;

where, LENGTH is the length of the roadway section, 100 is the conversion factor. It should be noted that:

- The conversation factor varies for different types of distresses (as shown in Table 4);
- For some types of distresses, there are only one or two severity levels, e.g., Light, or Light and Severe.
    - If there is only one level: Light, then the three equations are:

      distr_low = ALGTR_LOW_SF/(LENGTH*5280*7)*100;
      distr_med = 0;
      distr_high = 0;
    - If there are two levels: Light and severe, then the three equations are:

      distr_low = ALGTR_LOW_SF/(LENGTH*5280*7)*100;
      distr_med = 0;
      distr_high = ALGTR_HGH_SF/(LENGTH*5280*7)*100;

Step 2. Calculating the 98th percentiles of distr_low, distr_med, and distr_high

The 98th percentiles (P_98_distr_low, P_98_distr_med, and P_98_distr_high) for all seven families are calculated and averaged. As shown in Table 6.

Table 6: The 98th Percentiles of Alligator Cracking Severity Levels

Family	**P_98_distr_low**	**P_98_distr_med**	**P_98_distr_high**
Interstate	34.42135051	9.08017871	2.49792021
US_0_5k	44.80834699	7.699305372	2.672980614
US_5_15k	48.53958615	9.283778024	3.856958644
US_15kplus	48.98610162	8.915183778	5.272917728
NC_0_1k	35.78119498	4.756093282	4.166666667
NC_1_5k	40.3011744	5.878677323	2.102032133
NC_5kplus	38.9356734	5.388752953	2.911118417
AVG	**41.68**	**7.29**	**3.35**

Step 3. Determining low_sev_mae_in, med_sev_mae_in, and high_sev_mae_in

From the previous step, the MAE values are obtained. As follows:

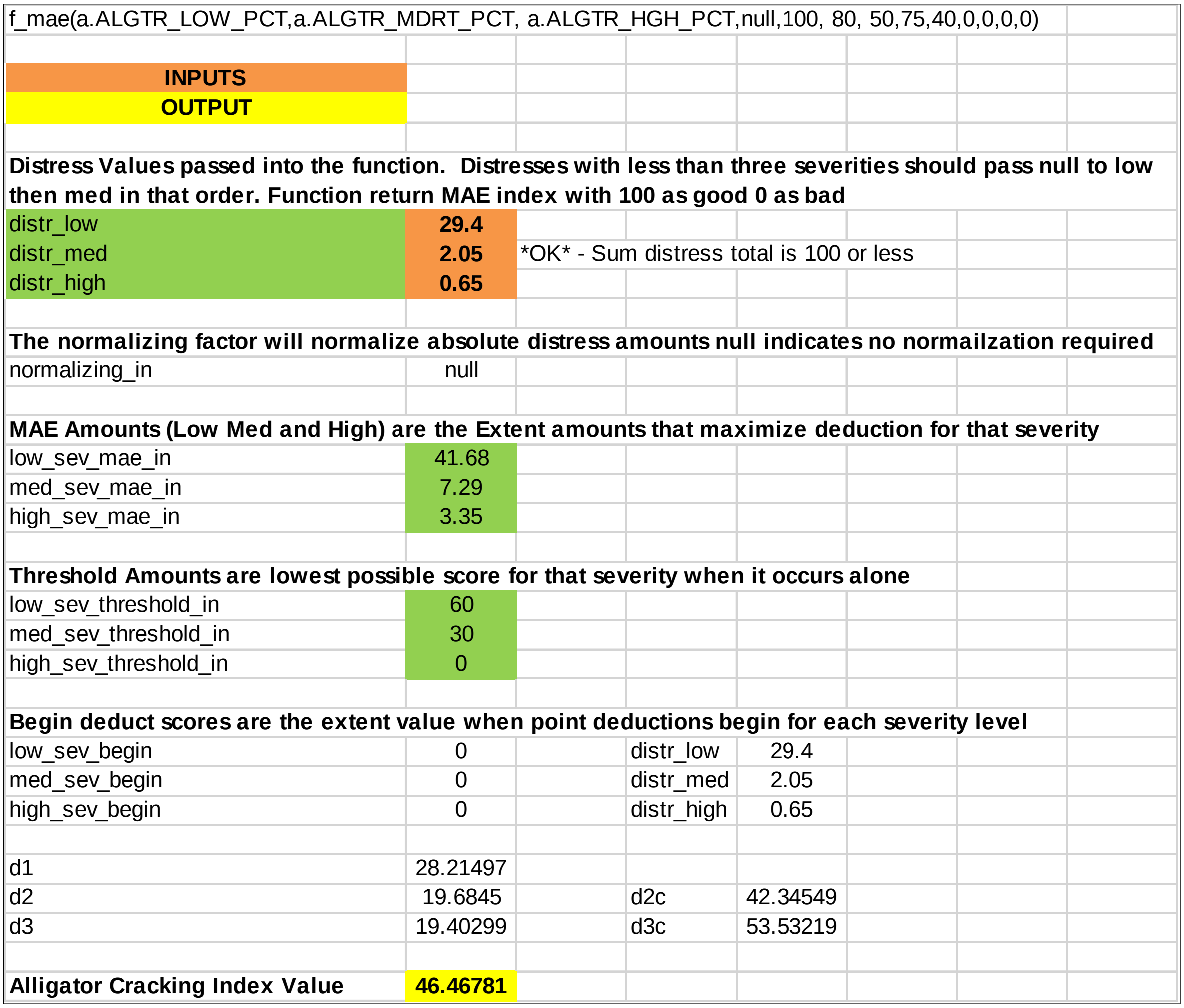
- low_sev_mae_in = average of P_98_distr_low = 41.68;
- med_sev_mae_in = average of P_98_distr_med = 7.29;
- high_sev_mae_in = average of P_98_distr_high = 3.35;

Step 4. Calculating Alligator cracking index values using the MAE functions

The same MAE functions used for calculating alligator cracking index values for the manual data was used in this research project – for the automated data, for all types of distresses (except for rutting), and for asphalt and JCP pavements. In the example, the alligator cracking value is calculated and rounded up to be 46.

There are some important information which are highlighted in green in Figure 3. As described below:

- distr_low, distr_med, and distr_high: these are the normalized data obtained in Step 1. For the manual data, these are the original raw data.
- low_sev_mae_in, med_sev_mae_in, and high_sev_mae_in: they are obtained in Step 3.
- low_sev_mae_in, med_sev_mae_in, and high_sev_mae_in: they are different than the threshold values used for the manual data, and were determined in the PMS I project.



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				
distr_low	**29.4**			
distr_med	**2.05**	*OK* - Sum distress total is 100 or less		
distr_high	**0.65**			
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	41.68			
med_sev_mae_in	7.29			
high_sev_mae_in	3.35			
Threshold Amounts are lowest possible score for that severity when it occurs alone				
low_sev_threshold_in	60			
med_sev_threshold_in	30			
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	29.4
med_sev_begin	0		distr_med	2.05
high_sev_begin	0		distr_high	0.65
d1	28.21497			
d2	19.6845		d2c	42.34549
d3	19.40299		d3c	53.53219
Alligator Cracking Index Value	**46.46781**			

Figure 3: An example of the MAE Method

The MAE values for asphalt and JCP pavements are summarized in Table 7.

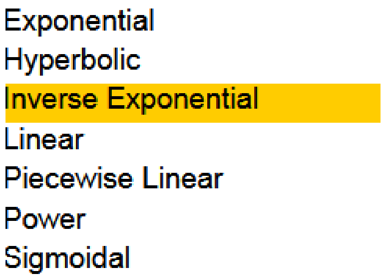
Table 7: MAE Values for Asphalt and JCP Pavements

	Distress	**low_sev_ mae_in**	**med_sev_ mae_in**	**high_sev_ mae_in**
Asphalt Pavement	Alligator Cracking	41.68 S.F.	7.29 S.F.	3.35 S.F.
	Longitudinal Cracking	4.58 L.F.	N/A	7.04 L.F.
	Longitudinal Lane Joint	1.57 L.F.	N/A	0.00176 L.F.
	Patching Area - Non Wheel Path	17.72 S.F.	N/A	N/A
	Patching Area - Wheel Path	13.11 S.F.	N/A	N/A
	Ravelling	34.92 S.F.	34.54 S.F.	31.45 S.F.
	Rutting	N/A	N/A	N/A
	Transverse Cracking	5.96 L.F.	3.62 L.F.	1.36 L.F.
JCP Pavement	Asphalt Patch	20.24	N/A	N/A
	Corner Break	6.01	N/A	N/A
	Joint Fault	60.21	10.03	1.40
	Longitudinal Cracking	43.28	N/A	26.60
	Longitudinal Joint Spalled	86.09	N/A	N/A
	PCC Patch	15.76	N/A	N/A
	Transverse Cracking	37.81	N/A	27.61
	Transverse Joint Spalled	91.27	28.66	22.92

Note: 1) N/A indicates the severity level was not measured during the automated surveys.
2) The unit of MAE values for JCP pavements is number of slabs.

4.4 Selection of the Model Form

As indicated in the Phase I report, the NCDOT PMS accepts 7 types of performance model forms (Figure 4), and that the sigmoidal form was proven to be an appropriate form to be used to develop the alligator cracking distress models because of its greater flexibility in predicting the deterioration of a roadway section. Because of its successful application in Phase I, the sigmoidal form was used in Phase II to develop all distress models.



Exponential
Hyperbolic
Inverse Exponential
Linear
Piecewise Linear
Power
Sigmoidal

Figure 4: Accepted Performance Model Forms in the NCDOT PMS

The mathematical expression a sigmoidal model is $y = \frac{a}{1 + e^{-\frac{x-b}{c}}}$

where
y: PCR rating, also referred to RTG_NBR
x: AGE
a, *b*, *c*: variables in the model.

4.5 Development of Distress Models

The same procedures in Phase I (Report No. FHWA/NC/2011-01, Chapter 4, sections 4.1 and 4.2) were followed to develop distress models for asphalt and JCP pavements. Two things that were different from Phase I were that: 1) For JCP pavements, only one distress model was developed for each type of distress because of the small sample size; and 2) For asphalt pavements, a few roadway families were combined because of their small sample sizes or similar deterioration trends. Distress models were developed for the following families:

- Interstate
- US 0-5k
- US 5-15k
- US 15kplus
- NC 0-1k
- NC 1-5k
- NC 5kplus

It should be noted that the automated data were collected only for Interstate and Primary routes (US and NC). Secondary routes (SR) continue to be surveyed by human raters. Therefore, no distress models were developed for SR routes in this research project.

Rutting is different from other distresses in that it was measured in inches. A power function was used to model rutting because it fit the data better than other model forms. The power function used was Rutting Index =100 - a*Age^1.5, where a is the model parameter.

The resulting models parameters are summarized in Tables 8 through 10. The models curves are included in Appendices A through H.

Table 8: Distress Models of Asphalt Pavements -- Model Parameters (I)

Distress	Family	a	b	c
Alligator Cracking	Interstate	102	13.44	-3.35
	US 0-5k	105	13.72	-4.46
	US 5-15k	109	11.35	-4.79
	US 15kplus	112	8.59	-3.90
	NC 0-1k	102	11.00	-2.91
	NC 1-5k	107	12.13	-4.63
	NC 5kplus	108	11.48	-4.54
Longitudinal Cracking	Interstate	100	16.57	-2.28
	US 0-5k	100	14.47	-1.91
	US 5-15k	100	15.32	-2.09
	US 15kplus	100	12.18	-1.34
	NC 0-1k	100	12.36	-1.28
	NC 1-5k	100	13.76	-1.65
	NC 5kplus	100	13.97	-1.59
Longitudinal Lane Joint	Interstate	100	18.76	-2.62
	US 0-5k	100	13.5	-1.80
	US 5-15k	100	15.93	-2.24
	US 15kplus	100	21.51	-3.06
	NC 0-1k	100	16.71	-2.29
	NC 1-5k	100	17.46	-2.39
	NC 5kplus	100	13.87	-1.86
Patching Area - Non Wheel Path	Interstate	100	18.77	-2.59
	US 0-5k	100	21.86	-3.26
	US 5-15k	100	24.41	-3.70
	US 15kplus	100	22.45	-3.63
	NC 0-1k	100	24.24	-3.73
	NC 1-5k	100	21.04	-3.10
	NC 5kplus	100	21.31	3.39
Patching Area - Wheel Path	Interstate	100	14.67	-1.96
	US 0-5k	100	18.14	-2.76
	US 5-15k	100	18.81	-2.92
	US 15kplus	100	20.5	-3.38
	NC 0-1k	100	20.07	-3.11
	NC 1-5k	100	18	-2.68
	NC 5kplus	100	18.39	-3.01

Table 9: Distress Models of Asphalt Pavements -- Model Parameters (II)

Distress	Family	a	b	c
Ravelling	Interstate	100	17.1	-2.78
	US 0-5k	100.3	30.41	-5.26
	US 5-15k	102	22.59	-5.66
	US 15kplus	105	20.95	-6.99
	NC 0-1k	101	16.45	-3.48
	NC 1-5k	100.5	22.64	-4.35
	NC 5kplus	100.5	21.18	-4.07
Rutting	Interstate	1.031		
	US 0-5k	0.989		
	US 5-15k	0.937		
	US 15kplus	1.020		
	NC 0-1k	0.954		
	NC 1-5k	1.001		
	NC 5kplus	0.942		
Transverse Cracking	Interstate	103	16.39	-4.82
	US 0-5k	101	10.91	-2.48
	US 5-15k	102	12.58	-3.04
	US 15kplus	102	11.33	-3.01
	NC 0-1k	101	9.54	-2.13
	NC 1-5k	101	11.13	-2.54
	NC 5kplus	102	10.75	-2.67

Table 10: Distress Models of JCP Pavements

Distress	a	b	c
Asphalt Patch	100	15.05	-2.20
Corner Break	100.23	17.55	-2.95
Joint Fault	100.32	25.70	-4.49
Longitudinal Cracking	102.5	14.36	-3.87
Longitudinal Joint Spalled	100	17.82	-5.31
PCC Patch	100	19.97	-3.20
Transverse Cracking	102	19.42	-5.11
Transverse Joint Spalled	100	14.94	-3.39

CHAPTER 5 PAVEMENT PERFORMANCE MODELS

In Phase I, the sigmoidal model form was used for pavement performance models because it fit the windshield data well. The same sigmoidal form was used in Phase II to allow comparison of Phase I models and Phase II modes.

As introduced earlier, pavement performance models describe the relationship between the dependent variable – Pavement Condition Rating (PCR) and the independent variable – pavement age. The NCDOT's PCR is a composite index representing the overall distress condition of a roadway section. Therefore, PCR values for asphalt pavements should be calculated to represent all distresses in asphalt pavements (Table 4), and PCR values for JCP pavements should also be calculated for all distresses in JCP pavements (Table 5).

5.1 Composite Performance Index for Asphalt Pavements

The NCDOT PMU has used a set of deduction values for PCR calculation for asphalt pavements. This set of deduction values was derived from NCDOT's engineers' years of experience based on the windshield condition data. Most of the windshield data were categorical (i.e., None/Light/Moderate/Severe). For the automated data, however, a different set of deduction values should be determined because these data are different in that they are all numerical. The relative importance between pavement distresses should be retained because it reflects NCDOT engineers' valuable experience and when developing the composite index, it can be used to calculate the weights of distresses.

Analytical Hierarchy Process (AHP) was used to develop PCR composite index for asphalt pavements. AHP is a Multiple-Criteria Decision-Making (MCMD) method that was originally developed by Thomas Saaty [18]. It has proven to be an effective decision-making tool for fields such as government, business, industry, healthcare, and education. To use AHP, the relative importance of one criterion over another is used to build a comparison matrix. The eigenvector of this matrix provides the weights of criteria, which can be used to develop a composite index. With this composite index, decision-makers can perform strategic planning by evaluating just one single index instead of examining all criteria. The key to obtaining an accurate composite index is to determine the appropriate relative importance. In this case, this relative importance can be derived from NCDOT's existing deduction algorithm for PCR calculation (Table 11).

In Table 11, the average values of deduction points of different types of distresses were calculated. These averages were used later to build a comparison matrix (Table 13). It should be noted that distress data of bleeding and oxidation were insufficient, and there were no models developed for these two types of distresses.

Once the averages were obtained, they were assigned to the corresponding types of distresses, as shown in Table 12. Since Longitudinal Lane Joint and Patching Area - Non Wheel Path are non-loaded related distresses, they were assigned the smallest calculated value which was 7. Longitudinal Cracking was assigned a values of 9 because it is considered load related distress, but has less impact on the overall pavement condition than alligator cracking and patching, and rutting.

