RESEARCH & DEVELOPMENT

Development of Performance Curves for Composite Pavements in PMS

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Development of Performance Curves for Composite Pavements in PMS

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16. Abstract

Due to their high performance, composite pavements have been used by highway agencies as a cost-effective alternative for high traffic volume roadways. In the NCDOT PMS, however, a function to allow engineers to select the composite pavement as the optimal pavement alternative for a project is lacking. The reason is that, historically, composite pavements have been classified as conventional asphalt pavements in North Carolina, even though these two types of pavements probably perform differently. This study was conducted to address this issue. Researchers identified composite pavement sections in the PMS, developed distress models and performance models for composite roadway families, and determined triggering distresses and recommended appropriate treatments. The findings of this study will help NCDOT engineers to build a new composite pavement maintenance system that can be added to its PMS. This new system, together with the existing asphalt and JCP systems, can provide engineers with a wider selection of pavement types and allow them to recommend appropriate treatments for maintenance and rehabilitation activities.

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EXECUTIVE SUMMARY

Our nation's roadway system is one of the largest infrastructure assets that needs massive resources to maintain and operate. However, highway officials are facing the challenges of managing "an ever-expanding, still-evolving, yet aging highway network" (FHWA, 1998) with inadequate and unsustainable resources. To address these challenges, it is essential for highway agencies to keep improving their pavement management systems (PMSs) so they can effectively manage roadway assets with limited resources.

An effective PMS allows engineers to precisely identify pavement types and recommend appropriate treatments. The transportation industry classically has had two types of pavements, flexible and rigid. A third hybrid pavement also exists, that includes both flexible and rigid pavements together, and is known as "Composite Pavements". There is currently not a separate maintenance system devoted specifically to composite pavements.

This study was conducted to address this issue. The first step was to extract composite pavement sections from a merged data set. Then their distress and performance models were developed, the distresses that triggered the first treatment after a pavement section was converted into a composite section were identified, and the corresponding treatments were recommended. All these findings can be used to develop a new maintenance system for composite pavements in the NCDOT PMS.

Major findings and conclusions of this study are:

- In North Carolina, Transverse cracking, Longitudinal cracking, and Alligator cracking are the main dominate distresses developed in composite pavements; while Longitudinal Lane Joint, Patching - Non Wheel Path, Patching - Wheel Path, and Rutting are not common distresses.
- For Transverse cracking, composite pavements have performed similarly to asphalt pavements. For longitudinal cracking, except for asphalt pavement families US 30K plus, NC 1-5K, NC 5-15K, and NC 15K plus which performed better, both types of pavements performed similarly. For alligator cracking, composite pavements out-performed asphalt pavements.
- Except for asphalt pavement families Interstate 50K plus and US 30K plus, overall, composite pavements out-performed asphalt pavements. This better performance is probably due to the strong stiff base in composite pavements that can better support heavy wheel loads and provide a driving surface that has less cracks.
- In North Carolina, The triggering distresses for composite pavements are Longitudinal cracking (NDR) and Alligator cracking (LDR). Alligator cracking is more likely to trigger treatments than Longitudinal cracking.

Recommendations for further avenues of research are:

- It is recommended to update the NCDOT PMS so that it incorporates a section for composite pavements. The triggering distresses and treatments in this study were determined using the flexible pavement section of the PMS. Triggering distresses that were

determined using only composite pavements would be more specific and have a better representation of the types of distresses that composite pavements experience.

- It is recommended to validate the developed composite pavement models using newly collected automated data. If the models are robust and they perform differently than asphalt models, a new decision tree for composite pavements is justified and suggested to be added to the NCDOT PMS.
- In this study, only the first 12 years of performance data was used to develop distress and performance models. Performance data after the first 12 years, even though contains valuable performance information, was not used because of the short data history. After more performance data is collected, it is recommended to reset pavement age and develop these models again for increased model accuracy.

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CHAPTER 1 INTRODUCTION

1.1 Background

America's roadway system is one of the largest infrastructure assets that needs massive resources to maintain and operate. By the 1990s, over one trillion dollars had been invested to the nation's highway and bridge systems, and over 62 billion was devoted annually to physical preservations and operational improvements (FHWA, 1997). In the 21st century, highway officials are facing the challenges of managing "an ever-expanding, still-evolving, yet aging highway network" (FHWA, 1998) with inadequate and unsustainable resources. To address these challenges, it is essential for highway agencies to keep improving their pavement management systems (PMSs) so they can effectively manage roadway assets with limited resources.

A typical PMS consists of three subsystems: information, analysis, and implementation (Hudson, et al., 1979). The information subsystem includes the information of pavement inventories, performance conditions, treatment histories, traffic loads, and costs. The analysis subsystem provides a variety of methods to interpret pavement performances and to identify cost-effective treatments and strategies. The implementation subsystem presents the final program and schedule for the new construction, rehabilitation projects, and the annual maintenance projects. The effectiveness of a PMS depends on a number of factors, including correct identification of pavement types, collection of pavement distresses, development of deterioration models, and implementation of a comprehensive decision tree.

The transportation industry classically has had two classes of pavements, flexible and rigid. A third hybrid pavement also exists, that includes both flexible and rigid pavements together, and is known as "Composite Pavements". The typical composite pavement structure is constructed with a rigid base layer, typically of some sort of concrete with a flexible pavement layer on top, such as hot mix asphalt to provide a smooth surface for a more comfortable ride. The difference in the two materials' properties allows for both a strong stiff base to support heavy wheel loads and a smooth comfortable driving surface [1]. There is currently not a separate maintenance system devoted specifically to composite pavements.

1.2 Research Needs and Significance

In addition to two common types of pavements, asphalt and concrete, composite pavements have been used by highway agencies as a cost-effective alternative for high traffic volume roadways due to their high performance. Usually these composite pavements are the results of concrete pavement rehabilitations and constructed with an asphalt surface layer over a concrete base. In the NCDOT PMS, a function to allow engineers to select the composite pavement as the optimal pavement alternative for a project is lacking. The reason is that, historically, composite pavements have been classified as conventional asphalt pavements in North Carolina, even though these two types of pavements probably perform differently. To improve the performance of the NCDOT PMS, it is necessary to identify composite pavement sections in the PMS and developed corresponding distress models and performance models. The findings of this study can help NCDOT engineers to build a composite pavement branch that can be added to the existing decision trees. This new branch, together with the existing asphalt and JCP branches, can provide engineers with a wider selection of pavement types and allow them to recommend appropriate treatments for maintenance and rehabilitation activities.

1.3 Research Objectives

The purpose of this study was to develop distress and performance curves of composite pavements that can be used by the NCDOT PMS. To achieve this goal, the following objectives were proposed:

- Identify composite pavements from existing databases;
- Clean the raw data and develop pavement distress and performances models;
- Identify the triggering distresses in composite pavements; and
- Recommend the treatment that the NCDOT should perform based on the triggering distress using the NCDOT PMS.

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. Research methodology is described in Chapter 3. Chapter 4 focuses on research findings and conclusions. Chapter 5 provides recommendations for future research. Implementation and technology transfer plan is included in Chapter 6.

Appendix A includes distress curves of all composite pavement families. Appendix B includes all composite pavement families' performance curves.

CHAPTER 2 LITERATURE REVIEW

Composite pavements and commonly observed distresses in composite pavements are reviewed in this chapter.

2.1 Composite Pavements

The Committee on Composite Pavement Design of the Highway Research Board defined composite pavements as “A structure comprising multiple, structurally significant, layers of different, sometimes heterogeneous composition. Two layers or more must employ dissimilar, manufactured binding agents” (Smith, 1963).

Long life composite pavements have been used for decades all over the world due to their ability to handle heavy traffic loads while providing a smooth riding surface; this is due to the combination of the rigid subbase substructure with the flexible HMA layer (Nunez, 2008). In the United States, most existing composite pavements are the result of concrete pavement rehabilitations that construct hot mixed asphalt (HMA) layers on top of concrete bases (Flintsch et al., 2008; FHWA, 2016). New composite roadways have also been constructed since the 1950s by various states and local highway agencies, such as the states of New Jersey and Washington and the cities of New York, Washington, D. C., and Columbus, Ohio (Rao, 2013).

Worldwide, composite pavements have been built in the last few decades, especially in European countries (Hassan et al., 2008; Rao, 2013). Countries such as Germany, France, and Spain have built 30% to 50% of their main road networks using long-life, semi-rigid (composite) structures (Thogersen et al., 2004; Flintsch et al., 2008). Other European countries like the United Kingdom and Italy also use composite pavements. They use a low noise HMA surface layer and Jointed Concrete Pavement (JCP) or Continuously Reinforced Concrete (CRC) as the base layer.

Past studies of pavement performance indicate that composite pavements possess potential advantages functionally, structurally, and economically compared to traditional methods of pavements (Nunez, 2007). Pavement structures, throughout their service life, tend to show development of different types of distresses which may be categorized as fracture, distortion or disintegration. Composite pavements are believed to resist most of these distresses when high quality hot mix asphalt (HMA) is used in the top flexible layer of the pavement.

Long-term studies were conducted on the performance of composite pavements in the United States and Canada during the 1950s and the 1970s. These studies showed that HMA/PCC composite pavements needed the lowest amount of maintenance (Nunez, 2008). In 1999, the United Kingdom had 649 km of composite pavements installed between 1959 and 1987, and carrying 8 to 97 million single axle loads per year. Composite pavements from the U.K., the Netherlands, and Hungary performed satisfactorily in terms of cracking, rutting, and deflections. Compared to flexible pavements, the expected life of composite pavements was longer even under heavy traffic loads. There is extensive use of composite pavements in Spain; however, instead of PCC they use various types of rigid bases that vary from each other in cement content, type of aggregate, and size of aggregate (Nunez, 2008).

2.2 Composite Pavement Materials

The rigid layer of a composite pavement undergoes deformation due to distresses such as curling and warping because of the concrete slab's expansion, which is caused by temperature changes and moisture gradient differences. The flexible asphalt layer acts as a moisture barrier and thermal insulator, which reduces the effect of vertical temperature and moisture gradients, helping prevent deformation of the rigid layer. The asphalt also acts as a wearing surface, which controls the wearing effect of the different wheel loads on the rigid surface layer (Caltrans, 2008).

During the placement of the HMA layer, the high temperature of the mix speeds up the evaporation of the moisture content on the surface of the rigid layer, which reduces relative humidity. Once placed, the HMA layer acts as an insulating material to the rigid layer after it cools, which reduces the development of warping stress (Tompkins, 2013). The mechanism by which curling stresses are reduced involves the HMA layer buffering the lower rigid layer from temperature fluctuations. This can have an effect of extending pavement life between total restorations, in some cases up to fourteen years (Chen, 2015).

2.3 Distresses in Composite Pavements

Distresses in composite pavements are similar to those in flexible pavements due to the same materials being used as the top layer, and all of these distresses could potentially affect the performance and the structural capacity of composite pavements (Von Quintus et al., 1979; Flintsch et al., 2008). Common distresses in Composite pavements are fatigue cracking, rutting, top-down cracking, shrinkage cracking, reflective cracking, and thermal fatigue cracking (Hernando, 2013).

Several studies indicated that reflective cracking was the major distress type for composite pavements (Von Quintus, 1979). Reflective cracking is defined as cracking that occurs because of pre-existing (prior to overlay) cracking on the base layer beneath. This distress is easily created in the asphalt overlay when it moves with the underlying cement layer as it expands and contracts due to change in temperature (Dave, 2010; Flintsch et al., 2008). The majority of the reflective cracks in composite pavements occur along the expansion joints in the cement base.

Top down cracking is a distress that, by contrast with reflective cracking, starts at the asphalt layer and propagates downward. North Carolina Department of Transportation (NCDOT) uses the term "longitudinal cracking" to refer to this top-down cracking behavior. This type of cracking typically appears around the wheel path and on the edges of a roadway. Rutting is a load related distress that occurs in composite pavements when pressure of the wheel load causes the flexible asphalt layer to be pushed outward and to the side, because the rigid base layer will not itself deform. Shrinkage cracking occurs mostly when an asphalt overlay is put directly on top of a newly constructed cement base. As the concrete base cures, shrinkage occurs that causes the asphalt layer to be put under stress and then cracking occurs. Thermal fatigue cracking occurs when stresses due to low temperatures act on the pavement structure under vehicular load. As the temperature of the pavement system drops, the material becomes more brittle, especially the top asphalt layer. Under these conditions, the material does not perform as well and can release stress in the form of thermal fatigue cracking (Wang, 2013).

2.4 Performance of Composite Pavements and Treatments

Merrill et al. (2006) reported that composite pavements constructed in the U.K., Netherlands, and Hungary performed well in terms of rutting, cracking, and deflection. Additionally, compared to asphalt pavements, composite pavements tended to have longer service lives. Similarly, in the United State, the FHWA Zero Maintenance Pavement Study identified composite pavements as one of the most promising low-maintenance pavements (Darter & Barenberg, 1976; Rao et al., 2003). More advantages were discovered by Rao et al. (2012). In their study, they listed various situations where composite pavements were the optimal maintenance solutions, and summarized their advantages as lower life-cycle cost, rapid renewal, sustainable concrete pavement treatment solution, noise reduction with flexible surface layer, and combination of the structural capacity of concrete and the functional characteristics of asphalt surfacing.

In another study, Flintsch et al. (2008) indicated that composite pavements were able to reduce both structural and functional problems that typical flexible or rigid pavements possess. Additionally, based on the results of the deterministic agent-cost life cycle cost analysis, they concluded that a composite pavement with cement-treated base is a cost-effective alternative for a typical interstate highway, and a composite pavement with a continuously reinforced concrete pavement base may be a cost-effective option for highways with very high traffic volumes.

Nunez et al. (2008) studied the benefits and past performance of composite pavements, concluded that the performance of the composite pavements can be subsequently improved by increasing the thickness of the asphalt top layer in the pavements.

A study was conducted in the U.K. (Parry et al. 1999) to analyze the existing composite pavements designed for 100 MSA (million standard axle). It concluded that deterioration of pavements was not directly related to traffic but instead to the temperature of the surrounding.

2.5 Maintenance of Composite Pavements

Reflective cracking is the most common type of distress in composite pavements with HMA overlay. If reflective cracking is left untreated, it can cause excessive riding noise and premature failure (Rodezno, 2005). In 2015, (Chen, 2015) studied factors affecting reflective cracking in composite pavements. This study identified the following treatments for composite pavements:

- HMA overlay
- HMA mill and Fill
- Heater scarification (SCR)
- PCC rubblization

The effectiveness of HMA overlay treatment for composite pavements depends on the amount of reflective cracking present prior to overlay. Per the Federal Highway Administration (FHWA), surface recycling is an acceptable method to remove reflective cracks before laying an HMA overlay. Two other treatment methods, HMA mill and fill and heat scarification (SCR), are commonly used in the state of Iowa to remove existing cracks from pre-existing HMA overlays. In HMA mill and fill, new asphalt is mixed and used for repaving after milling. However, in the SCR treatment, recycling agents are used in addition to pulverized pavement materials for repaving. The main goal of the PCC rubblization process is to produce a sound base without any distresses and joints, which prevents reflective cracks. This is achieved by breaking the existing concrete pavement and overlaying it with HMA. In this study, a reflective cracking index (RCI) was used to quantify the severity of cracking and its corresponding threshold value was developed. Along with Reflective cracking index, International Roughness Index and pavement condition index were used to indicate the condition of the pavement (Chen, 2015). Among the several distresses found in composite pavements, reflective cracking was the most common distress (Akkari, 2012; Leng, 2006; Lytton et al., 1987). Reflective cracking is developed when cracks extend all the way from the PCC base to the surface of the HMA overlay. Subsequent penetration of moisture and other environmental components cause the failure of the pavement. According to Bennert and Maher (Bennert, 2007), state highway authorities reported that composite pavements were subject to reflective cracking within the first four years and other state highway authorities found reflective cracking within the first two years.

In a study conducted by Michigan Department of Transportation (MDOT) in 2010 (Ram, 2014), the performance of preventive maintenance treatments was evaluated. MDOT has a capital maintenance program (CMP) through which preventive maintenance treatments are implemented to slow down the process of deterioration and to correct surface irregularities on asphalt surfaced pavements. These preventive maintenance treatments postpone major rehabilitation and construction activities, thus saving money. A Distress Index (DI) is used to quantify various distresses. A DI value of 50 is set as the threshold value by MDOT for rehabilitation activities and the value is set to 40 for preventive maintenance activities. It was found that the first preventive maintenance activities could extend a composite pavement’s life by nine years.

Louisiana Department of Transportation and Development (LADOTD) conducted a study to develop pavement treatment performance models for overlay treatment of composite pavements (Khattak, 2014). In this study, pavements with HMA overlays in the state of Louisiana were analyzed and international roughness index models were developed. In this study, it was found that the following maintenance treatments have been used by LADOTD to maintain composite and flexible pavements:

- Replacement
- Structural (thick) overlay
- Non-structural (thin) overlay
- Crack sealing
- Chip deals
- Micro-surfacing
- Patching
- Full-depth concrete repair
- White Topping

In New York City, a study (Simpson, 2013) was conducted to identify the most cost effective and efficient method to mitigate reflective cracking in composite pavements. In order to evaluate the various treatment methods, performance of composite pavements with several treatment methods was compared with pavements without any treatment. Visual condition surveys, falling weight deflectometer surveys, forensic coring and material testing were used for the evaluation process.

In this research, the following treatments used to mitigate reflective cracking by New York City Department of Design and Construction (NYCDDC) were studied:

- Saw and seal the HMA overlay
- NYCDDC standard, nonwoven polypropylene fabric
- NYCDDC alternative fabric at the HMA surface and HMA binder interface
- Heavy-duty membrane interlayer or membrane
- Stress-absorbing interlayer composite
- Fiberglass reinforcement layer of Type 1
- Fiberglass reinforcement layer of Type 2

The study concluded that the saw and seal method gave the best performance. It was also concluded that 15-foot joints perform better that 20-foot joints in controlling high severity cracking.

In 2006, the New Jersey Department of Transportation (NJDOT) conducted a survey to study the various practices and HMA designs used by state highway agencies in the United States to mitigate reflective cracking. The following mitigation methods were identified:

- Paving fabrics and geotextiles (PFGs)
- Geogrids (GEOs)
- Stress-absorbing membrane interlayers (SAMIs)
- Reflective crack relief interlayer mixes–Strata-type mixes (RCRIs)
- Crack arresting layers (CALs)
- Excessive overlay thickness (EOT)

In addition to the above mitigation methods, some treatments were applied on PCC even before HMA overlays were laid in order to extend the life of the HMA overlay. These treatments are:

- Repair Cracks
- Replace Joints & Slabs
- Underseal
- Void Fill
- Crack & Seat
- Rubblize
- Edge Drains

Transverse cracking can be caused by many factors. One of the factors is shrinkage, both plastic and drying, which causes transverse cracking early in the pavements life. Another common factor is surface cracks deteriorating over time and becoming transverse cracks due to heavy traffic loads or climatic variations in temperature and/or moisture conditions that cause expansion and contraction of the base layer. This movement in the base layer induces interface friction between the overlay and the base layer, which can lead to transverse cracking (Frabizzio, 1999). Crack sealing is the traditional method used to treat transverse cracking. There are several other treatments which can be used before overlay is laid. Some of these treatments include fiberglass–polyester paving mat, hot-mix patching, hot-mix patching combined with fiberglass–polyester paving mat, and crack sealing.

CHAPTER 3 RESEARCH METHODOLOGY

This chapter presents the methodology used to generate the data set, develop distress and performance models, identify triggering distresses and recommend appropriate treatments for composite pavements.

3.1 Overview of the Research Methodology

To develop distress and performance models for composite pavements, the first step is to generate a data set that includes all the necessary information, such as pavement route numbers, mile posts, age, AADT, and distress ratings. Once this data set is generated and its outliers cleaned, distress and performance models for composite pavements families can then be developed. This work flow is illustrated in Figure 1.

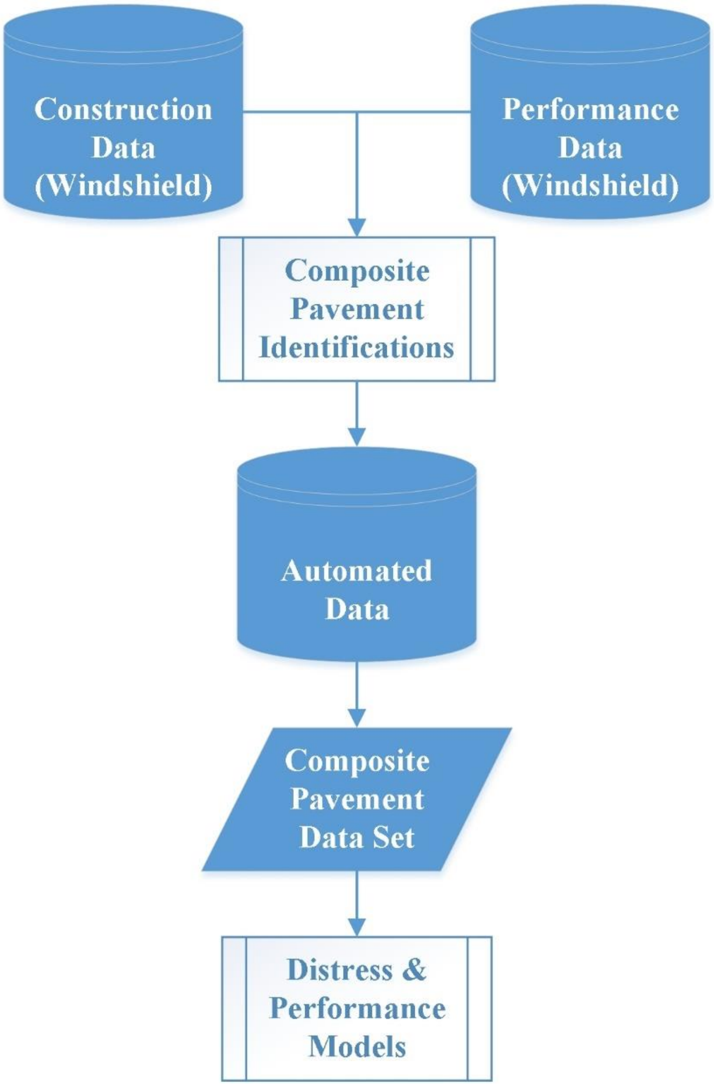


Figure 1: Flow Chart of Research Methodology

3.2 Research Data

3.2.1 Data Sources

The construction and the performance data sets used by this study were provided by the NCDOT.

The construction data set contains the historical treatments applied to the NC roadway system from the early 1900s to 2015. In this data set, treated pavement sections are identified by the county name, the route number, the mileposts, and the treatment year. Other information, such as the treatment types and materials, is also included.

The performance data set includes roadway survey results and severity ratings of different types of distresses. In this data set, pavement sections are identified by the county name, the route number, the mileposts, and the effective year which indicates the year when the data was collected. Based on data collection methods, two types of performance data have been generated and maintained by NCDOT: the windshield and the automated data. The NCDOT had launched windshield roadway surveys since the early 1980s, and the available windshield data are from 1982 to 2010. In 2011, the NCDOT started using the automated technique to collect distress data. The automated data used in this research are from 2013 to 2015.

The North Carolina's windshield data has a much longer history than the automated data; the automated data contain more types of distresses than the windshield data. For example, patching in the windshield data is been further categorized into wheel path and non-wheel path patching in the automated data; longitudinal cracking and reflective cracking are new types of distressed that have been added to the automated data. The measurements of distresses are also different. In the windshield data, alligator cracking is the only distress that was measured using continuous ratings, other distresses are rated with discrete ordinal ratings, such as "None", "Light", "Moderate", and "High". While in the automated data, all the distresses were measured using continuous ratings. Table 1 summarizes distress measurements, data processing methods and analysis processes of the windshield and the automated data in a previous study (Chen et al., 2014). It should be noted that in Table 1, in the "Analysis Process" column, "I" represents Data Normalization; "II" represents Distress Composite Index; "III" represents Numeric Data Transformation; and "IV" represents Calculation of Performance Composite Index (Chen et al., 2014). It should also be noted that the automated Raveling data was not used in this study because of the data quality issue.

3.2.2 Data Merging Process

To identify composite pavement sections from the automated data, several steps were performed as shown in the flow chart below (Figure 2).

Step One: Merge the windshield performance data and the construction data

The windshield performance data (from 1982 to 2010) and the construction data (from 1900 to 2015) were merged using section identifications, including the county name, the route number, the mileposts, and the effective year. Since the mileposts of the same pavement section in these two data sets were not always the same, a threshold of 50% of the length between the starting and ending mileposts was used to merge these two data sets.

Step Two: Identify past treatments for each pavement section

After the first step, a merged data set that contains each pavement section and its past treatment information is obtained. Then from the construction data, the material of the top layer used for each treatment, either asphalt or concrete, can be identified.

Step Three: Identify the year when pavement sections converted to composite pavements

For a roadway section, if its top layer material has changed from concrete to asphalt, then this section can be identified as a composite pavement section after its first asphalt treatment. In addition, the year of the latest treatment before the performance data was collected was considered as the "reborn" year of a composite pavement section and was used to calculate the age of this composite pavement section.

Step Four: Obtain identification information of composite pavements

In this step, identification information of composite pavement sections, i.e., county names, route names, and mileposts, was extracted from the merged windshield data. Two assumptions were made. They are: 1) once a concrete pavement section was converted to a composite section, it would stay as a composite section, and 2) composite pavement sections in the automated data (from 2013 to 2015) would use the same identification information as that of in the windshield data.

Step Five: Extract composite pavements from the automated performance data

The identification information obtained from the previous step was used to identify and extract composite pavements from the automated performance data.

Step Six: Merge the composite pavement performance data (automated) with the construction data

After Step Five, the automated performance data set of composite pavements, referred to as the composite pavement data, was obtained. However, the latest treatment in the windshield data was not necessarily the latest treatment in the automated data because the automated data was collected after the windshield data was collected. Therefore, this extracted automated performance data was merged again with the construction data to find out the year of the latest treatment was applied. This information was used to calculate the age of a composite pavement.

3.2.3 Date Cleansing

To improve the quality of the composite pavement data, data cleansing was implemented in the merging process based on engineering judgement and statistical methods.

Firstly, errors and abnormalities in the windshield performance data were identified and fixed based on engineering judgement. For instance, a low performance index value at early ages and a high performance index value at late ages are considered as outliers and thus removed.

Table 1: Comparison of the windshield and the automated data in North Carolina

Data	Distresses	Data Type	Severity Level	Unit	Analysis Process			
					I	II	III	IV
Windshield	Alligator cracking	Interval/ continuous	4	Percentage	No	Yes	No	No (already calculated in raw data)
	Transverse cracking	Ordinal/ discrete	4	N/A	Assigning discrete values	No	Yes	
	Rutting							
	Raveling							
	Oxidation							
	Patching							
	Bleeding							
Automated	Alligator cracking	Interval/ continuous	3	Square feet	Yes	Yes	No	Used with weight factors
	Raveling		3			Yes		
	Wheelpath patching		1			No		
	Non-wheelpath patching		1			No		
	Transverse cracking		3	Linear feet		Yes		
	Reflective cracking		3			Yes		
	Longitudinal cracking		2			Yes		
	Longitudinal lane joint		2			Yes		
	Bleeding		2	Square feet		Yes		Not included
	Delamination		1	Square feet		No		

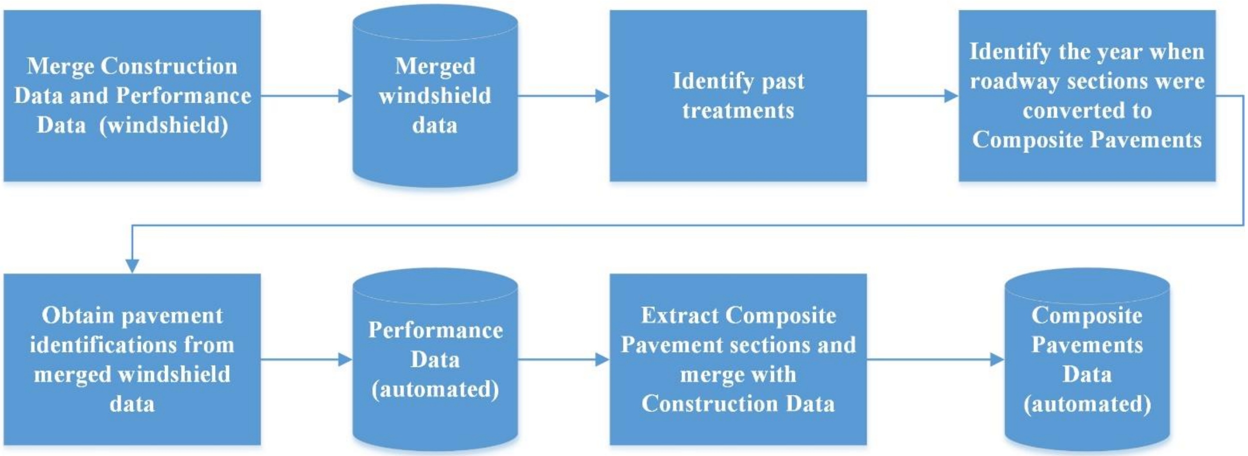
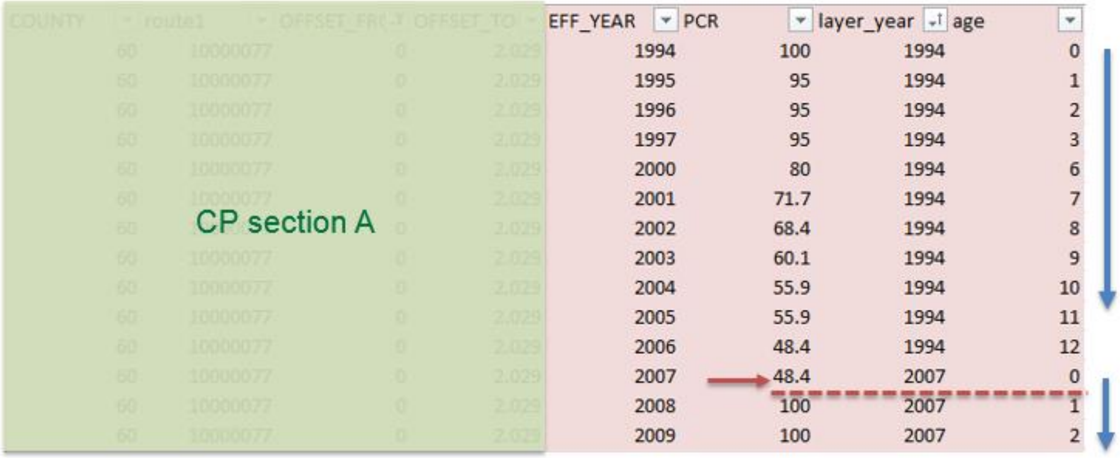


Figure 2: Data Merging Process

Special attention should be given to the age of the windshield performance data identified in *Step Three* in the date merging process. In this step, if the performance data was collected in the same year when it was treated but right before the treatment, the performance rating would be fairly low and the pavement age would be reset to 0. An example of these abnormalities is shown in Figure 3 (the "layer_year" column indicates the corresponding latest treatment year of the performance data). In this example, the first treatment was performed in 1994, and the second was in 2007. The condition data (Pavement Condition Rating (PCR) of 48.4) in the year of 2007 should have an age of 13 instead of 0. In the construction data set, 2007 can be either the year that this roadway section was open to traffic, or the year the contract was signed. To address this issue, all the performance data at age of 0, with PCR values less than 95, were removed. This was because if a pavement section was just treated, it should have a PCR value close to 100.



COUNTY	route1	OFFSET_FR	OFFSET_TO	EFF_YEAR	PCR	layer_year	age
60	10000077	0	2.029	1994	100	1994	0
60	10000077	0	2.029	1995	95	1994	1
60	10000077	0	2.029	1996	95	1994	2
60	10000077	0	2.029	1997	95	1994	3
60	10000077	0	2.029	2000	80	1994	6
60	10000077	0	2.029	2001	71.7	1994	7
60	10000077	0	2.029	2002	68.4	1994	8
60	10000077	0	2.029	2003	60.1	1994	9
60	10000077	0	2.029	2004	55.9	1994	10
60	10000077	0	2.029	2005	55.9	1994	11
60	10000077	0	2.029	2006	48.4	1994	12
60	10000077	0	2.029	2007	48.4	2007	0
60	10000077	0	2.029	2008	100	2007	1
60	10000077	0	2.029	2009	100	2007	2

Figure 3: An Example of Abnormalities of Pavement Age

It was observed that some pavement sections had obvious PCR jumps but no associated treatments were found. To address this issue, these sections after jumps were assigned a pavement age of 0, and were considered as the results of treatments that have not been recorded in the construction data.

Secondly, outliers of distress and performance index values at each age were removed using interquartile ranges (IQRs).

An IQR is defined as:

$$IQR = Q_1 - Q_3$$

$$Bottom\ Boundary = Q_1 - 1.5 * IQR$$

$$Upper\ Boundary = Q_3 + 1.5 * IQR$$

where Q_1 is the 25th percentile, Q_3 is the 75th percentile, and IQR is the interquartile range. Data at each age beyond the corresponding bottom and upper boundaries were considered as outliers and removed. John Tukey was an American mathematician best known for inventing the boxplot and the 1.5*IQR rule. The constant 1.5 was used to avoid been too exclusive (too many outliers) and too inclusive (too few outliers). Within ±1.5*IQR, about 1% of data would be declared as outliers. This is a reasonable compromise, under assumptions of Normality.

3.2.4 Pavement Families

After the composite pavement data was cleaned, sample sizes of composite pavement sections were obtained and are presented by pavement families in Table 2. Several families are combined with others due to their small sample sizes. The final 5 composite pavement families studied are: Interstate, US_0-5K, US_5K plus, NC_0-5K, and NC_5K plus. It should be noted that the Secondary Route (SR) family was not studied because the automated data provided by NCDOT does not include SR sections.

Table 2: Composite Pavement Families

Initial Pavement Family	Initial Sample Size	Final Pavement Family	Final Sample Size
Interstate 0-50K	1,012	Interstate	1,161
Interstate 50K plus	149		
US_0-5K	1,324	US_0-5K	1,324
US_5-15K	1,154	US_5K plus	1,448
US_15K plus	294		
NC_0-5K	705	NC_0-5K	705
NC_5K plus	487	NC_5K plus	487

3.3 Development of Distress Models

3.3.1 Calculation of Distress Index Values

The composite pavement data contains distress information such as distress types and amounts of distress at different severity levels. To develop distress models, it is necessary to calculate a distress index for each distress, and the value of this index summarizes different severity ratings of the distresses in each roadway section. These distress indices are composite indices and can be calculated using the Maximum Allowable Extent (MAE) functions (Chen et al., 2014).

Two steps were involved in the distress index calculations. The first step was to normalize the raw data into percentages at each severity level. Then, composite distress index values were calculated using the MAE spreadsheet provided by NCDOT. The algorithm and details of the distress index calculation was presented by Chen et al. (2018). Table 3 presents the MAE input values used in this study. In this table, *L*, *M*, and *H* represent the Low, Moderate, and High severity level, respectively. *Single* indicates that there is only one severity level.

3.3.2 The Range of Pavement Age

Graphic analysis of the composite pavement data was conducted to investigate the basic features of the distress index values. From automated data collected in 2013, 2014, and 2015, a common deterioration trend was observed in the first 12 years of all the composite pavements for all types of distresses; then the same trend repeats itself afterwards. Most likely composite pavements follow the second trend were treated at the end of the 12th year, and their corresponding pavement age should be adjusted. However, this adjustment to pavement age was not performed using the three-point method (Chen et al., 2014) because of the short data period (from 2013 to 2015). To use the best available data, it was decided to use the first 12 years of distress data to develop distress models.

The boxplot of Alligator cracking of the US_0-5K family was used as an example to illustrate the pattern of the abovementioned deterioration trend. In Figure 4, the x axis represents the pavement age, and the y axis represents alligator cracking index. The diamond inside each box represents the average distress index value at each age, which can be used to visually characterize the deterioration trend.

Table 3: MAE Input Values for Composite Pavements

Pavement	**Distress**	**Severity**	**MAE Input**	**MAE Threshold**
Composite Pavement	Transverse Cracking & Reflective Transverse Cracking	L	1.2000	60
		M	0.8000	30
		H	0.4000	0
	Longitudinal Cracking	L	0.7041	60
		H	0.6165	0
	Longitudinal Lane Joint	L	0.2500	60
		H	0.1500	0
	Alligator Cracking	L	30.9077	60
		M	4.7015	30
		H	2.0000	0
	Patching - Non Wheel Path	Single	16.0566	0
	Patching - Wheel Path	Single	23.2562	0
	Rutting	Single	99.3600	NA

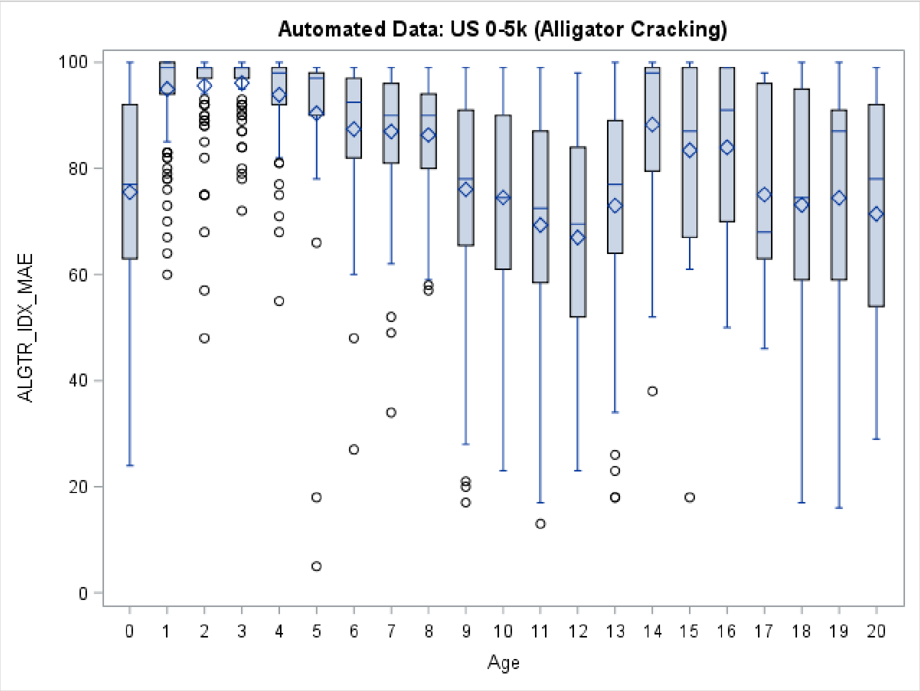


Figure 4: Boxplot of Alligator Cracking (US_0-5K)

3.3.3 Distress Models

The sigmoidal equation (Chen et al., 2014; Chen & Mastin, 2015) was used to develop distress models for different pavement families. The equation can be written as

$$y = \frac{a}{1 + e^{\frac{-x+b}{c}}} \qquad (1)$$

where y is distress index value; x is pavement age; a, b, and c are model parameters.

Figures 5 through 11 are boxplots of distresses by pavement families. From these boxplots, it can be observed that transverse cracking, Longitudinal cracking, and Alligator cracking are the main dominate distresses developed in composite pavements; while Longitudinal Lane Joint, Patching - Non Wheel Path, Patching - Wheel Path, and Rutting are not common distresses in composite pavements, and this was justified by the fact that their fitted model curves are fairly flat.