Table 11: Asphalt Pavement Deduction Values for PCR Calculation

Distress	Severity Level	Deduction	Average
Alligator Cracking	(L)ight	3.3 points - 10% to 90%; 1 point > 90% (3.3*9 + 1*0.1 = 29.8 points)	42
	(M)oderate	7.5 points - 10% to 40%; 2 points > 40% (7.5*4 + 2*6 = 42 points)	
	(S)evere	15 points - 10% to 20%; 3 points > 20% (15*2 + 3*8 = 54 points)	
Transverse Cracking	(L)ight	5 points	17
	(M)oderate	15 points	
	(S)evere	30 points	
Rutting	(L)ight	5 points	18
	(M)oderate	20 points	
	(S)evere	30 points	
Raveling	(L)ight	2 points	7
	(M)oderate	5 points	
	(S)evere	15 points	
Bleeding	(L)ight	10 points	Models not developed
	(M)oderate	20 points	
	(S)evere	30 points	
Patching	(L)ight	5 points	12
	(M)oderate	10 points	
	(S)evere	20 points	
Oxidation	(L)ight	0 points	Models not developed
	(S)evere	5 points	

Table 12: Asphalt Pavement Average Values for PCR Calculation

Distress	Average	Remark
Alligator Cracking	42	
Transverse/Reflective Transverse Cracking	17	
Longitudinal Cracking	9	
Longitudinal Lane Joint	7	Use the smallest value as it is non-load related
Ravelling	7	
Patching Area - Wheel Path	12	
Patching Area - Non Wheel Path	7	Use the smallest value as it is non-load related
Rutting - Maximum Average Depth	18	

Table 13 shows the comparison matrix developed using the average values listed in Table 12. The main diagonal of the matrix is highlighted in yellow. The eigenvector of this matrix provides the weights of each type of distress in asphalt pavements, as shown in Table 14. Then the PCR index can be calculated as:

PCR = 0.354*ALGTR + 0.141*TRA + 0.077*LNG + 0.059*LNG_JNT + 0.059*RVL + 0.10*WP + 0.059*NWP + 0.15*RUT

Table 13: Comparison Matrix for Asphalt Pavements

Distress	ALGTR	TRA	LNG	LNG_JNT	RVL	WP	NWP	RUT
Alligator Cracking (ALGTR)	42/42 = 1.00	42/17 = 2.47	42/9 = 4.67	42/7 = 6.00	42/7 = 6.00	42/12 = 3.50	42/7 = 6.00	42/18 = 2.33
Transverse/Reflective Transverse Cracking (TRA)	17/42= 0.40	17/17 = 1.00	17/9 = 1.89	17/7 = 2.43	17/7 = 2.43	17/12 = 1.42	17/7 = 2.43	17/18 = 0.94
Longitudinal Cracking (LNG)	9/42 =0.21	9/17 = 0.53	9/9 = 1.00	9/7 = 1.29	9/7 = 1.29	9/12 = 0.75	9/7 = 1.29	9/18 = 0.50
Longitudinal Lane Joint (LNG_JNT)	7/42 = 0.17	7/17 = 0.41	7/9 = 0.78	7/7 = 1.00	7/7 = 1.00	7/12 = 0.58	7/7 = 1.00	7/18 = 0.39
Ravelling (RVL)	7/42 = 0.17	7/17 = 0.41	7/9 = 0.78	7/7 = 1.00	7/7 = 1.00	7/12 = 0.58	7/7 = 1.00	7/18 = 0.39
Patching Area - Wheel Path (WP)	12/42 = 0.29	12/17 = 0.71	12/9 = 1.33	12/7 = 1.71	12/7 = 1.71	12/12 = 1.00	12/7 = 1.71	12/18 = 0.67
Patching Area - Non Wheel Path (NWP)	7/42 = 0.17	7/17 = 0.41	7/9 = 0.78	7/7 = 1.00	7/7 = 1.00	7/12 = 0.58	7/7 = 1.00	7/18 = 0.39
Rutting - Maximum Average Depth RUT)	18/42 = 0.43	18/17 = 1.06	18/9 = 2.00	18/7 = 2.57	18/7 = 2.57	18/12 = 1.50	18/7 = 2.57	18/18 = 1.00

Table 14: Weight Factors for Asphalt Pavement PCR Calculation

Distresses	**Weight Factor**
Alligator Cracking (ALGTR)	0.354
Transverse/Reflective Transverse Cracking (TRA)	0.141
Longitudinal Cracking (LNG)	0.077
Longitudinal Lane Joint (LNG_JNT)	0.059
Ravelling (RVL)	0.059
Patching Area - Wheel Path (WP)	0.100
Patching Area - Non Wheel Path (NWP)	0.059
Rutting - Maximum Average Depth RUT)	0.150

5.2 Development of Performance Models for Asphalt Pavements

Nonlinear regression analysis similar to the one used in Phase I was conducted to derive parameters for performance models. The results of sigmoidal models are summarized in Table 15. Model curves are included in Appendix I.

Table 15: Sigmoidal Performance Models Parameters for Asphalt Pavements

Family	***a***	***b***	***c***
Interstate	103.4	12.68	-3.83
US 0-5k	110	14.57	-6.29
US 5-15k	112	14.23	-6.74
US 15kplus	112	11.55	-5.43
NC 0-1k	110	12.30	-5.33
NC 1-5k	112	13.58	-6.52
NC 5kplus	112	13.51	-6.39

5.3 Composite Performance Index for JCP Pavements

A similar procedure was used to develop the composite performance index for JCP pavements. Table 16 includes a set of deduction values that has been used by the NCDOT PMU. The sums of deduction points of different types of distresses were calculated (Table 16), and used to build the comparison matrix (Table 17). Then the weights of each type of distress, i.e., eigenvector of this matrix, were obtained, as shown in Table 18.

It should be noted that 1) since distresses of shoulders were not included in the scope of this research project, Shoulder Drop-off was not studied; and 2) Patching can significantly impact the performance of JCP pavements, thus it was assigned the largest value, which was 18.

From the calculated weights (Table 18), the PCR index can be calculated as:

PCR = 0.111*TRNSVRS_CRK + 0.111*LNGTDNL_CRK + 0.2087*CON_PATCH +
0.208*ASPHLT_PTCH + 0.098*TRNSVRS_SPLL + 0.098*LNGTDNL_JNT_SPLL +
0.066*CRNR + 0.098*FAULT

5.4 Development of Performance Models for JCP Pavements

Nonlinear regression analysis similar to the one used in Phase I was conducted to derive parameters for performance models. The results of sigmoidal models are summarized in Table 19. Model curves are included in Appendix J.

Table 16: JCP Pavement Deduction Values for PCR Calculation

Distress	Severity Level	Deduction	Sum
Cracking (all types)	(L)ight	0.2 points / 1% (0.2*10 = 2.0)	9.6
	(M)oderate	0.5 points / 1% to 60%; 0.1 points / 1% > 60% (0.5*6 + 0.1*4 = 3.4)	
	(S)evere	0.75 points / 1% to 40%; 0.2 points / 1% > 40% (0.75*4 + 0.2*6 = 4.2)	
Corner Breaks	(L)ight	0.1 points / 1% (0.1*10 = 1.0)	5.7
	(M)oderate	0.15 points / 1% (0.15*10 = 1.5)	
	(S)evere	0.375 points / 1% to 80%; 0.1 points / 1% > 80% (0.375*8 + 0.1*2 = 3.2)	
Joint Seal Damage	(L)ight	0.1 points / 1% (0.1*10 = 1.0)	8.9
	(M)oderate	0.6 points / 1% to 50%; 0.1 points / 1% > 50% (0.6*5 + 0.1*5 = 3.5)	
	(S)evere	1.0 points / 1% to 30%; 0.2 points / 1% > 30% (1.0*3 + 0.2*7 = 4.4)	
Spalling of Joints	(L)ight	0.15 points / 1% (0.15*10 = 1.5)	8.5
	(M)oderate	0.375 points / 1% to 80%; 0.1 points / 1% > 80% (0.375*8 + 0.1*2 = 3.2)	
	(S)evere	0.5 points / 1% to 60%; 0.2 points / 1% > 60% (0.5*6 + 0.2*4 = 3.8)	
Shoulder Drop-off	(L)ight	5 points	Not Applicable
	(M)oderate	15 points	
	(S)evere	25 points	
Patching		3.75 points per patch to 8 patches; > 8 patches - 1 pt. / patch	18

Table 6: Comparison Matrix for JCP Pavements

Distress	TRNSVRS_CRK	LNGTDNL_CRK	CON_PATCH	ASPHLT_PTCH	TRNSVRS_SPLL	LNGTDNL_JNT_SPLL	CRNR	FAULT
Transverse Cracking (TRNSVRS_CRK)	9.6/9.6 = 1.0	9.6/9.6 = 1.0	9.6/18 = 0.53	9.6/18 = 0.53	9.6/8.5 = 1.13	9.6/8.5 = 1.13	9.6/5.7 = 1.68	9.6/8.5 = 1.13
Longitudinal Cracking (LNGTDNL_CRK)	9.6/9.6 = 1.0	9.6/9.6 = 1.0	9.6/18 = 0.53	9.6/18 = 0.53	9.6/8.5 = 1.13	9.6/8.5 = 1.13	9.6/5.7 = 1.68	9.6/8.5 = 1.13
PCC Patch (CON_PATCH)	18/9.6 = 1.88	18/9.6 = 1.88	18/18 = 1.0	18/18 = 1.0	18/8.5 = 2.12	18/8.5 = 2.12	18/5.7 = 3.16	18/8.5 = 2.12
Asphalt Patch (ASPHLT_PTCH)	18/9.6 = 1.88	18/9.6 = 1.88	18/18 = 1.0	18/18 = 1.0	18/8.5 = 2.12	18/8.5 = 2.12	18/5.7 = 3.16	18/8.5 = 2.12
Transverse Joint Spalled (TRNSVRS_SPLL)	8.5/9.6 = 0.89	8.5/9.6 = 0.89	8.5/18 = 0.47	8.5/18 = 0.47	8.5/8.5 = 1.0	8.5/8.5 = 1.0	8.5/5.7 = 1.49	8.5/8.5 = 1.0
Longitudinal Joint Spalled (LNGTDNL_JNT_SPLL)	8.5/9.6 = 0.89	8.5/9.6 = 0.89	8.5/18 = 0.47	8.5/18 = 0.47	8.5/8.5 = 1.0	8.5/8.5 = 1.0	8.5/5.7 = 1.49	8.5/8.5 = 1.0
Corner Break (CRNR)	5.7/9.6 = 0.59	5.7/9.6 = 0.59	5.7/18 = 0.32	5.7/18 = 0.32	5.7/8.5 = 0.67	5.7/8.5 = 0.67	5.7/5.7 = 1.0	5.7/8.5 = 0.67
Joint Fault (FAULT)	8.5/9.6 = 0.89	8.5/9.6 = 0.89	8.5/18 = 0.47	8.5/18 = 0.47	8.5/8.5 = 1.0	8.5/8.5 = 1.0	8.5/5.7 = 1.49	8.5/8.5 = 1.0

Table 18: Weight Factors for JCP Pavement PCR Calculation

Distress	**Weight Factor**
Transverse Cracking (TRNSVRS_CRK)	0.111
Longitudinal Cracking (LNGTDNL_CRK)	0.111
PCC Patch (CON_PATCH)	0.208
Asphalt Patch (ASPHLT_PTCH)	0.208
Transverse Joint Spalled (TRNSVRS_SPLL)	0.098
Longitudinal Joint Spalled (LNGTDNL_JNT_SPLL)	0.098
Corner Break (CRNR)	0.066
Joint Fault (FAULT)	0.098

Table 19: Sigmoidal Performance Models Parameters for JCP Pavements

Family	***a***	***b***	***c***
Overall JCP	100.3	20.49	-3.48

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

Conclusions of this research project and recommendations for future research are summarized in this chapter.

6.1 Conclusions

The Model Development Process

The process of developing distress and performance models for the automated data was established. In the Phase I of this research project, the strict sample size requirement of nonlinear regression analysis was met because the NCDOT has maintained large amounts of windshield data. For Phase II, only two years' worth of data (2012 and 2013) were collected because the NCDOT just began the automated data collection efforts. Therefore, some families defined in Phase I were combined because of the small sample sizes. Pavement age was not reset because condition data collected over three consecutive years are yet available for them to be used by the age reset algorithm. Despite these limitations, the process of model development has been successfully developed, which allows quick future updates of existing models once new automated condition data are collected.

Composite Indices

An approach to derive composite indices was developed and successfully used to develop distress and performance models. The automated data usually contain several severity ratings for each distress. These ratings need to be consolidated into one index (i.e., a composite distress index) in order to be used as the dependent variable for the distress model development purpose. Similarly, various distresses in both asphalt and JCP pavements were surveyed. The composite indices of these distresses need to be consolidated into another single composite index (i.e., PCR) in order to develop performance models. The approach involved the following steps:

- For composite distresses indices, the MAE method used by the NCDOT PMU to calculate the composite index of alligator cracking windshield data was modified and applied to the automated data. The 98th percentiles of distresses were calculated and averaged, entered into the MAE functions, and then composite distress indices of asphalt and JCP pavements were calculated and used to develop distress models.
- For composite indices of the overall performance (i.e., PCR), deduction values used by the NCDOT PMU were analyzed to calculate the relative importance between pavement distresses, the Analytical Hierarchy Process (AHP) was used to obtain the weight factor of each distress, and then PCR values were calculated and used to develop performance models for asphalt and JCP pavements. AHP has proven to be an effective method because the magnitudes of weight factors match with NCDOT engineers' experience regarding the extent of impact of an individual distress on pavement performance.

Distress and Performance Models

The newly developed models from the automated data performed reasonably well. Even though statistics such as Standard Error of the Regression and R-square values can be used to test goodness-of-fit of nonlinear models (e.g., sigmoidal) and linear models (e.g., power), a direct visual comparison of Phase I and Phase II model curves is an more effective way. The reason is that if two groups of model curves are comparable, the characteristics of pavement performance are correctly captured and summarized by these two groups of models, and the appropriateness of the models is further confirmed by the fact that these models were developed from condition data collected using two different methods. To make a fair comparison, the model form applied to the same distress in Phase I and Phase II should be the same. In Appendices A through J, Phase I and Phase II model curves are overlaid on top of each other if they belong to the same type of distress. Among the curves that have the same model forms, alligator cracking curves are comparable except for the US 15kplus curve, asphalt performance curves are comparable, and JCP performance curves are not comparable possibly because of the small sample size of the automated data. In addition, a separate observation of the automated data distress model curves indicated that these curves start showing a decreasing trend at around 10~13 years. This concurred with the NCDOT's maintenance practice that is documented in "Proposed Life Cycle Cost Analysis Procedure Summary [19]." Based on these observations, it can be concluded that the newly developed models are robust.

6.2 Recommendations

- It is recommended to update the newly developed models after new condition data are collected. With three years' worth of data, pavement age can be reset, and more accurate pavement distress and performance models are expected.

The following recommendations were proposed in Phase I, and they are also applicable to this research project:

- To improve data quality for increased PMS performance, it is recommended that 1) raters should record maintenance activities when observed. This allows pavement age to be accurately reset instead of judging from the magnitudes of PCR jumps; and 2) a centralized database should be developed that contains both pavement performance ratings and pavement construction history. This database eliminates the need to merge multiple databases, and more importantly preserves pavement sections presenting valuable pavement performance information that otherwise are purged during the database merging process.
- This research project focused on asphalt and JCP pavements, and composite pavements are considered as a part of asphalt pavements, even though they perform differently. It is recommended that deterioration models for composite pavements be developed in future efforts.
- It is recommended to subdivide the current 18 roadway families into three regions. The reason is that for example, Interstate 0-50k routes in the Mountains region perform

differently than the ones in the Piedmont region, and similarly roadways belong to other families perform differently in different regions. Therefore, additional models (e.g., Interstate 0-50k_Mountains, Interstate 0-50k_Piedmont, and Interstate 0-50k_Coastal) should be developed, if possible, to enhance functionality of the NCDOT PMS.

- It is recommended that additional weight factors be developed that consider highway use categories such as Statewide (National Highway System), Regional and Subregional (local) roads.

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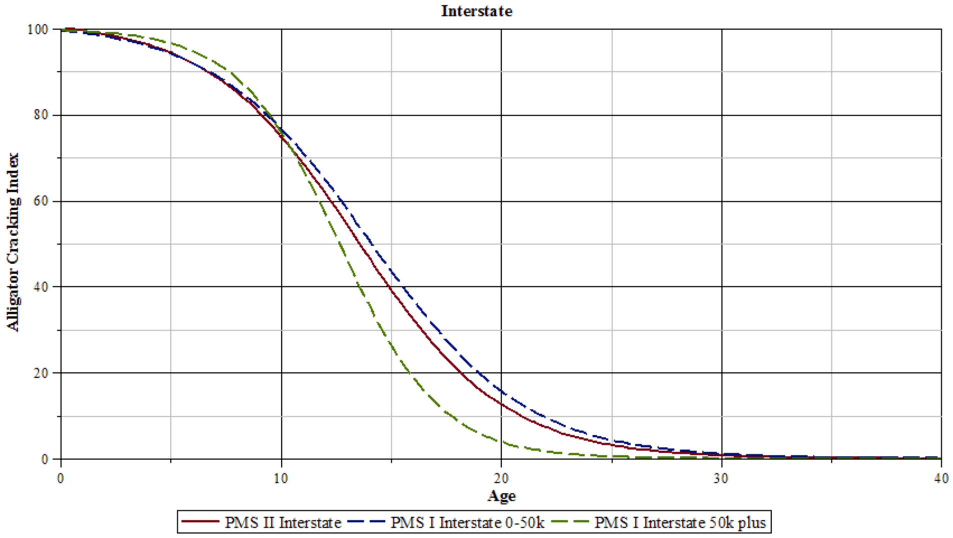
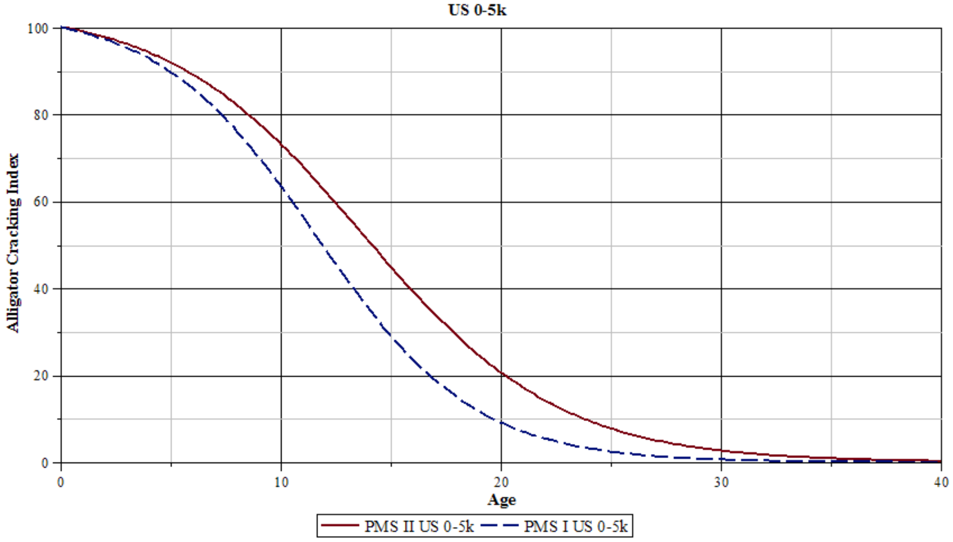
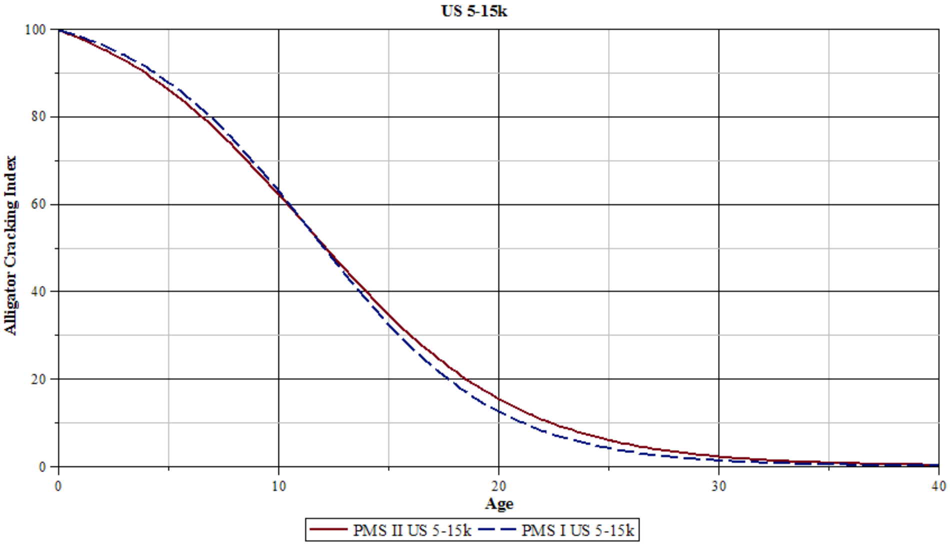
Appendix A – Alligator Cracking Curves



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Alligator Cracking Index
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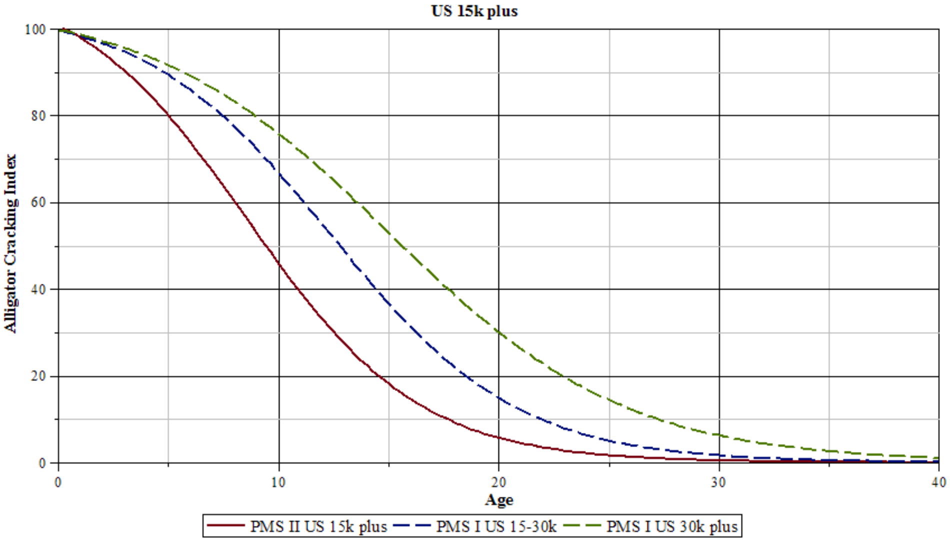
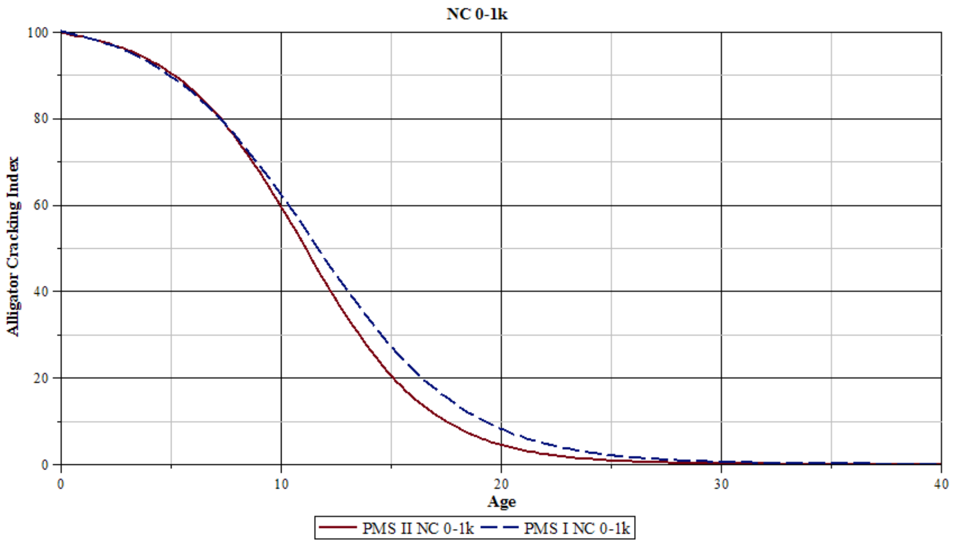
80
60
40
20
0
0
10
20
30
40
Age
PMS II US 5-15k
PMS I US 5-15k


US 15k plus
Alligator Cracking Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II US 15k plus
PMS I US 15-30k
PMS I US 30k plus


NC 0-1k
Alligator Cracking Index
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60
40
20
0
0
10
20
30
40
Age
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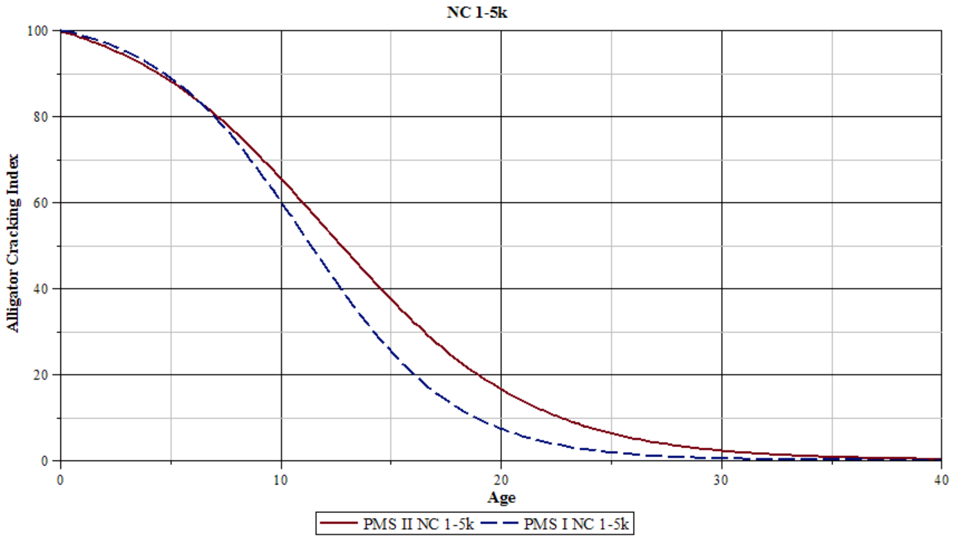
PMS I NC 0-1k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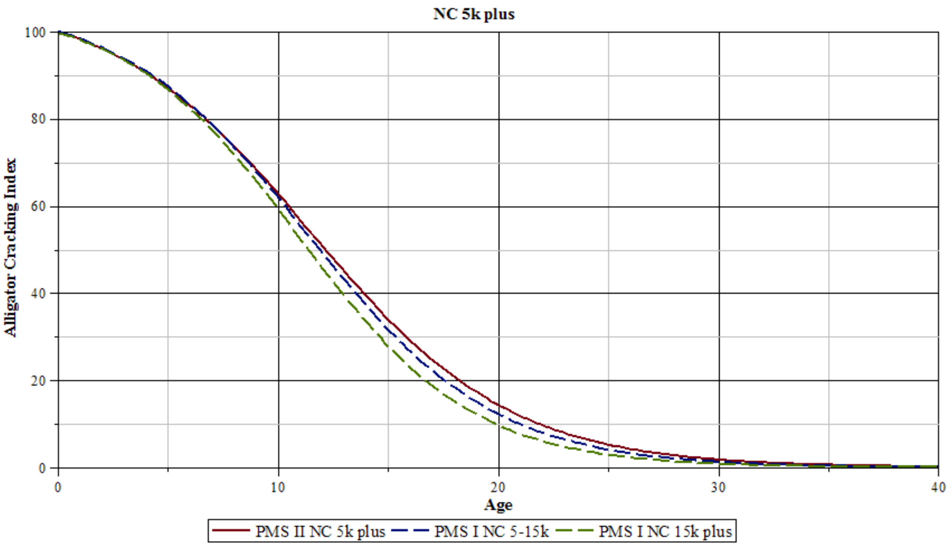
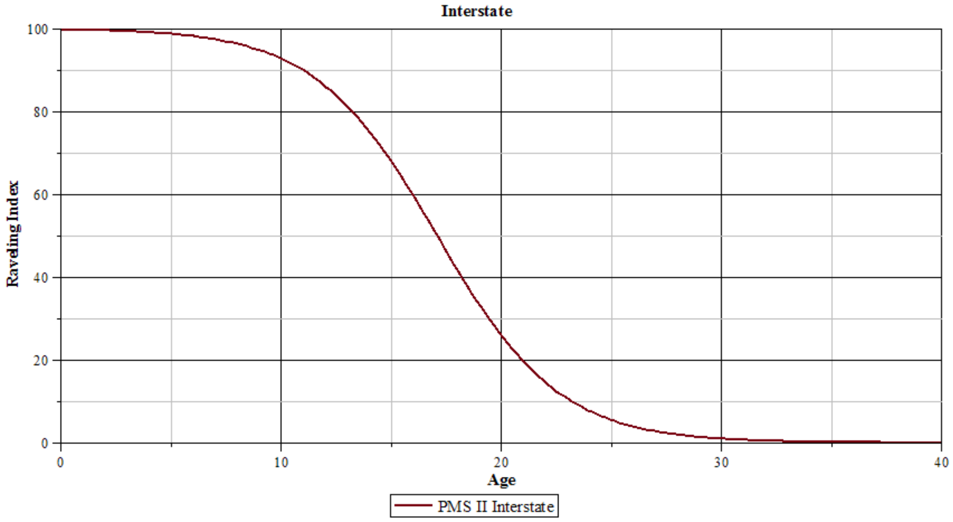
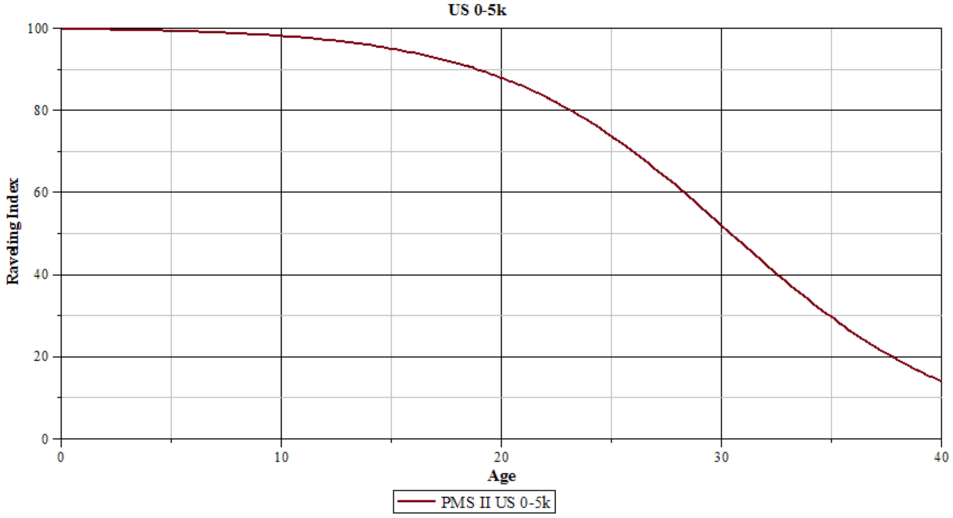
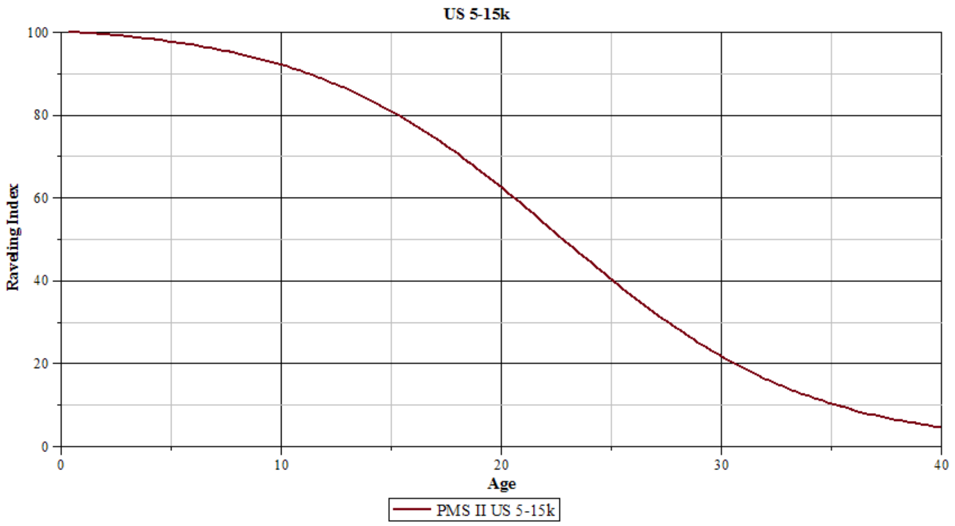
60
40
20
0
0
10
20
30
40
Age
PMS II NC 1-5k
PMS I NC 1-5k


NC 5k plus
Alligator Cracking Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 5k plus
PMS I NC 5-15k
PMS I NC 15k plus

Appendix B –Raveling Curves



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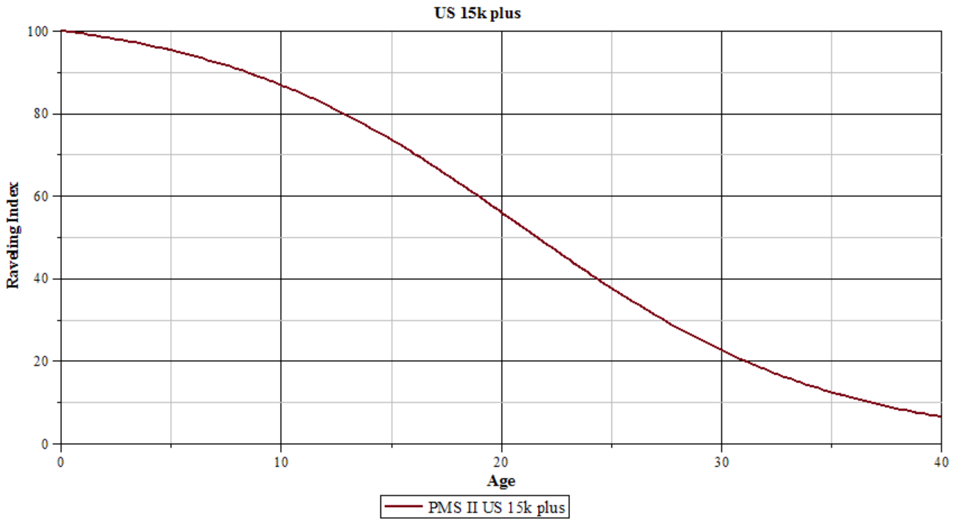
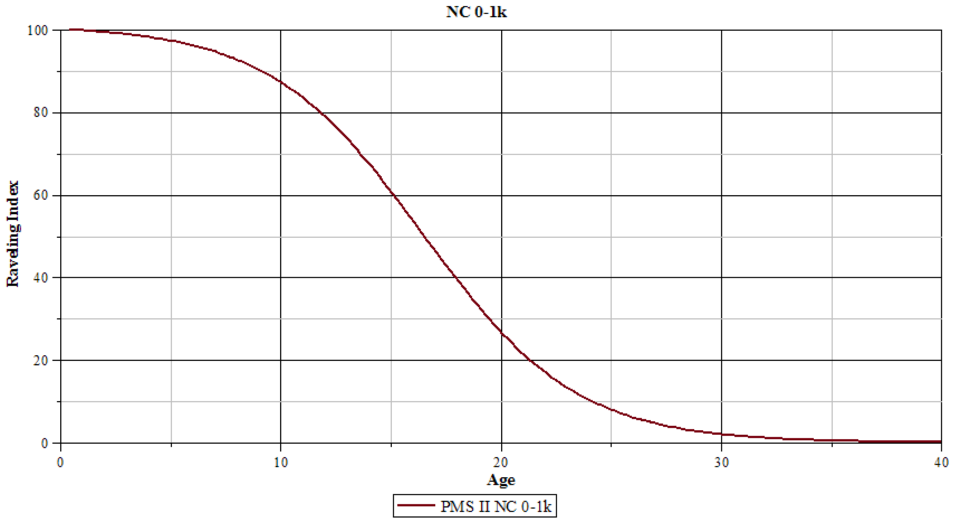
Raveling Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II US 5-15k