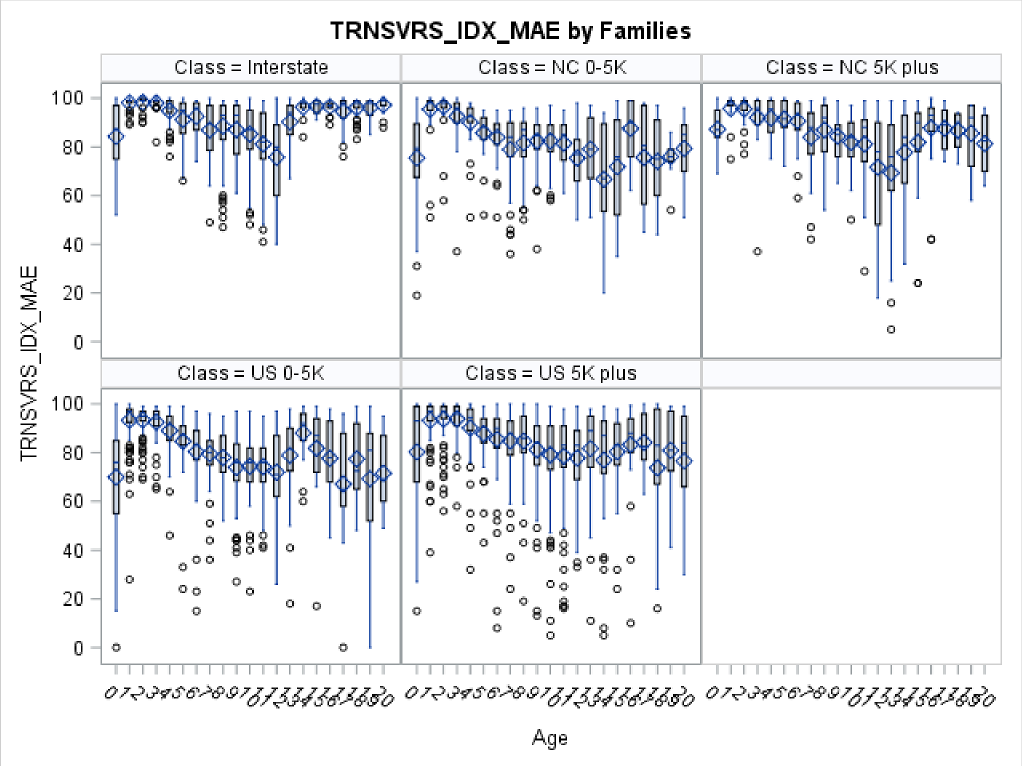


Figure 5: Transverse Cracking by Families

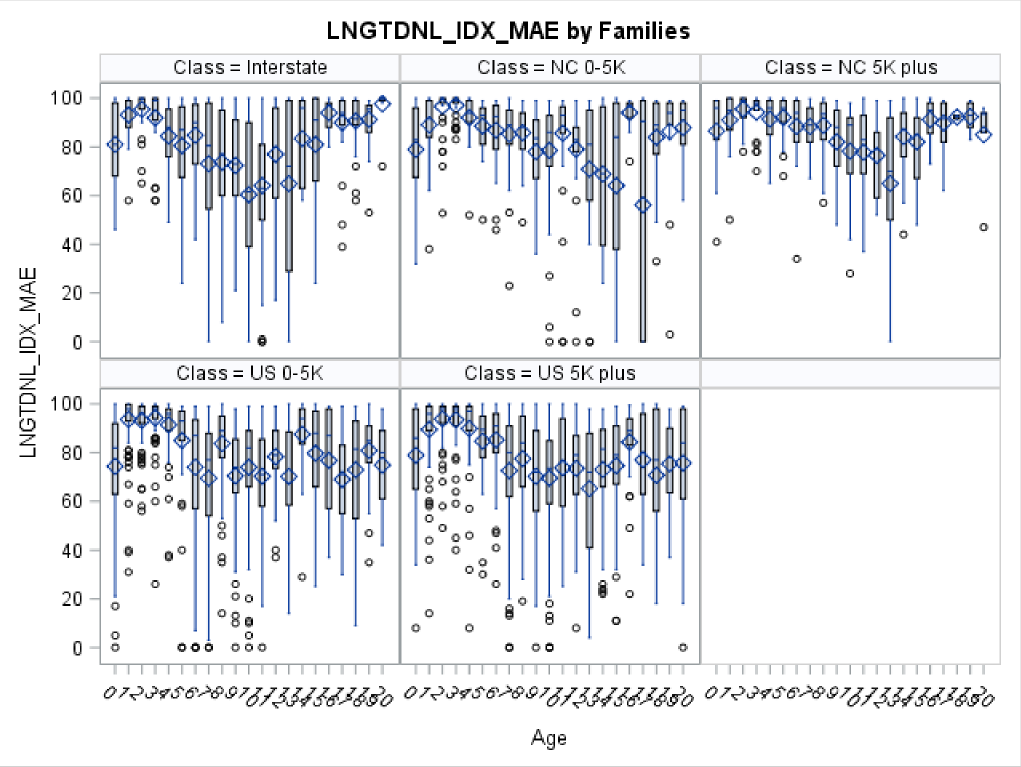


Figure 6: Longitudinal Cracking by Families

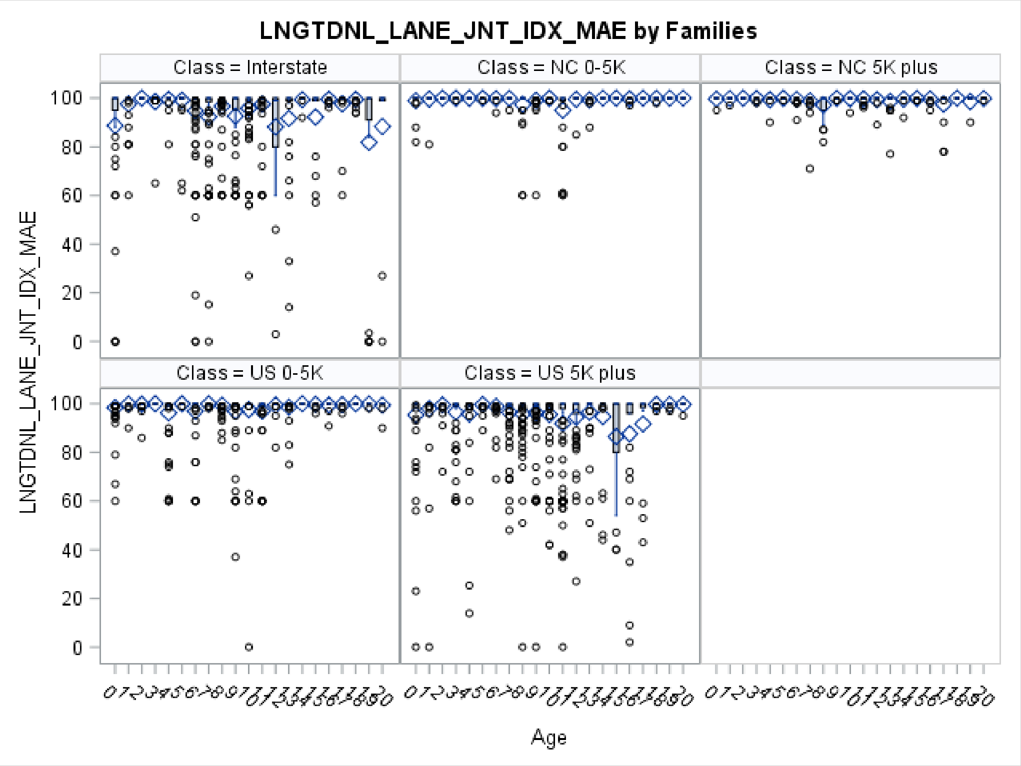


Figure 7: Longitudinal Lane Joint by Families

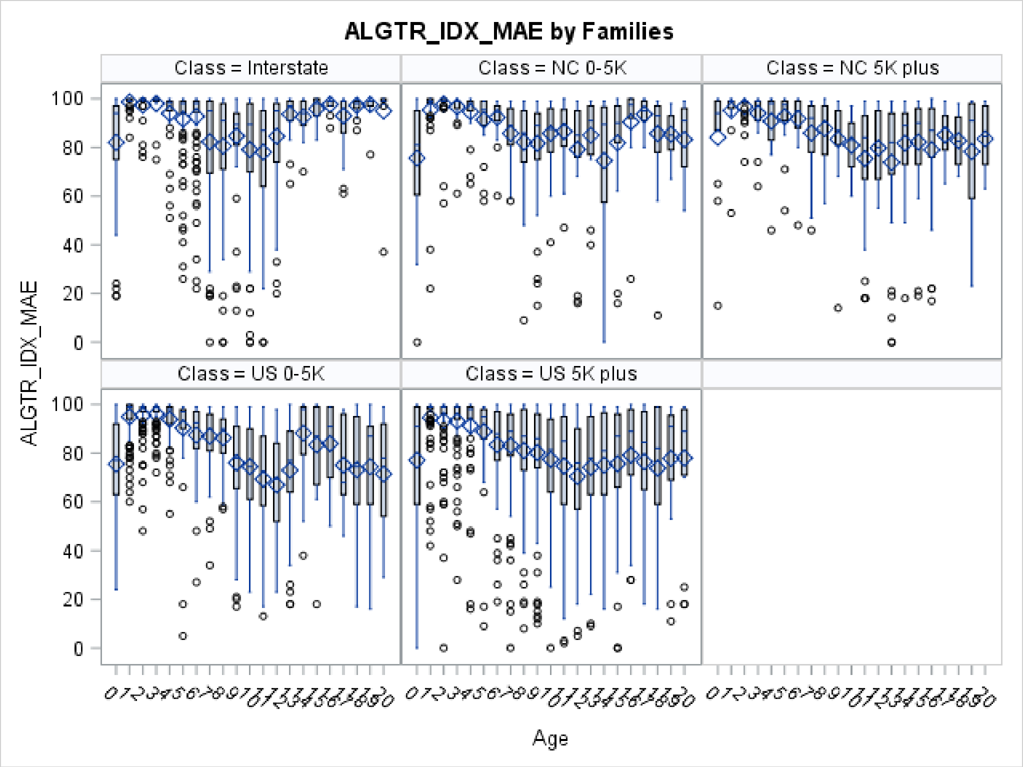


Figure 8: Alligator Cracking by Families

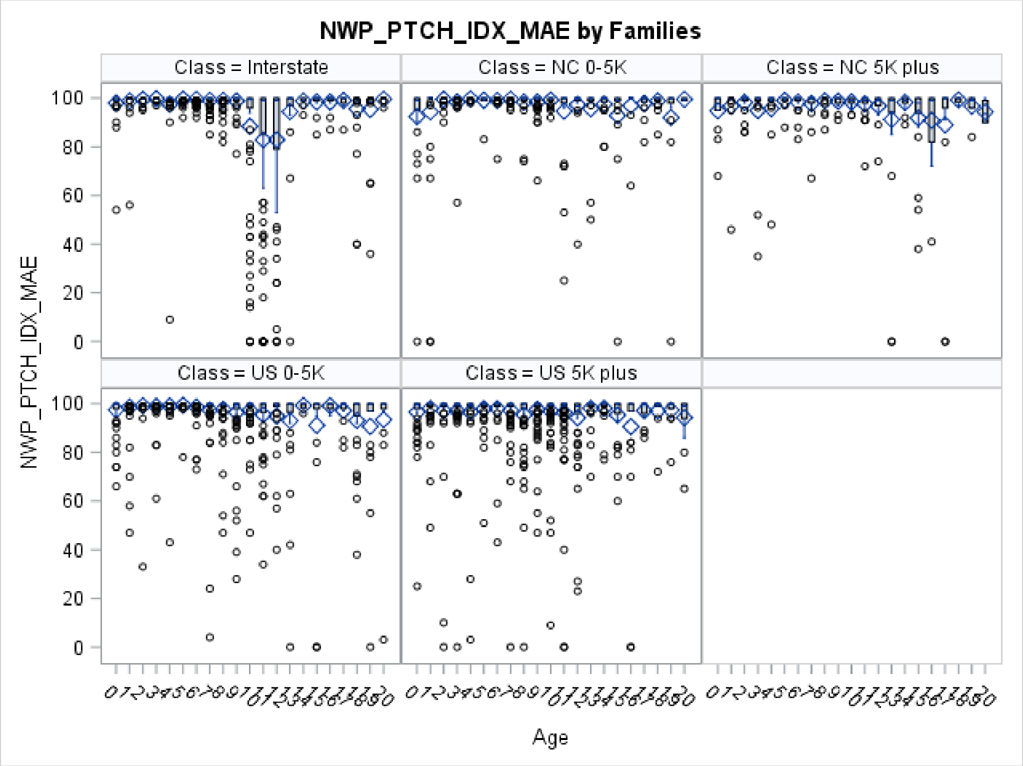


Figure 9: Patching - Non Wheel Path by Families

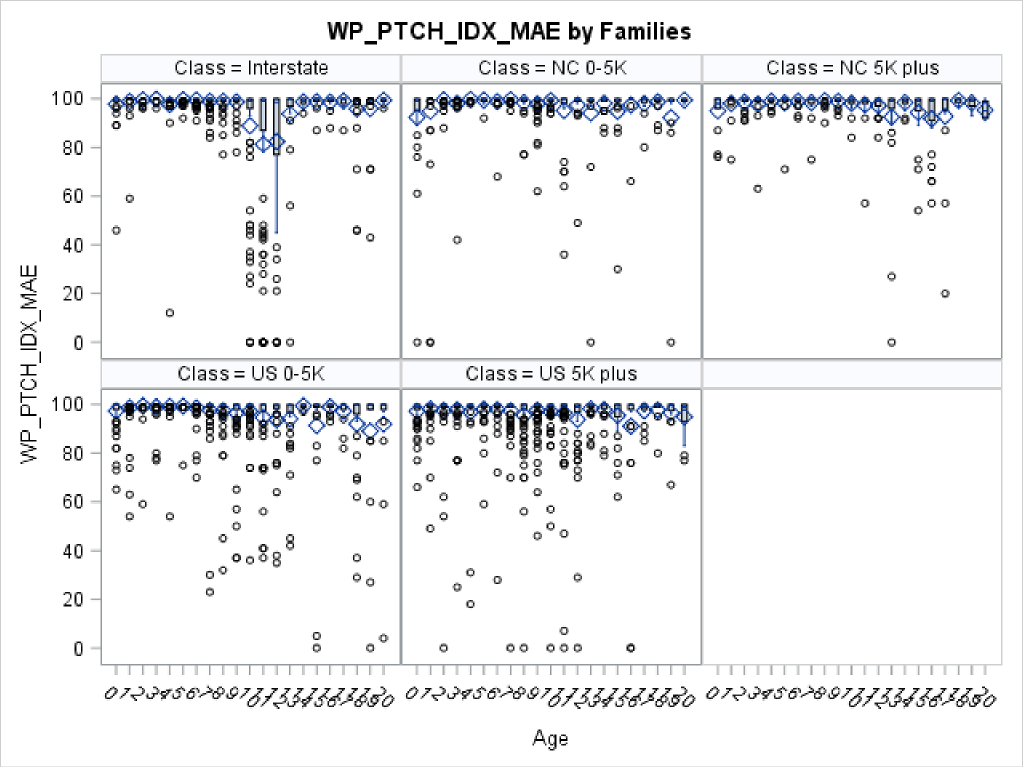


Figure 10: Patching - Wheel Path by Families

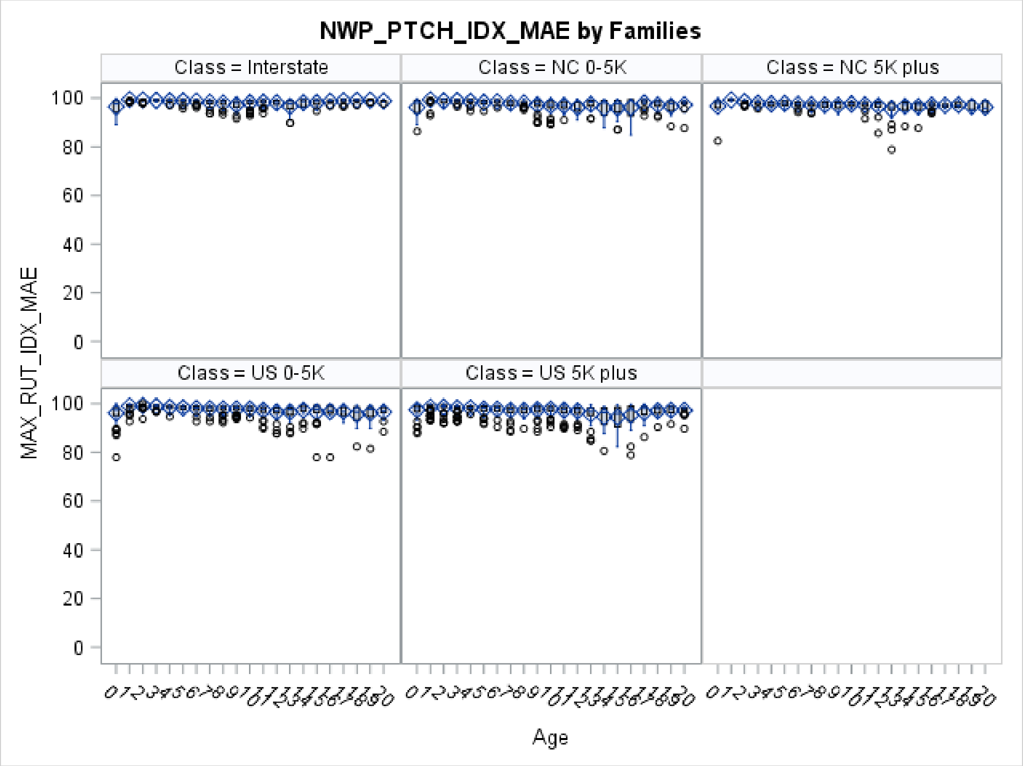


Figure 11: Rutting by Families

Nonlinear regression analyses were performed to calculate model parameters, a, b, and c. The results are included in Table 5. Italic rows in the table represent uncommon distresses. The distress curves of these uncommon distresses are very flat and thus unreasonable.

Table 4: Model Parameters for Distress Models

Distress	**Family**	***a***	***b***	***c***
Transverse Cracking	Interstate	100.9	17.5566	-3.6928
	US 0_5K	103.2	14.8184	-4.2641
	US 5K plus	102.0	18.3420	-4.6737
	NC 0_5K	101.6	15.7333	-3.8034
	NC 5K plus	101.6	18.0070	-4.3046
Longitudinal Cracking	Interstate	101.6	14.1752	-3.3995
	US 0_5K	101.2	13.8530	3.0886
	US 5K plus	101.5	15.1512	3.5397
	NC 0_5K	100.9	17.1224	3.6156
	NC 5K plus	101.0	17.0652	3.6468
Longitudinal Lane Joint	*Interstate*	*100.0*	*59.7034*	*-7.9677*
	US 0_5K	*100.0*	*554.6891*	*-79.6606*
	US 5K plus	*100.0*	*238.4999*	*-34.3569*
	NC 0_5K	*100.0*	*682.0773*	*-98.0610*
	NC 5K plus	*100.0*	*946.8519*	*-137.2032*
Alligator Cracking	Interstate	100.9	17.4969	-3.6336
	US 0_5K	103.0	14.4567	-4.1232
	US 5K plus	101.8	17.1453	-4.2275
	NC 0_5K	101.6	15.3624	-3.7018
	NC 5K plus	101.5	17.5145	-4.1092
Patching - Non Wheel Path	*Interstate*	*100.0*	*39.1869*	*-5.0954*
	US 0_5K	*100.0*	*66.0057*	*-9.1705*
	US 5K plus	*100.0*	*146.7378*	*-22.6580*
	NC 0_5K	*100.0*	*81.1939*	*-11.3582*
	NC 5K plus	*100.0*	*58.9699*	*-8.8263*
Patching - Wheel Path	*Interstate*	*100.0*	*37.2514*	*-4.8811*
	US 0_5K	*100.0*	*63.6702*	*-8.8267*
	US 5K plus	*100.0*	*173.2665*	*-27.0673*
	NC 0_5K	*100.0*	*79.1079*	*-11.1130*
	NC 5K plus	*100.0*	*54.9689*	*-8.1536*
Rutting	*Interstate*	*100.0*	*53.9260*	*-10.7780*
	US 0_5K	*100.0*	*42.0477*	*-8.4492*
	US 5K plus	*100.0*	*52.6824*	*-11.2848*
	NC 0_5K	*100.0*	*34.9669*	*-6.7342*

	NC 5K plus	*100.0*	*58.6495*	*-13.4422*

Figures 12 through 14 below present distress model curves. Individual distress model curves are included in Appendix A.

Visual comparisons of distress curves between composite pavements developed in this study and asphalt pavements developed in a previous study (Chen et al. 2017) are shown in Figures 15 through 17. In these figures, composite pavement curves are thicker solid lines, while asphalt pavement curves are thinner dashed lines. For Transverse cracking, composite pavements have performed similarly to asphalt pavements. For longitudinal cracking, except for asphalt pavement families US 30K plus, NC 1-5K, NC 5-15K, and NC 15K plus which performed better, both types of pavements performed similarly. For alligator cracking, composite pavements out-performed asphalt pavements.

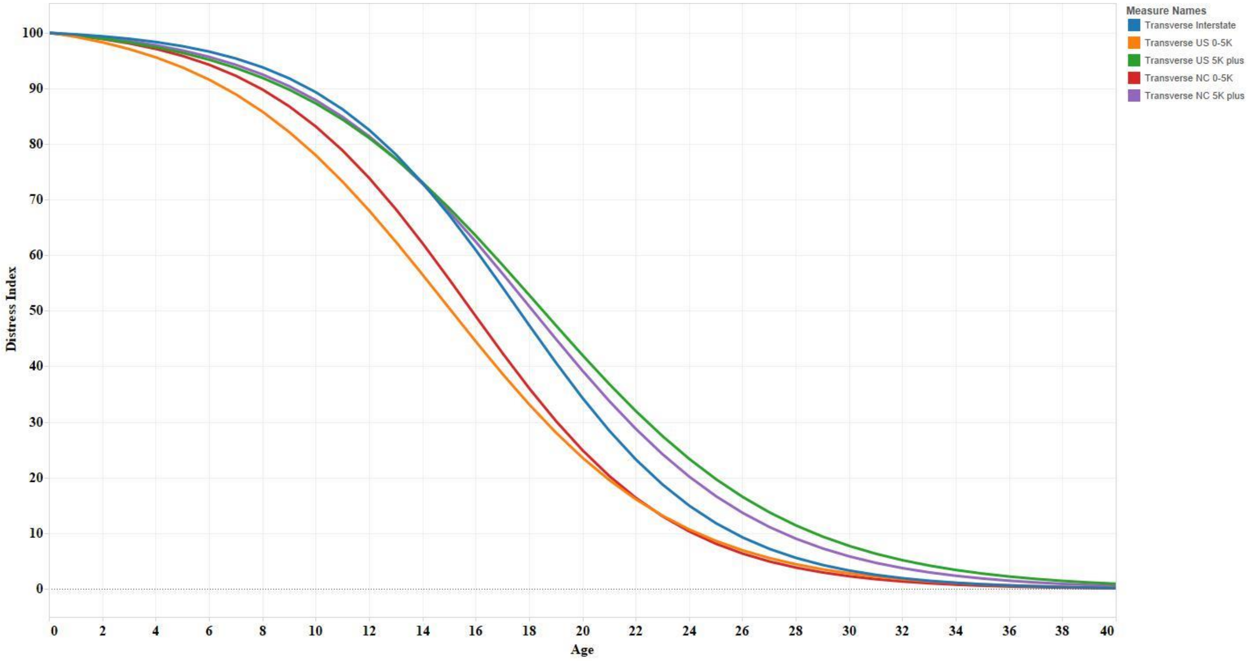


Figure 12: Transverse Cracking Curves

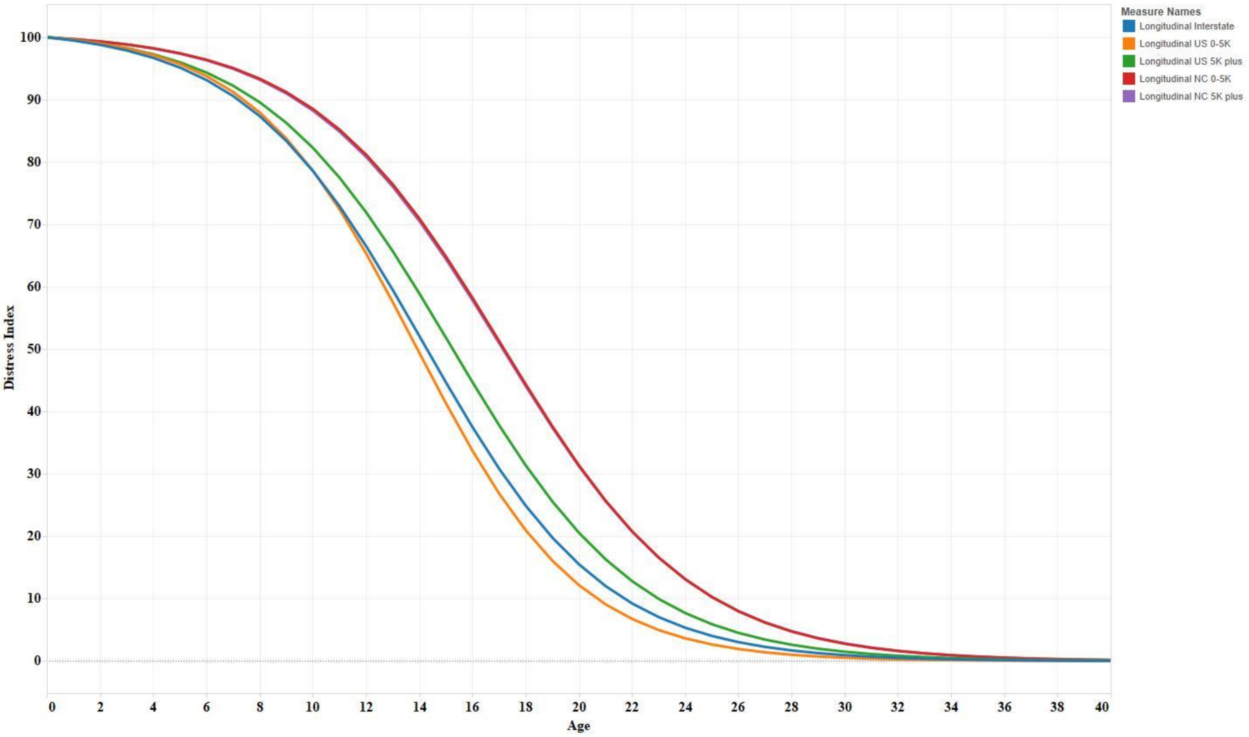


Figure 13: Longitudinal Cracking Curves

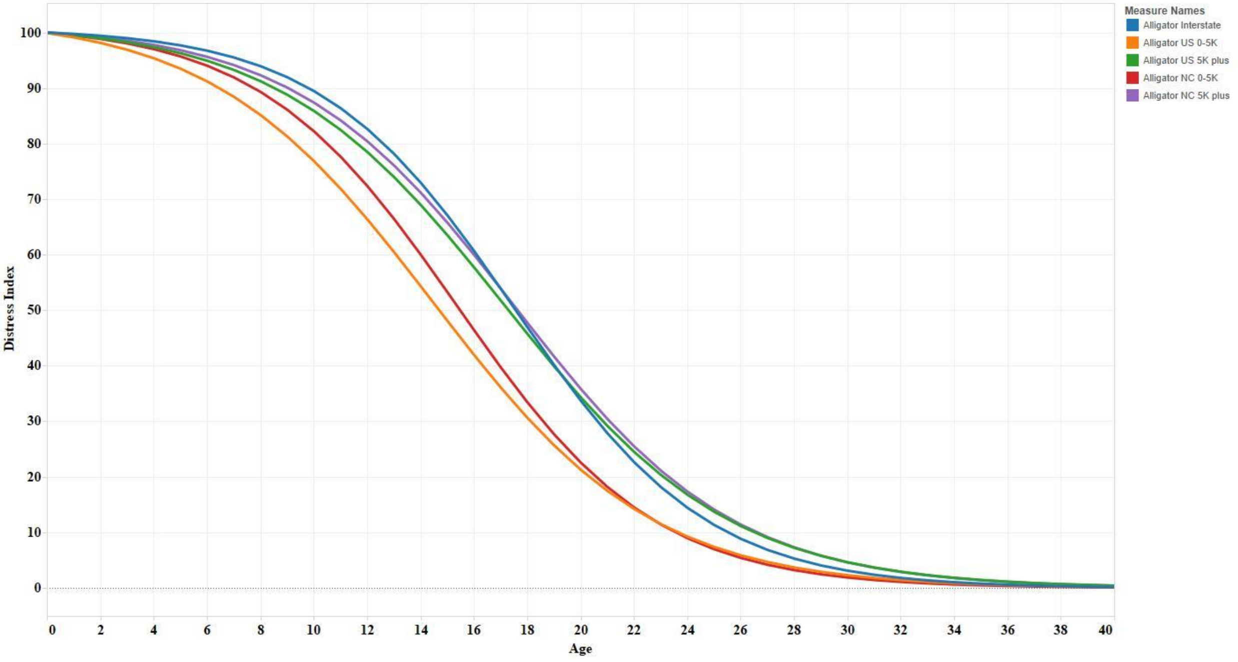


Figure 14: Alligator Cracking Curves

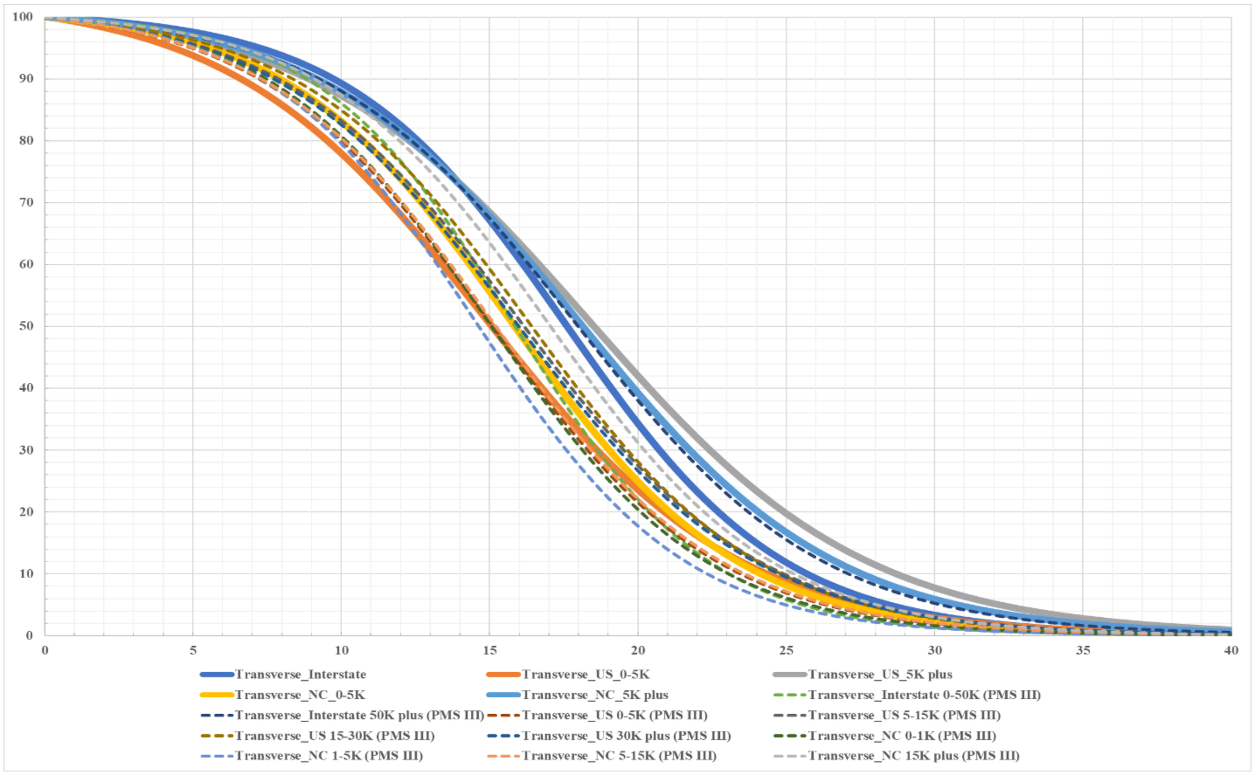


Figure 15: Comparison of Transverse Cracking Curves

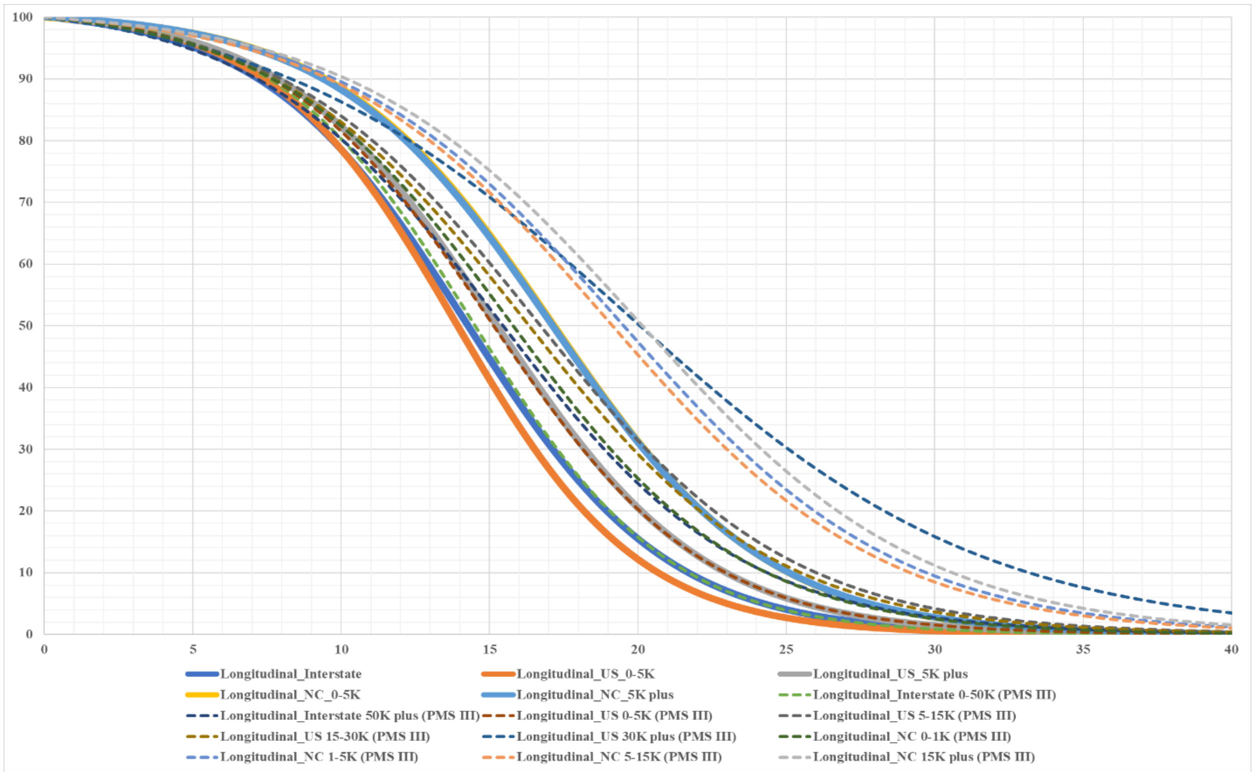


Figure 16: Comparison of Longitudinal Cracking Curves

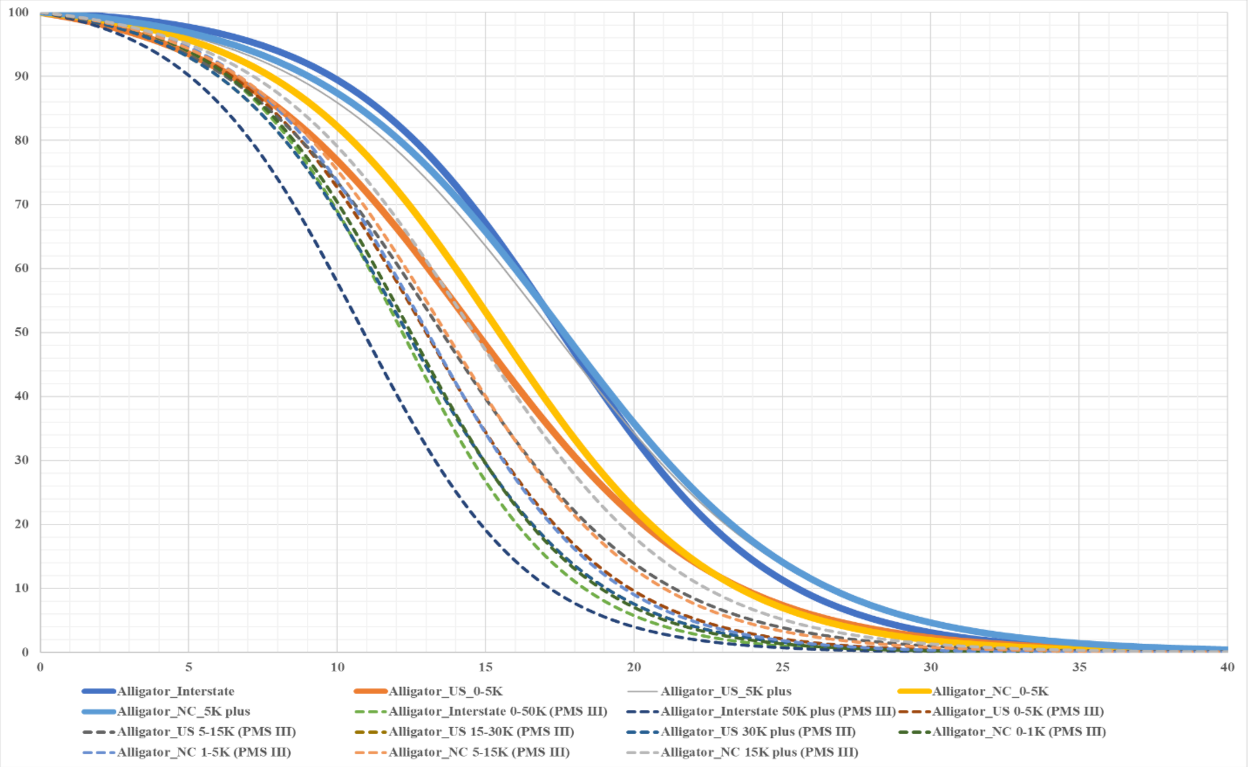


Figure 17: Comparison of Alligator Cracking Curves

3.4 Development of Performance Models

3.4.1 Calculation of Pavement Condition Rating (PCR)

As a pavement performance indicator, PCR was calculated using distress index values of different distress types and their corresponding weight factors. The weight factors were determined by a study conducted by Chen et al. (2017) and are summarized in Table 5. In this study, distresses are categorized into load-related (LDR) and non-load related (NDR), and the PCR value is the smaller value of LDR and NDR index values. LDR, NDR, and PCR were calculated using equations 2, 3, and 4, respectively.

Table 5: Weight Factors of Asphalt Pavements

	Distress	**Weight Factor**
LDR	Alligator Cracking (ALGTR)	0.5316370
	Patching Area - Wheel Path (WP)	0.1520450
	Patching Area - Non Wheel Path (NWP)	0.0887566
	Rutting - Maximum Average Depth (RUT)	0.2275610
NDR	Transverse/Reflective Transverse Cracking (TRA)	0.5152640
	Longitudinal Cracking (LNG)	0.2729290
	Longitudinal Lane Joint (LNG_JNT)	0.2118080

$$NDR = 0.5152640 * TRA + 0.2729290 * LNG + 0.2118080 * LNG\_JNT \quad (2)$$

$$LDR = 0.5316370 * ALGTR + 0.1520450 * WP + 0.0887566 * NWP + 0.2275610 * RUT \quad (3)$$

$$PCR = \min(LDR, NDR) \quad (4)$$

3.4.2 The Range of Pavement Age

A similar graphic analysis of the composite pavement data was conducted to investigate the basic features of PCR values. Again a common deterioration trend was observed in the first 12 years of all the composite pavements; then the same trend repeats itself afterwards. An example of this deterioration trend can be observed in Figure 18. To use the best available data, a similar decision was made to use the first 12 years of distress data to develop performance models.

3.4.3 Performance Models

The sigmoidal equation (Chen et al., 2014; Chen & Mastin, 2015) was used to develop performance models for different pavement families. The equation can be written as

$$y = \frac{a}{1+ e^{\frac{-x+b}{c}}} \quad (1)$$

where y is PCR value; x is pavement age; a, b, and c are model parameters.