US 15k plus
Raveling Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II US 15k plus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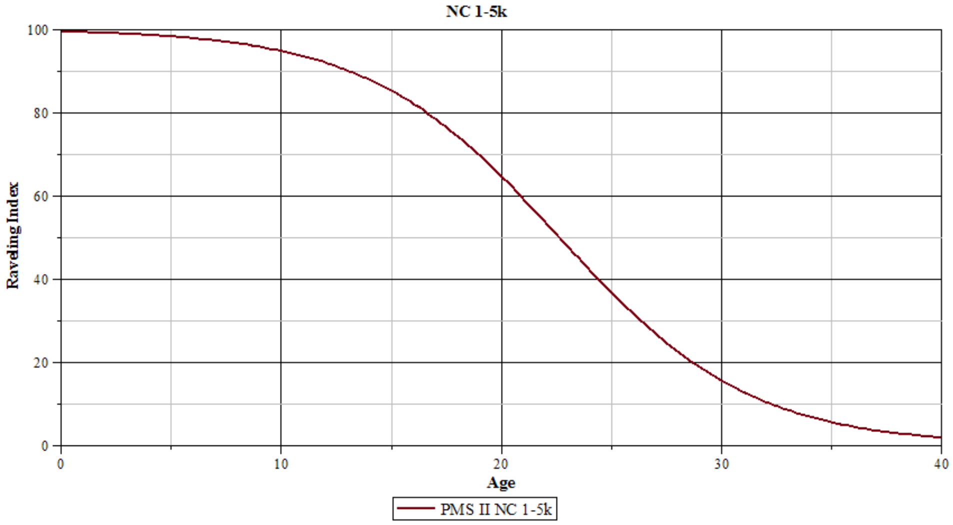
Raveling Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 0-1k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Raveling Index
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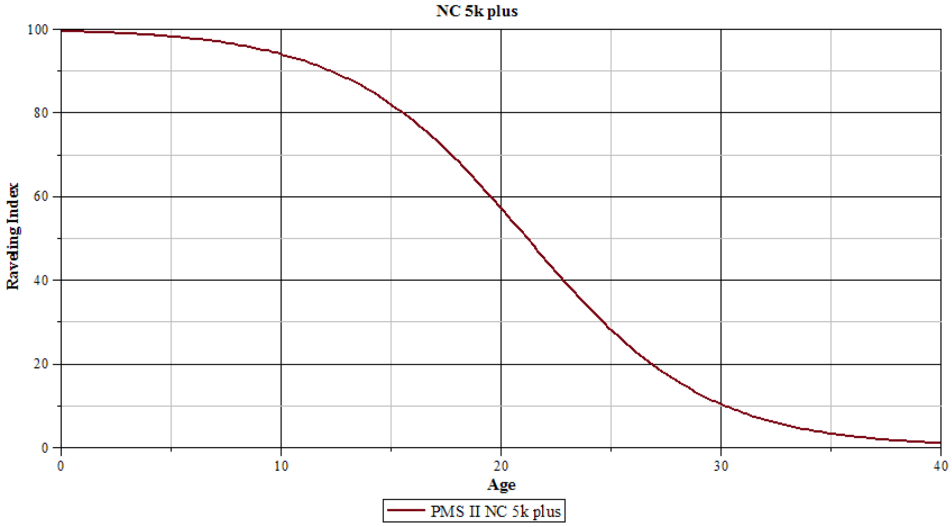
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 1-5k


NC 5k plus
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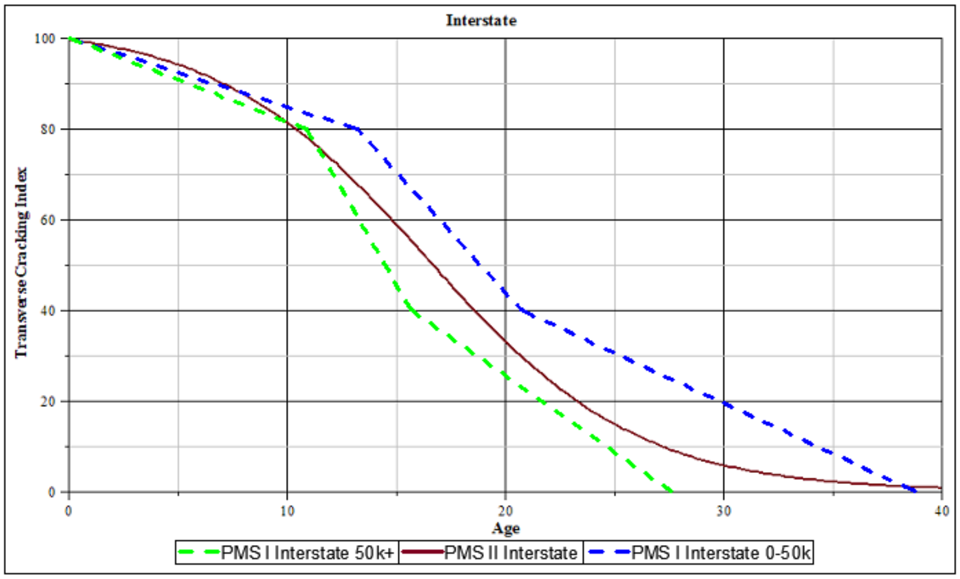
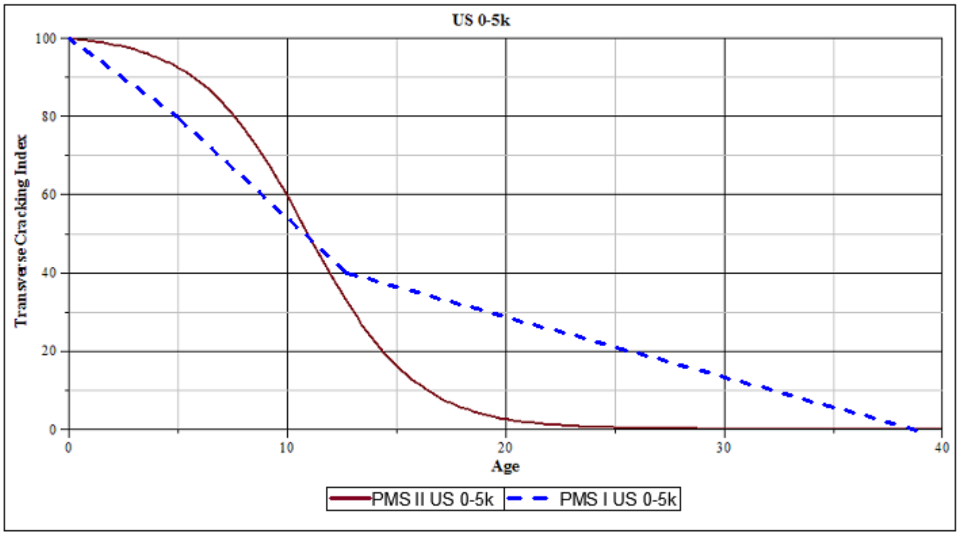
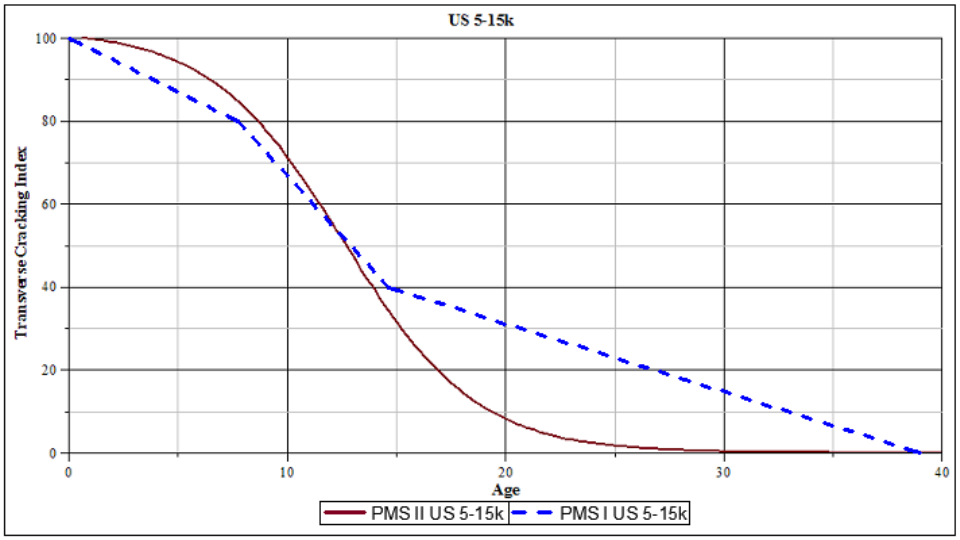
60
40
20
0
0
10
20
30
40
Age
PMS II NC 5k plus

Appendix C –Transverse Cracking Curves






US 5-15k
Transverse Cracking Index
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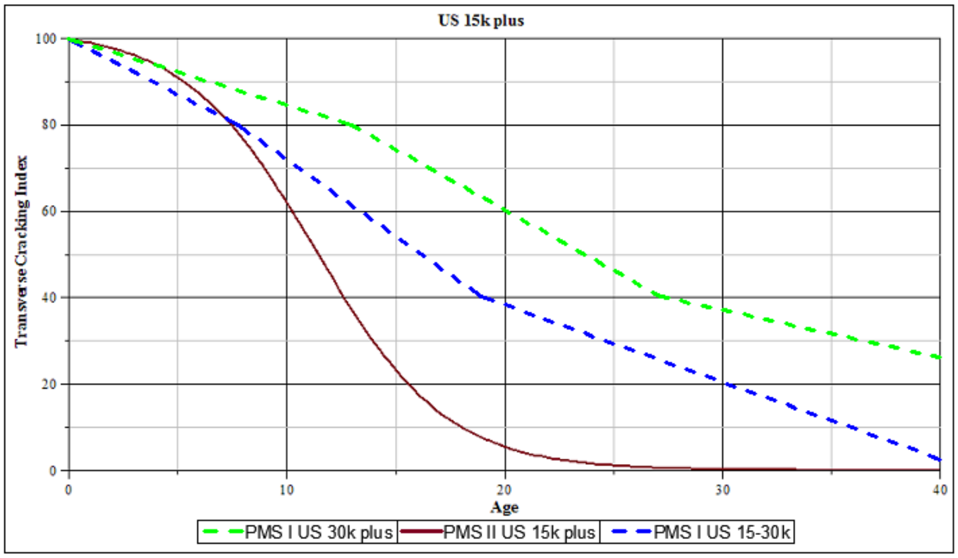
80
60
40
20
0
0
10
20
30
40
Age
PMS II US 5-15k
PMS I US 5-15k


US 15k plus
Transverse Cracking Index
100
80
60
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10
20
30
40
Age
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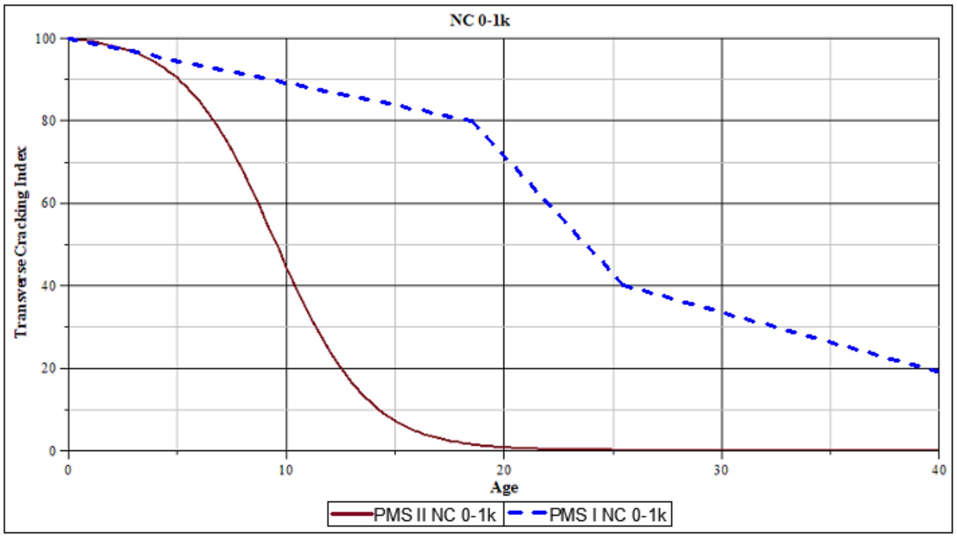
PMS II US 15k plus
PMS I US 15-30k


NC 0-1k
Transverse Cracking Index
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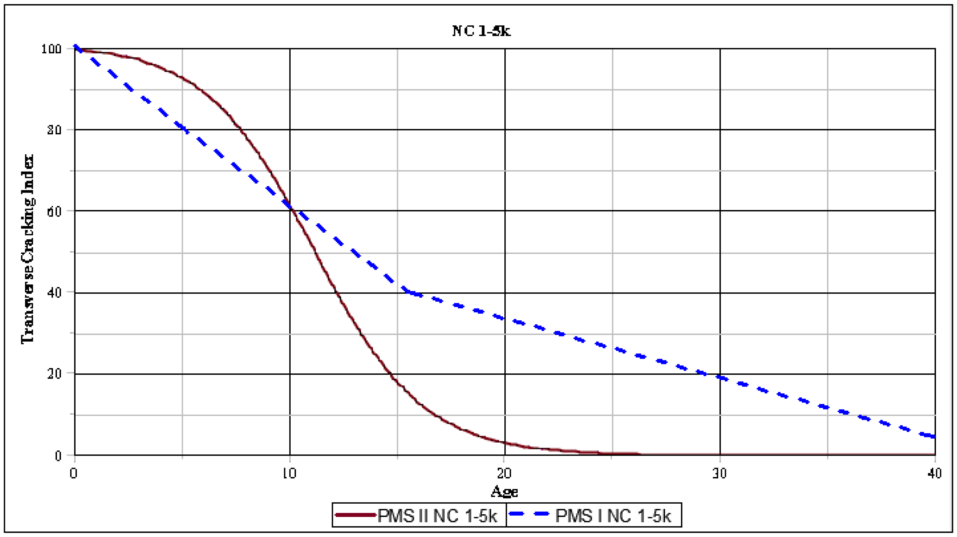
60
40
20
0
0
10
20
30
40
Age
PMS II NC 0-1k
PMS I NC 0-1k


NC 1-5k
Transverse Cracking Index
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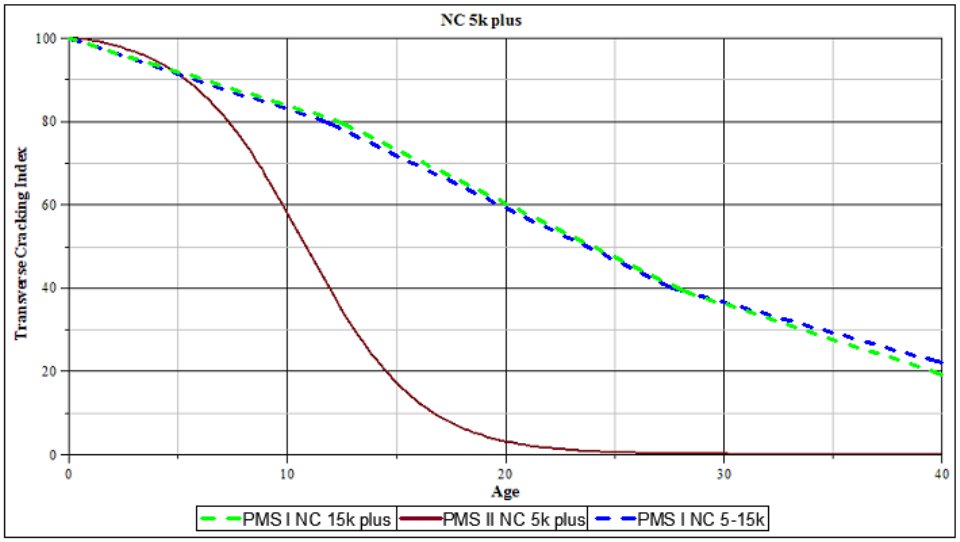
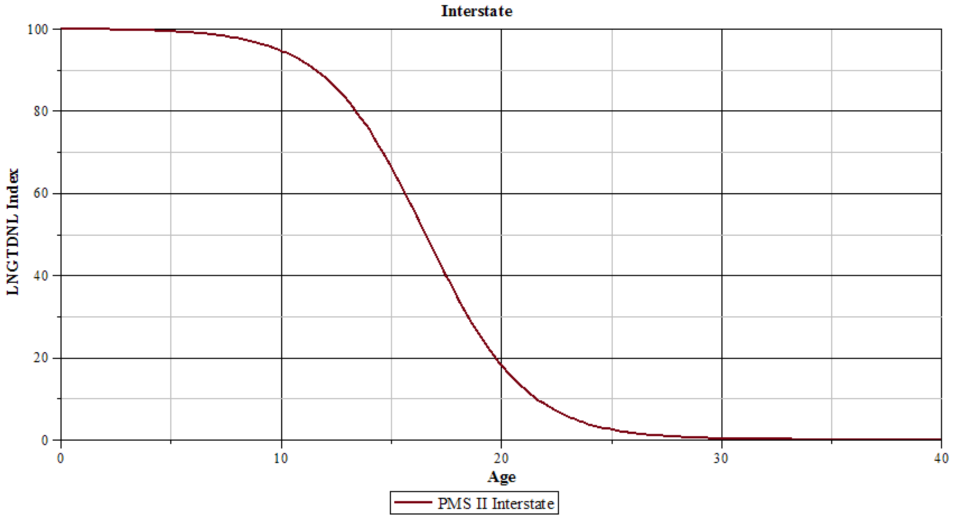
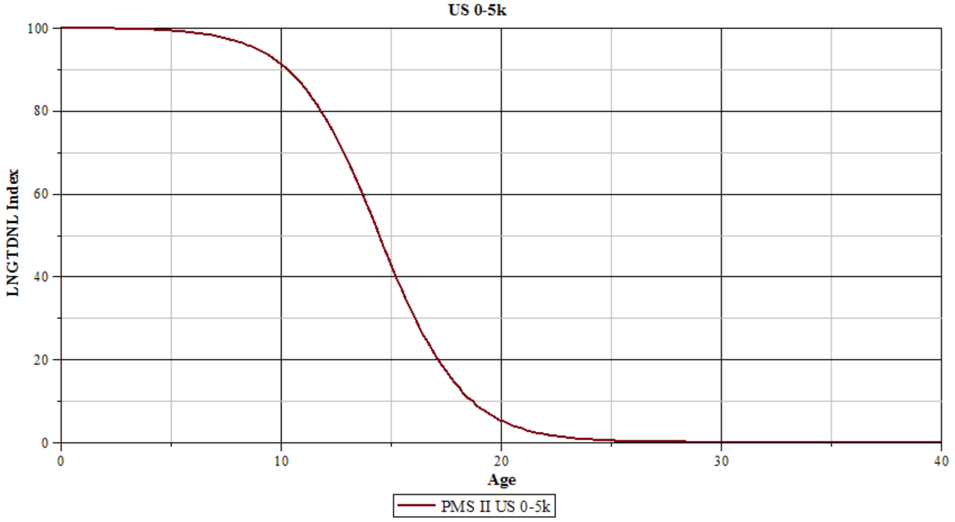
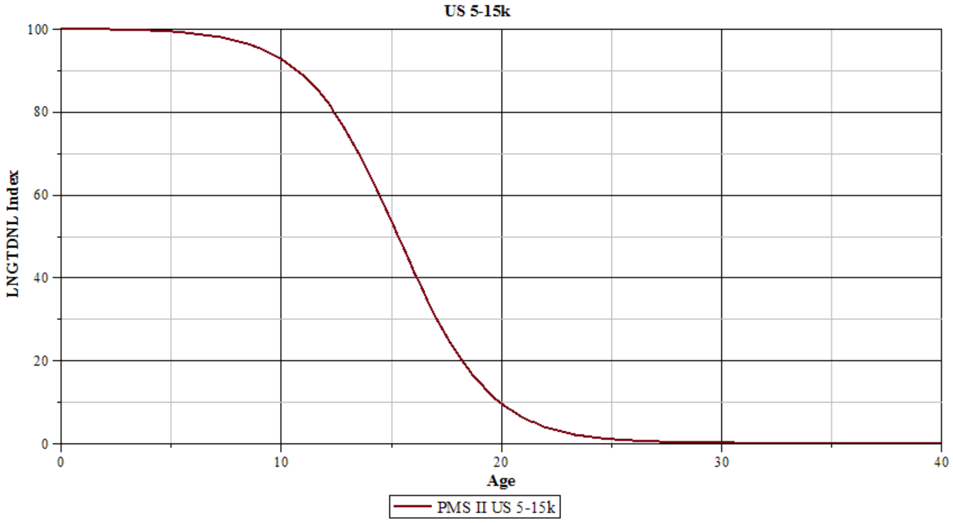
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 1-5k
PMS I NC 1-5k


NC 5k plus
Transverse Cracking Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS I NC 15k plus
PMS II NC 5k plus
PMS I NC 5-15k

Appendix D – Longitudinal Cracking Curves



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LNGTDNL Index
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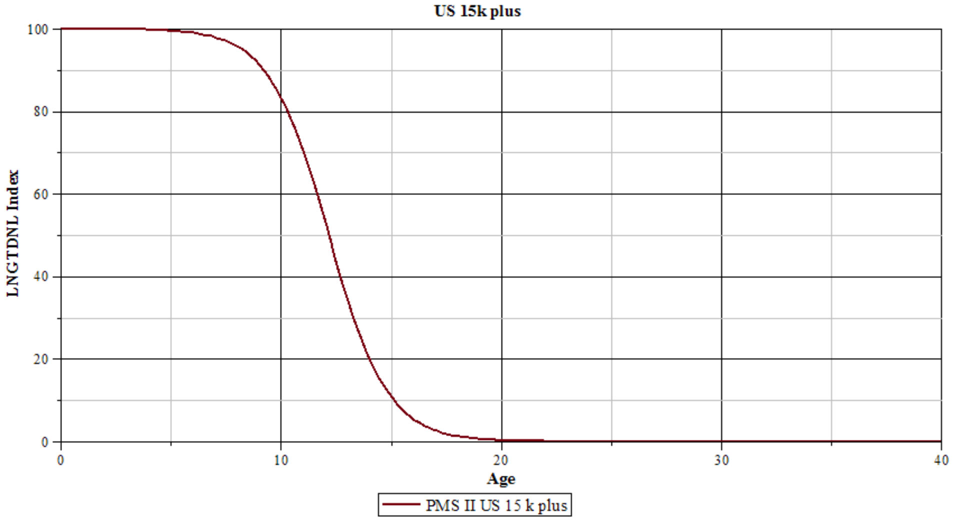
80
60
40
20
0
0
10
20
30
40
Age
PMS II US 5-15k


US 15k plus
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40
20
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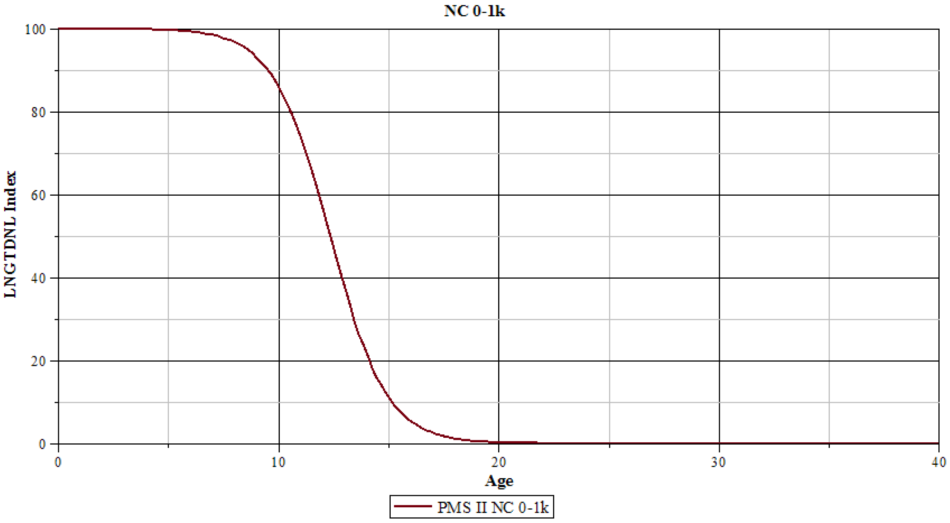
0
10
20
30
40
Age
PMS II US 15 k plus


NC 0-1k
LNGTDNL Index
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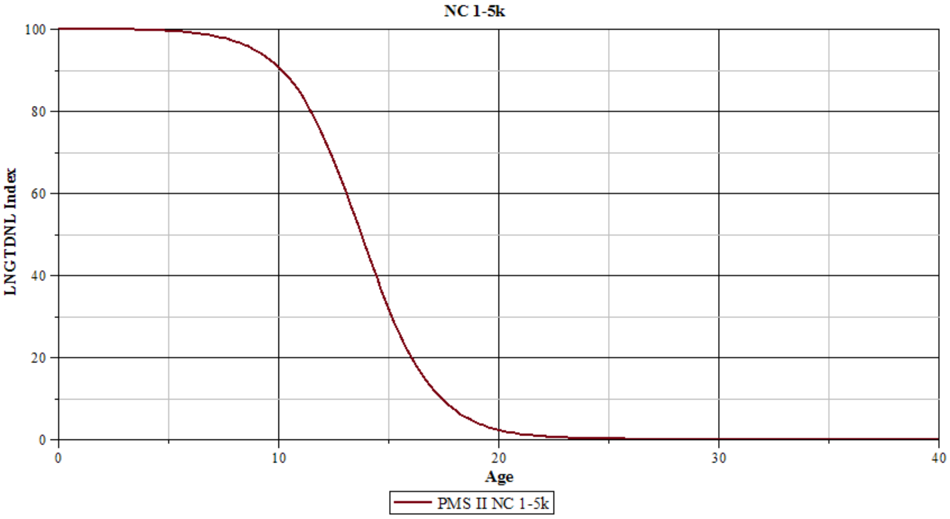
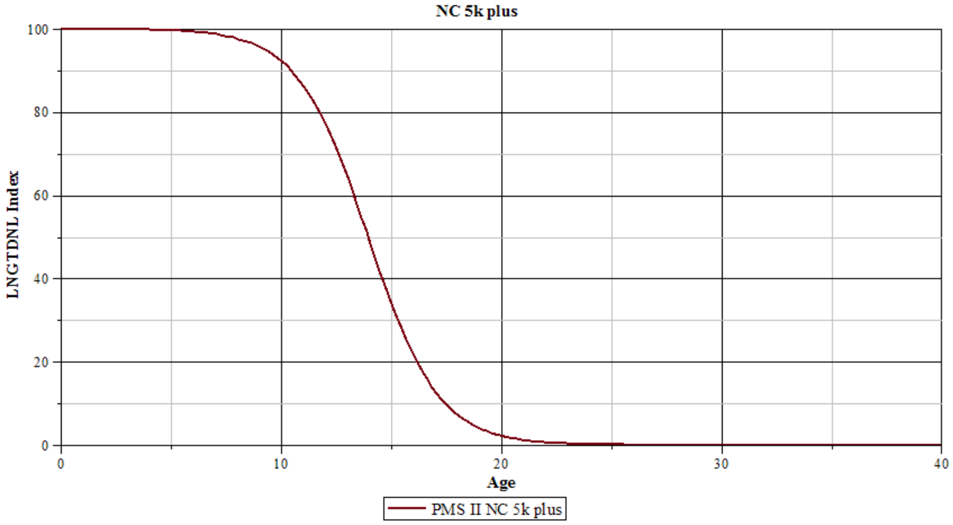
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 0-1k


NC 1-5k
LNGTDNL Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 1-5k


NC 5k plus
LNGTDNL Index
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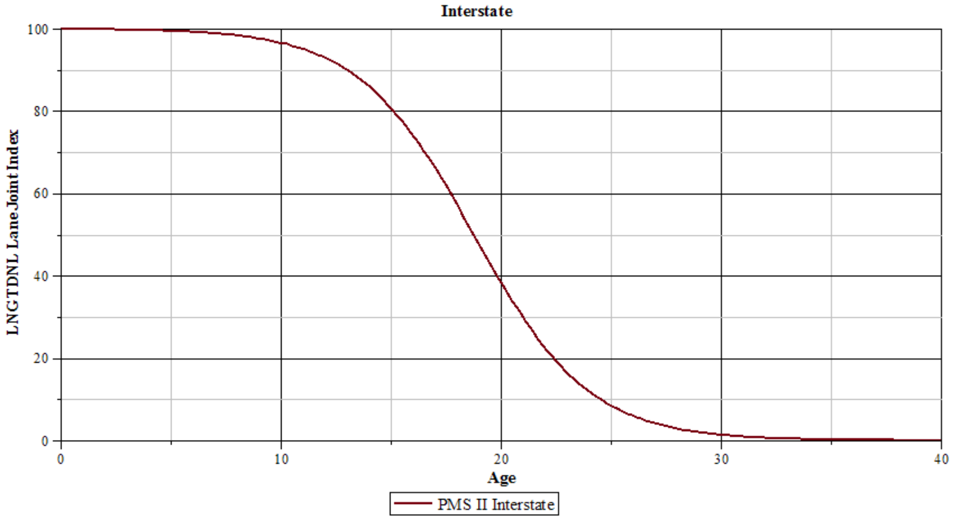
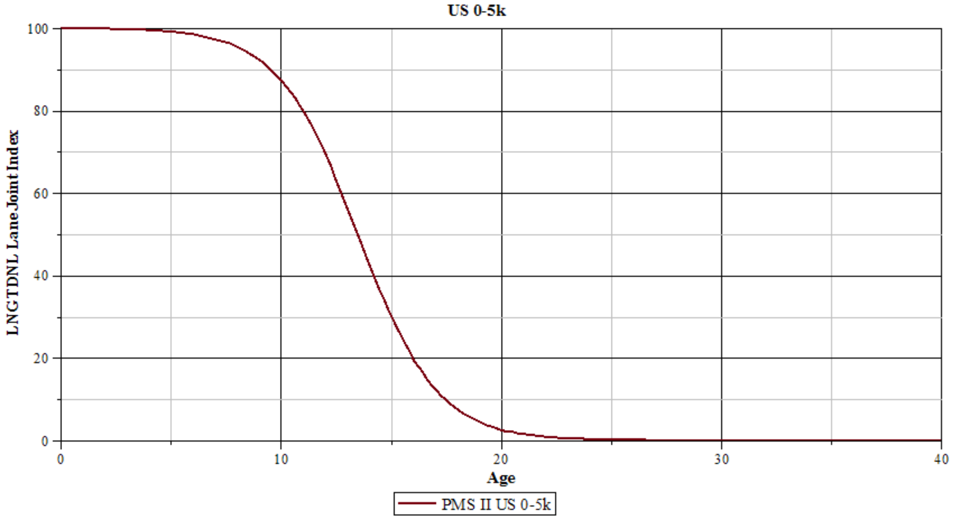
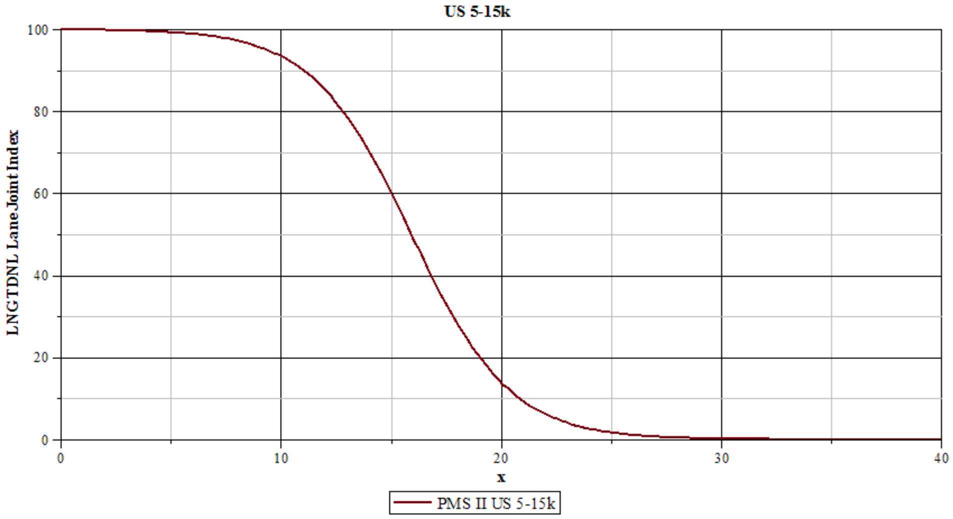
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 5k plus

Appendix E –Longitudinal Lane Joint Curves






US 5-15k
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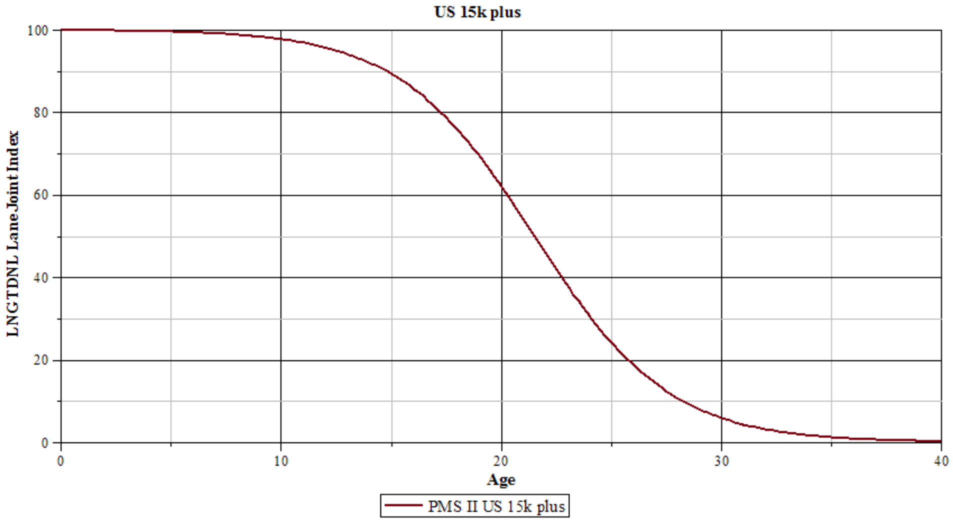
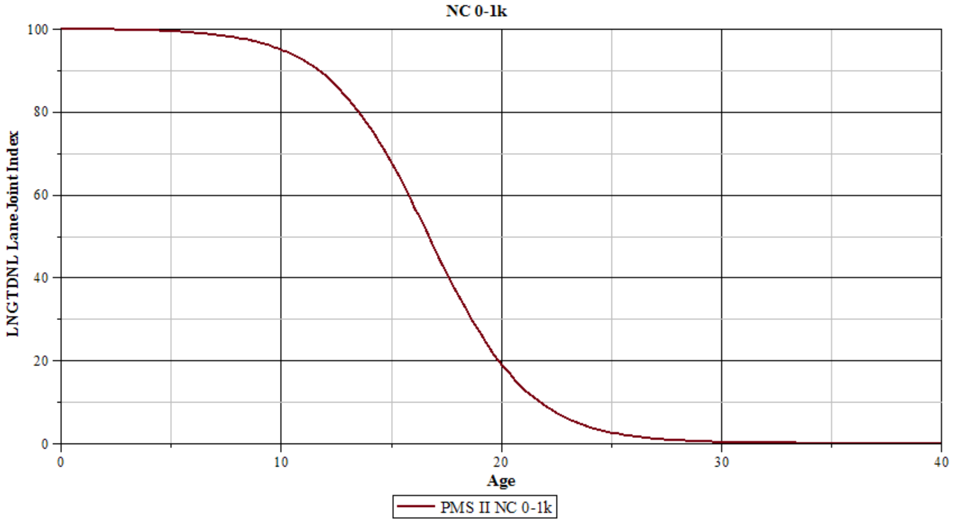
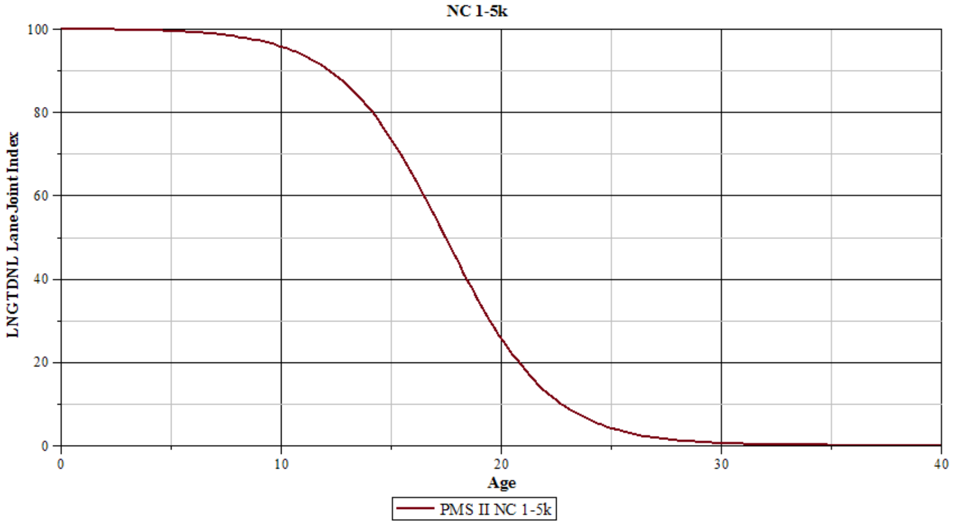
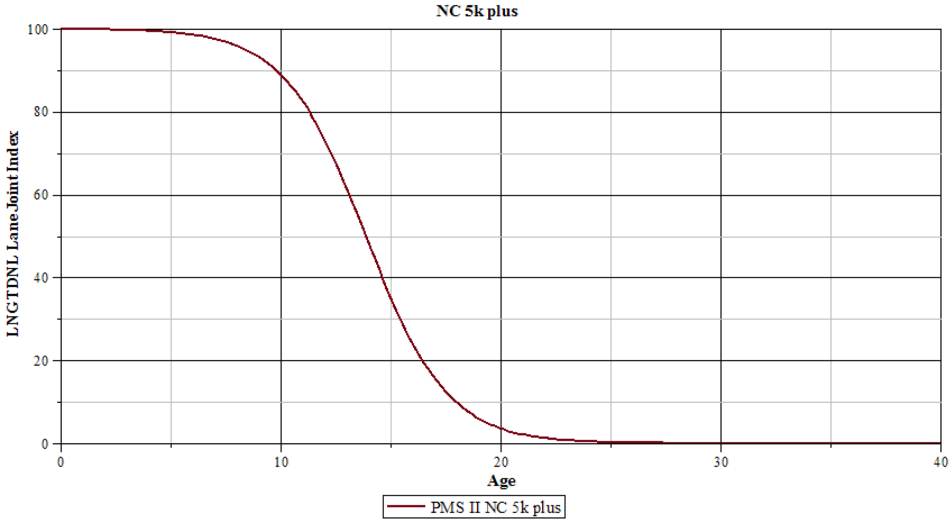
80
60
40
20
0
0
10
20
30
40
x
PMS II US 5-15k