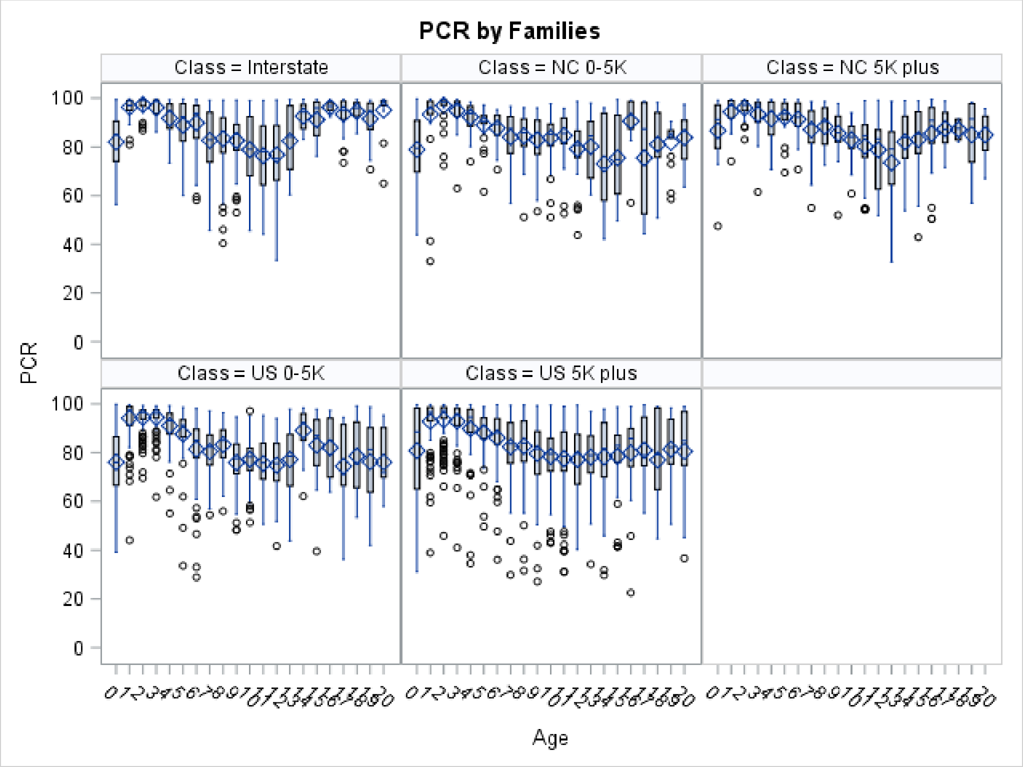


Figure 18: PCR by Families

Nonlinear regression analyses were performed to calculate model parameters, a, b, and c. The results are included in Table 6.

Table 6:Model Parameters for Performance Models

Family	***a***	***b***	***c***
Interstate	100.9	17.4969	-3.6336
US 0_5K	103.0	14.4567	-4.1232
US 5K plus	101.8	17.1453	-4.2275
NC 0_5K	101.6	15.3624	-3.7018
NC 5K plus	101.5	17.5145	-4.1092

Composite pavement families' performance curves are shown in Figure 19. Individual distress model curves are included in Appendix B.

Visual comparisons of performance curves between composite pavements developed in this study and asphalt pavements developed in a previous study (Chen et al. 2017) are shown in Figure 20. In this figure, composite pavement curves are thicker solid lines, while asphalt pavement curves are thinner dashed lines. Except for asphalt pavement families Interstate 50K plus and US 30K plus, overall, composite pavements out-performed asphalt pavements.

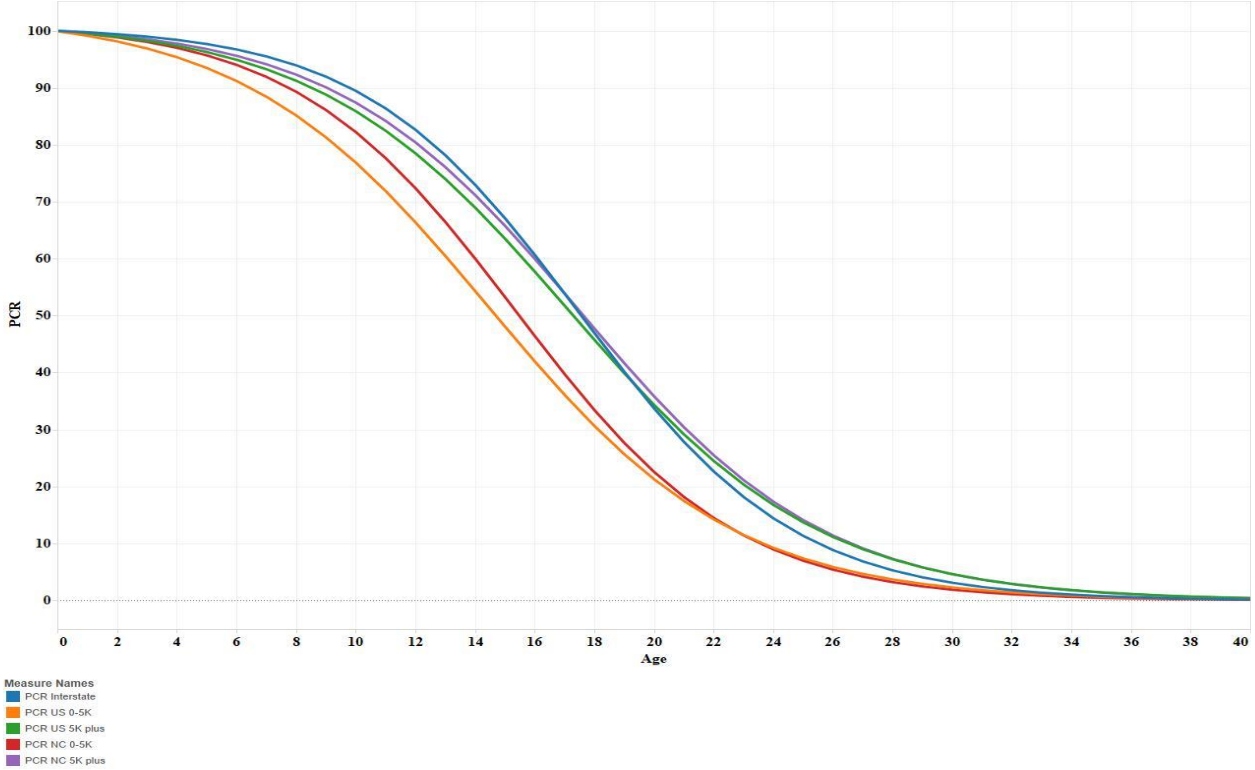


Figure 19: PCR Curves

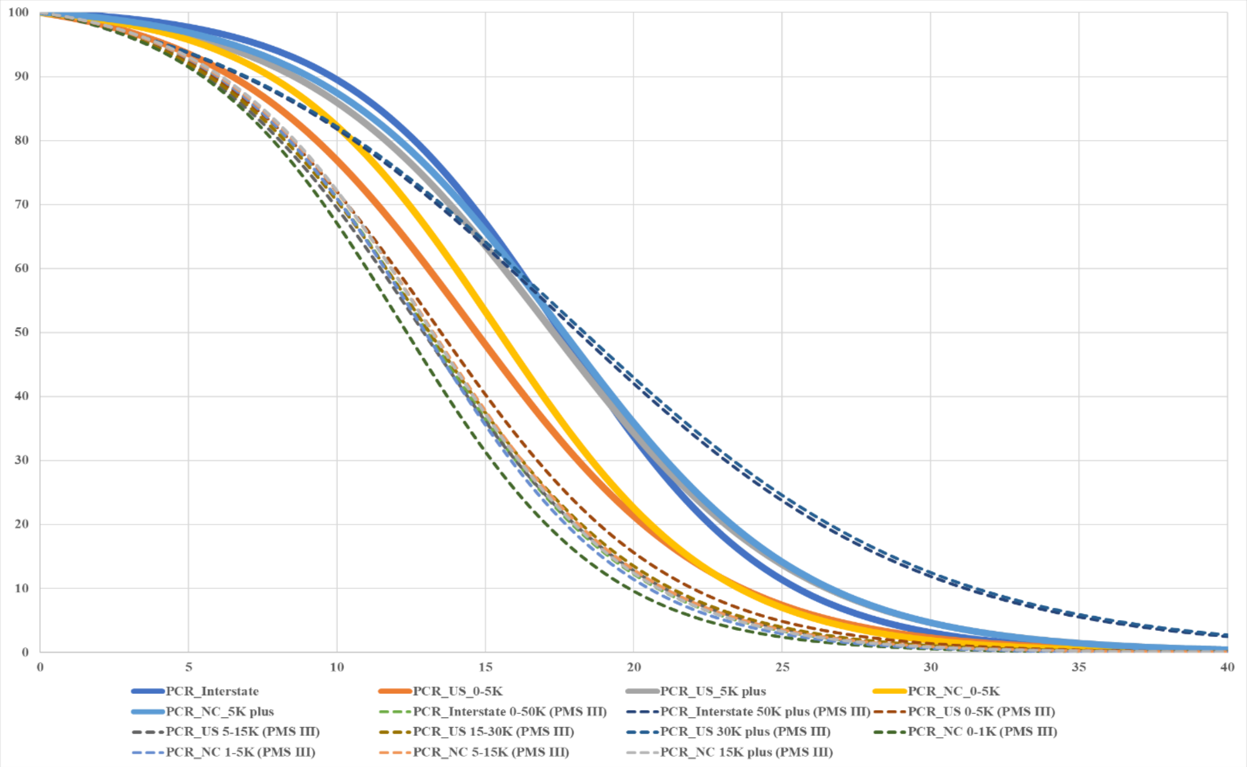


Figure 20: Comparison of PCR Curves

3.5 Identification of Triggering Distresses and Corresponding Treatments

3.5.1 Triggering Distresses

Coefficients of variables, or weights, in equations 2 and 3 were used to identify triggering distresses that can trigger the first treatment after a roadway section was converted into a composite pavement section.

From equation 2 for NDR, most likely Transverse cracking and Longitudinal cracking are the trigger distresses because of their heavy weights, 51.5% and 27.3%, respectively. Together these two distresses contribute to 78.8% of NDR, meaning that these two distresses have the most chance of causing maintenance to be triggered. Since Longitudinal cracking does not have prescribed maintenance in the NCDOT's PMS, Transverse cracking was the only NDR triggering distress.

From equation 3 for LDR, most likely Alligator cracking and Rutting are the trigger distresses because of their heavy weights, 53.2% and 22.8%, respectively. Together these two distresses contribute to 76.0% of LDR, meaning that these two distresses have the most chance of causing maintenance to be triggered. The only LDR distress that might trigger any maintenance was Alligator cracking. The reason was that Rutting is not a common distress in pavements in North Carolina.

3.5.2 Data Preparation

Pavement Condition Rating (PCR) is a composite performance index that represents how a section of roadway is performing as a whole that incorporates all different types of distresses, and it has been used by the NCDOT to trigger different types of treatments. In this study, a PCR value of 60 was used as the treatment threshold value. This means that when a roadway section's PCR value drops to 60, a treatment is needed.

Equations 2, 3, and 4 below indicate that when either the non-load related (NDR) distress index value or the load related (LDR) distress index value, whichever is smaller, is less than 60, a treatment will be triggered because PCR falls below the treatment threshold value of 60. This situation can occur only when at least one of the variables in equations 2 and 3, e.g., TRA, LNG, or LNG_JNT in equation 2, is less than 60.

$$NDR = 0.5152640 * TRA + 0.2729290 * LNG + 0.2118080 * LNG\_JNT \tag{2}$$

$$LDR = 0.5316370 * ALGTR + 0.1520450 * WP + 0.0887566 * NWP + 0.2275610 * RUT \tag{3}$$

$$PCR = \min(LDR, NDR)$$

Individual roadway sections that meet the abovementioned condition, i.e., at least one of the variables less than 60, were extracted from the composite pavement data. These sections were further analyzed to identify trigger stresses and corresponding treatments. In this study, the maintenance decision tree for flexible pavements was used to find corresponding treatment, due to the lack of a composite pavement decision tree in the NCDOT's PMS.
Table 7 below shows an example of a roadway section that would have been removed (Section A) and one that would have remained (Section B). The values in Section B would be retained and analyzed because with one distress index value less than 60 there is a possibility for the PCR to be less than 60 as well. This can trigger a corresponding treatment.

Table 7: Data Preparation Example

Roadway Section	TRA	ALGTR	LNG	LNG_JNT	WP	NWP	RUT
A	92	87	66	100	93	75	61
B	83	43	63	100	100	100	99.51

3.5.3 Recommended Treatments Based on the Triggering Distresses

The data set obtained from the previous section 3.5.2 was analyzed to identify treatments triggered by the triggering distresses. These historic treatments are then recommended to NCDOT for future maintenance. Tables 8 through 21 show the information of treatments and their triggering distresses for the Interstate, US 0-5K, US 5K plus, NC 0-5K, and NC 5K plus family. It should be noted that treatments in these tables are the ones prescribed by the decision trees in the NCDOT PMS. The actual treatments obtained from the construction data were not used due to wide discrepancies between actual treatments and prescribed treatments. It was decided to use prescribed treatments in this study because researchers assume that the decision trees are correct and thus should be used as the guideline for selecting appropriate treatments. It should also be noted that these treatments have been applied to asphalt pavements, not specifically to composite pavements. The reason is that in current NCDOT PMS, all treatments are developed for asphalt pavements only.

3.5.3.1 Results for the Interstate Family

Table 8: Summary of Treatments for Interstate

Cause of Treatment	Triggering Distress	Occurrence	% of Occurrence
LDR	Alligator cracking	639	79%
NDR	Transverse cracking	165	21%
	Total	804	100%

Table 9: Treatments Triggered by Alligator Cracking for Interstate

Treatment	Occurrences	% of Occurrence
Interstate -Patching	16	11.8%
Interstate - 1.5 in. Overlay (D Level)	11	8.1%
Interstate Full Depth Patching/1.5 in. Overlay (D Level)	13	9.6%
Interstate - Mill 2.5 in. & Replace/1.5 in. Overlay (D Level)	2	1.5%
Interstate - Mill 2.5 in. & Replace/3.0 in. Overlay (D Level)	14	10.3%
AC Reconstruction - AADT >15000	80	58.8%
Total	136	100%

Table 10: Treatments Triggered by Transverse Cracking for Interstate

Treatment	Occurrences	% of Occurrence
Interstate - Rout & Seal Cracks /1.5 in. Overlay (D Level)	131	91.6%
Interstate - Mill 2.5 in. & Replace / 1.5 in. Overlay (D Level)	12	8.4%
Total	143	100%

3.5.3.2 Results for the US 0-5K Family

Table 11: Summary of Treatments for US 0-5K

Cause of Treatment	Triggering Distress	Occurrence	% of Occurrence
LDR	Alligator cracking	38	43%
NDR	Transverse cracking	50	57%
	Total	88	100%

Table 12: Treatments Triggered by Alligator Cracking for US 0-5K

Treatment	**Occurrences**	**% of Occurrence**
Patching	0	0.0%
1.5 in. Overlay (C Level)	0	0.0%
Full Depth Patching / 1.5 in. Overlay (C Level)	0	0.0%
Mill 1.5 in. & Replace / 1.5 in Overlay (C Level)	0	0.0%
Mill 2.5 in. & Replace / 3.0 in. Overlay (C Level)	2	9.1%
AC Reconstruction - 5,000<= AADT < 15,000	20	90.9%
Total	22	100%

Table 13: Treatments Triggered by Transverse Cracking for US 0-5K

Treatment	**Occurrences**	**% of Occurrence**
Interstate - Rout & Seal Cracks /1.5 in. Overlay (D Level)	14	36.8%
Interstate - Mill 2.5 in. & Replace / 1.5 in. Overlay (D Level)	24	63.2%
Total	38	100%

3.5.3.3 Results for the US 5K plus Family

Table 14: Summary of Treatments for US 5K plus

Cause of Treatment	Triggering Distress	Occurrence	% of Occurrence
LDR	Alligator cracking	137	54%
NDR	Transverse cracking	117	46%
	Total	254	100%

Table 15: Treatments Triggered by Alligator Cracking for US 5K plus

Treatment	Occurrences	% of Occurrence
Patching	0	0.0%
1.5 in. Overlay (C Level)	0	0.0%
Full Depth Patching / 1.5 in. Overlay (C Level)	0	0.0%
Mill 1.5 in. & Replace / 1.5 in Overlay (C Level)	1	1.0%
Mill 2.5 in. & Replace / 3.0 in. Overlay (C Level)	4	4.1%
AC Reconstruction - 5,000<= AADT < 15,000	92	94.8%
Total	97	100%

Table 16: Treatments Triggered by Transverse Cracking for US 5K plus

Treatment	Occurrences	% of Occurrence
Rout & Seal Cracks	54	52.9%
Rout & Seal Cracks / 1.5 in Overlay (B Level)	48	47.1%
Total	102	100%

3.5.3.3 Results for the NC 0-5K Family

Table 17: Summary of Treatments for NC 0-5K

Cause of Treatment	Triggering Distress	Occurrence	% of Occurrence
LDR	Alligator cracking	12	67%
NDR	Transverse cracking	6	33%
	Total	18	100%

Table 18: Treatments Triggered by Alligator Cracking for NC 0-5K

Treatment	**Occurrences**	**% of Occurrence**
Patching	0	0.0%
1.5 in. Overlay (C Level)	0	0.0%
Full Depth Patching / 1.5 in. Overlay (C Level)	0	0.0%
Mill 1.5 in. & Replace / 1.5 in Overlay (C Level)	0	0.0%
Mill 2.5 in. & Replace / 3.0 in. Overlay (C Level)	0	0.0%
AC Reconstruction - 5,000<= AADT < 15,000	11	100.0%
Total	11	100%

Table 19: Treatments Triggered by Transverse Cracking for NC 0-5K

Treatment	**Occurrences**	**% of Occurrence**
Rout & Seal Cracks	5	83.3%
Rout & Seal Cracks / 1.5 in Overlay (B Level)	1	16.7%
Total	6	100%

3.5.3.4 Results for the NC 5K plus Family

Table 20: Summary of Treatments for NC 5K plus

Cause of Treatment	**Triggering Distress**	**Occurrence**	**% of Occurrence**
LDR	Alligator cracking	0	0%
NDR	Transverse cracking	6	100%
	Total	6	100%

Table 21: Treatments Triggered by Transverse Cracking for NC 5K plus

Treatment	**Occurrences**	**% of Occurrence**
Rout & Seal Cracks	3	100.0%
Rout & Seal Cracks / 1.5 in Overlay (B Level)	0	0.0%
Total	6	100%

Results of all composite pavement families were summarized and included in Figures 21 through 23.

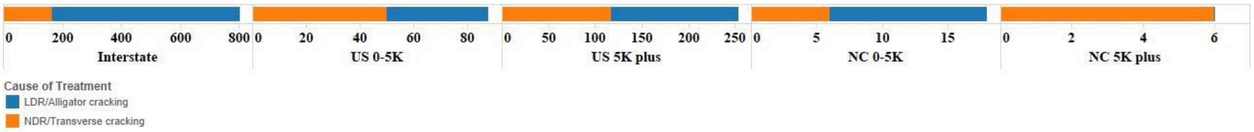


Figure 21: Summary of Treatments

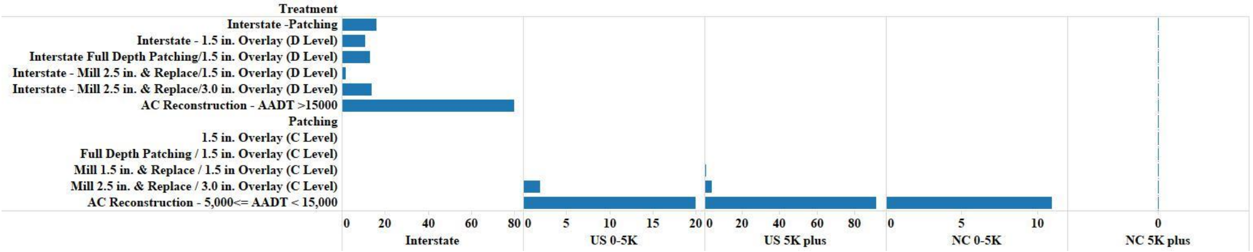


Figure 22: Summary of Treatments Triggered by Alligator Cracking

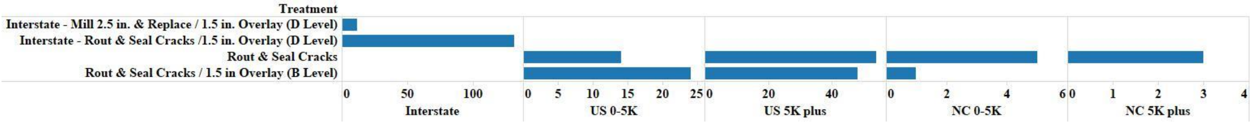


Figure 23: Summary of Treatments Triggered by Transverse Cracking

Figure 21 indicates that Alligator cracking (LDR), represented by the blue bars, is more likely to trigger treatments than Longitudinal cracking (NDR), represented by the orange bars. Among treatments triggered by Alligator cracking, “AC Reconstruction” were the most often used treatments for Interstate, US and NC 0-5K families, assuming the roadways are asphalt (Figure 22). Among treatments triggered by Transverse cracking, “Rout & Seal Cracks” at different levels was the most often used treatment for all families (Figure 23).

CHAPTER 4 FINDINGS AND CONCLUSIONS

This study was conducted to develop a maintenance system for composite pavements in North Carolina. To this end, composite pavement sections were extracted from a merged data set, their distress and performance models were developed, the distresses that triggered the first treatment after a pavement section was converted into a composite section were identified, and the corresponding treatments were recommended. All these findings are summarized below which can be used to include composite pavements as an important component into the NCDOT PMS.

- A total of 5,125 composite pavement sections were identified in this study. Among these sections, 1,161 sections (23%) were from the Interstate family, 2,772 sections (54%) were from the US family, and 1,192 sections (23%) were from the NC family. The Secondary Route (SR) family was not studied because the automated data provided by NCDOT does not include SR sections.
- The first 12 years of pavement data was used to develop distress and performance models. Pavement data after the first 12 years was excluded from this study because pavement age cannot be reset using only three years of data (2013, 2014, and 2015).
- In North Carolina, Transverse cracking, Longitudinal cracking, and Alligator cracking are the main dominate distresses developed in composite pavements; while Longitudinal Lane Joint, Patching - Non Wheel Path, Patching - Wheel Path, and Rutting are not common distresses.
- For Transverse cracking, composite pavements have performed similarly to asphalt pavements. For longitudinal cracking, except for asphalt pavement families US 30K plus, NC 1-5K, NC 5-15K, and NC 15K plus which performed better, both types of pavements performed similarly. For alligator cracking, composite pavements out-performed asphalt pavements.
- Except for asphalt pavement families Interstate 50K plus and US 30K plus, overall, composite pavements out-performed asphalt pavements. This better performance is probably due to the strong stiff base in composite pavements that can better support heavy wheel loads and provide a driving surface that has less cracks.
- In North Carolina, The triggering distresses for composite pavements are Longitudinal cracking (NDR) and Alligator cracking (LDR). Alligator cracking is more likely to trigger treatments than Longitudinal cracking.
- Among treatments triggered by Alligator cracking, “AC Reconstruction” were the most often used treatments for Interstate, US and NC 0-5K families. Among treatments triggered by Transverse cracking, “Rout & Seal Cracks” at different levels was the most often used treatment for all families. Therefore, “AC Reconstruction” and “Rout & Seal Cracks” are the recommended treatments to fix Alligator cracking and Transverse cracking in asphalt pavements, respectively.

CHAPTER 5 RECOMMENDATIONS

Based on the observations during this study and the final findings, several recommendations are provided for further avenues of research. They are:

- It is recommended to update the NCDOT PMS so that it incorporates a section for composite pavements. The triggering distresses and treatments in this study were determined using the flexible pavement section of the PMS. Triggering distresses that were determined using only composite pavements would be more specific and have a better representation of the types of distresses that composite pavements experience.
- It is recommended to validate the developed composite pavement models using newly collected automated data. If the models are robust and they perform differently than asphalt models, a new decision tree for composite pavements is justified and suggested to be added to the NCDOT PMS.
- In this study, only the first 12 years of performance data was used to develop distress and performance models. Performance data after the first 12 years, even though contains valuable performance information, was not used because of the short data history. After more performance data is collected, it is recommended to reset pavement age and develop these models again for increased model accuracy.

CHAPTER 6 IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

The outcomes of this study will be disseminated through the following venues:

- Providing project deliverables. Project deliverables, in both hard copy and digital format, will be provided to NCDOT.
- Generating research publications. Research findings will be published in peer reviewed journals, such as Transportation Research Record (TRR) and ASCE journals.
- Presenting at national/international professional conferences, for example, TRB annual conference and ASCE conferences.
- Transferring the technology to NCDOT. Short course or demonstrations can be provided to NCDOT personnel regarding approaches of developing models, identifying trigger distresses, and recommending appropriate treatments for composite pavements.
- Integrating research findings into engineering courses at UNC Charlotte. In the past several years, the PI has integrated the methodologies and findings of previous NCDOT studies into a senior level undergraduate course entitled “Highway Design and Construction”. This integration resulted in increased interest in working in the transportation industry, and increased participation in transportation related research among undergraduate students. The PI will continue this holistic approach in this study.

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Appendix A – Distress Curves