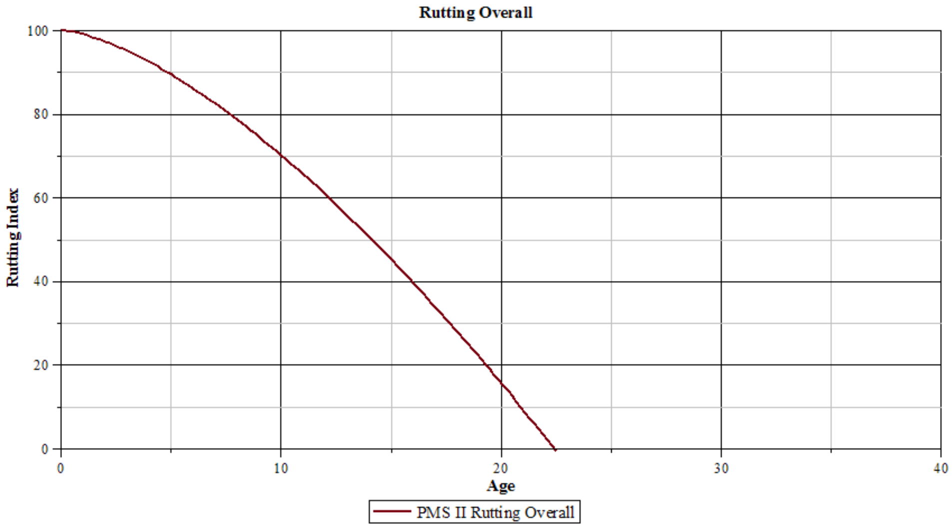

US 15k plus
LNGTDNL Lane Joint Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II US 15k plus

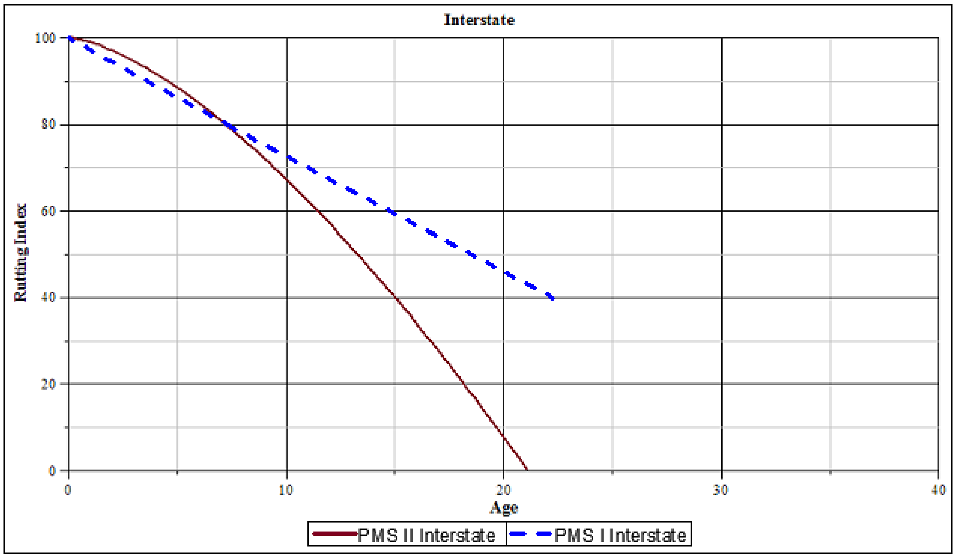

NC 0-1k
LNGTDNL Lane Joint Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 0-1k

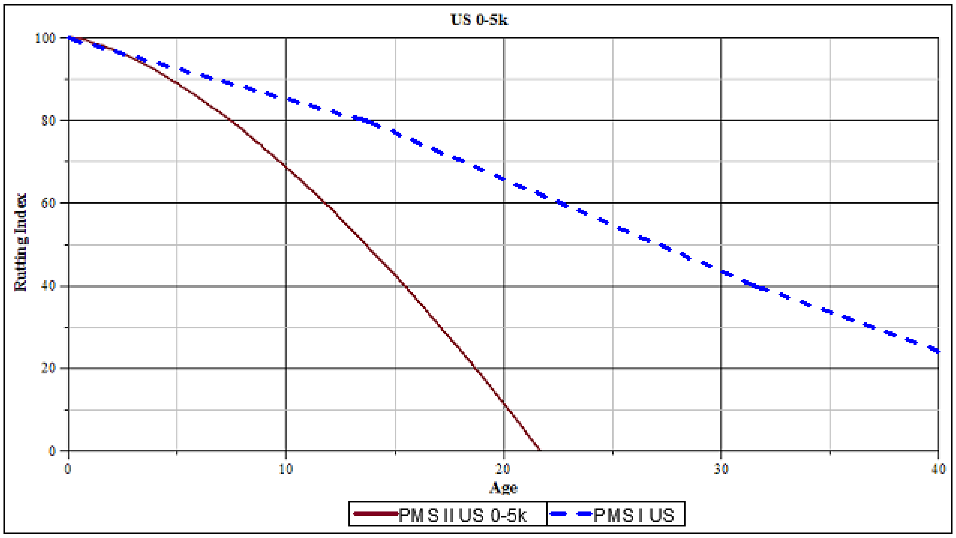

NC 1-5k
LNGTDNL Lane Joint Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 1-5k

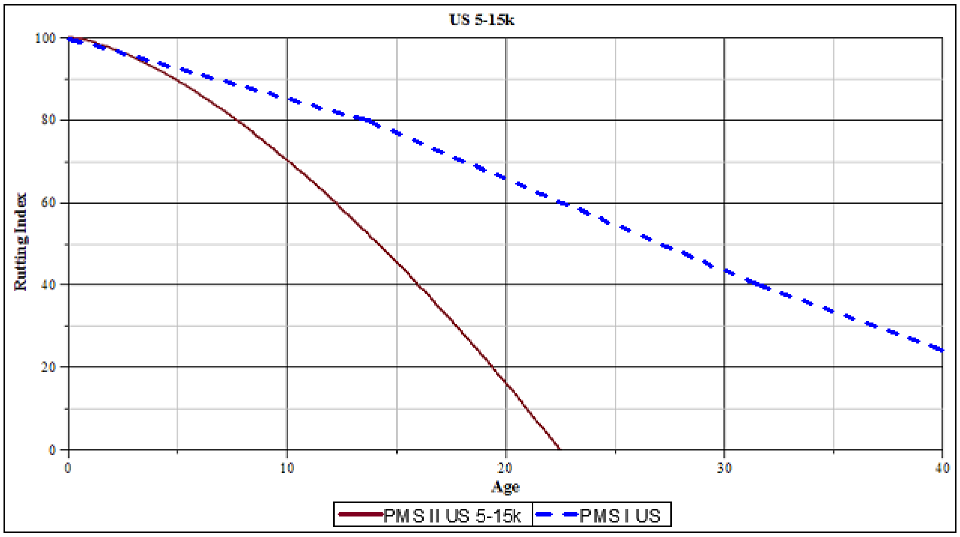

NC 5k plus
LNGTDNL Lane Joint Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 5k plus

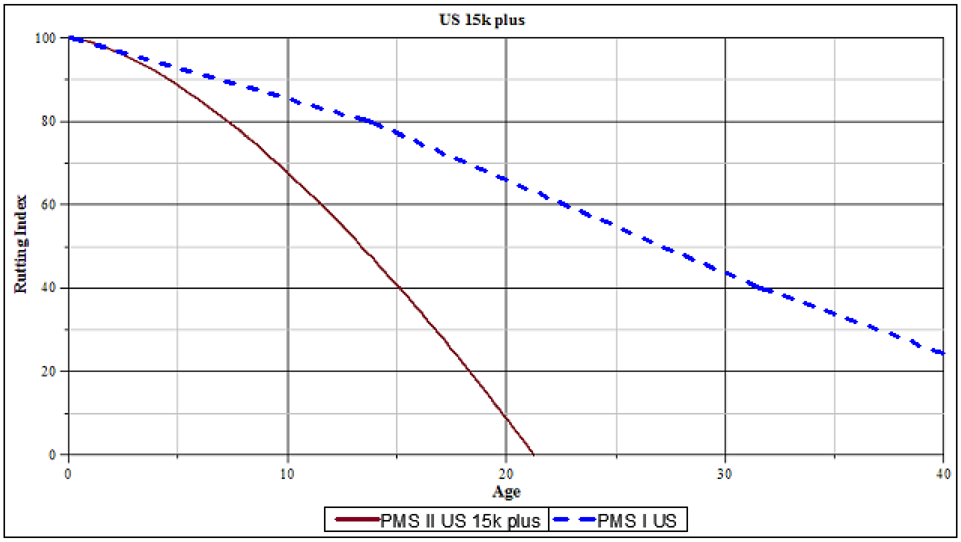
Appendix F – Rutting Curves

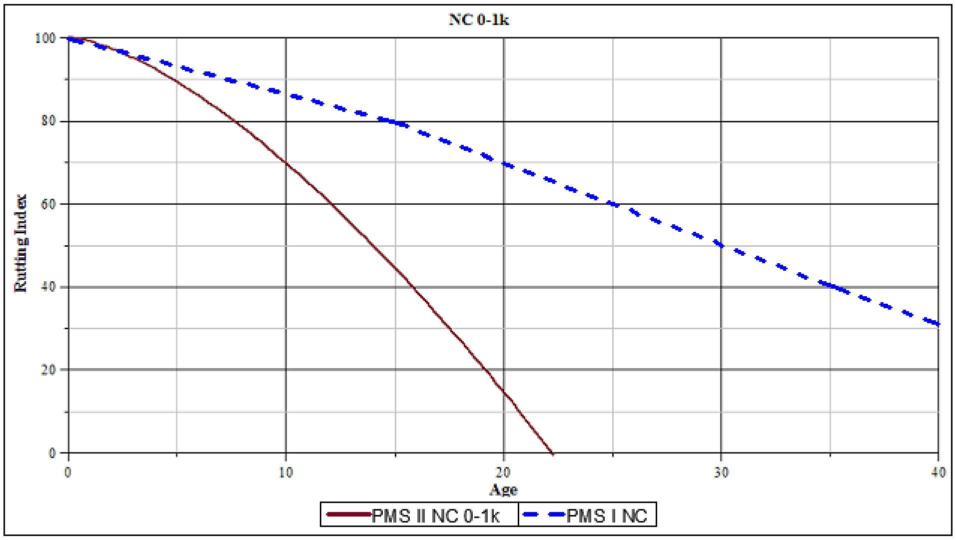


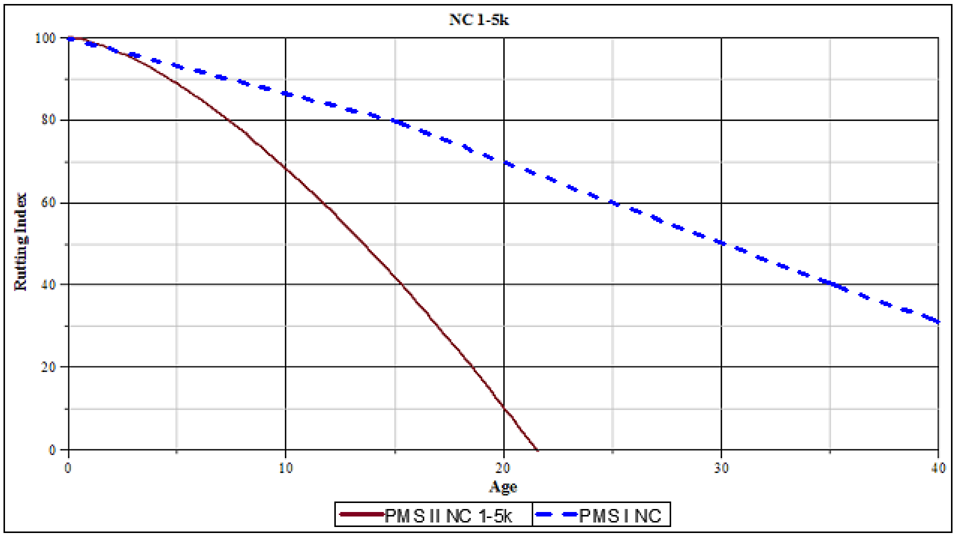


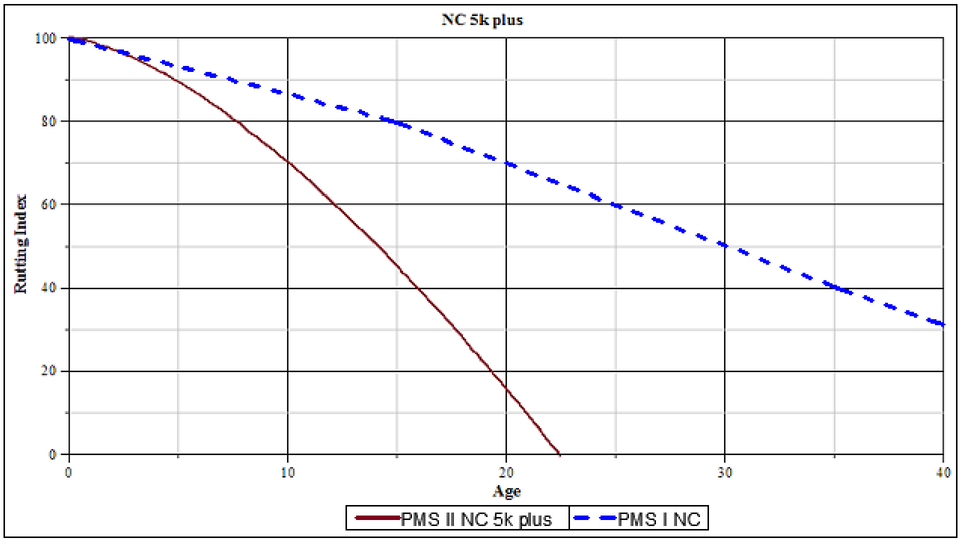

US 0-5k
Rutting Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II US 0-5k
PMS I US


US 5-15k
Rutting Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II US 5-15k
PMS I US

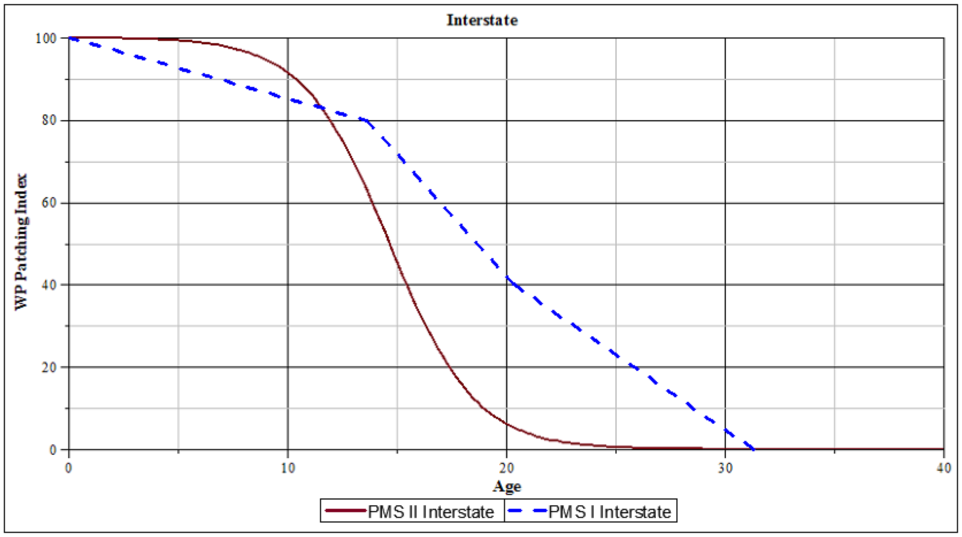

US 15k plus
Rutting Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II US 15k plus
PMS I US

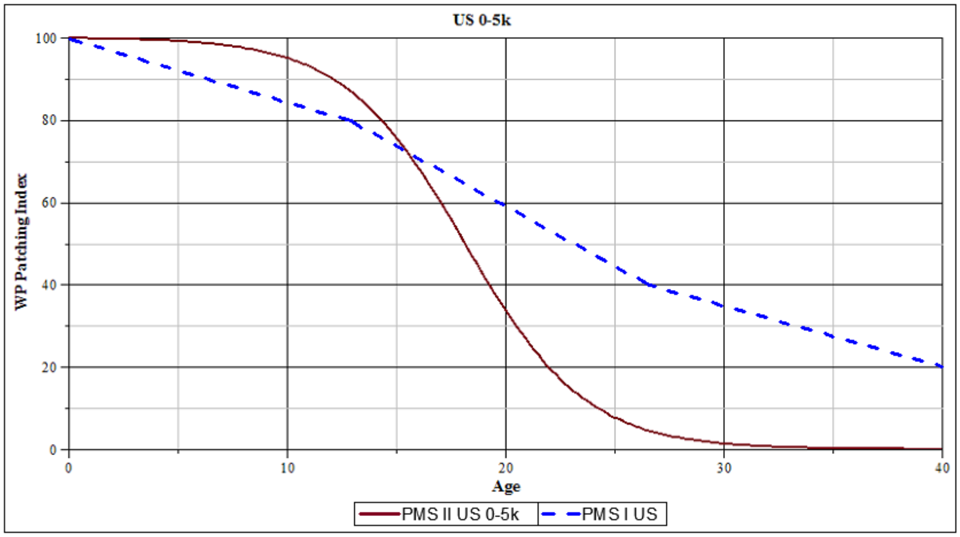

NC 0-1k
Rutting Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 0-1k
PMS I NC