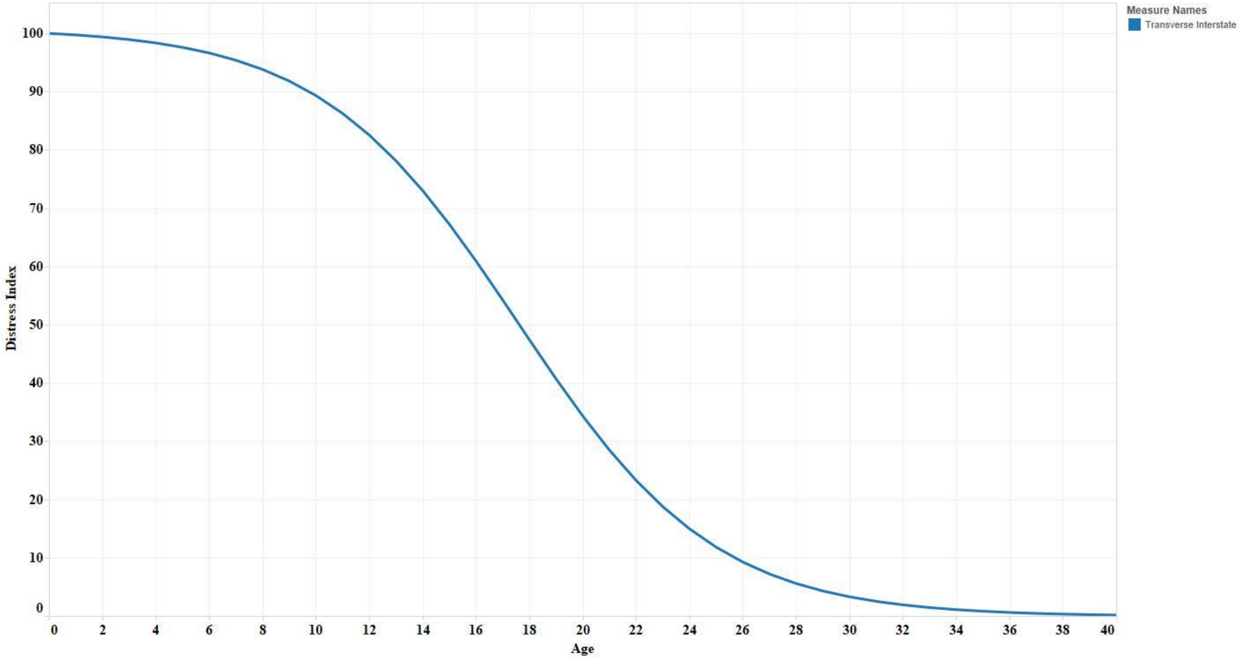

Figure 24: Transverse Cracking_Interstate

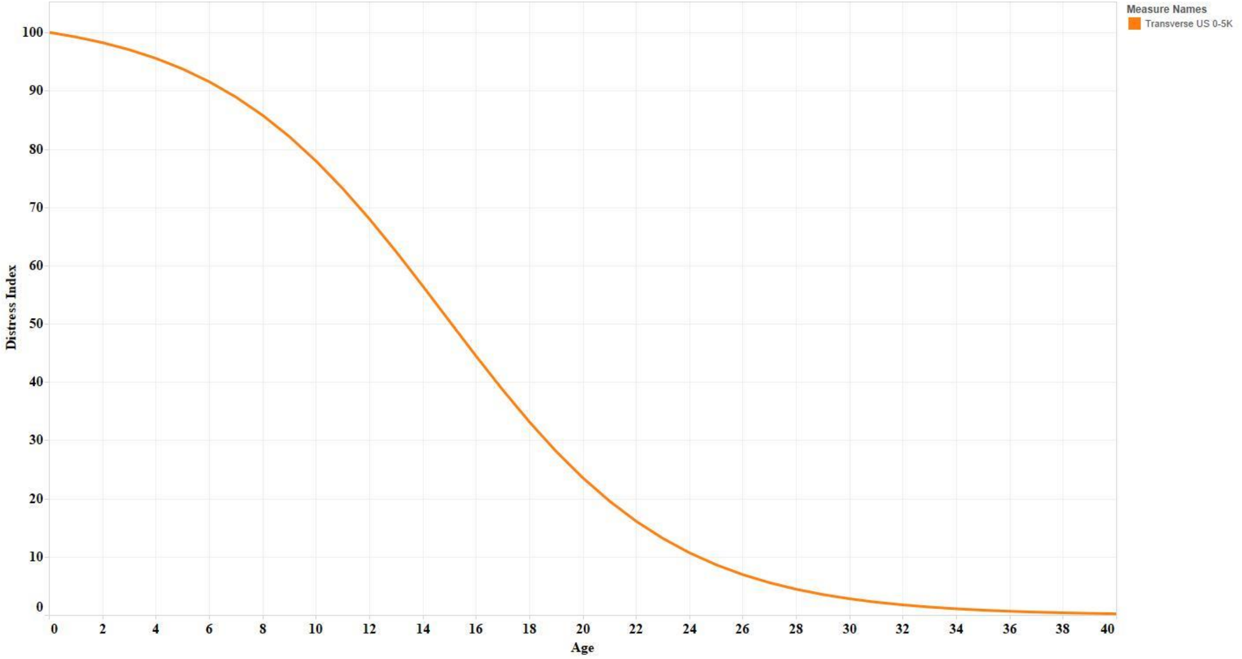

Figure 25: Transverse Cracking_US 0-5K

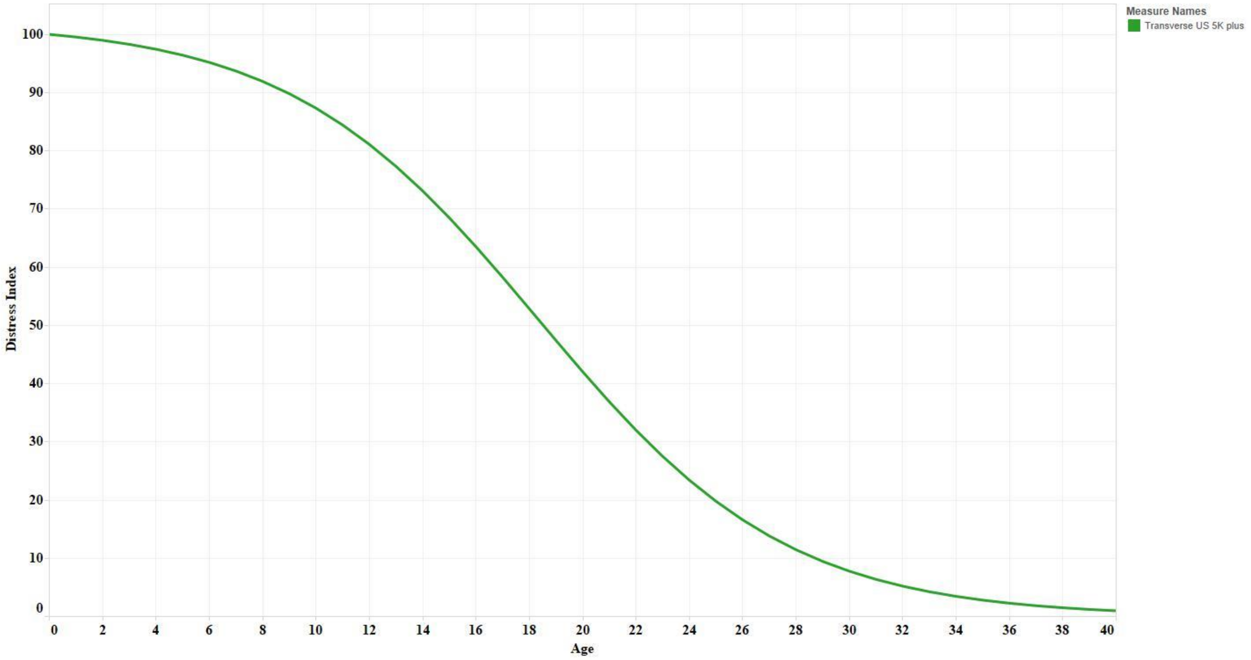

Figure 26: Transverse Cracking_US 5K plus

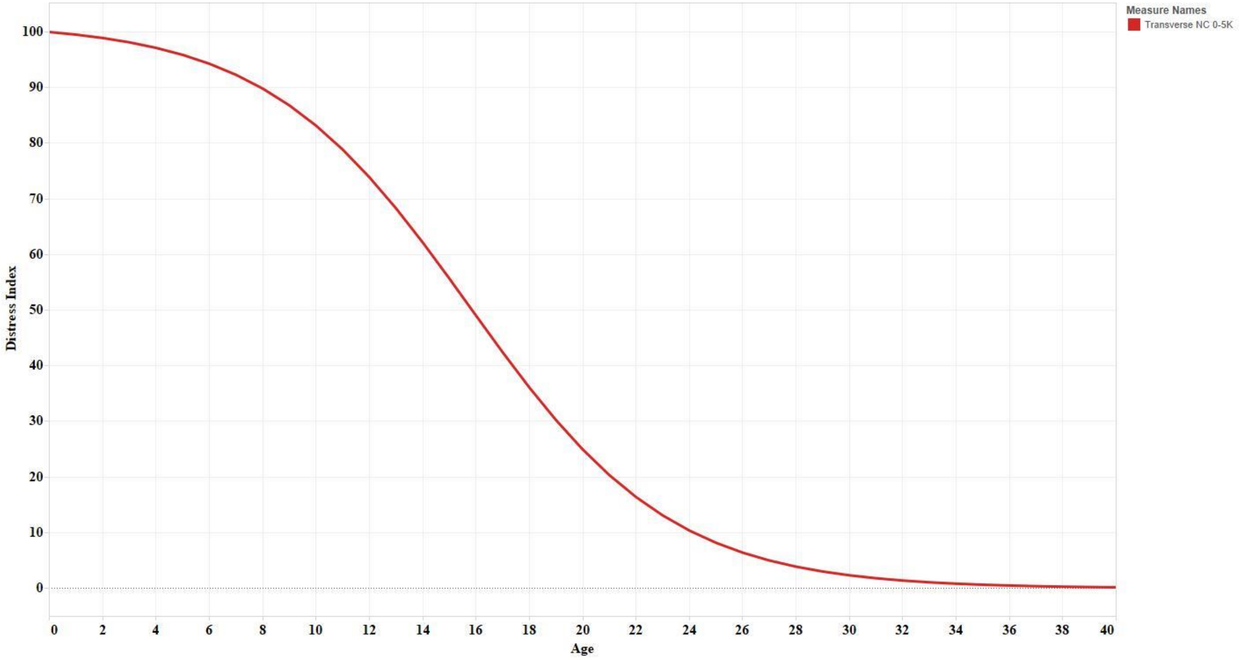

Figure 27: Transverse Cracking_NC 0-5K

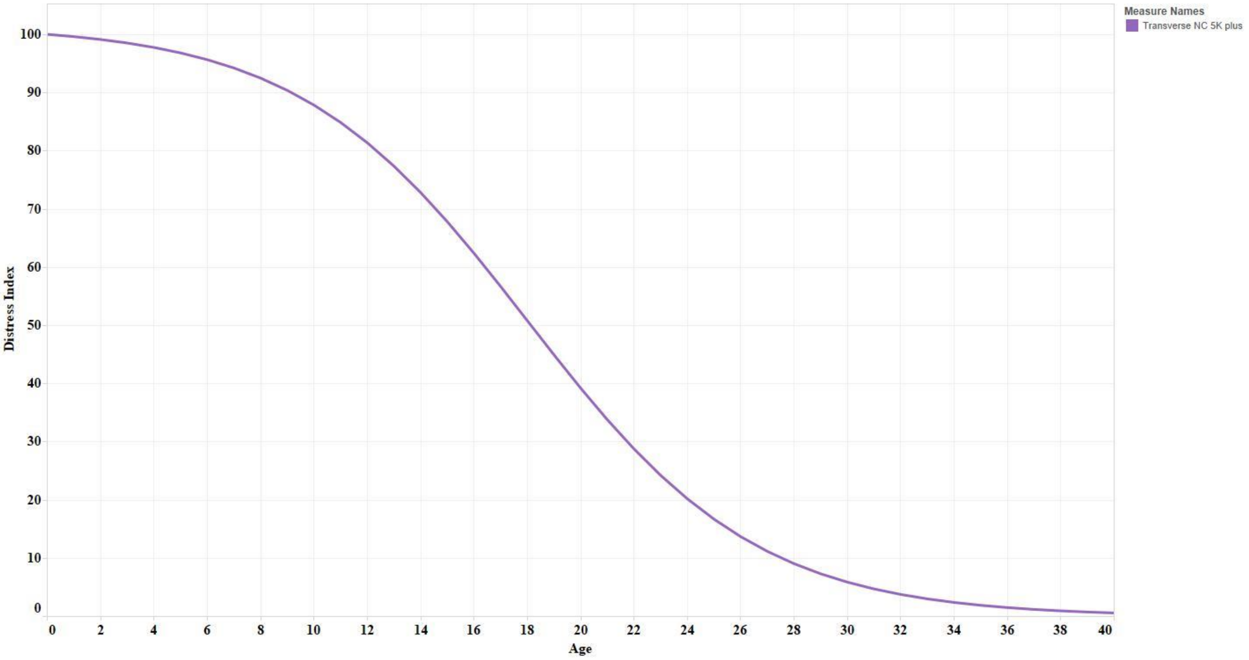

Figure 28: Transverse Cracking_NC 5K plus

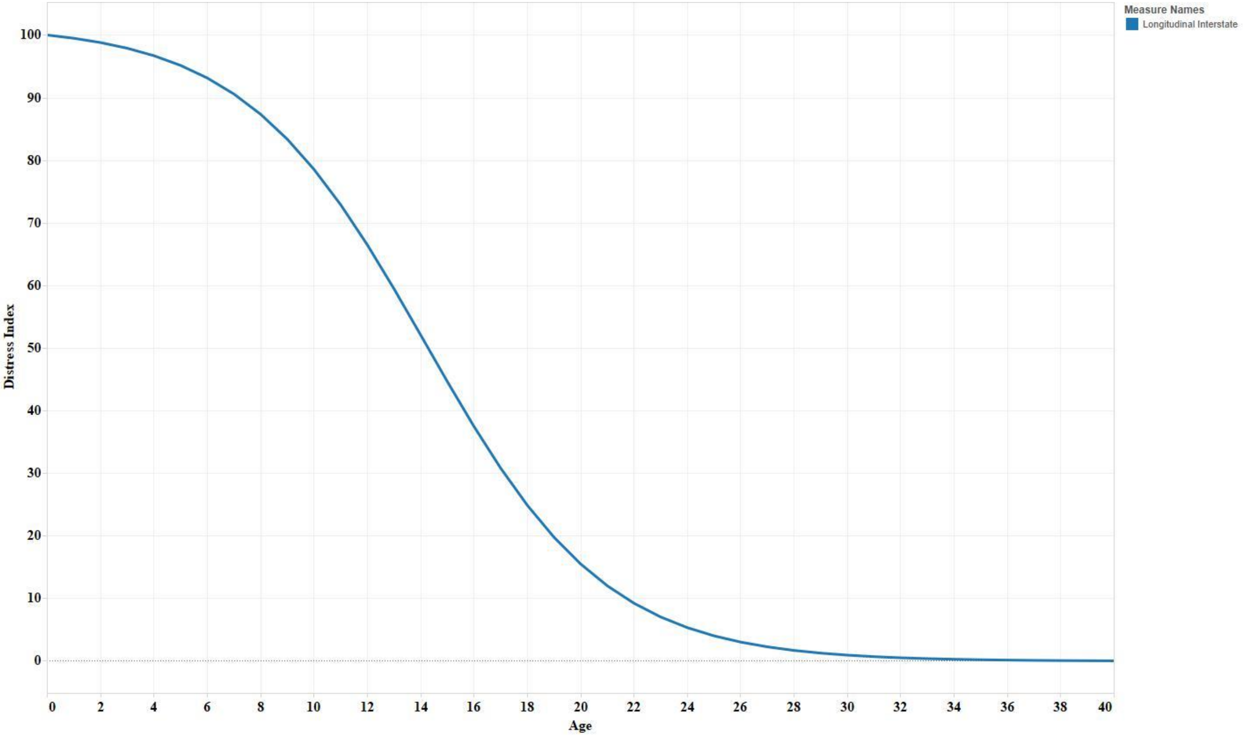

Figure 29: Longitudinal Cracking_Interstate

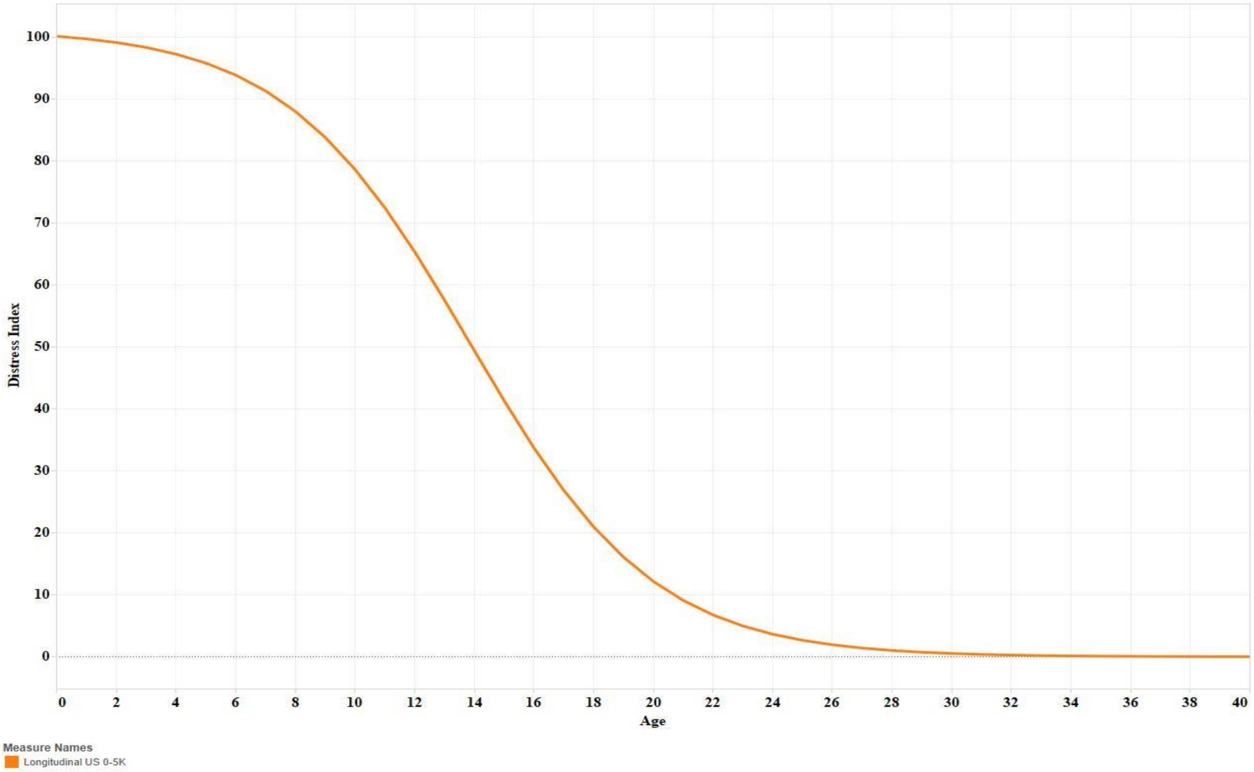

Figure 30: Longitudinal Cracking_US 0-5K

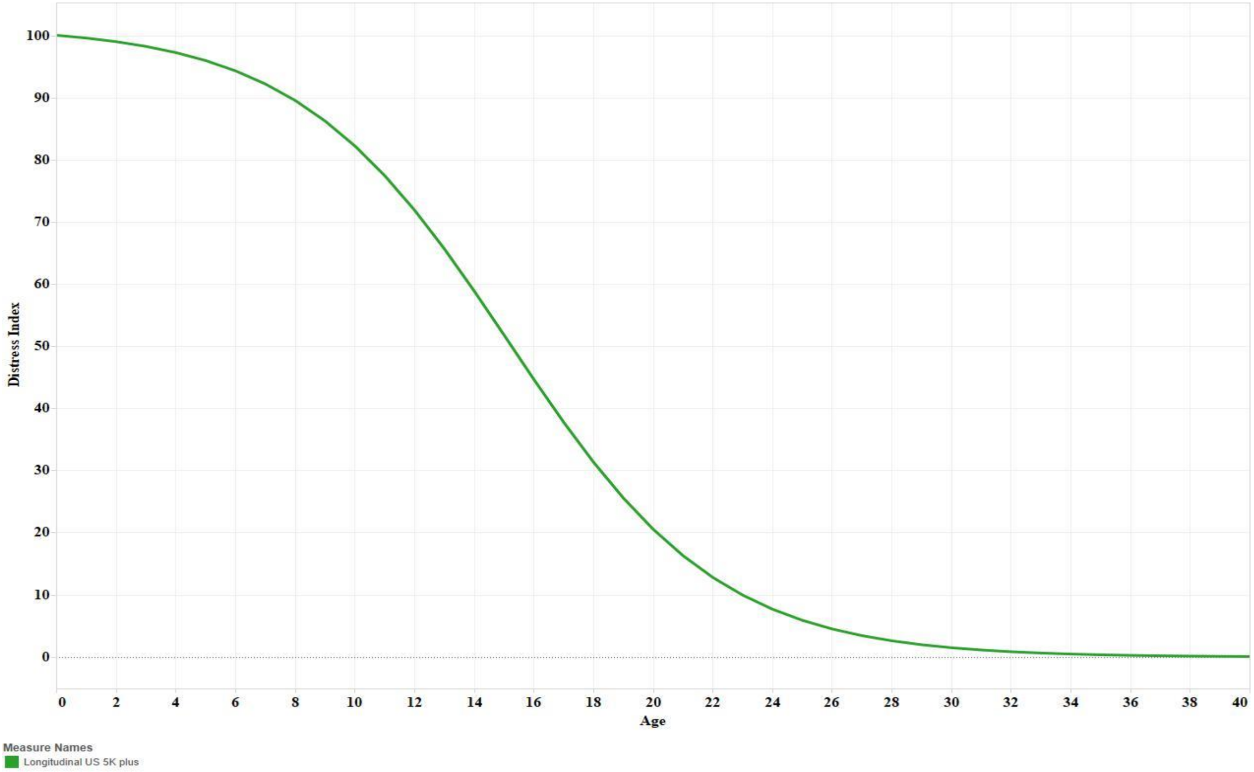

Figure 31: Longitudinal Cracking_US 5K plus

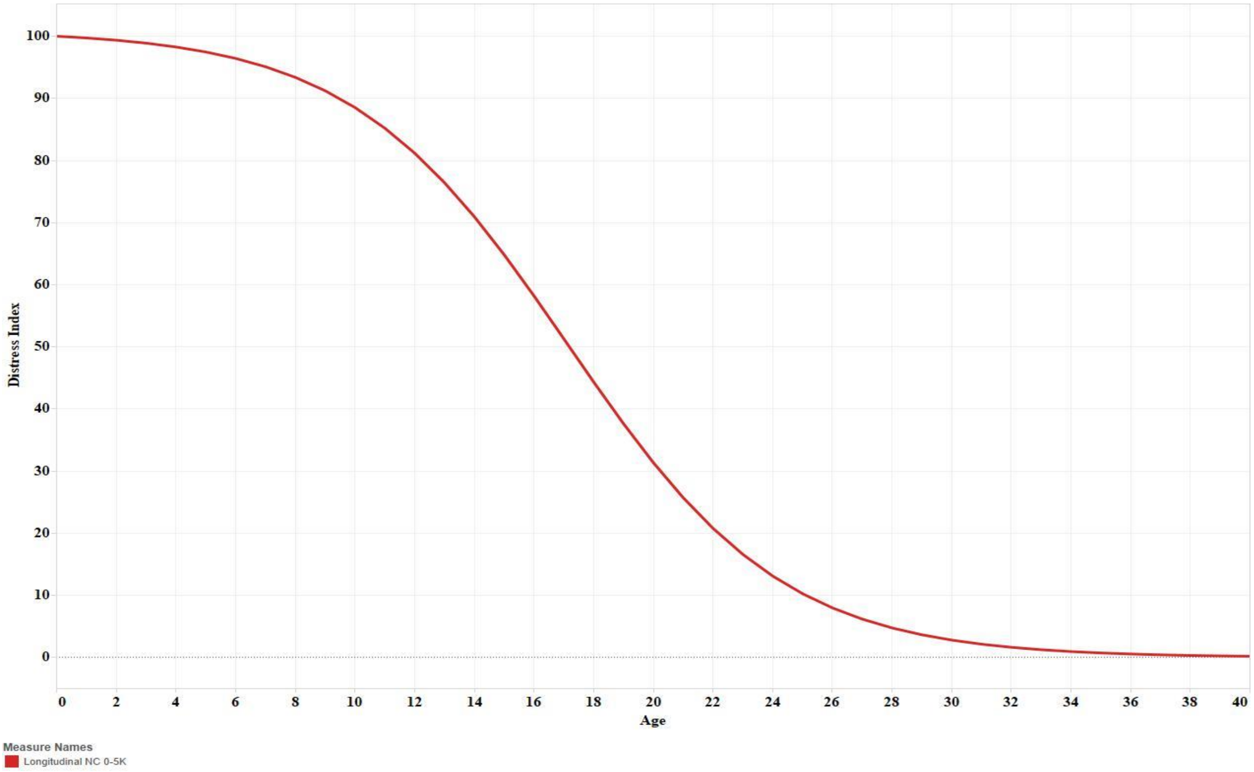

Figure 32: Longitudinal Cracking_NC 0-5K

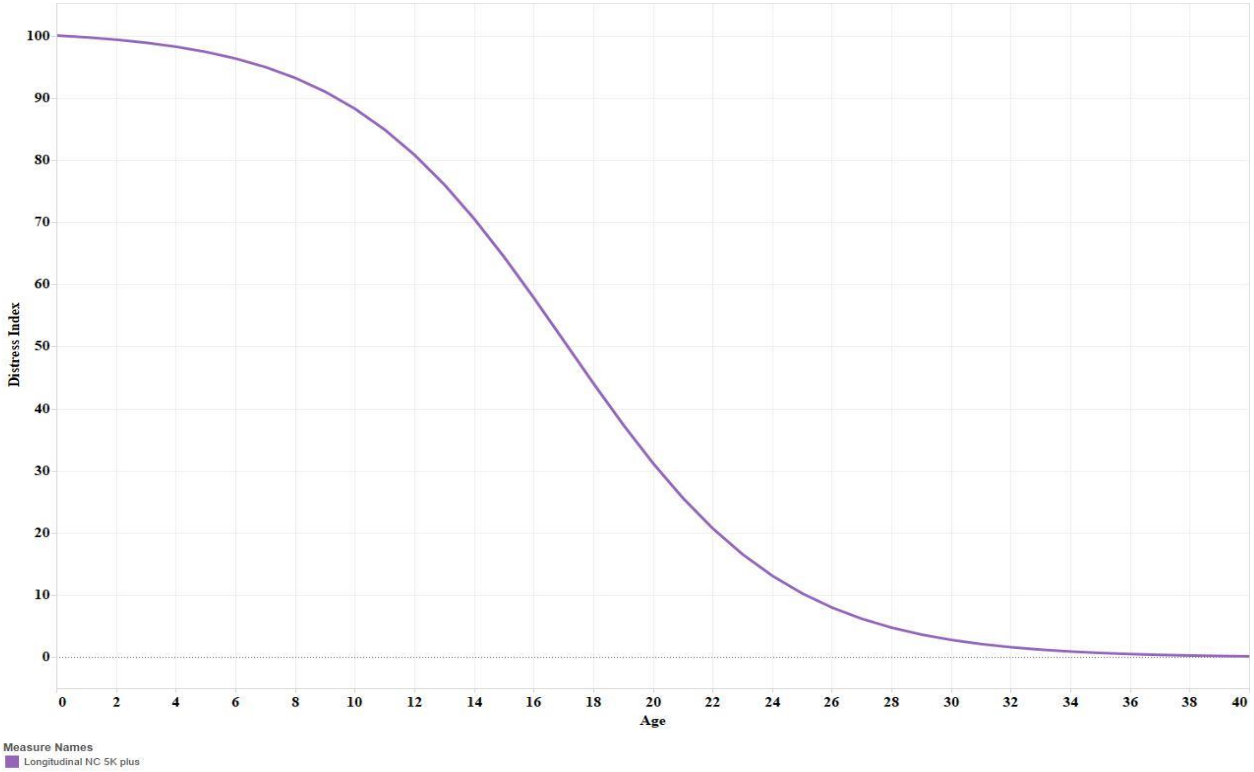

Figure 33: Longitudinal Cracking_NC 5K plus

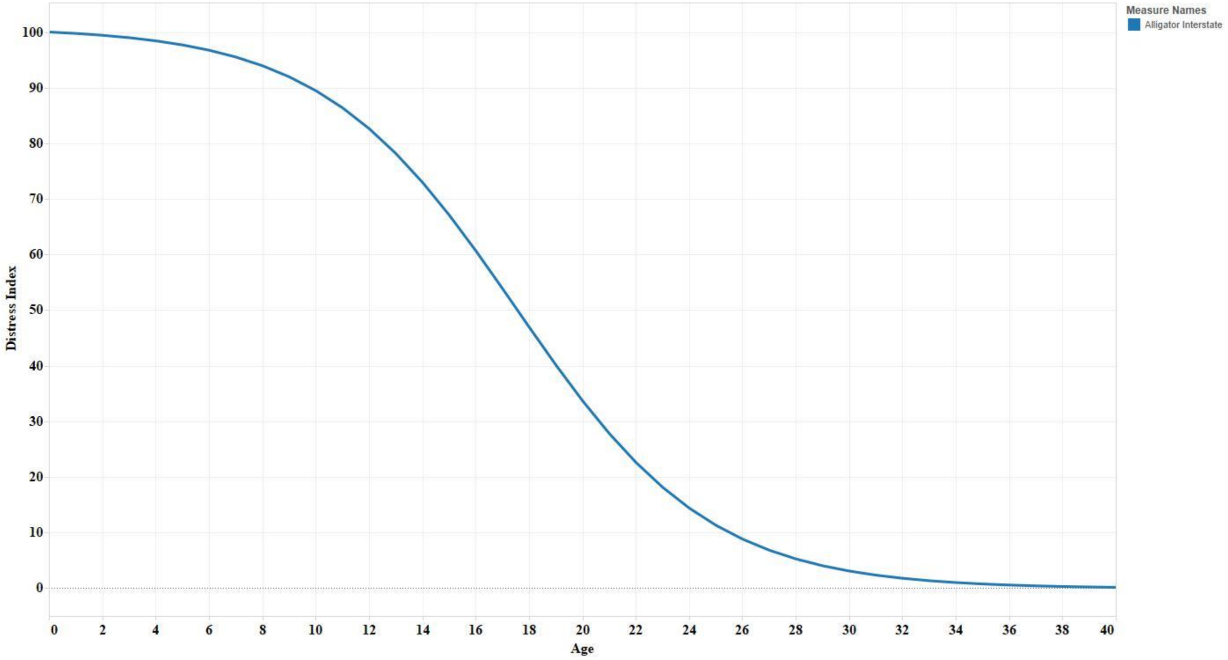

Figure 34: Alligator Cracking_Interstate

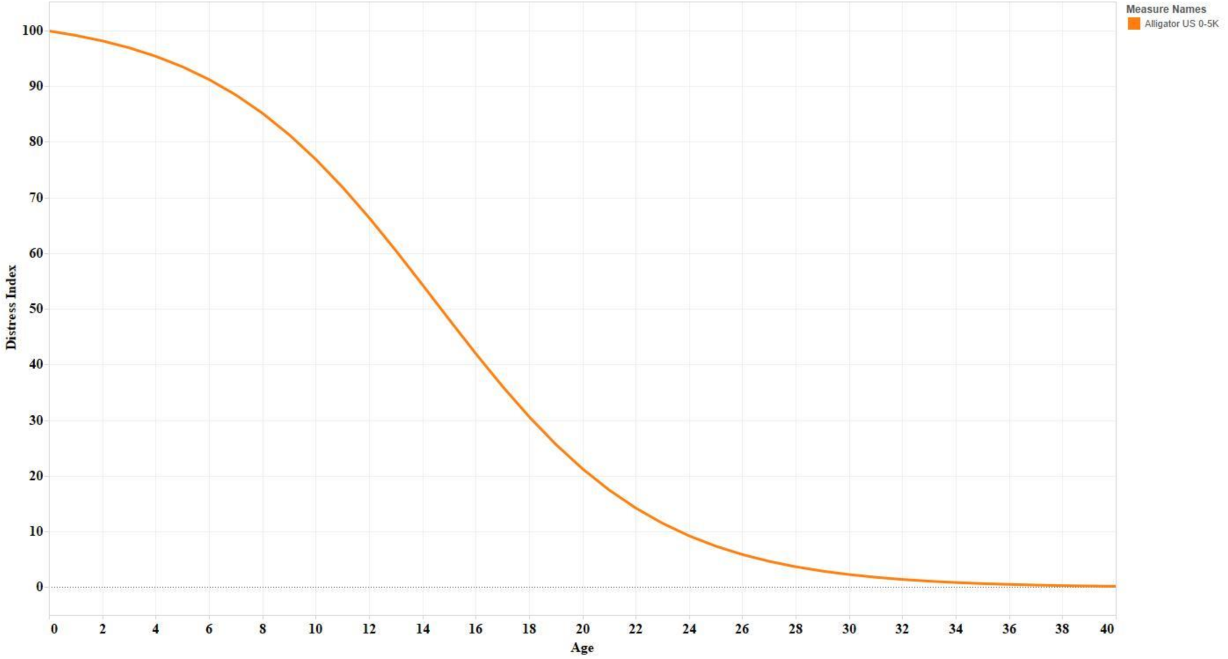

Figure 35: Alligator Cracking_US 0-5K

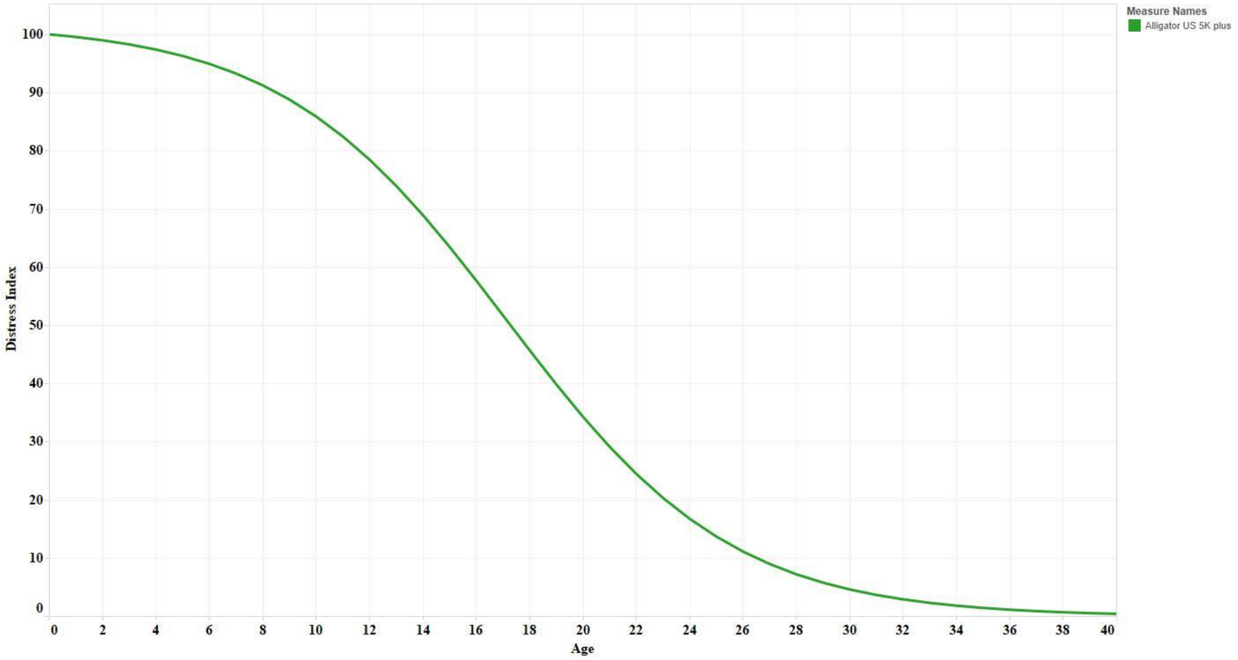

Figure 36: Alligator Cracking_US 5K plus

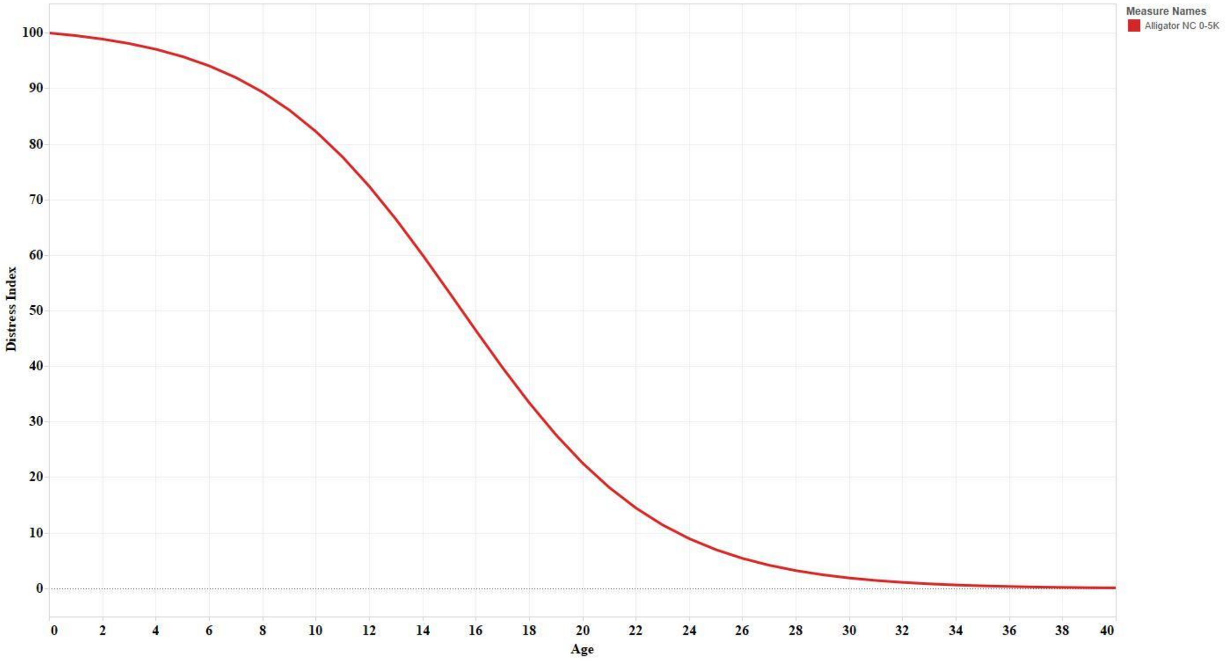

Figure 37: Alligator Cracking_NC 0-5K

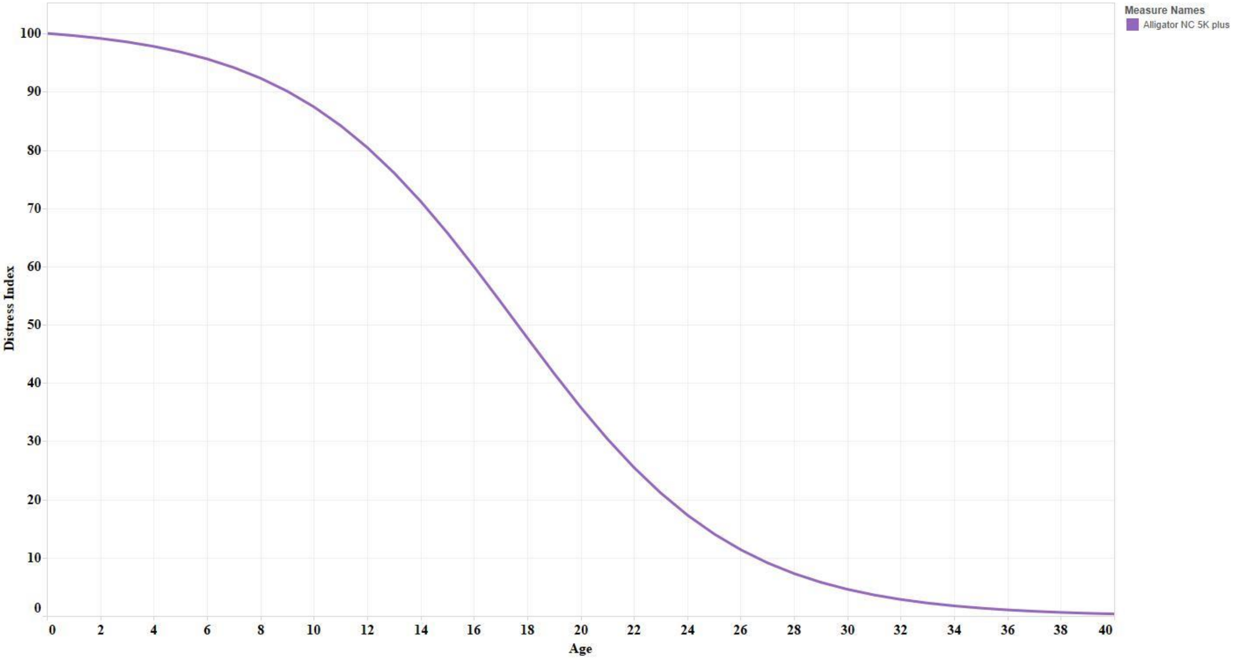

Figure 38: Alligator Cracking_NC 5K plus

Appendix B – Performance Curves

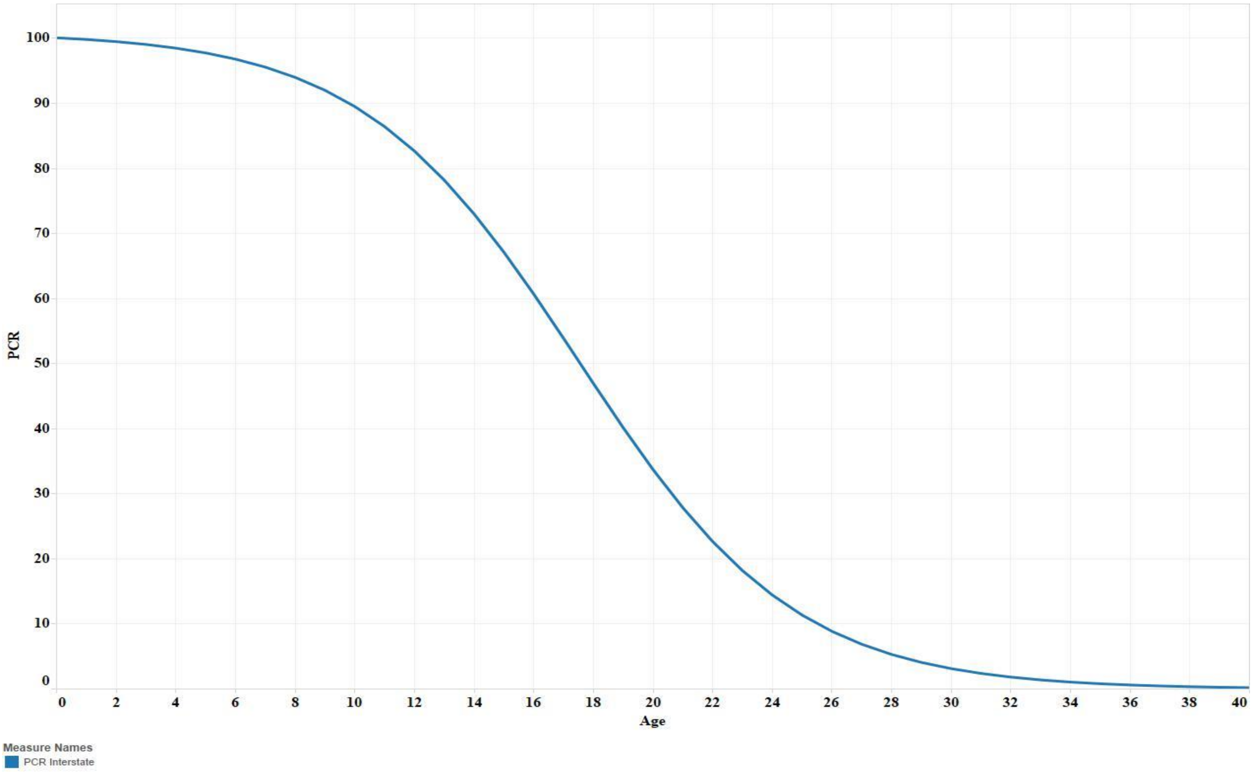

Figure 39: PCR Curve_Interstate

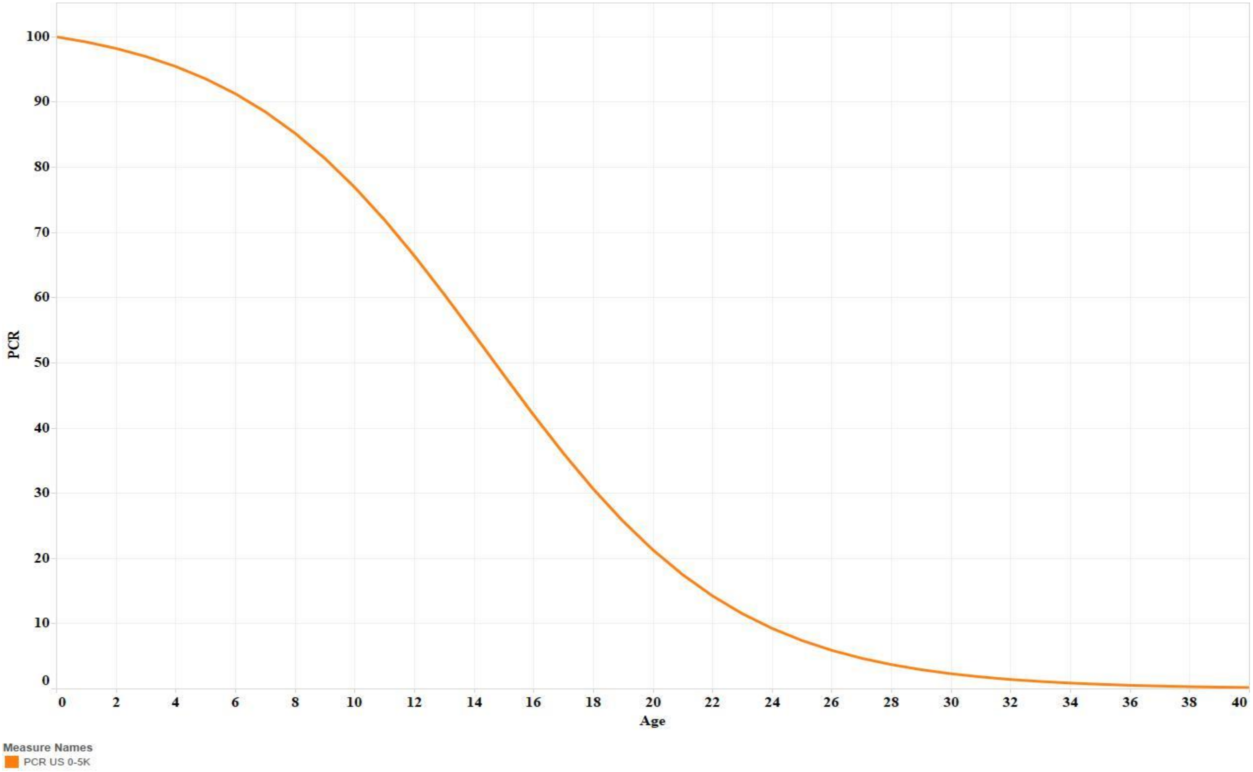

Figure 40: PCR Curve_US 0-5K

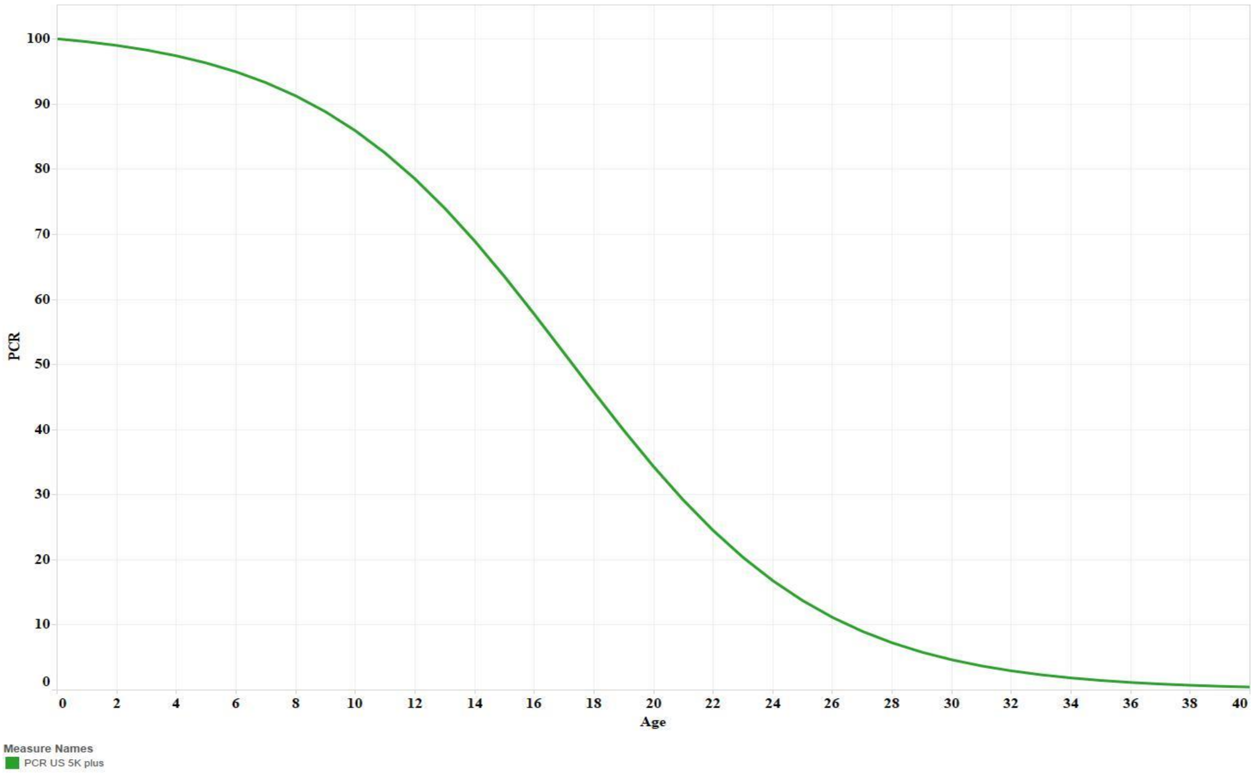

Figure 41: PCR Curve_US 5K plus

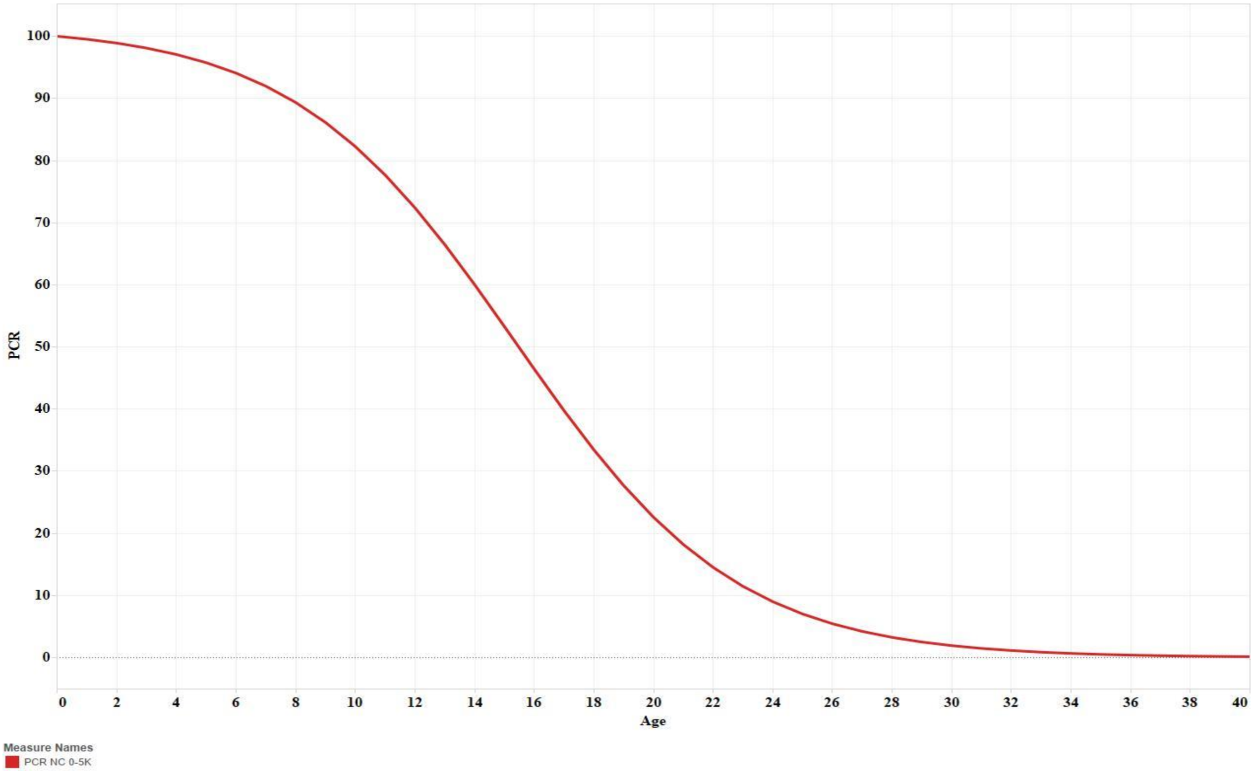

Figure 42: PCR Curve_NC 0-5K

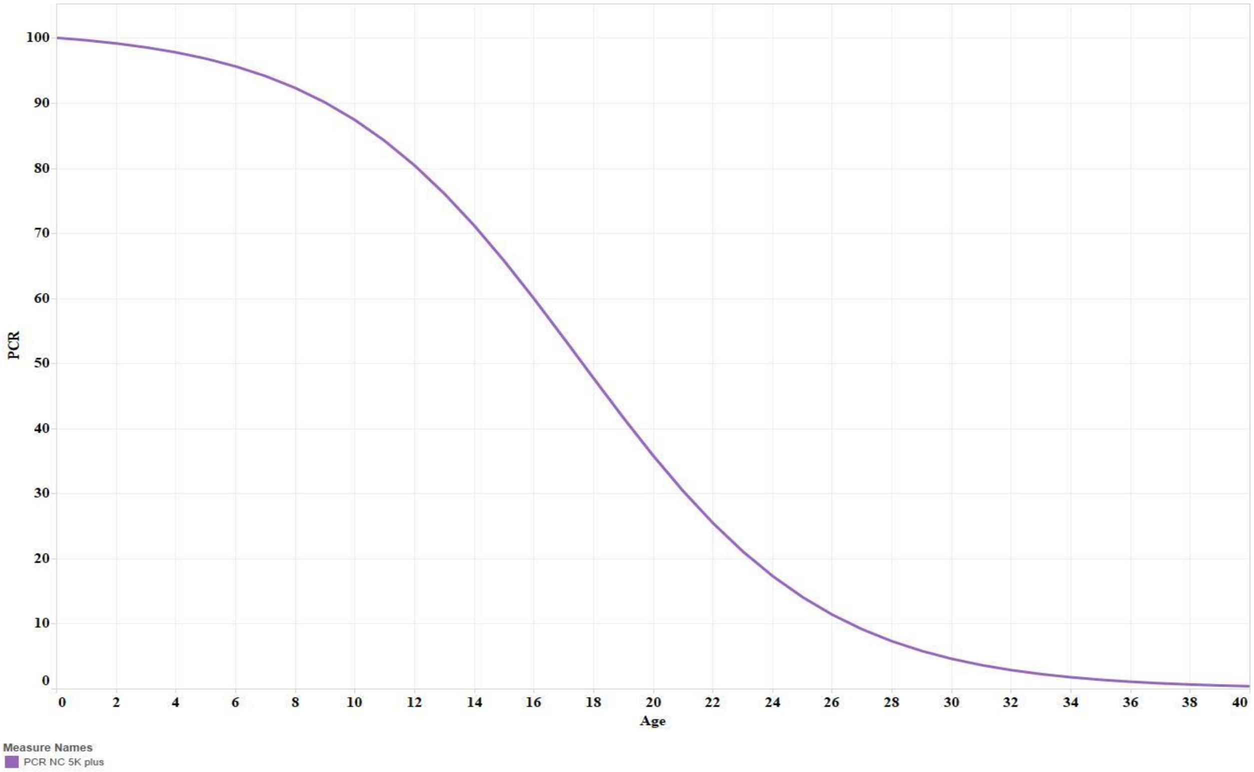

Figure 43: PCR Curve_NC 5K plus