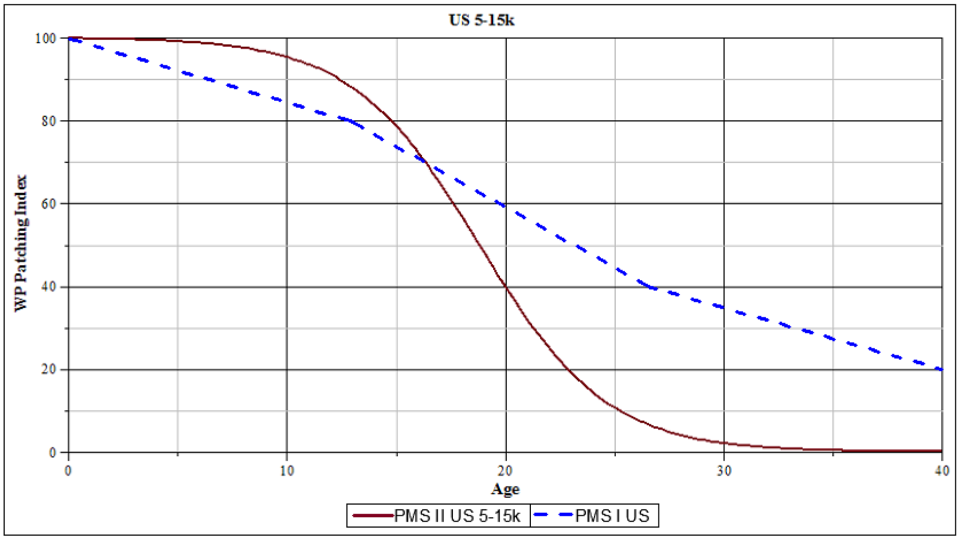

NC 1-5k
Rutting Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 1-5k
PMS I NC

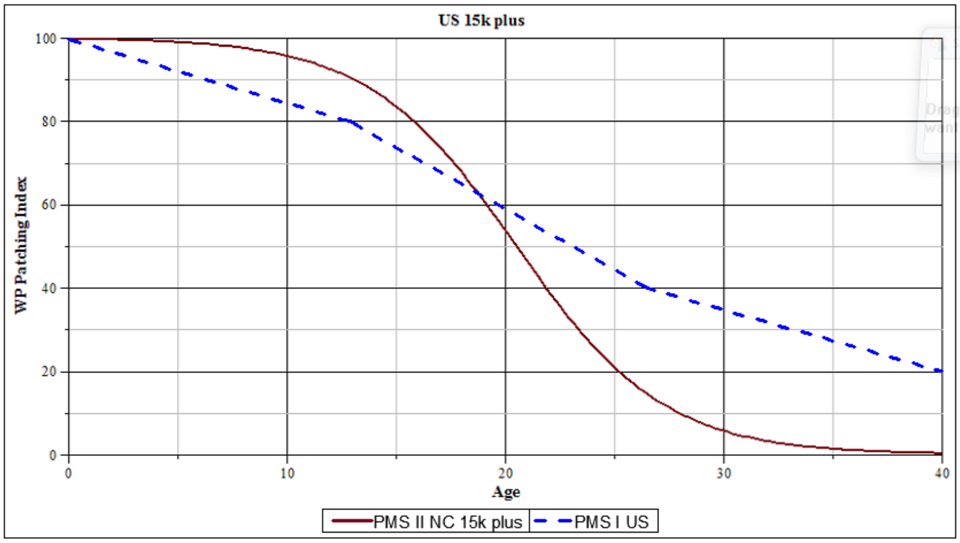

NC 5k plus
Rutting Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 5k plus
PMS I NC

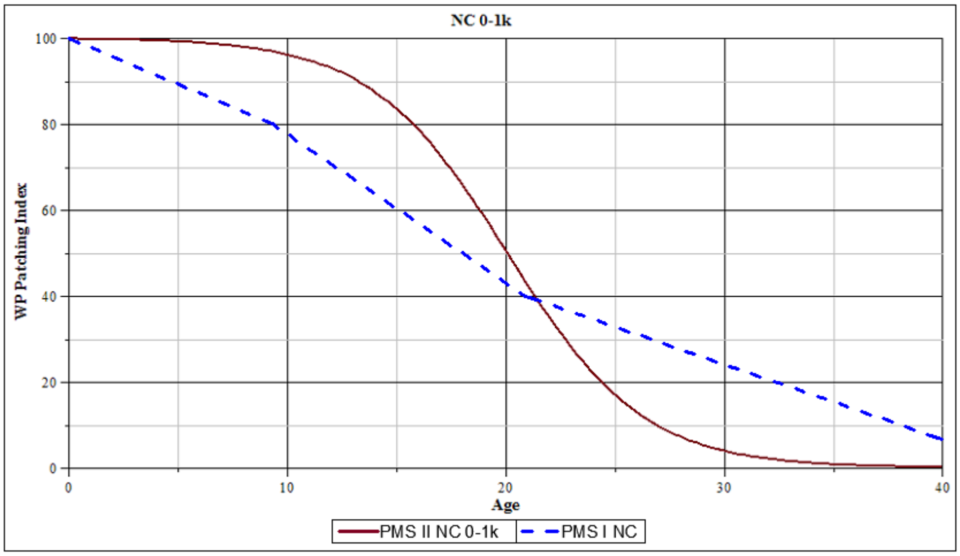
Appendix G –Wheel Path Patching Curves

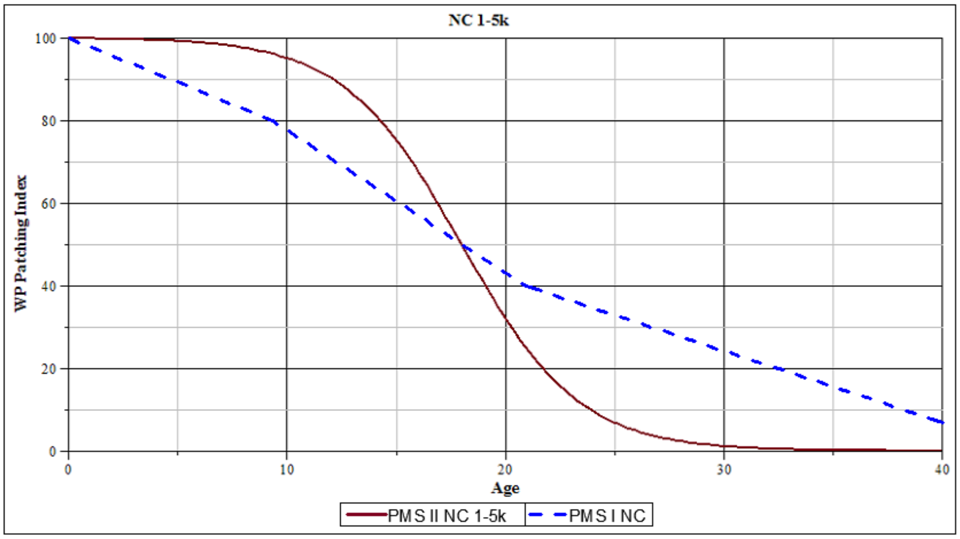


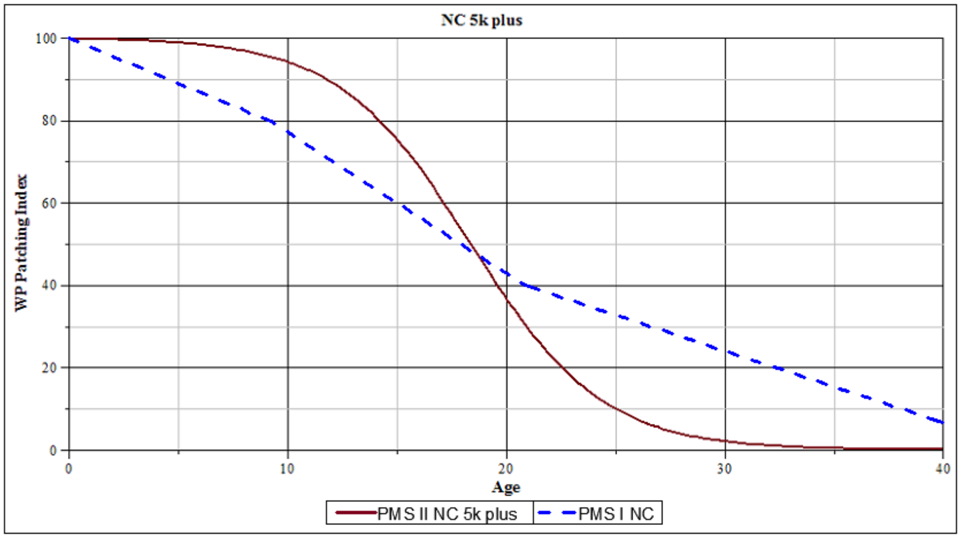



US 5-15k
WP Patching Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II US 5-15k
PMS I US

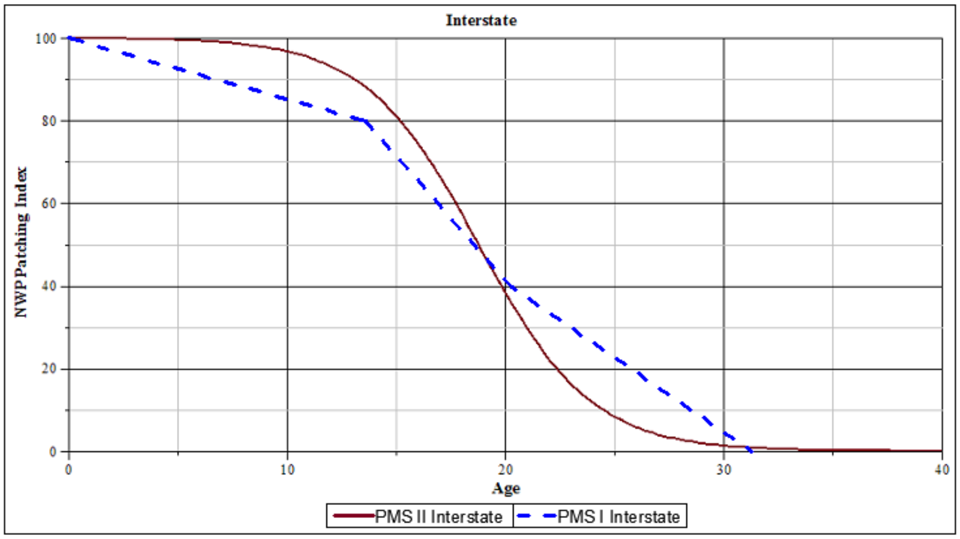

US 15k plus
WP Patching Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 15k plus
PMS I US

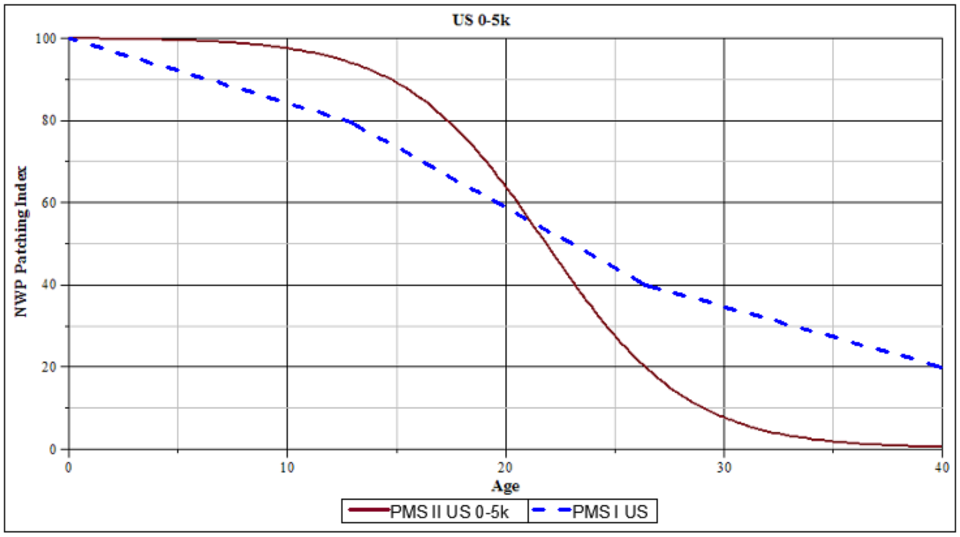

NC 0-1k
WP Patching Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 0-1k
PMS I NC

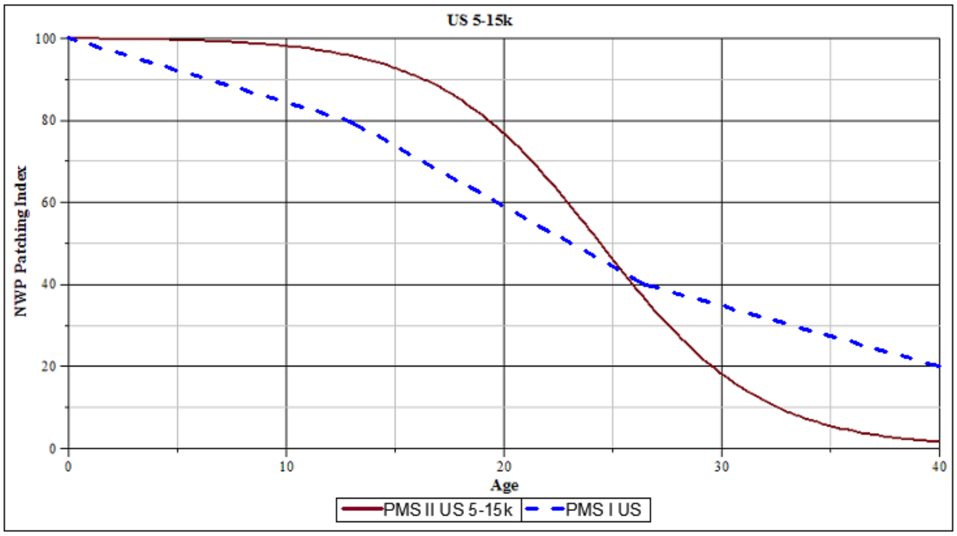

NC 1-5k
WP Patching Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 1-5k
PMS I NC

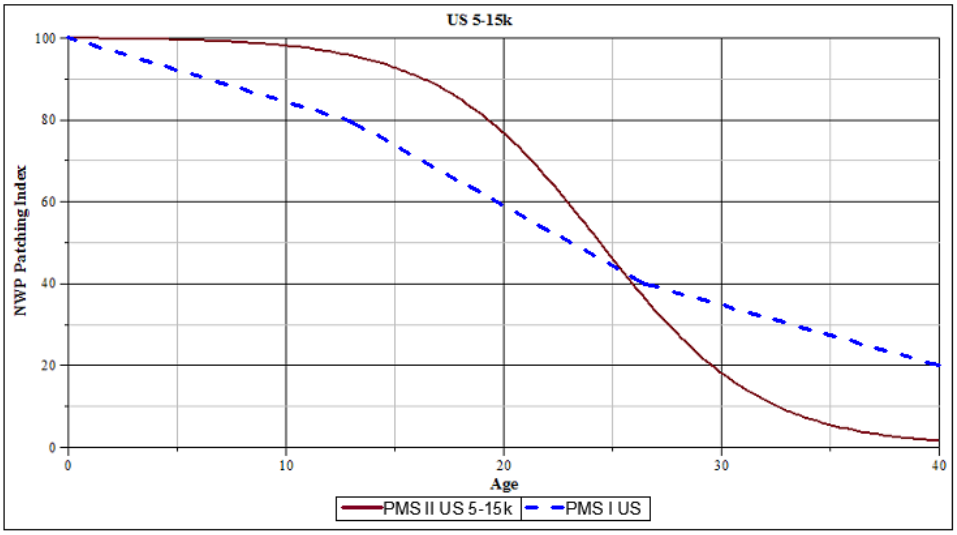

NC 5k plus
100
80
60
40
20
0
WP Patching Index
0
10
20
30
40
Age
PMS II NC 5k plus
PMS I NC

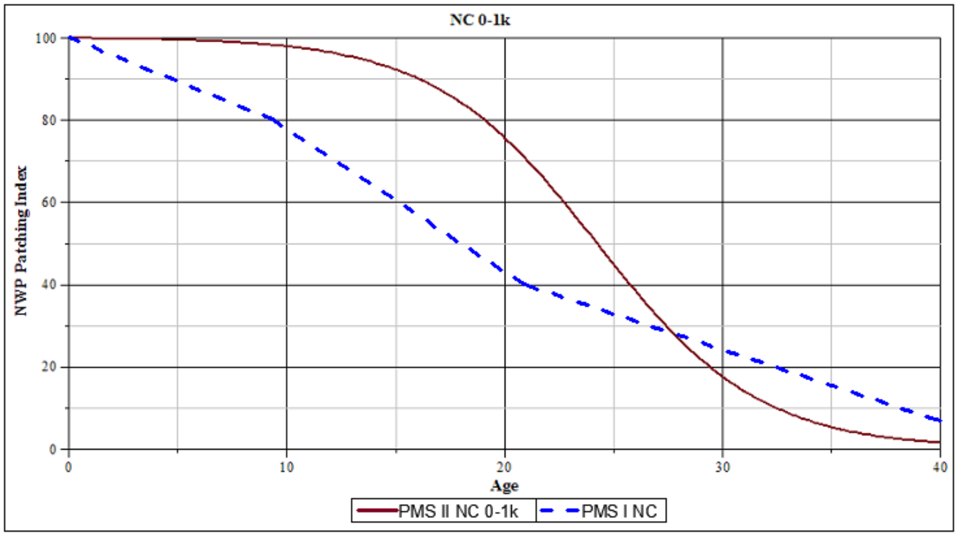
Appendix H –Non-Wheel Path Patching Curves

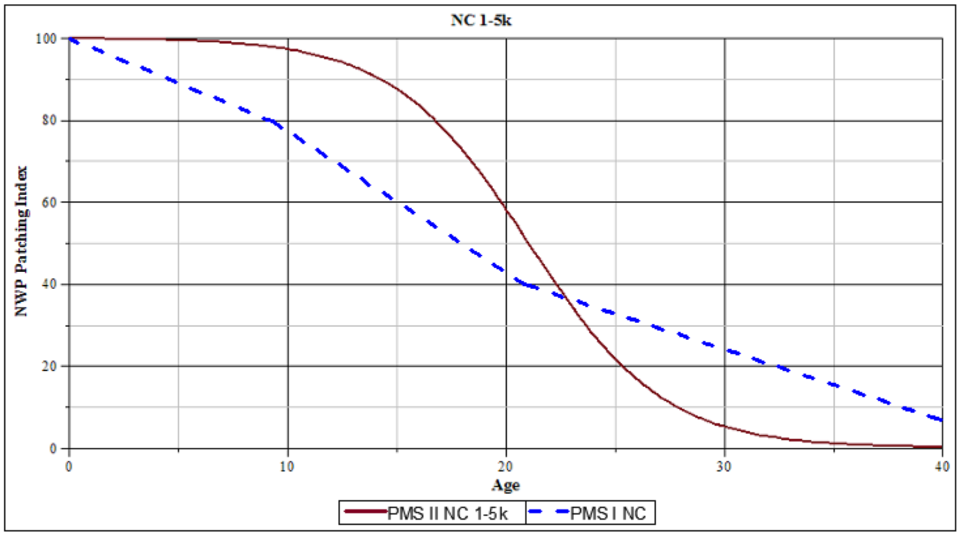


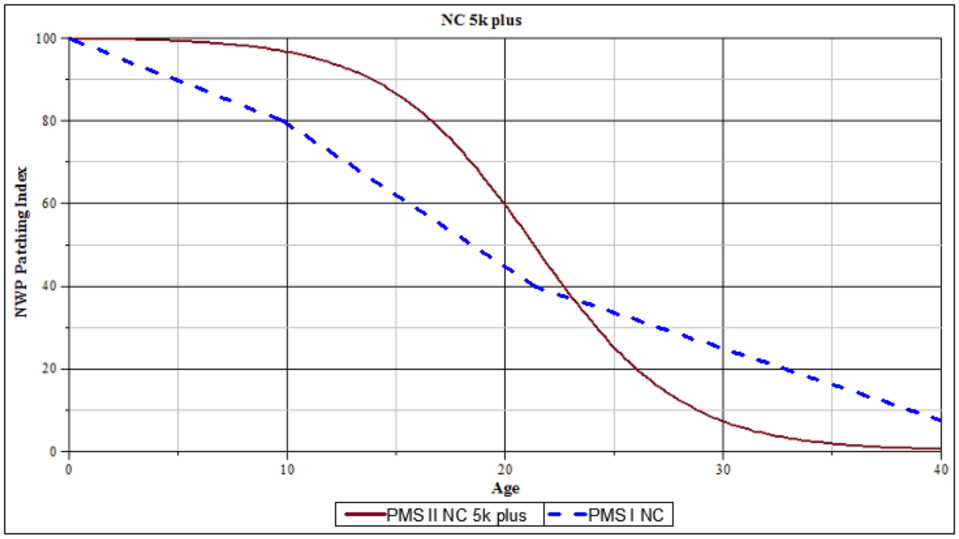



US 5-15k
NWP Patching Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II US 5-15k
PMS I US

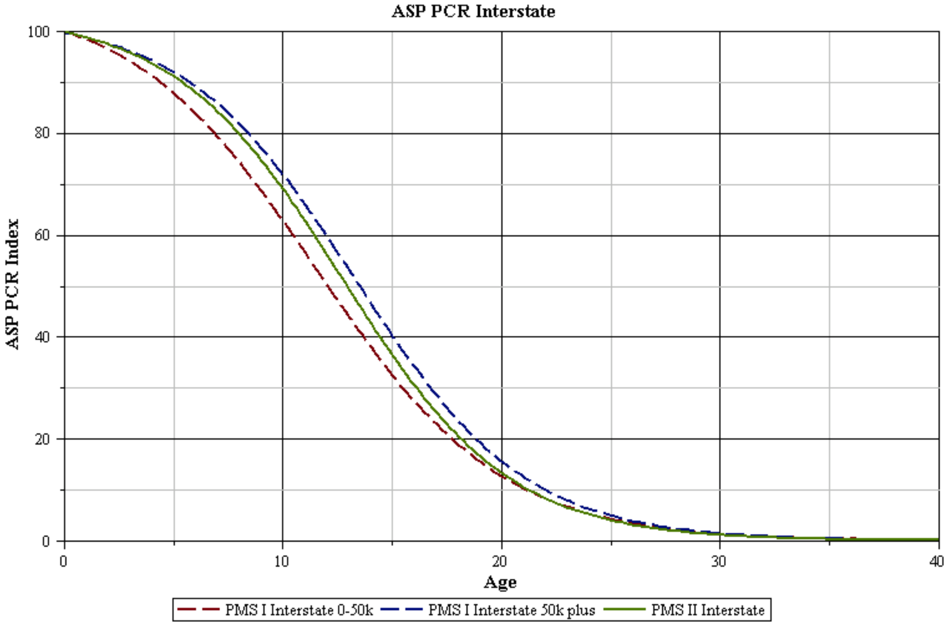

US 5-15k
NWP Patching Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II US 5-15k
PMS I US

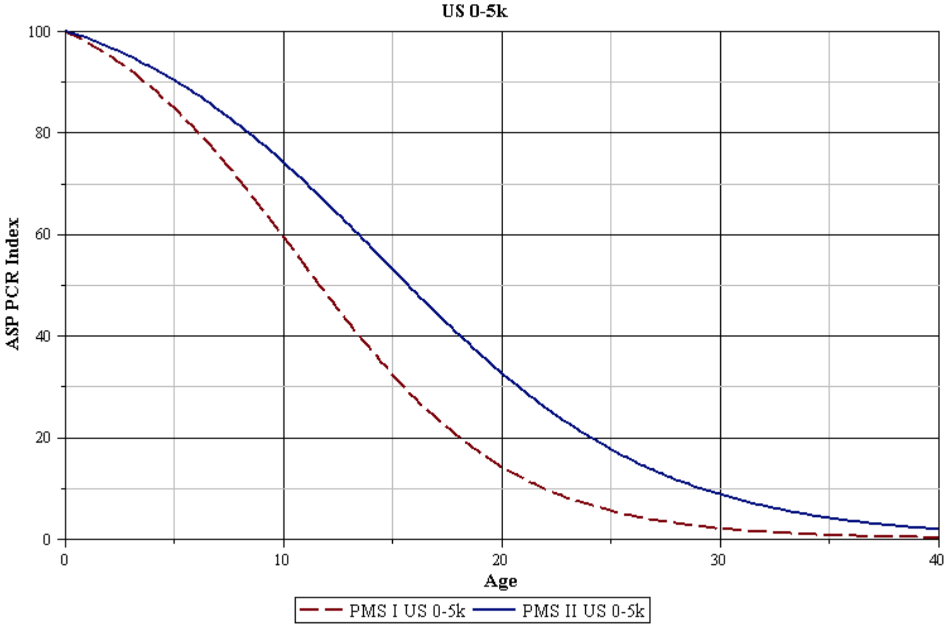

NC 0-1k
NWP Patching Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 0-1k
PMS I NC

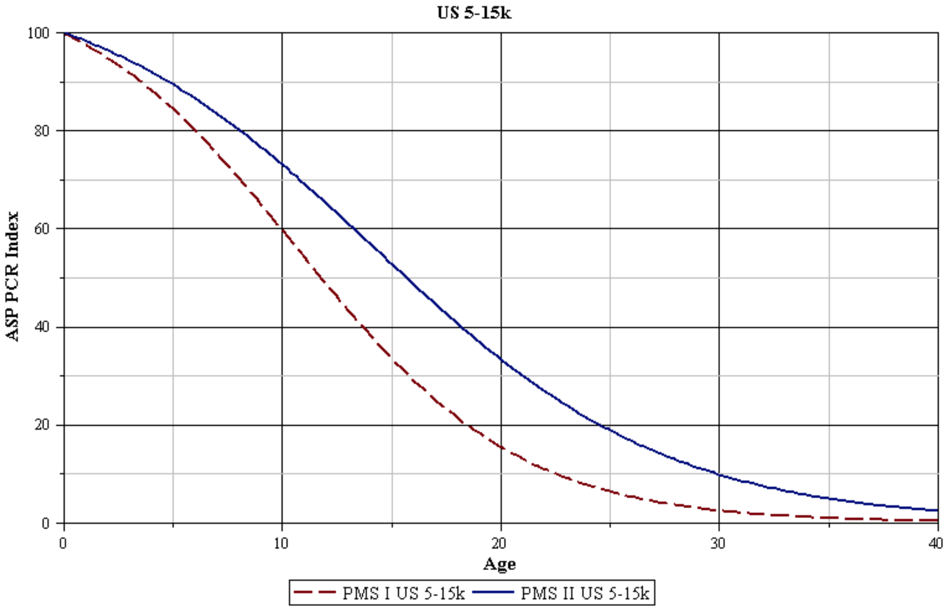

NC 1-5k
NWP Patching Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 1-5k
PMS I NC

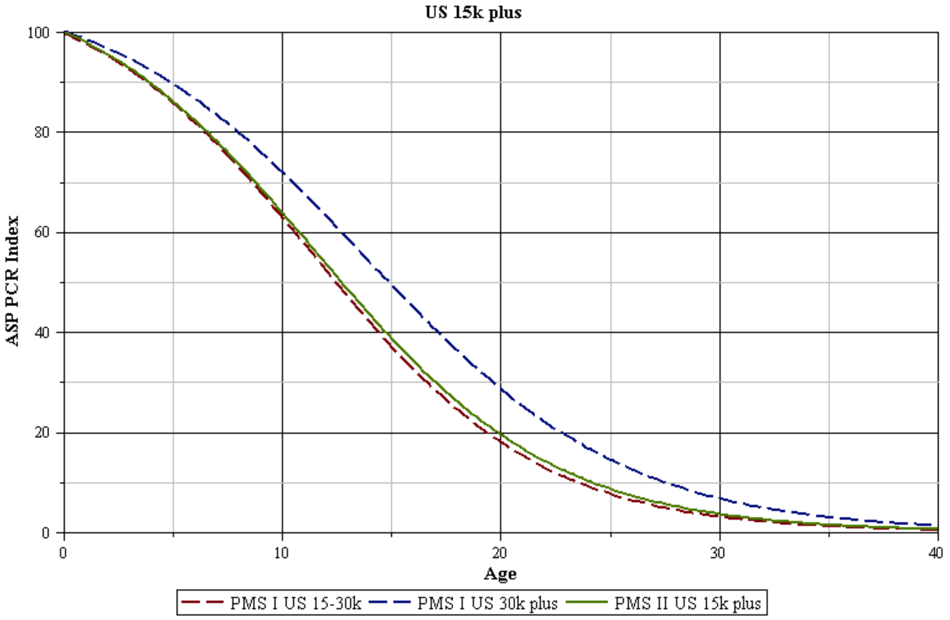

NC 5k plus
NWP Patching Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS II NC 5k plus
PMS I NC

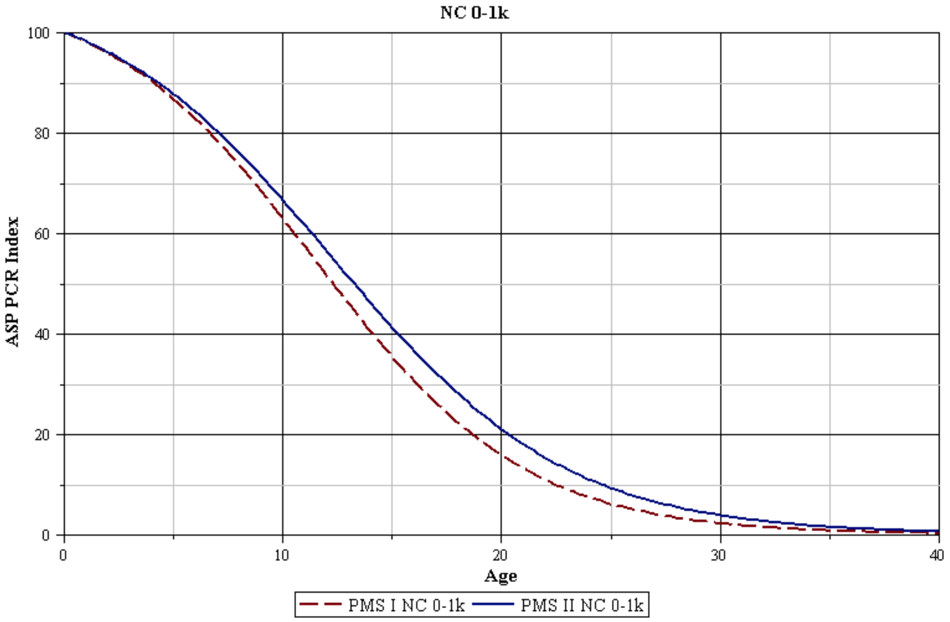
Appendix I –Asphalt Pavement Performance Curves

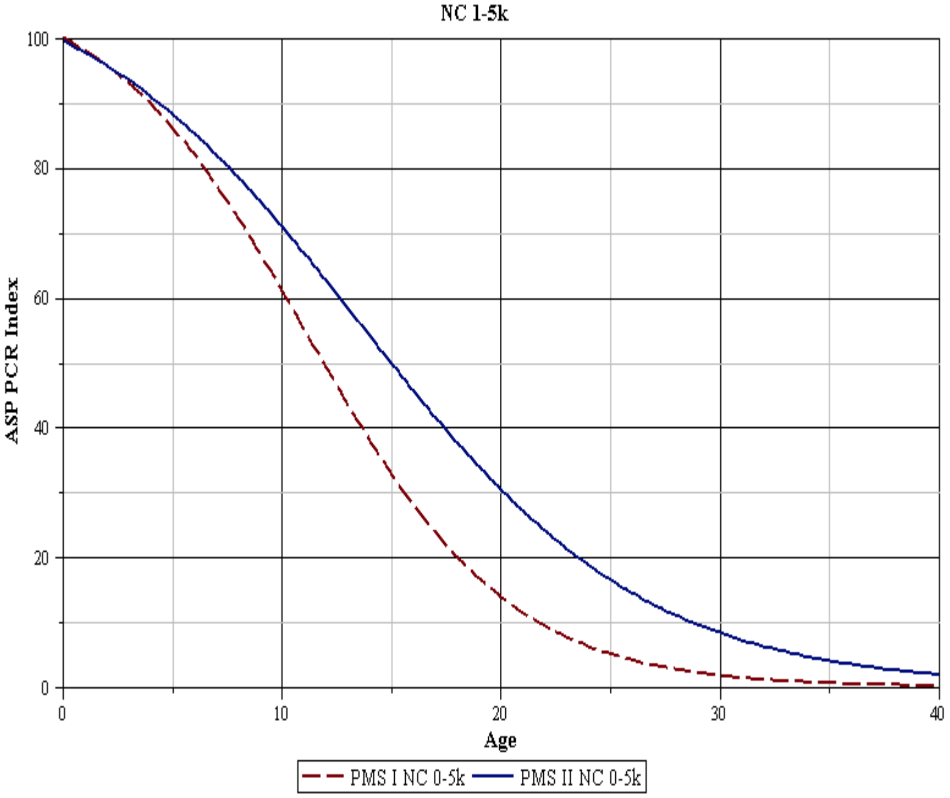


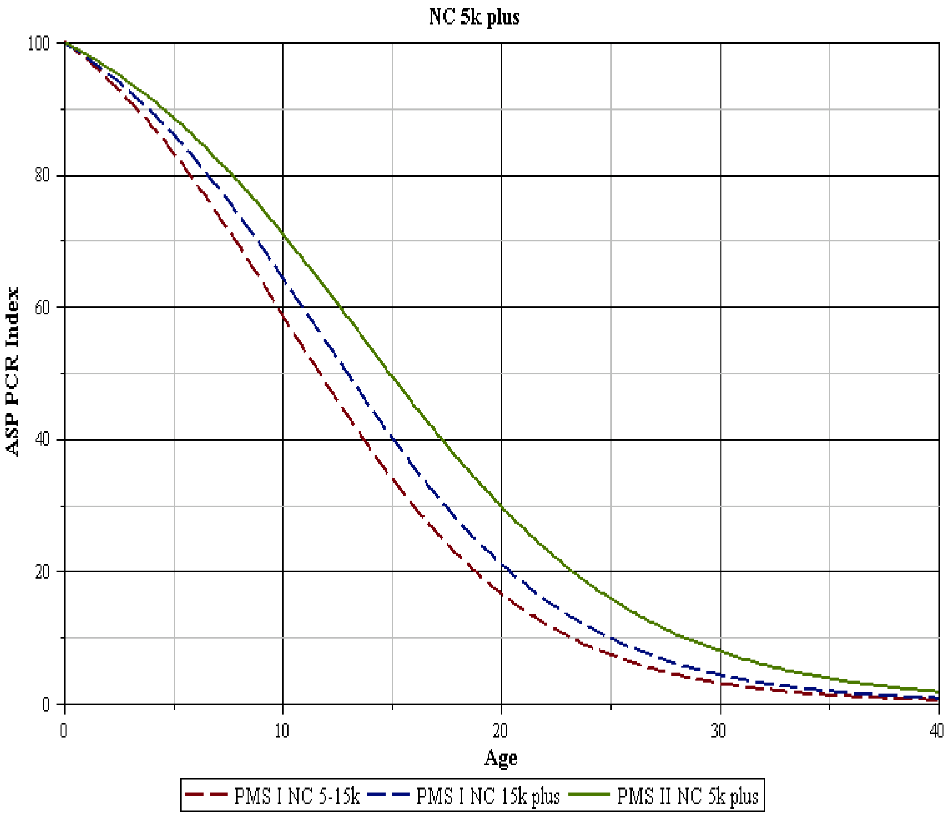



US 5-15k
ASP PCR Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS I US 5-15k
PMS II US 5-15k


US 15k plus
ASP PCR Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS I US 15-30k
PMS I US 30k plus
PMS II US 15k plus


NC 0-1k
ASP PCR Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS I NC 0-1k
PMS II NC 0-1k


NC 1-5k
ASP PCR Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS I NC 0-5k
PMS II NC 0-5k


NC 5k plus
ASP PCR Index
100
80
60
40
20
0
0
10
20
30
40
Age
PMS I NC 5-15k
PMS I NC 15k plus
PMS II NC 5k plus

Appendix J – JCP Pavement Performance Curves